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Abstract
Measurements of completed projects confirm significant gaps between the predicted and actual energy performance of buildings. This is due to: actual occupant behaviour; weather conditions; workmanship/installation errors; systems' control settings and modelling issues. Recent developments in automated meter reading (AMR) and monitoring and targeting (M&T) make the performance gap visible to owners/operators. Bridging the gap becomes even more important if the industry intends to 'occupant/climate change proof' buildings. This paper reviews energy performance gap literature, the findings of a workshop on the subject, and presents ongoing work in this area. It concludes that the energy performance gap can only be bridged through better definition and joint efforts across all actors involved in the design, construction and operation of buildings/building (sub) systems.

Keywords energy performance prediction, energy use measurement, performance gap

1. Introduction

With energy efficiency targets becoming more stringent and energy prices going up, there is a growing interest in the building sector in the discrepancy between predicted and measured energy use. It appears that this difference, between building energy use as predicted at the building design stage and measured energy use once a building is operational, is quite significant, in the order of a factor 1.5 to 2. For evidence, see for instance the CarbonBuzz website (www.carbonbuzz.org) or Turner and Frankel [1] . This difference between predicted and measured energy performance is now commonly called the 'energy performance gap'. Various reports and scientific papers have been published on the issue; see for instance Zero Carbon Hub [2], Carbon Trust [3] and Menezes *et al* [4]. . While this might be interesting for those operating in building science, this energy performance gap is a serious problem for the industry: it underlines an issue with products of this industry not meeting quantified ambitions, which is detrimental to customer confidence and does not help the credibility of the building design and engineering disciplines. Moreover, if a performance gap already exists for buildings that are designed to function within today's occupancy schedules and climate conditions, the industry is even less well-placed to develop buildings that are resilient and robust toward further changes in use and climate conditions. Without bridging the performance gap the industry cannot expect to move forward towards new business models such as performance contracting, where a client pays for a specified indoor climate rather than for hardware (building and subsystems) with unspecified operation conditions.

This paper addresses the energy performance gap through four main sections. The first of these provides an overview of recent work on the energy performance gap, discussing the literature on the subject. The second briefly presents a case study conducted by the first author, investigating a probabilistic approach to the performance gap. The third section reports on the findings of a workshop with experts on the subject. The fourth and final section presents work that is currently ongoing.

2. Review of present understanding of the energy performance gap

A review of literature on the energy performance gap indicates that there is a whole range of contributing factors which span the building life cycle from project inception to building operation.

During the design stage, miscommunication between the client and design team (or between different actors within the team) about the future performance of the building can be a root cause for the later performance gap issues [5]. The design itself might constitute an initial issue, incorporating inefficient systems, wrong or missing construction details, or lack simplicity and buildability. During design, a significant contributing factor is that it is hard to predict the future occupancy and use of the building and the control regimes that will be applied to key services [4]. The drive towards energy efficient buildings also leads to a tendency to include Energy Saving Technologies (EST) in many buildings; often these have teething problems leading to a performance gap once the building is operational [6]). In many cases EST do not meet the manufacturer’s performance specifications and are subject to degradation over time.

Predictions made in the design stage fundamentally rely on analysts making sound use of models, calculations and software tools to quantify future energy use. Obviously this requires the use of appropriate tools and models and adequate training of the analyst. However, any prediction inherently includes some degree of uncertainty. Testing, validation and verification in the field of building energy modelling are emerging areas that still need further development [7][8].

The actual construction process also contributes to the energy performance gap [9]. Achieving the required insulation and airtightness levels are sometimes challenging; errors and defects might be hidden from view due to the fact that constructions are typically layered. There are also direct impacts of change orders and value engineering. Where change orders might appear to substitute equivalent products these might in fact not be so from a detailed thermal point of view. Value engineering might actually remove elements of the thermal system that are seen to be overly expensive but which were critical in achieving a target performance. Building commissioning and hand-over are also difficult processes that typically do not allow for full performance testing due to budget and time constraints [10].

Once a building becomes operational, a key issue is that actual building use and real weather conditions seldom match assumptions made during the design process. Control settings of thermostats and within the Building Energy Management System (BEMS) might not represent assumptions, or simply might not be programmed as intended. Furthermore, one also needs to accept that metering itself comes with issues and uncertainties [11]; this is especially true when it comes to capturing contextual factors such as weather data and occupant behaviour. Measurement can often have issues with accuracy, missing or incomplete data, as well as implausible values, which lead to a ‘level’ of error in the results collected from metering. Post-processing and cleaning of metering data is therefore essential, but can introduce further threats to the validity of the results.

