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Changing the approach to energy compliance in residential buildings re-imagining EPCs

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ABSTRACT

As our need for energy information of buildings evolves, and the tools and methods at our disposal increase in scale and complexity, it is perhaps reasonable to expect a similar level of change in the way energy in buildings is assessed within national energy compliance frameworks. By comparing the available opportunities for building energy modelling with the current methodologies underlying Energy Performance Certificates, this study proposes future directions for standardised energy assessment of residential buildings and the impact this could have on different facets of energy policy. In carrying out this exercise, a number of criteria are proposed that could be used to appraise methodologies that align with future requirements of energy assessment, with two potential candidates for future energy assessment considered as part of this appraisal. An argument is thus proposed for better aligning future forms of standardised energy assessment with directions and requirements of future low-carbon energy policy.

1. Introduction

The Energy Performance in Buildings Directive [1] has been one of the more visible initiatives for improving the energy efficiency of the European building stock. Alongside a series of other objectives, this directive helped cement the concept of Energy Performance Certificates (EPC) and, a focus of this paper, a framework for standardised energy modelling approaches that EU member states could follow.

The success and impact of EPCs has been well-documented, and will further be discussed in this study. However, the danger of such a successful and well-known approach to rating the energy performance of the building stock is when our needs for energy assessment change. Furthermore, as advancements are made in how we can model buildings (in terms of both software and also the hardware used to process that modelling), it can be difficult for any energy assessment framework to accommodate such developments when that framework is so deeply entrenched in energy policy.

This paper will explore whether the success of current EPC frameworks, particularly in the UK (but informed by the situation in other European countries), creates a level of inertia that restricts the ability to reflect the latest research on energy modelling within a useable energy assessment framework. This discussion will be aided by modelling of the authors (and those elsewhere) that corresponds to two different approaches to energy assessment: i) greater reliance on dynamic simulation modelling, and ii) greater incorporation of data science through the use of empirical data; and the contrast between these approaches and the largely steady-state theoretical modelling of many EPC approaches in Europe.

As we look towards new requirements of building energy assessment, an argument for a different approach becomes clearer. Not only may we wish for a more empirically-based energy rating for a building but, based on our expectations of the operation of future energy systems, there is a need for greater synergy between energy supply and demand. With this goal in mind, understanding the transient demand of millions of buildings (and how those energy signals aggregate together within stock-wide assessments) is becoming more important, particularly in relation to demand-side management and response. There is also the growing use of EPCs in energy policy for potentially punitive action on building owners, such as restricting the selling and renting of properties [2]. This is a step-change from merely using EPCs to indicate, approximately, the energy efficiency of properties such that energy-saving recommendations can be generated, and financial support identified, along with more stock-wide ambitions to monitor building market transformation.

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The question posed by this study is, therefore, should evolving needs of energy assessment be met by a co-evolving energy assessment framework, including a review of the fundamental underlying energy modelling within that framework? And how does the requirement for standardisation, in the way defined in the UK, prevent us from directing this evolution towards well-documented innovations and opportunities in fields of energy modelling?

The paper will focus on the residential building stock, but there are undoubtedly parallels with the non-residential sector (though additional modelling challenges exist in that sector). The discussions will also be mostly concerned with the UK, but it is important to note the response of different EU member states to the EPBD; by looking at quite different interpretations to the requirements of the EPBD, we can understand whether potential changes to energy assessment could still satisfy the EPBD, exist within a reformed EPBD, or be essentially EPBD non-compliant. Whilst the paper should not necessarily be seen as a critique of EPCs as historically applied, it will attempt to gauge whether our approach to energy assessment is fit for the future and, if not, identify other avenues that could be explored.

2. Reviewing the current picture

2.1. Response to EPBD across EU member states

The EPBD was introduced by the European Union in 2003 and was revised in 2010 and 2018. The recast directive [3] confirmed the requirements for the production of Energy Performance Certificates (EPC) when a building is constructed, sold or rented out. The EPBD describes the elements that must be considered when determining the energy use of a building but notes that the energy performance of a building shall be determined on the basis of the calculated or actual energy that is consumed to meet the different needs associated with its typical use. The directive also confirmed that the energy performance calculations may be differentiated at national and regional level and that the energy performance of both multi-family and single-family buildings could be based on the assessment of a representative building. The recast EPBD required the EPC to include reference values for the energy performance of the building and recommendations for options to improve the energy performance. The recast EPBD also confirmed the requirement for each EU state to maintain a publicly-accessible depository for EPC information.

