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Towards measurement and verification of energy performance under the framework of the European directive for energy performance of buildings

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A B S T R A C T

Directive 2002/91/EC of the European Parliament and Council on the Energy Performance of Buildings has led to major developments in energy policies followed by the EU Member States. The national energy performance targets for the built environment are mostly rooted in the Building Regulations that are shaped by this Directive. Article 3 of this Directive requires a methodology to calculate energy performance of buildings under standardised operating conditions. Overwhelming evidence suggests that actual energy performance is often significantly higher than this standardised and theoretical performance. The risk is national energy saving targets may not be achieved in practice. The UK evidence for the education and office sectors is presented in this paper. A measurement and verification plan is proposed to compare actual energy performance of a building with its theoretical performance using calibrated thermal modelling. Consequently, the intended vs. actual energy performance can be established under identical operating conditions. This can help identify the shortcomings of construction process and building procurement. Once energy performance gap is determined with reasonable accuracy and root causes identified, effective measures could be adopted to remedy or offset this gap.

1. Introduction

Energy efficiency is one of the key objectives of the European policies to address the challenges of energy security and climate change. Substantial steps have been taken towards increasing energy efficiency, notably in the appliances market and construction sector [1]. Energy consumption of buildings in the European Union accounts for around 40% of total final energy use and 36% of total CO_2 emissions of the EU Member States [2]. Therefore, it is vital to devise appropriate policies to improve energy efficiency of the existing and new building stock. The Energy Performance of Buildings Directive (EPBD), European Directive 2002/91/EC, came into force in 2003 [3]. This Directive underpins the majority of policies and regulations adopted by the EU Member States to improve energy performance of buildings in the last decade.

Article 3 of the EPBD requires all EU Member States to adopt a methodology to calculate energy performance of buildings. Such calculation shall include, as a minimum, energy use related to heating, hot water, cooling, ventilation and lighting under standardised conditions prescribed by national regulations [3, p. L 1/67]. This Article is the cornerstone of the Directive as the calculation methodologies developed are used to ensure the energy performance requirements set out for new and existing buildings are met. These calculation methodologies also underpin the energy performance certificate schemes implemented in the EU countries to indicate energy efficiency of building stock.

The recast of the EPBD, Directive 2010/31/EU, aims to extend the scope of the original Directive by reducing area thresholds that make the EPBD requirements applicable to new and existing buildings. It also mandates the Member States to set minimum cost-optimal requirements for energy performance of buildings to ensure there is a right balance between the investments involved and the energy costs saved throughout the lifecycle of a building. The Member States must draw up national plans to increase the number of 'nearly zero-energy' buildings. The nearly zero or very low energy performance could be achieved by a combination of

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energy efficiency improvements and renewable energy produced on-site or nearby [4]. Furthermore, there is more emphasis in the recast of the EPBD on quality assurance requirements to improve the accuracy and robustness of energy performance assessments [5].

To implement Article 3 of the EPBD, the EU member states developed various calculation methodologies. Most countries opted for whole-building simulation, using thermal modelling software developed in accordance with national calculation methodologies, to determine energy performance of their building stock [6].

Thermal modelling is a useful method to calculate energy performance of a building through mathematical equations that relate physical properties of the building such as external envelope's thermal conductivities, air permeability, type and efficiency of heating, ventilation and air conditioning systems, and intensity of lighting to the building's energy use under specific climatic conditions. There are also a number of operating conditions that need to be defined and used in these calculations. Examples include building occupants' density, temperature set points, occupancy profiles and operation schedules of building services. These operating conditions are often unknown in the design of new buildings or subject to a lot of uncertainty in existing buildings. Furthermore, the extent of small power loads such as plug-in and ICT equipment is often unknown prior to building completion. These uncertainties can compromise the accuracy and effectiveness of energy performance calculations. This justifies the use of *standardised* operating conditions under the EPBD. This is helpful for regulators as they can assess energy efficiency of construction projects under standard conditions, defined in the national calculation methodologies, and decide whether they meet minimum requirements. However, calculating energy performance under standard conditions means the outcome of such calculation cannot be directly compared with the actual performance as actual operating conditions often differ from standardised conditions. An unintended consequence of this policy set-up is where actual energy use of a building is higher than what is calculated under the EPBD framework, it is often very difficult to identify what proportion of this discrepancy is due to deviations from standardised operating conditions and what proportion is down to specific procurement issues associated with the building construction. Another unintended consequence is that energy efficiency measures are tailored to comply with the Building Regulations' requirements under standardised conditions only, and do not necessarily reflect procurement and operational risks [7].

In theory, the calculated energy performance of a building after completion must reflect the as-built status including any procurement issues. However, as the supply side of the construction industry is fragmented [8], it is often not feasible to check all design intents have been met in the immediate aftermath of building completion. Furthermore, the evidence suggests there are shortcomings in complying with the EPBD requirements, enforcement of the regulations, and the existing quality control schemes in all EU Member States [9]. As actual energy use is not directly comparable with the calculated energy use, there is a significant risk that energy-related procurement issues go unnoticed with any discrepancy between actual and calculated energy being justified solely on the basis of expected differences in operating conditions. This can seriously compromise energy efficiency of building stock in the EU.

The aim of this paper is to show how a measurement and verification plan can be integrated into the existing EPBD framework to ensure actual energy performance is in line with the theoretical assessment carried out after completion of a building. First, a brief overview of the background literature is provided to highlight the significance of the discrepancy between actual and predicted energy performance. Subsequently, a methodology is presented for measurement and verification of energy use under the EPBD framework. An example is also provided as proof of the concept. Finally, it is explained how this measurement and verification plan could be scaled up and integrated into the EPBD. The UK education sector and the National Calculation Methodology (NCM) implemented in England and Wales have been used to demonstrate the concept. However, in principle, the framework outlined in this paper could be applied to other countries within the European Union.

2. Background literature

The drastic increase in oil prices in 1990s, following the world energy crisis in late 1970s, raised governmental concerns regarding energy security. European countries' dependence on imported energy resources and the large contribution of building stock to national energy use prompted the European governments to introduce energy regulations. Europe developed regulations related to air tightness and building fabric in the late 1970s. Energy regulations related to building services were subsequently introduced in various European countries [10].