3. A probabilistic view of the performance gap

Most work on the performance gap is based on deterministic predictions and measurements. Work at Plymouth University has piloted a probabilistic approach. This was based on the premise that both predictions and measurements ought to capture uncertainties and hence be represented by probability distributions or histograms. If these could be established one might then study the equality between prediction and measurement through a statistical test, such as the two-sample Kolmogorov-Smirnov (K-S) test [12].

This concept was tested by means of a pilot study which focussed on the Roland Levinsky Building at Plymouth University. An impression of the full complexity of this building both in terms of geometry and services is provided by Figure 1. A detailed EnergyPlus model of this building has been developed which will be used to obtain 'as simulated' data; this model includes 105 zones and the EnergyPlus "Input Data File" (IDF) comprises 41,614 lines of text and has been used in previous studies [13]. Thise IDF model describes the geometry, construction materials, and control settings of the building. Access was gained to two years of full automated meter readings (electricity and gas) at 30 minute intervals for the building, thus providing the 'as measured' component. This has been compared with simulation results from an EnergyPlus model of the same building.

Figure 1: Roland Levinsky Building at Plymouth University, UK

In order to propagate design uncertainties in the EnergyPlus model, this was linked to the GeorgiaTech Uncertainty and Risk Analysis Workbench GURA-W [14].

In studying the need for uncertainty propagation through GURA-W, it became obvious that the comparison between energy efficiency prediction at the design stage and measurements on a real building needs to cover a lot of different types of uncertainties, such as intentional but unanticipated changes (due to value engineering and change orders), errors during construction, variation in material properties and dimensions, physical coefficients, occupant behaviour, control settings, weather conditions, system performance degradation, impact of facility management and others. For some of these, such as the uncertainty in material properties, significant bodies of literature are available and uncertainty propagation is feasible. For others, such as the impact of value engineering on the properties of the final product, this is at present not possible due to lack of information. Results obtained with GURA-W, propagating only a limited set of those parameters which are at present quantifiable (still covering uncertainties in no less than 120 different model parameters), are presented in Figure 2. For further background on this work, see de Wilde *et al* [15].

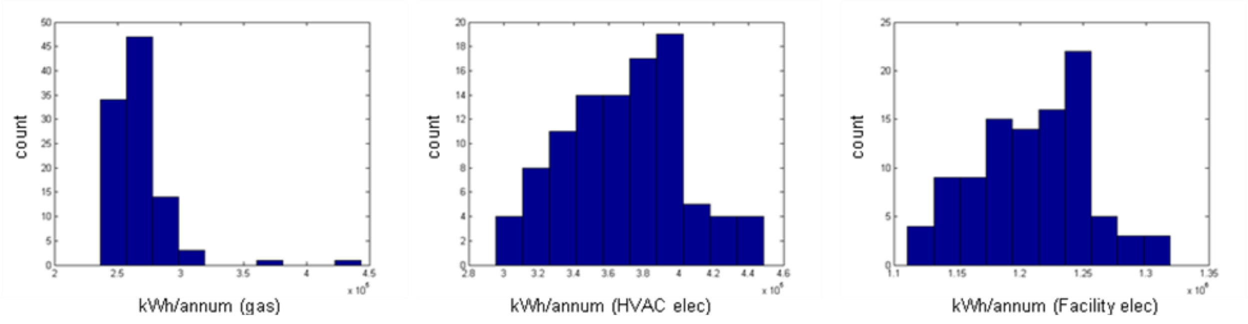

Figure 2: Histograms for prediction of annual consumption of (left) gas for heating, (middle) annual HVAC electricity use and (right) total annual electricity use

These results were compared with the existing measurement data. This revealed another problem: while it is relatively straightforward to develop a histogram for simulated data, this is not the case for metered data. Two years of data, even when captured at 30 minute intervals, still only give two data points at an annual level. Increasing the resolution to monthly level does not solve this problem as it shifts emphasis away from the quantity of interest. Figure 3 shows this effect, with actual values represented in Table 1.

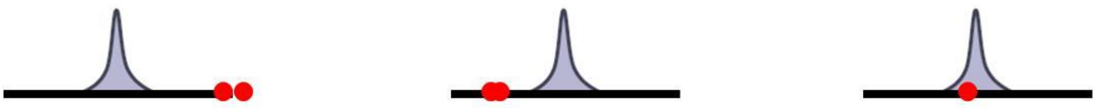

Figure 3: Comparison of histograms with actual measurements, which only comes in single points. (Left) gas for heating, (middle) annual HVAC electricity use and (right) total annual electricity use.

It is obvious from both figure and table that the predicted values of gas are far below the actual energy consumption. For electricity, the HVAC values slightly over predict, but this effect disappears when looking at the total electricity consumption.