The implementation of the EPBD has been monitored across the EU by, amongst others, the Building Performance Institute Europe (BPIE). They noted [4] that 14 EU states used only theoretical (non-empirical) methods to assess the energy performance of buildings. Of those states which also use actual energy consumption, different criteria were used in each EU state to identify which buildings could be assessed using each method. These criteria include building types, construction dates, locations, and the availability of energy consumption information. A technical assessment commissioned by the EU [5] noted that the 28 member states of the EU had 35 calculation methodologies in place which could be used to generate EPCs for new and existing buildings. Of these 35 methodologies, 13 used actual energy consumption to assess the energy performance of residential buildings. This is worth emphasising for those countries that, currently, only use theoretical calculations to satisfy EPBD requirements; there is actually considerable flexibility and different degrees of standardisation in EPCs across Europe.

As the BPIE has identified, every EU state provides at least one calculated method for assessing the energy performance of buildings. This calculated method may be used only for new buildings or it may be available for all buildings. Some EU states provide alternative calculated methods for assessing the energy performance of individual buildings; however, research [6] suggests that cost is the dominant factor when building owners are selecting which method to use for their energy assessment and, for this reason, the simplest method available is selected by the majority of building owners. For existing buildings, where not all construction details are available, most EU states provide a calculated method which uses assumed values for unknown construction details. The methods using assumed values may be described as either separate calculation methods or as variations on the calculation method used for new buildings. Methods used to create EPCs under the EPBD can therefore be categorised as:

- calculation using detailed construction information
- calculation using assumed construction information
- assessment based on similar reference dwelling
- measured energy consumption

The EPBD also requires EU states to hold assessment results within a central registry and suggests that financial measures which are intended to improve the energy efficiency of buildings should be linked to the indicated energy performance and the recommendations from the energy performance certificates. Possible financial measures are listed as free or subsidised technical assistance and advice, direct subsidies, subsidised loan schemes or low interest loans, grant schemes and loan guarantee schemes [3]. Examples of financial policy instruments which are (or have been) explicitly linked to the outputs of EPCs are:

- Greece Energy Saving at Home public financing for renovation of buildings with an energy rating of D or lower
- France Energy Transition Tax Credit provides funding via income tax for renovations which have a certified effect on a buildings energy performance
- Austria - Multi-storey Renovation Programme provides funding for renovation measures as cited on EPCs
- Lithuania Housing Modernization Programme whereby low-interest commercial loans can be translated to grants if the resulting renovations achieve an energy rating of at least C
- Belgium (Flanders) discount on property tax of between 20% and 100% depending on energy performance rating
- United Kingdom Access to feed-in-tariffs for onsite generation (requiring that the EPC rating of the property is already D or above) and qualification for energy efficiency financial support

The effect of EPC rating on sale and rental values of buildings has been examined in a number of member states including Austria, Belgium, France, Ireland and United Kingdom [7]. An increase in energy performance is generally seen as having a positive but limited effect on sale and rental prices. This is worth noting for the future role of EPCs in the development of building energy policy.

2.2. UK approach to standardised energy assessment

As noted above, there is considerable scope for different responses to the EPBD. Assessments that meet more general criteria about visibility and standardisation of the energy rating can use either actual or modelled energy consumption and can choose whether to have regional disaggregation within a country or not. The UK takes a relatively standardised approach to the EPBD with little in the way of regional disaggregation (though the EPC document itself is slightly different in Scotland compared to England/Wales) and a relatively homogenised approach to input generation.

Specifically, the response of UK Government to the EPBD was to formalise the Standard Assessment Procedure (SAP) for assessing energy use in all residential buildings. A reduced input version of this procedure, known as Reduced Data SAP (RdSAP) [8], is used for buildings constructed after 2009. Although SAP has been regularly updated since its genesis in 1995, RdSAP inputs were established in 2009 and were still in place in 2014. However, an updated version of the overall SAP methodology, SAP 10 [9], is currently being introduced in the UK.