Before 1970s post-occupancy studies that compare actual performance of buildings with design intents were predominantly focused on architectural aspects of building performance, environmental psychology and human behaviour in buildings [11–13]. With the ever-increasing significance of energy, the focus of post-occupancy evaluations gradually shifted towards energy and indoor environmental quality. In the United Kingdom, this trend was accelerated by the Latham report which was commissioned by the government to investigate the root causes for the poor quality offered by the UK construction industry [14]. Over the last two decades, this has led to a large body of empirical evidence that could be used to investigate the root causes of shortfalls in operational energy use.

2.1. Energy performance gap: the context

The Post-occupancy Review of Buildings and their Engineering (PROBE) was the first systematic post-occupancy evaluation programme carried out in the UK with special focus on energy and indoor environmental quality [15]. Detailed study of 16 non-domestic buildings that perceived to be exemplar designs over the period 1995–1999 revealed energy was often poorly specified in briefing and design criteria. Actual energy use of most buildings in the sample was higher than expectations. It was also found that there was very little connection between the values assumed in design estimations and computer models and actual values found in the completed buildings [16].

More recent studies confirm the findings of the PROBE programme, and reveal that despite technological advances there is still a significant gap between actual performance and design intents. For example, a long-term post-occupancy study of five secondary schools in England that were intended to be *low-energy* buildings found that 80% of these buildings use more energy than expected. The energy performances of these buildings were between the 35th and 82nd percentile of the national building stock. The introduction of IT into the schools' curriculum, improved internal environmental standards, extended operating hours for extracurricular activities, and poor control of building services were identified as major reasons for higher than expected energy consumption [17].

Another study carried out on 28 new-build properties in the UK that used the EBPD compliant software for energy calculation found that 75% of the case studies did not perform as well as expected. The projects covered a variety of building types including retail, education, offices and mixed use residential buildings. The identified root causes for this discrepancy were: reliance on calculated performance under standardised conditions rather than performance in-use, inadequate prediction of energy use during design stages, complexity of control strategies, poor construction practices, inadequate commissioning, insufficient means of managing the building systems' performance once operational, and lack of designers/contractors involvement in fine-tuning buildings after completion. In the worst case scenario, combination of these factors led to operational energy use being almost five times higher than design estimate [7].

CarbonBuzz is a collaborative research platform that aims to share information about calculated and actual energy use of buildings with a view to narrow this so-called *energy performance gap*. As of June 2013, energy performance records for 600 projects had been reported to CarbonBuzz with the largest contingents being offices (around 40%) and educational buildings (around 30%). Table 1 provides the mean data for design and actual energy use in office and education sectors based on the latest audit on CarbonBuzz data.

Most construction projects registered in CarbonBuzz are based in the UK. Case studies carried out for non-domestic buildings in other European countries indicate discrepancies of up to 30% between measured performance and energy performances derived from the EPBD compliant software [19,20].

In Housing sector, studies carried out in Europe often report energy savings less than expected for retrofit projects and energy use higher than expected for new builds. Indoor temperatures in heating season are often higher than modelling assumptions as building occupants expect to be more comfortable in new buildings. This type of behavioural response to energy efficiency improvements which leads to shortfall in expected energy savings is called the *rebound effect* [21]. An investigation into the impact of occupant behaviour on energy consumption of dwellings in Austria provided evidence for a rebound effect between 20% and 30% in space heating [22]. A more recent review of the empirical evidence for the direct rebound effect in household heating that covers evidence from the UK, Austria, Norway in Europe in addition to Canada and the US reveals a shortfall in expected energy savings of up to 68% with most UK studies reporting a mean shortfall above 50% [23]. Also it is likely that any perceived financial saving on energy is spent on appliances that in turn increase energy use [24,25]. A review of the English House Condition Survey (EHCS) consisting of 2531 unique cases found that homes with better energy ratings often consume more energy than less efficient homes. It is suggested that, while energy efficiency upgrades must be adopted for homes with poor energy ratings, a combination of behavioural strategies and economic incentives should be used to ensure energy efficiency measures already implemented in housing stock lead to energy saving [26].

Overall, there is strong evidence for energy performance gap in European non-domestic sector and housing stock that must be addressed to ensure ever stringent energy policies such as nearly zero-energy buildings, which will be enforced in the EU for all new buildings by 31 December 2020 [5], are effective.

2.2. *Policy gap: measurement and verification of performance in-use*

Excess in energy use over regulatory limit is often attributed to actual operating conditions and human behaviour that are not adequately predicted at design stages [19,27]. However, a review of the implementation of the energy-related Building Regulations across all EU Member States, Switzerland and Norway points out there is little attention to enforce these sustainable regulations. It also highlights the shortage of qualified people with appropriate level of technical expertise to undertake the building control function in most European countries [9]. This finding is reinforced by another study on 404 new-build dwellings in England and Wales that revealed only a third of these buildings were compliant with the energy efficiency requirements set out in the Building Regulations. The study also pointed to the lack of adequate knowledge about energy efficiency requirements of the Building Regulations among the supply and building control side of the construction sector [28]. Therefore, it is expected that part of excess in actual energy use over regulatory limit is related to construction and building procurement process.

The discrepancy between actual and calculated energy performance of buildings could be perceived as a sub-set of a more generic problem called energy *efficiency gap* first formulated in 1990 [29]. Energy efficiency gap indicates the discrepancy between actual and optimal energy use and is essentially a market failure. An effective energy policy must be able to translate investments in energy savings to economic value [30]. To bridge energy efficiency gap in each sector, various structural and behavioural barriers must be identified and addressed. This paper deals with a specific structural barrier related to policy making in the context of the EPBD that is the lack of a requirement to verify energy performance in-use.

The current energy assessment framework prescribed by the EPBD is overwhelmingly based on *theoretical* performance [6]. For example, the UK Building Regulations require that total energy performance of every new building, calculated based on annual CO_2 emissions, be no greater than total energy performance calculated for a notional building that possesses minimum acceptable specification. The minimum specification is updated with every new version of Building Regulations to set out ever more stringent CO_2 targets [31]. The updates in minimum specification should pave the way to a low carbon future that is in line with the national energy saving targets. The risk is national energy saving targets may not be achieved in practice if actual performance of building stock is significantly higher than this theoretical performance [32].