	Gas (kWh/annum)	**Elec HVAC (kWh/annum)**	**Elec total (kWh/annum)**
Simulated	$2.75 \pm 0.50 \times 10^5$	$3.80 \pm 0.80 \times 10^5$	$1.23 \pm 0.08 \times 10^6$
2011	8.81×10^5	1.20×10^5	1.19×10^6
2012	6.68×10^5	1.29×10^5	1.21×10^6

Table 1: Comparison of simulated with metered data.

A similar effect, and similar discrepancies between predicted and measured results, have been reported from other studies (Cherry Building in Atlanta, USA; PhD study in progress). Better correspondence can be obtained by re-running the simulations and correcting the design assumptions for weather and occupant behaviour with actual observations, thus compensating for some of the external unknowns at design stage. If all other uncertainties are left unchanged, the crude picture that emerges is as follows:

- Energy use predictions at design stage, where the weather and occupant behaviour must be guessed, can be as far away from measurement values as a factor three.
- After re-running models with weather data and occupant behaviour that are in line with the measurement context, models will be within roughly 40% of metered values.

At present we do not have sufficient observational data to construct a detailed distribution that allows the application of a meaningful statistical test. Also note that, even with two points only, the resulting performance gap will be different from year to year and thus varies over time.

4. Current status and opinions

The current views on the energy performance gap within the UK industry were discussed at a workshop at Plymouth University on 25 October 2013; see Figure 4. This workshop consisted of presentations by invited speakers as well as a forum discussion. Access to the workshop was available for a small admission fee; with the event having been announced widely through networks like IBPSA-England (the regional affiliate of the International Building Performance Simulation Association) and Constructing Excellence. The delegates were self-selected.

Figure 4: Delegates at the Plymouth University workshop, 25/10/2013. Image by Jim Carfrae

An overview of the presentations on the day is presented in Table 2.

Speaker	Affiliation	Title of presentation
P. de Wilde	Plymouth University, UK	*Introduction and overview of the energy performance gap*
M. Colmer	Technology Strategy Board, UK	*Building Performance Evaluation: early programme findings*
A. de Menezes	AECOM, UK	*Predicting operational energy use at design stage - can it be done?*
C. Martinez-Ortiz	University of Exeter, UK	*Automated meter reading, monitoring and targeting and machine learning - bridging the energy performance gap*
D. Mumovic	University College London, UK	*Bridging the credibility gap: total performance of school buildings*
R. Bunn	Building Services Research and Information Association, UK	*Whose performance gap?*
R. Quincey	Integrated Environmental Solutions, UK	*Bridging the performance gap: IES and VE Scan*
D. Johnston	Leeds Metropolitan University, UK	*Bridging the fabric performance gap*
D. Miles-Shenton	Leeds Metropolitan University, UK	*Measuring the fabric performance gap*
W. Plokker	VABI, the Netherlands	*The impact of air supply temperatures on the performance gap*
P. de Wilde	Plymouth University, UK	*A probabilistic view of the performance gap*

Table 2: Speakers at Performance Gap Workshop, Plymouth, 25/10/2013

The presentations during the day and the forum discussion at the end of the workshop highlighted the following issues and views on the performance gap:

- There are clearly different types of performance gaps that vary over time and with context, and that depends on the point of view of those looking at building performance. One might, for instance, define the energy gap as the difference between the design at a conceptual stage and as measured once operational, but just as well as the performance of the design at a stage where detailed constructions have been prepared and the project goes out to tender and as measured once operational; more often than not this is not fully defined. Also, apart from the energy performance gap one might look at an air quality performance gap, lighting performance gap, and others.

- There clearly is a strong tension between the energy performance certificates (EPC) produced by Standard Assessment Procedures (SAP) and Simplified Building Energy Model (SBEM) calculations, and display energy certificates (DEC) based on measured energy use. It is rather unfortunate that both result in very similar colour coded ratings with categories from A to G. This in spite of the fact that EPC and DEC differ fundamentally in the energy usages that are being covered. While the work by CIBSE TM54 goes some way towards bridging this issue, the fundamentals are hard to convey to the general public.
- Various speakers raised the issue of communication and perception and whether the energy performance gap is in fact a perception gap rather than one of discrepancy between predicted and measured energy use.
- There is an issue to be addressed in terms of who can be made responsible for a performance gap and bears the risk of future litigation. Aligned with this issue is the question of who should take the initiative to bridge the performance gap. On the one hand there appears a challenge for building designers and engineers to make better predictions, or for building scientists to develop better prediction tools. On the other hand the findings of the day suggest that the performance gap is due to a multitude of underlying factors and that bridging the gap therefore will require collaboration of all actors involved in the design, construction and operation of buildings and building (sub)systems.
- It appears that most research into the energy performance gap focusses on non-domestic buildings; dwellings seem to be overlooked in this discussion. This might be due to the fact that domestic buildings are less likely to be subject of transient building simulation and advanced metering/monitoring; however, it risks missing out on a key sector of buildings.