A good example of the approach to inputs, and the degree of standardisation, in RdSAP is discussed by the authors elsewhere [10] in relation to U-value inputs. Here, a series of look-up tables is available to assign thermal transmittances by property age and generic description of construction (e.g. wall type). There are minor differences between the constituent countries of the UK but, otherwise, these values can be generically applied across the UK. Although reasonably rigid in terms of linking age and envelope U-value, these tables do, for example, provide 141 default U-values for external walls ranging between 0.32 W/m2K to 3.90 W/m2K.

2.3. Critiquing current EPC methods

Most EPC frameworks in EU member states have some form of quality control for the assessments themselves, such as re-assessing a small sample of lodged EPCs to validate outputs. However, there is a now a growing body of evidence that two distinct problems exist with EPC assessments across EU member states, though the extent of these problems may differ with chosen methodology in specific countries.

The first problem relates to the Performance Gap or what may be deemed the accuracy of the EPC in terms of its relation to real energy data. This issue is well documented in literature [11,12] and is not a new finding. Indeed, there is an argument that EPCs were not designed to accurately generate real energy bill estimates and, rather, are merely the result of an energy compliance tool that allows for indicative ratings of building assets (for a typical household) to be estimated. However, the growing use of EPCs for applications beyond basic energy compliance (such as detailed design of buildings, structuring loan repayments for energy efficiency investments, or punitive actions on homeowners to encourage energy retrofits) magnify the importance of this issue. The implication of this potential mission-creep of EPCs is discussed in Section 5 of this paper.

A second identified problem is arguably a more fundamental issue for a standardised energy assessment: consistency. Central to the EPBD is the idea that a replicable, standardised assessment can be carried out in the same way for any building. Effectively ignoring any subtlety relating to household behaviour (by focussing on the building asset only) makes this somewhat more straightforward but there still exists multiple inputs for an EPC that require some level of judgement from, and training of, an EPC assessor. With the lodgement of EPCs on a central database being part of the guidance of the EPBD, and with some degree of access to that database possible in most countries, many studies (some noted below) have been carried out that question the extent that EPCs are reliably consistent. Without this consistency, any advice emanating from EPCs (let alone any discussion about accuracy) is to be questioned. For this reason, this paper will focus on consistency as an essential requirement for any replicable energy assessment.

Previous work by the authors [13] has noted that multiple assessments of a small sample of 29 dwellings (as part of a Mystery Shopper exercise) do not necessarily return the same results, even when those assessments are carried out within a similar time period (i.e. where assessed homes have not undergone any changes between assessments). A study of a larger number of assessments for a single dwelling [14] also suggested a lack of consistency due to different interpretations and approaches of energy assessors.

Studies looking at lodged EPCs over time for the same properties have the added difficulty of dealing with changes that have occurred to those properties (such as energy retrofits and extensions), as well as updates to the EPC methodology. However, a number of studies have accessed the large sample of dwellings in EPC lodgement databases to make more generalisable conclusions not always possible from smaller samples. One study [15] identified different flags in the UK EPC database that indicated two assessments of the same home having differing underlying assumptions (such as floor plans, chosen built form and wall type). From a selection of 15 million homes, 27% were flagged as having inconsistent assessments with a suggestion that 30% of homes could have been placed in the wrong EPC energy rating band (i.e. A to G). Other work [16] attempts to quantify a measurement error in EPCs, looking at a sample of 1.6 million dwellings that had exactly two EPCs in England/Wales. 52% of dwellings were found to change energy band between the two EPCs. Whilst many of these homes would have achieved this through a genuine improvement in energy performance (through active energy efficiency programmes between the two EPC assessments), 19% of the 1.6 million showed a lower (i.e. worse) energy rating in the second assessment. A semi-parametric model is used to distinguish between genuine changes in homes and actual errors, with the suggestion that the database shows significant risk of energy rating misclassification. Similarly, another study [17] uses data analytics to highlight quality issues and changing applications of EPCs over time. Other studies note that more advanced forms of data collection could help efforts at standardisation. The use of CityGML files [18] to better describe the building stock could be used as part of an information flow for efficiently characterising energy performance of buildings. Techniques have also demonstrated how to determine thermal characteristics of many buildings simultaneously that, as well as useful for building energy stock modelling, could play a role in a refined energy compliance process for individual buildings [19].