Discrepancy between actual and theoretical performance may be attributed to four major sources:

- Inaccuracies and uncertainties associated with modelling inputs [27,33]
- Inadequacies of modelling methods and tools [34,35]
- Procurement issues including construction process and building commissioning [7,36]
- Building management & operational inefficiencies [36,37].

Table 1
Calculated vs. actual energy performance for offices and educational buildings in the UK [18].

Category	Mean desgin total heat consumption (kWh/m^2/annum)	Mean actual total heat consumption (kWh/m^2/annum)	Performance gap factor change (actual to design)	Mean desgin total electricity consumption (kWh/m^2/annum)	Mean actual total electricty consumption (kWh/m^2/annum)	Performance gap factor change (actual to design)
Office	46	73	1.59	71	121	1.71
Education	57	84	1.48	56	106	1.90

Unless a like-for-like comparison is made between calculated and actual energy performance, it would be very difficult to differentiate and address these root causes. In this paper, a method is proposed to make such comparison feasible by reverting a calibrated thermal model developed post-occupancy to the EPBD standardised conditions.

3. Methodology

First, a theoretical discussion is presented to establish how a measurement and verification plan for energy performance of buildings could be drawn up under the EBPD framework. Next, a brief description of the case study building used for proof of the concept is provided along with the criteria used for calibrating the thermal model with the actual performance.

3.1. Measurement and verification of energy performance

The results derived from a thermal model compliant with the EPBD are not directly comparable with actual performance for the following reasons:

- The use of standardised conditions/assumptions
- A number of loads are not included in energy performance calculations (e.g. actual small power and equipment load).

The International Performance Measurement & Verification Protocol (IPMVP) provides a framework to develop calibrated thermal models for energy saving projects where whole-building simulation is required [38]. Calibration is achieved by adjusting the thermal model of a building to reflect the as-built status and actual operating conditions. In the context of IPMVP, whole-building calibrated simulation after one year of steady post-refurbishment occupancy could be used to establish energy savings achieved when pre-refurbishment energy performance is not available or difficult to establish (e.g. multiple buildings on one site without sub-metering). Once the thermal model is calibrated with actual performance post-refurbishment, systems and settings may be changed to pre-refurbishment conditions to establish the initial baseline. The energy saving achieved is the difference between energy performance derived from calibrated thermal model under pre-refurbishment conditions, and the actual energy performance measured after refurbishment work.

The principle and techniques outlined by the IPMVP for calibrating whole-building thermal models could be used to draw up a measurement and verification plan under the EPBD framework. A thermal model that reflects the steady post-occupancy operation of a building for at least 12 months could be developed and calibrated with actual energy use. Once calibration is achieved under actual operating conditions, the model could be reverted to the EPBD standardised settings to establish the verified performance under the EPBD conditions. The following definitions can help separate different aspects of actual vs. theoretical energy performance:

$$\text{Procurement gap} = \text{EPBD}_{\text{verified}} - \text{EPBD}_{\text{intended}} \quad (1)$$

$$\text{Operational gap} = \text{Actual Energy} - \text{EPBD}_{\text{verified}} \quad (2)$$

$$\text{Total energy performance gap} = \text{Procurement gap} + \text{Operational gap} \quad (3)$$

where,

$\text{EPBD}_{\text{verified}}$: energy performance derived from a calibrated thermal model under the EPBD settings
$\text{EPBD}_{\text{intended}}$: EPBD calculation carried out following completion of a building
Actual Energy: measured energy performance based on metering or utility bills

In practice, project teams have thermal models developed during design stages, which are used to demonstrate compliance with the EBPD requirements following completion of buildings. In the United Kingdom, the main construction contractor is often liable for building defects for at least one year after building handover. Consequently, introducing a new requirement for measurement and verification of energy performance within the first year of building operation would not be onerous and the benefits achieved during the life-cycle of a building far outweigh the incurred costs. Depending on the project type and contractual arrangements, the measurement and verification plan could also be extended to allow a building achieve its steady mode of operation before verification of energy performance is carried out.

Fig. 1 depicts the principle of using calibrated thermal models to verify the performance calculated under the EBPD standardised conditions. The forward path shows how actual energy performance could be significantly higher than calculated performance under the EBPD conditions. The backward path shows how a calibrated thermal model could be used to verify the EPBD calculation and establish if there is any procurement gap. Procurement gap in this context represents shortcomings in building design, construction process, system installation, implementation of control strategy, and building commissioning.

3.2. Case study building

The case study building, used for proof of the concept, is a secondary school in North West England with total useful floor area of 10,418 square meters and nominal occupancy of 1150 pupils (see Fig. 2).

It was constructed as a low carbon building in accordance with the UK Building Regulations 2006 and was completed in 2008. The building is located under the air path of Manchester airport.

The building is designed as a sealed envelope to screen the ambient noise from the airport. Full mechanical ventilation with heat recovery is provided to all teaching and office spaces. Variable speed fans were part of the design strategy to save energy when the

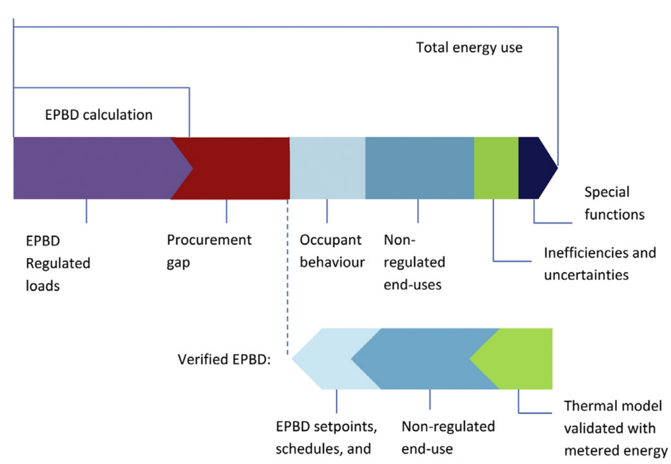

Fig. 1. Measurement & verification plan for energy performance of buildings.