5. Ongoing and future work

Ongoing work by the authors is concentrated in two key areas. Firstly, further work continues on the Roland Levinsky case study building; secondly, a domestic line of investigation is currently under development.

The work on the Roland Levinsky Building at Plymouth University is moving forward in several ways. Further measurement data continues to be captured from the building energy management system and energy metering. Additionally, work is under way to capture actual use of the building in more detail. Analysis will compare and contrast the current system control settings, timetabled activities within the building, and surveys of actual building utilisation. Findings will be used to start a campaign of calibration of the existing EnergyPlus model, while keeping track of all calibration activities along the way using version control software as recommended by Raftery et al [16]. Furthermore, there are initial contacts in place that will lead to a review of the original energy calculations and simulations that were done at the design stage of the building by the actual engineering team, which can be compared with the parallel efforts of the academic research team.

In terms of the performance gap in the domestic part of the building sector, work has started on the evaluation of homes on a new-build development in Torquay, Devon; see Figure 5. In this case, monitoring equipment has been installed in a series of identical properties as far as construction and building systems installed are concerned. Data capture includes 5 minutely gas and electricity usage, indoor air temperature and relative humidity in different rooms, occupancy of the dwellings and window and door opening. Climate data is being captured for the whole site. The monitoring will be undertaken for a minimum of three years and the data is being exported off site in near real time via general packet radio service (GPRS). The research will include a socio-technical household survey with the building occupants to gather information about their socio-economic characteristics, comfort, ownership of domestic appliances, environmental attitudes and behaviour. A detailed post-occupancy evaluation will be completed on the monitored homes and researchers will work with the occupants to improve understanding and operation of the energy saving technologies installed, such as the mechanical ventilation and heat recovery (MVHR) system. Thus this work will provide a data rich context to study how the gap between predicted and measured energy consumption for these properties develops over time.

Due to the fact that the monitoring relates to identical properties, this project also provides a unique opportunity to develop an energy use distribution that reflects the impact of design independent factors to the performance gap, such as occupant behaviour, variation in plug in equipment, and others. On the design side, the team has access to the SAP calculations done at the design stage. These will be compared to transient EnergyPlus simulations of the same building design, conducted by the researchers. This allows for model calibration.

The variations in energy demand between the identical monitored homes will be correlated with occupant behavioural factors, such as the frequency and duration of window and door opening, daily heating period, chosen heating set point temperatures, proportion of home heated and operation of the MVHR system.

Figure 5: Monitored domestic development in Torquay, Devon. Image by Rory Jones

6. Conclusions

This paper has summarized the existing literature on the energy performance gap, discussed recent work at Plymouth University, as well as the findings from a workshop held on the subject, and has presented some avenues of ongoing and future work in this area. The key conclusions of this paper are:

- There are different types of energy performance gap that vary over time and with context. One can also extend beyond the 'energy performance gap' and look at issues of indoor environmental quality. A clear definition of the performance gap needs to be devised to account for these emerging multi-faceted concepts and interpretations. Without personalizing the 'performance gap' and positioning it in a clearly defined context the concept is not meaningful.
- In the UK, there clearly is a strong tension between the energy performance certificates (EPCs, based on calculations) and display energy certificates (DECs based on measured energy use). As EPCs and DECs are presented in a very similar format but represent different figures, with EPCs not including unregulated energy flows, this fuels the national debate on the energy performance gap.
- An emerging debate relates to the communication and perception of the energy performance gap. It is suggested by some that in fact the energy performance gap is rather a perception gap rather than one of discrepancy between predicted and measured energy use. However, other evidence seems to indicate that there is a need to fundamentally review the way we currently predict and measure performance. This view especially holds true in terms of accounting for uncertainties.
- Although significant recent developments in automated meter reading and building monitoring are providing actual energy consumption and environmental data for buildings, the amount and types of data required to clearly understand the root causes of the energy performance gap are still severely lacking.
- At present, the responsibility for the performance gap has not been apportioned to different actors in the design, construction and operation stages of the building process and therefore it is unclear who should take the initiative to bridge the performance gap.
- Most research into the energy performance gap focusses on non-domestic buildings; dwellings seem to be overlooked in this discussion, therefore a whole key sector of buildings is currently overlooked and the extent of the performance gap in this sector remains unclear. The authors are currently undertaking a domestic performance gap project in Torquay, Devon, to address this need, with results due in Summer 2014.

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