It is also clear, and is noted in Section 2.1, that key differences exist in terms of member state response to the EPBD. It has been described elsewhere [10] how quite stark differences in calculation methodology exist between countries, despite the common goal of standardisation proposed by the EPBD. This can be extended to consistency of application, with studies suggesting that only 60 80% of EPCs are good quality, with half of EPCs in Spain, for example, deemed incorrect [20]. Further inconsistencies have been noted in other European countries that relate to the evolution of schemes over time, with work in Denmark [21] and Sweden [22] describing disagreements in inputs behind, what should be, comparable EPCs for the same homes. The latter study found that 15% of multifamily homes in Sweden had multiple EPCs that were not comparable due to significant disagreements between assessors (e.g. significantly different heated floor area recorded).

The above studies suggest that, whilst we may wish to address the accuracy and applicability of EPC methods as we go forward, we need enhanced scrutiny to ensure there is a high level of consistency across EPC assessments. This paper will argue that more detailed levels of calculation do not have to be at the expense of this consistency and, therefore, could still exist within a standardised framework.

2.4. Other forms of energy assessment

Informed by current research, the below suggestions are intended to broaden the description of energy modelling beyond conventional steady-state calculations of dwellings. Section 3 will attempt to direct this work towards a more actionable energy assessment framework.

2.4.1. Dynamic simulation of urban energy modelling

Various forms of building simulation have existed since the 1960 s. Early frequency-domain methods gave way to the time-domain long before simulation techniques were commonplace in industry, due to their ability to handle nonlinear thermodynamic processes. Comprehensive descriptions of these methods are provided elsewhere [23].

By the late 2000 s, it was standard practice in the UK construction industry to use building simulation for three distinct purposes relating to non-domestic buildings: to design buildings for heating, cooling and ventilation purposes; to assess energy performance for accreditation; and to provide EPCs via mandatory simulation (for all permanent buildings above 50 m^2). For the latter two, typical occupant behaviour is stipulated via the National Calculation Methodology. On this basis, there is an understanding that the simulation outputs will not reflect as-built energy use, however, the simulations can pragmatically be used to support design decisions. These applications have driven necessity for both commercial and open source simulation tools, which are designed to handle large and complex HVAC systems on a scale up to that of airports, hospitals and university campuses.

In contrast to non-domestic construction, it is uncommon for simulation to be used for single dwellings outside research activities. Urban-scale simulation of multiple dwellings is, however, drawing significant interest from policy makers, network operators, and local/housing authorities. This stems from a need to provide aggregate intra-day demand patterns for sections of buildings stock, to understand network constraint issues, to understand integration difficulties around renewables, battery storage and other low or zero carbon technologies, and to identify targeted communities for grants and support to alleviate fuel poverty. These contemporary issues are at the forefront of policy development, and while they lean on well-established methods, much of the data infrastructure (including the EPC register) is stretched beyond its intended purpose.

A number of research tools have emerged over the last decade, which make direct use of dynamic simulation for the purpose of Urban Building Energy Modelling. A recent review [24] specifically highlighted the use of EnergyPlus, ESP-r, and Modelica in various tools which support simulation at a timestep of less than 1 h. One of these tools, TEASER [25], falls within the broader Integrated District Energy Assessment by Simulation (OpenIDEAS) framework, which incorporates a Time Use Survey-derived stochastic occupancy model StROBe [26]. Integration with GIS data was also investigated [27].

A new approach proposed for this paper [28] has been to directly interface with three key data sources: the EPC register, GIS data from the UKs national mapping agency (Ordnance Survey), and smart meter data. Integration of EPC and GIS data in particular presents difficulties around underlying taxonomy; however, there are significant opportunities for unifying and extrapolating data to make better model descriptions at a community level. There are a number of shortcomings of the existing EPC framework with regard to providing data for this purpose. EPCs do not provide data to describe the temporal response of dwellings to behaviour under time-of-use tariffs, suitability for demand response or distributed energy storage systems. These issues are discussed further in Section 3.1.