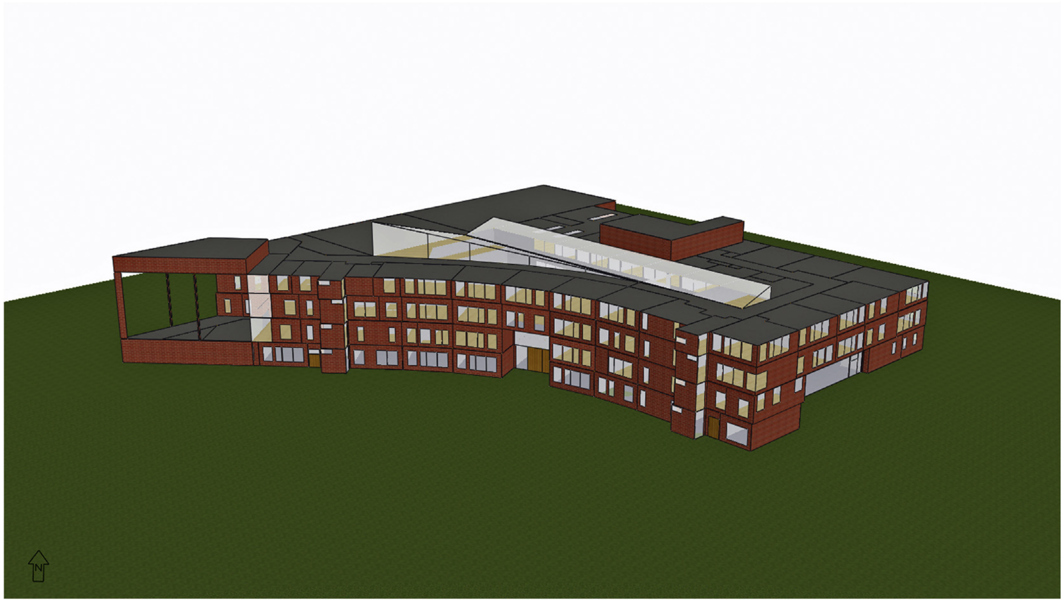

Fig. 2. Axonometric view of the thermal model developed for the case study building.

building is not fully occupied. Four closed-loop ground source heat pumps with vertical boreholes act as the lead system for heating and are supplemented by gas fired condensing boilers. Domestic hot water is provided by the boilers via a calorifier. The ground source heat pumps also provide limited amount of cooling to ICT enhanced classrooms via chilled beams. Classrooms are designed to have a minimum 2% daylight factor. Electrical lights installed in teaching and office spaces are high efficacy fluorescent lighting with efficiency better than 2.5 W/m^2/(100 lux). The building follows the normal England and Wales secondary schools' calendar with some extracurricular activities and a night school that runs two days per week during term time.

The building emissions rate calculated for the building following its completion, using dynamic simulation with IES Apache software, was 27.2 kg CO_2/m^2/annum. This accounts for all fixed building services including heating, hot water, cooling, lighting and auxiliary energy use under the EBPD standardised conditions defined in the National Calculation Methodology (NCM) for England and Wales.

The authors performed a post-occupancy evaluation on this building over the period 2011–2013. Total annual energy performance of the building, based on the latest utility bills and metered data, was 93.6 Kg CO_2/m^2.[1] This accounts for all fixed building services, small power, server room load, external lights, lifts and other miscellaneous loads not regulated under the EPBD.

A thermal model was developed for the building based on post-occupancy information and observations with the same software used for the original EPBD calculation. The model was calibrated with the actual performance including all loads. Where it was not possible to define some energy end-uses in the model, the results were adjusted to ensure a like-for-like comparison is made between modelling results and actual total performance. Notably, external lights and lifts' energy use were added to the modelling results. Under the IPMVP framework, the data used to calibrate a thermal model shall contain, as a minimum, monthly utility data for 12 months [38]. It is also possible to use hourly calibration data. The monthly calibration method was used for this building. The following criteria were used for calibrating the model with the actual performance:

- Calibration based on monthly utility data to achieve a CVRMSE of 15% or better and an NMBE (Normalised Mean Bias Error) of 5% or better for gas and electricity use [38,39]. The Coefficient of Variation of the Root Mean Square Error (CVRMSE) and Normalised Mean Bias Error (NMBE) are defined as follow:

$$\mathrm{CVRMSE} = 100 \times \left[\sum_{i=1}^{n} (y_i - \hat{y}_i)^2/(n-1)\right]^{1/2} \Big/ \bar{y} \tag{4}$$

$$\mathrm{NMBE} = \frac{\sum_{i=1}^{n} (y_i - \hat{y}_i)}{(n-1) \times \bar{y}} \times 100 \tag{5}$$

where:

y_i: measured monthly gas or electricity use
$\hat{y}_i$: monthly gas or electricity use derived from thermal modelling
$\bar{y}$: average monthly gas or electricity use for the measurement period
n: number of data points ($n = 12$ for calibration based on 12 months of data)

In addition to the criteria set out by the IPMVP, the following criteria were set to ensure reasonable consistency between actual and calculated annual performance is achieved:

- Total annual gas within 5% of the measured performance per kWh/m^2
- Total annual electricity within 5% of the measured performance per kWh/m^2
- Total annual energy performance calculated per kg CO_2/m^2 within 5% of the measured performance

[1] Carbon emissions conversion factors used for gas and electricity are 0.19 kg CO_2/kWh and 0.55 kg CO_2/kWh respectively.

Table 2
The inputs used for the calibrated thermal model based on post-occupancy evaluation.

Building characteristics	Calibrated thermal model inputs
Heating	21% of heating demand is satisfied by the Ground Source Heat Pumps (sub-metered); gas fired boilers supplement the GSHPs. Coefficient of Performance for the GSHPs: 4.1 Gross efficiency of gas-fired boilers in condensing mode: 95.2% Gross efficiency of gas-fired boilers in non-condensing mode: 88%
Ventilation	Overall system Specific Fan Power of 4.02 W/L/s based on the commissioning results, no demand control ventilation enabled. All main air handling units have thermal wheels installed for heat recovery.
Air conditioning	Ground source heat pumps Energy Efficiency Ratio: 5.2 Server room DX units Energy Efficiency Ratio: 3.27
Hot water	Hot water tank capacity: 2000 L with 0.0026 kWh/L/day loss.
Lighting	All lighting wattages based on as-built drawings; average lighting density is 12.2 W/m^2. Automatic daylight sensing with an average daylight factor of 2% within 6 m of the building perimeter, absence detection sensors in classrooms and presence detection sensors in circulation areas
External envelope	The building external wall is brick block with insulated cavity. Average U value for the external envelope including glazing: 0.48 W/m^2°K Impact of thermal bridges on average U value: 7.9%
Air permeability	9.2 m^3/h/m^2 @ 50 Pa (based on the pressure test results)
Equipment and other miscellaneous loads not regulated by the Building Regulations	Sub-metered non-regulated energy; all electric unless stated otherwise (kWh/m^2/annum): ICT equipment (including servers) : 18.6 Small power: 8.9 Central catering (gas): 7.9 Central catering : 5.6 Distributed catering: 2.8 External lights: 4.6 Lifts: 0.2

Once these criteria were satisfied, the model was reverted to the EPBD standardised settings to establish the procurement and operational gaps.