2.4.2. Statistical modelling from empirical data

Conventional approaches for energy compliance often lean heavily on physical, theoretical energy demand models. However, many examples exist for the use of empirical data to inform (or generate) energy demand models in the UK and elsewhere though it may be questioned whether these all lend themselves to energy compliance assessments of buildings. MARKAL (MARKet ALlocation) [29], the UK TIMES Model [30], and the CREST demand model [31] are all well-established models that are informed by real energy data to different degrees, though not necessarily focussed on the individual dwelling. With data now available at a scale and quantity not seen before, it is essential to identify good-quality, high-resolution data for delivering ambitious carbon targets and facilitate the development of robust data-centric decision-making tools. To address these challenges, there is now a growing body of research focussing on representing physical systems through the application of data-driven modelling techniques [32,33].

A range of statistical and hybrid approaches has been developed and applied in the building energy domain. Some of the widely applied techniques include: Box-Jenkins methods (e.g. Autoregressive Integrated Moving Average (ARIMA) Models [34]), Artificial Neural Networks (ANN) [35], Support Vector Machine [36], Deep Learning model [37], Monte Carlo Simulation [38] and Markov Chain Models [39].

Focussing on areas of applicability for building energy assessment, residential energy demand profiles for individual dwellings, available through smart meter data, can be statistically analysed to extract various household characteristics, such as those related to socio-economic class/status, dwelling properties, and appliances [40,41]. Specifically, high-resolution (e.g. 5 min and below) electricity demand profiles can be analysed to communicate energy behaviour characteristics that would not be discernible through the use of purely physical modelling. For example, the authors developed a novel framework of statistical models that couples a Hidden Markov model (HMM), a Seasonal-Trend Decomposition procedure based on Loess process (STL), and a Generalised Pareto (GP) distribution for simulating dynamics of high-resolution (5 min and below) electricity demand profiles [42]. The application of STL facilitates temporal decomposition of stochastic components of demand profiles from deterministic features. Seasonal features are attributed to various overlapping, repeating activities embedded in typical demand profiles and are linked to distinct time periods. This level of information can be organised to develop a portfolio of specific activities occurring at specific times in the household, which can be effectively linked to understand various causal factors [43]. Crucially, there is the potential to develop templates of activity from these causal factors which could lend themselves to a more standardised approach for energy assessment. When combined with other contextual information related to the household, this can be further applied to infer the causes of those specific activities and the quantifiable impact that these activities could have on overall energy consumption [44].

In data-rich areas, there is a need to efficiently characterise and categorise that data in order to obtain more generalisable meaning from that data. One route towards this is the use of simple k-means based clustering techniques for time-of-use categorisation of specific demand features, as presented in Section 3.2. Such clustering-based techniques coupled with a demand disaggregation technique has the potential to categorise and map different types of building, linked to specific demand features. This has a similar objective to, for example, research using machine learning techniques to extract key household characteristics from electricity consumption measurements, recorded from 4232 smart meters at a 30-minute resolution [40]. Thus, a purely data driven modelling approach can be developed to generate standardised template demand profiles specific to the certain household type though it may still be questioned whether this standardisation is, or could be, consistent with the EPBD.

However, research is now suggesting that a path may exist to greater use of empirical data in the energy rating of buildings. A Domestic Operational Rating (DOR) scheme has been developed for assessing the energy performance of occupied dwellings [45]. The DOR method utilises standard statistical approaches to analyse daily smart meter data (collected from 114 homes) alongside contextual information collected as part of an energy/household-based survey. The DOR scheme provides a performance metric for rating overall energy performance of the house based on the actual energy efficiency of dwelling. In addition to this, several other possible applications can be developed for such a modelling system, such as optimising energy consumption at individual household level, feature selection for classification of customers, designing flexible tariff plans, and understanding key behavioural attributes for designing future energy saving policies [46]. This greater level of detail of individual dwelling energy performance is likely to have considerable value as we design our future low-carbon energy systems with a more complex relationship between demand and supply.

3. Identifying new options for energy assessment

There are a multitude of different methods for assessing energy use in buildings, and many have already been indicated in Section 2. Below are two options, or rather two areas of research from which options could emanate, that could characterise energy demand in the building stock in a way that better reflects the current state of research in those areas. Firstly, there is a modelling approach that, although borrowing aspects of current stock modelling, uses dynamic building physics as the core modelling engine. Secondly, an approach aiming to classify (and potentially rate) buildings based on empirical transient demand characteristics is proposed.