While calibration based on monthly data was used for this building, hourly electrical power demand data available from the utility supplier were also compared with the electrical power demand derived from thermal modelling to assess the level of information required to make calibration based on hourly data feasible. This would provide an insight about the level of monitoring and the data points required to get accurate hourly predictions if higher level of accuracy is targeted in future projects.

4. Results

Input data: Table 2 includes the inputs of the calibrated thermal model for building services, building fabric, equipment and miscellaneous loads based on post-occupancy observations and measurements. Table 3 compares the actual operating conditions observed in the building with the standardised operating conditions used for the EPBD calculations. Lower occupant density, higher heating set points in classrooms, lower cooling set points, higher ventilation rates, and longer hours of operation in the actual building are among the major differences between actual and standardised operation.

Monthly calibration: Fig. 3 and Fig. 4 show the calculated vs. measured monthly gas and electricity use respectively. The measured data is based on utility bills and the calculated data is based on thermal modelling. The heating components of gas consumption derived from dynamic simulation using Test Reference Year (TRY) [40] weather file for Manchester have been weather corrected based on actual heating degree-days experienced over the measurement period. The electricity consumption derived from modelling has been adjusted to allow for external lights and lifts.

The coefficient of variation of the root mean square errors and the normalised mean bias errors for gas and electricity are listed in Table 4 and are all within the acceptable limits set out for the study.

Calculated gas is reasonably close to the measured gas except in June and July. As the heating consumption is very low in these months, the modelling outcome is sensitive to slight changes in occupancy pattern which determine domestic hot water requirements. However, sensitivity to items that will be standardised for the EPBD calculations is not a major concern as long as the average error is within acceptable limits. Calculated electricity is generally very close to the measured electricity. However, percentage of error grows in summertime when the building occupancy and use are highly erratic and difficult to fully capture within the model. Again, this poses no problem for verification of the EPBD calculations as long as the overall error is within the limits set out for calibration.

Annual performance: The outcomes of the model satisfy the criteria set out for calibration. Therefore, following the backward path of Fig. 1, the model is reverted to the EPBD settings and conditions. This process involves removing actual small power and equipment load that are not regulated under the EPBD and replacing them with the EPBD default loads, using standard occupancy density and profile, standard heating and cooling set points, standard airflow rates for the ventilation system, and the standardised schedules of operation.

Most commercially available software for the EPBD calculations in the UK are capable of replacing actual settings with the EPBD standardised settings automatically. Therefore, once the model is calibrated based on the measured performance, following the backward path of Fig. 1 is not time or resource intensive. Fig. 5 compares the measured performance with the outcomes of the calibrated thermal model, the verified EPBD calculation, and the initial EPBD calculation. All energy end-uses are also sub-metered and compared with the modelling results. Table 5 reports the annual performance for gas, electricity and total energy.

Comparison between the verified and intended EPBD calculations reveals that the verified auxiliary energy use associated with fans, pumps and control under the EPBD conditions is significantly higher than the intended performance. Auxiliary energy use is also the highest energy end-use in the measured performance. Post-occupancy studies revealed that poor implementation of the control strategy specified for the mechanical ventilation system led to failure of demand-controlled ventilation (a procurement issue). This was in turn compounded by poor building management (an

Table 3
Standardised vs. actual operating conditions.

Operating conditions	Standardised EPBD conditions for schools in England & Wales	Actual operating conditions for the case study building
People density (pers./m^2)	Classrooms: 0.55 Open office space: 0.11 Cellular office space: 0.07	Classrooms: 0.50 Open office space: 0.09 Cellular office space: 0.06
Heating Set point (°C)	Classrooms: 18 Offices: 22	Classrooms: 21 ± 2 Offices: 21 ± 2
Cooling Set point (° C)	Classrooms: 23 Offices: 24	Classrooms: 21 Offices: 21
Ventilation rate (L/s/p)	Classrooms: 5 Offices: 10	Classrooms: 8 Offices: 14
Schedules of operation:	Occupancy: 7:00–18:00 Weekdays; term time (standard diversity factors applied) Heating & Cooling: 5:00–18:00 (weekdays; term time) Mechanical Ventilation:7:00–18:00 (weekdays; term time)	Occupancy: 7:00–18:00; extended to 21:00 on Tuesdays & Thursdays for night school (diversity applied based on post-occupancy studies) Heating, Cooling and Mechanical Ventilation: 6:00–18:00 weekdays; extended to 21:00 on Tuesdays & Thursdays for night school (Weekdays and school holidays)

operational issue) and led to excessive auxiliary and heating energy use. This shows the knock-on effect of procurement gap on operational gap and the necessity to address it in the early stages of post-occupancy.

To assess the effect of procurement issues on operational gap, the identified root causes for the procurement gap were addressed in the thermal model. Fig. 6 illustrates that addressing the root causes of the procurement gap in the case study building would not only bridge the procurement gap but also narrow the operational gap by one forth.