These are not, in this instance, proposed as directly comparable to current SAP-based modelling, and formatted EPC generation more generally. They are not, for example, designed to generate formal Asset Ratings or use terminology currently familiar with energy assessors in the UK. They also differ from current approaches in that they are chosen to reflect future applications of energy assessment, such as the need to characterise demand flexibility. These methods are therefore very much outside current industry practice, and later sections will attempt to critique these approaches against a set of criteria that the authors suggest are important for future energy characterisation of buildings. Following this evaluation, a judgement can then be made about whether this type of modelling could perform a role in standardised energy assessment.

3.1. Standardising transient dynamic modelling approaches

Following Section 2.4.1, a potential approach to assessment through building simulation is discussed here. In some respects, the notion of including simulation methods for assessing the residential stock suggests a prohibitive increase in complexity. The argument, however, is that our main concern should be the avoidance of unnecessary complexity on a surveyor and practitioner level, as we are already aware of the inadequacies of manual data collection and lack of consistency in asset rating evaluations between different practitioners [13]. In theory, approximate simulations can be constructed that reflect the data that surveyors already collect albeit, preferably, with some additional information from other surveys. The question should then become, how is it possible to make effective individual dwelling simulations out of limited and highly contextualised data? To discuss this, we draw here on parallels with archetype-based stock modelling, and on modern approaches to distributed computing.

Archetype-based stock simulations involve preconceived simulation models, tailored automatically for specific dimensions, proportions, construction type, fabric and so on. Increasing use of GIS and EPC data in stock modelling was discussed previously; but an important facet of this approach is the collation and integration of data. Existing data methods used for stock-modelling could be used for enhancing the quality of the survey database and to enrich the data where necessary to allow simulation. In the present context, given a scenario where results from a new survey have just been logged, these direct survey records (i.e. EPC modelling inputs) could be viewed by a third-party verifier on a macro-basis against the surrounding area. Discrepancies may reflect reality (which is of great importance); however, irregularities could be investigated for repeated survey work. This could introduce a completely new idea of accountability and quality control in energy surveying.

Regarding distributed computing, SAP was developed to follow what is now a reasonably outdated software paradigm of download, install, run-on-local-machine. In this context, a calculation engine that was computationally lightweight and robust was sensible. Many modern software packages involve either fully web-based processing or have lightweight client tools which link to server(s) via Application Program Interfaces (APIs). The way in which energy assessments are carried out could conceivably change, to include server-based computations, automation, machine supervision by both practitioners and regulators, and systematic third-party verification. Part of this automation could include multiple simulations of all plausible archetypes; where glazing configuration is not clear in terms of faÓade area, for example, a series of simulations may be carried out which reflect a limited range of possibilities. The same could apply to different occupancy patterns, crucial in the generation of transient energy demand profiles. This would begin to introduce formal uncertainty procedure into the energy assessment methods.

During the development of building modelling, tractability issues around processing time have diminished significantly, and for dwellings computational time is trivial. The savings in manual handling and checking of data, iterating through calculations on laptops, would likely far outweigh this cost. Much of the underlying technical software already exists in the form of open source simulation engines (e.g. EnergyPlus) and batch processing and analysis libraries (e.g. Python). There would still be considerable work required to build and maintain this process and adapt to new regulations, but significant opportunities would arise from either a centralised or federated system.

A clear procedure can therefore be distilled from the above data and modelling environments:

1. Obtain construction and geometrical data of dwelling for the target building via GIS data and automatically generate a set of building variants
2. Obtain thermal characteristic and service (e.g. heating) technology information from survey data (including existing EPC input surveys), for the purpose of generating a new EPC
3. Generate multiple occupancy profiles from available smart meter data to infer transient activity schedules
4. Run multiple dynamic simulations via an embedded calculation engine from the above input data to treat occupant-driven uncertainty
5. Although being of use for aggregated energy calculations, being a bottom-up model, the above will generate multiple individual energy consumption metrics which could be aligned to a similar standardised framework as current EPCs

This describes how a powerful approach to dynamic stock modelling can be repurposed to efficiently generate energy ratings at scale, whilst having an underlying calculation architecture allowing for different forms of performance metrics to be outputted (as described in Section 4).