Hourly electrical demand profiles: Fig. 7 and Fig. 8 show the calculated vs. measured electrical power demand curves for typical days in heating and free running seasons respectively. The measured data is based on hourly electricity data provided by the utility supplier. The calculated data is derived from the thermal model and adjusted to allow for external lights and lifts. The baseline demands, peak demands, and the shape of the demand curves predicted by the model reasonably match the measured data. However, these graphs reveal that further information is required to achieve better consistency if a whole-building calibration method based on hourly calibration is targeted. Occupancy profiles after normal school occupancy hours are very erratic and require detail attention for hourly calibration. For monthly calibration, on-site observations during night school and extracurricular activities along with semi-structured interviews with building users were used to determine the occupancy pattern for out-of-hours' activities. Using school attendance sheets (if available and reliable) or occupancy sensors can help collate data with finer resolution for hourly calibration. There is also evidence of unnecessary plant room operation in early hours of the day during the free running season (Fig. 8). Depending on the level of accuracy required, appropriate sensors could be installed and data points defined within the Building Management System to capture detail information about building operation on an hourly basis. However, it is important to strike the right balance between calibration cost and accuracy. The analysis carried out on the case study building demonstrates monthly calibration method can achieve acceptable level of accuracy and uncertainty with reasonable amount of effort that is scalable for wider application in the construction industry. The monthly calibration method is also the preferred option under the IPMVP [38, p. 35].

5. Discussion

First, the root causes for procurement and operational gaps in the case study building are briefly reviewed. Next the implications of the proposed measurement and verification plan and the ways to integrate this plan to the existing policy framework are discussed.

5.1. Energy performance gap in the case study building

The total measured energy performance of the case study building is 93.6 kg CO_2/m^2/annum. This is almost twice the energy performance of the median stock reported in CarbonBuzz and in the 90th percentile of the energy performance of secondary schools in England and Wales [41]. Therefore, this school is one of the worst performers in this building category. The measurement and

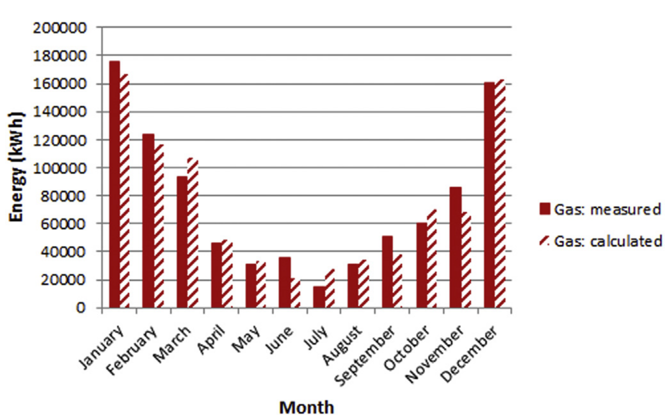

Fig. 3. Monthly gas use: calculated vs. measured.

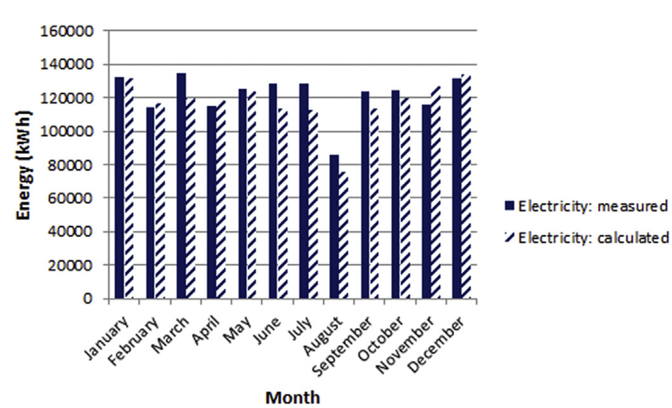

Fig. 4. Monthly electricity use: calculated vs. measured.

Table 4
Modelling errors for calibration based on monthly energy use.

Fuel	CVRMSE (%)	NMBE (%)
Natural Gas	14.4	1.4
Electricity	8.0	3.9

Table 5
Annual performance for gas, electricity and total energy.

Annual performance	Measured	Calculated	Difference
Gas [kWh/m^2/annum]	87.2	86.1	1.3%
Electricity [kWh/m^2/annum]	140.1	135.1	3.6%
Total Energy [kg CO_2/m^2/annum]	93.6	90.7	3.1%

verification plan helped differentiate the root causes. The single most influential factor in procurement gap is poor installation of the mechanical ventilation system. The default ventilation strategy for schools in the UK is natural ventilation. Mechanical ventilation is only used if natural ventilation is not feasible. Concerns about the ambient noise levels led the design team to opt for full mechanical ventilation. Due to the power law relation between airflow and fan power, mechanical ventilation strategy can have detrimental effect on energy performance unless demand-controlled ventilation is specified. The building services' designers specified variable speed drives for all airflow fans and performed the EPBD calculation assuming demand-controlled strategy is adopted. In practice, inverters were installed on all supply and extract fans, but were only used to balance the system at the commissioning stage. The fans' speed could be manually adjusted. However, contrary to the design intent, there is no CO_2 sensor installed in classrooms or extract ductwork to trigger automatic regulation of fan speed based on occupancy level. Therefore, the demand-controlled strategy has failed and all fans are running at their full capacity regardless of actual demand. The commissioning results also reveal that specific fan powers at full load are higher than the maximum allowable under the UK Building Regulations. Another root cause for the procurement gap is poor actuator control at the sliding header interface between ground source heat pumps and gas-fired boilers which led to low contribution of the ground source heat pumps to heating, almost half the design intent.

The most influential factor related to the operational gap is the schedules of operation set for the heating and ventilation systems. Schools are seasonally occupied buildings. This means that not all building services need to serve all zones of a building at all times. The building is open to public in half term breaks and a number of teaching and admin staff may work in the building. However, facilities managers can take advantage of heating and ventilation zoning to isolate parts of building that are not used. The schedules of operation of these systems and the set points could be optimised to save energy. None of these materialised in the case study building, which led to poor energy performance.

Addressing the issues related to demand-controlled ventilation and ground source heat pumps along with optimised seasonal operation of heating and ventilation systems would have significantly improved actual performance of the building.

This case study confirms the feasibility of using calibrated thermal models for measurement and verification of energy performance under the EPBD framework.

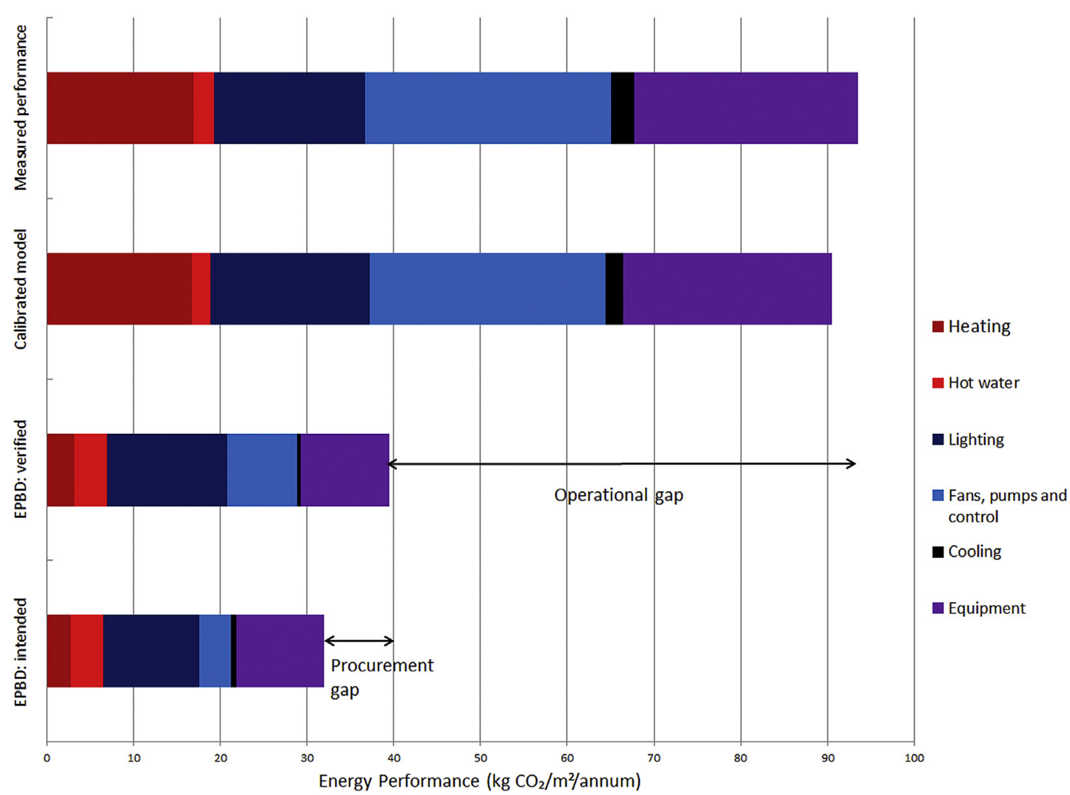

Fig. 5. Breakdown of measured and calculated energy performance. Small power and ICT equipment loads are not regulated under the UK Building Regulations. However, an allowance is made for equipment load as part of the EPBD standardised settings to estimate building's heating and cooling demand. Energy consumed by this standard equipment load is reported for the EBPD calculations in Fig. 5 to include all energy end-uses on the graph. The equipment energy reported for the measured and calibrated performance reflect the actual loads.

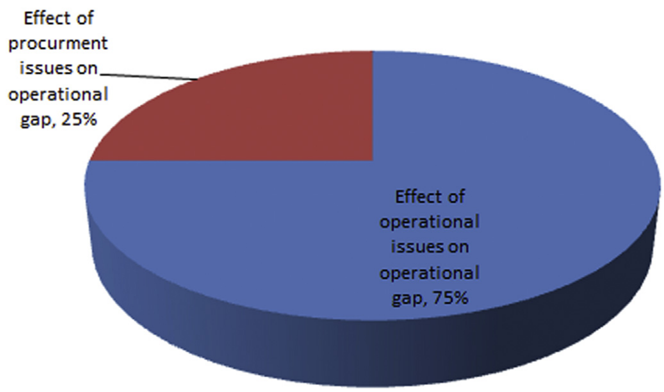

Fig. 6. Knock-on effect of procurement gap on operational gap.

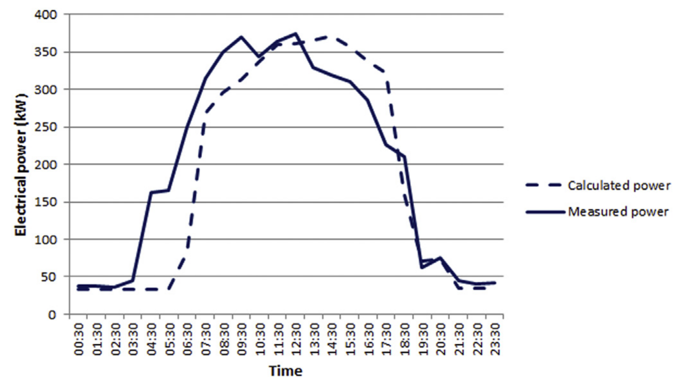

Fig. 8. Typical hourly electrical power demand curve: free running season (summertime).

5.2. *Integration of M&V plan into the EPBD*

The Energy Performance of Buildings Directive has been greatly successful in reshaping the energy policy landscape in the EU Member States. For example, following inception of the EPBD, whole-building energy performance calculations, energy certification for buildings, protocols for inspection of air conditioning systems, and provision of advice for boilers, have led to better understanding of energy efficiency of buildings in the UK. The evidence available from other Member States also confirms the pivotal role of the EPBD in achieving a low carbon built environment for the future of the EU [42]. However, regulatory frameworks that are based on uncalibrated thermal modelling may hinder the EU countries in achieving their ambitious energy efficiency targets.

One of the main contributions of the EPBD in the last decade has been the development of a growing body of professional practitioners that have been formally trained and are qualified for thermal modelling. The cornerstone of the framework proposed in this paper is to integrate a measurement and verification plan into the EPBD to ensure measured energy performance is consistent with the intended performance under identical operating conditions. The requirement of having identical operating conditions is satisfied by a thermal model that reflects actual performance and is calibrated in accordance with the International Performance Measurement & Verification Protocol. Enablers for successful implementation of this proposal are:

- The existing body of energy assessors trained for thermal modelling,
- Possibility of using the existing methods and tools with minor adjustment for measurement and verification,
- Growing awareness of energy performance gap (credibility gap) and necessity to address it,
- Cost effectiveness of the scheme given that thermal models are already being used for whole-building performance calculation of new buildings and major renovations. Updating these models after building handover and when steady mode of operation is achieved could be done with reasonable amount of time and resources.
- Measurement & Verification of energy performance post-occupancy is already an optional credit in the LEED sustainability rating system [43]. Total energy performance is calculated based on *predicted operating conditions* under LEED rating system. The framework presented in this paper makes it possible to use a measurement and verification plan under the EPBD *standardised operating conditions*.

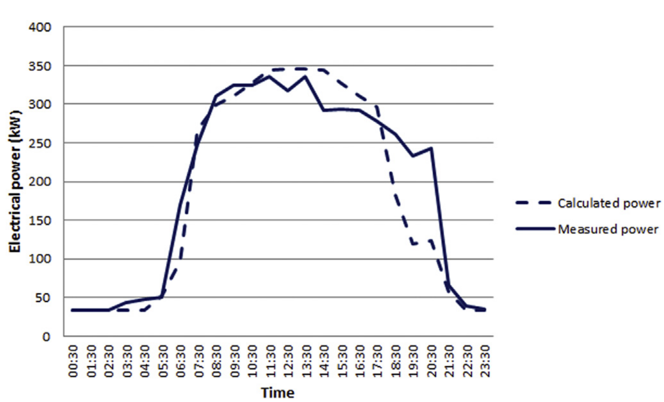

Fig. 7. Typical hourly electrical power demand curve: heating season.

It is suggested that, depending on contractual arrangements, designers or the main construction contractor should take responsibility for implementation of the measurement and verification (M&V) plan, and report the results to the building control body at the end of M&V period. In the context of United Kingdom, designers can take responsibility for M&V plan in traditional contracts where they are supposed to witness the installation of systems and confirm the design intents have been met following building completion. For design & build contracts, where the main construction contractor takes full responsibility for building procurement following the design stages, contractors can take responsibility for implementation of M&V plans. The experts who carry out the measurements and calculations must be registered with the existing EPBD energy assessment schemes, and subject to regular quality assurance checks. If poor building maintenance within the measurement and verification period has compromised the operation of building services, this can be identified by the designer or contractor and confirmed by the building manager before final calculations. An adjustment could then be made in final calculations to reflect this. Otherwise, designers and contractors should be held accountable for any procurement gap. The operational gap, on the other hand, is the responsibility of building users. The measurement and verification process can help differentiate the procurement and operational root causes of energy performance gap. Furthermore, it can lead to a more proactive engagement from the construction team post-occupancy that will help fine-tune a building and provide effective training to building users. Therefore, intangible benefits and tacit knowledge gained from such measurement and verification plan could outweigh the regulatory contribution of it.

National and regional energy targets set for the built environment reflect countries' concerns about climate change and energy security. However, the regulatory limits are often not directly comparable with measured energy performance. The framework proposed here would enable effective measurement of any excess in energy use over the regulatory limit set out for a building. It could be argued that the social cost associated with this excess in energy use is greater than the cost associated with the regulatory limit. For example, if the regulatory limit ultimately stems from the necessity to limit global warming to 2 °C in accordance with the recommendations of the Intergovernmental Panel on Climate Change [44], any excess over this regulatory limit could cause disproportionate environmental damage and, therefore, should be charged at a different rate or be subject to an environmental tax. Excess in energy use over the regulatory limit set for buildings is an economic negative externality that has not so far been addressed partly because it cannot be effectively *measured* under the current policy framework. The argument put forward here follows the notion of Pigouvian tax that is used to reduce or eliminate environmental negative externality by imposing a tax on a polluter equal to the social cost of pollution [45]. The Stern Review estimated the social cost of carbon, in 2005 prices, at $85 per tonne of CO_2 for the business as usual scenario, defined by the Intergovernmental Panel on Climate (scenario A1B) [46]. This review adopted a public policy framework that takes an ethical stance for the future generations by including low discount rates in its net present value calculations to estimate the social cost of carbon. This price effectively reflects the risk of failure of climate change mitigation policies. Therefore, it is justified to impose such an environmental levy on any excess in buildings' energy performance over the regulatory limit under identical operating conditions. Measurement and verification of the energy performance of new-build and retrofit projects can identify any procurement gap which could be subject to environmental levies. Operational gap may not be subject to these levies under the current policy frameworks as it is influenced by the way users operate a building. However, addressing the procurement gap can also help narrow the operational gap as a result of building fine-tuning and training provided to building users.

The M&V plan introduced in this paper makes it possible to determine the procurement gap regardless of any potential dispute about its root causes. However, robust protocols that clearly distinguish the root causes for procurement gap from operational issues would be beneficial to assess the effect of procurement gap on operational gap. To this end, future work will focus on analysing the root causes for procurement and performance gaps in a number of buildings that were investigated by the authors as part of the Building Performance Evaluation Programme instigated by the Technology Strategy Board [47,48].

It is also suggested that the M&V plan introduced here could first be applied to projects under voluntary and flexible frameworks such as Soft Landings before wider applications. This provides the opportunity to further improve the M&V plan, and assess cost implications along with any possible unintended consequences. The Soft Landings framework is focused on performance in-use and extends the after-care duties of construction teams up to three years post-handover [49].

6. Conclusion

The Energy Performance of Buildings Directive has helped the quest for energy efficiency and low carbon buildings in the EU. However, there is no requirement under the EPBD to verify buildings' energy performance in-use. Furthermore, the use of standardised operating conditions in energy performance assessment makes it difficult to compare actual performance with theoretical performance calculated under the EPBD. Integration of an appropriate measurement and verification plan into the EPBD could help separate procurement issues from operational inefficiencies. A framework for this integration is proposed, and a case study is used to prove the concept. The case study confirms that calibrated thermal models could reasonably match actual performance and, hence, be used to establish energy performance of a building under different sets of conditions, including the EPBD standardised operating conditions. It is suggested that, depending on contractual arrangements, building designers or construction contractors could take the responsibility of verifying energy performance of their buildings after completion. This could lead to a more proactive engagement from the construction team in fine-tuning buildings post-handover. A concerted action from the construction team and building users could pave the way to improved building performance. Comparing actual energy performance with theoretical performance under identical operating conditions could also help measure any excess in energy use over the regulatory limit that stem from poor construction practices. In the context of climate change, the social cost of excess in energy use over the regulatory limit is disproportionately high. Therefore, this excess in energy use could be considered a negative externality that must be measured and treated effectively. Integration of measurement and verification plan into the existing policy framework can facilitate this.

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