3.2. Characterising performance from empirical data

Section 2.4.2 referred to clustering techniques for building energy categorisation. An example of this will be proposed here as a potential route to standardised classification of energy use based on empirical data, applying a simple k-means clustering approach to a case-study (Fintry community [47]). 30 minutely data was collected for 56 dwellings over a period of six months and has been analysed to extract seven distinct annual demand-related statistical features. These features are used to exploit the use of higher resolution energy data; that is, the focus is not purely on annual or monthly energy consumption but, rather, characteristics of demand that provide a richer understanding of transient energy consumption. Despite this objective differing from standard energy compliance frameworks, there is still an avenue towards energy rating classification. Whilst, for simplicity, such a technique could be applied to purely physical parameters (e.g. peak demand, annual costs/energy use), the approach can yield more closely defined statistical groupings if exploring the use of proxy variables that combine several different features of the data simultaneously. Three chosen statistical features are cost function based: i) half-hourly cost of supply, ii) non half-hourly cost of supply, and iii) cost of supply depending on time of use and consumption pattern. The other three features are load factor based: iv) daily load coefficient of variation, v) average annual load factor (average/peak demand), and vi) total consumption. There is also a weather related feature: vii) degree day correlation. These seven features are analysed using Principle Component Analysis (PCA), a widely applied mathematical approach for transforming a high dimensional correlated dataset into a smaller set of uncorrelated principle components. Two separate PCA procedures were applied: i) for three cost function related variables, and ii) for three load function related variable. These features are proposed for demonstration, and have value to applications discussed in this study, but the approach of transient feature identification, a PCA-based reduction of number of features, and then a clustering analysis of half-hourly demand data using those proxy variables, could be applied for different starting features to match a required output index for purposes of energy demand classification.

The aforementioned dataset for the month of February 2017 (chosen due to completeness of data, but the process would work for larger time periods) was used to form clusters around the three PCA components extracted from the seven annual features. The proportion of total variance described by the three PCA parameters (PC1, PC2 and PC3), for cost and load functions, is presented in Table 1. This provides an indication of the importance of each PCA parameter in terms of correlation with the cost- and load-related values generated above.

As most of the cost function related information (more than 97%) is captured in the first component, and more than 80% of load function related information is captured in its first two components, the k-means clustering is applied to a total of 4 variables: PC1 for cost function, PC1 and PC2 for load function, and a degree day correlation variable. All the variables are standardised, and the k-means clustering is applied using the functions fviz_cluster in the R package factoextra [48]. An elbow method is applied to obtain an optimal cluster number for the 56 dwellings. Further details on the k-means procedure and its implementation in R is described elsewhere [49]. Fundamentally, the aim is to have household demand values clustered into clear, distinct groups, that could form the basis of an energy classification procedure. Table 2 presents standard summary statistics for assessing the intrinsic characteristics of the clustering presented in Fig. 1, including the Within Cluster Sum of Square (WCSS) metric, the squared average distance of all points within a defined cluster. The Between Cluster Sum of Square (BCSS) metric shows the variation between the clusters in terms of squared average distance between all centroids. Thus, a smaller WCSS ensures less dispersion within a cluster (and potentially a validation of that cluster as a chosen classification) whereas a larger BCSS indicates a good separation achieved across the different clusters. Further, Silhouette (Si) analysis is conducted to measure how well each observation is clustered. Si can range between 1 and 1. A value of 1 indicates observations are very well clustered, a value around 0 indicates observation lies in two clusters, and a negative value indicates possibly incorrect clustering. Individual and cluster-average Si values for all observations (56 dwellings) are found to be positive. Some other indicators, such as the Partition coefficient index and the classification entropy, are not used for the present study but could be used for judgement of suitable clusters in future applications of this method (and is currently being explored further by the authors).

As with any k-means analysis, different sensitivities of clustering can be proposed, but this study demonstrates the result of using four clusters for the 56 dwellings, shown in Fig. 1. The axes of Dim1 and Dim2 represent the chosen proxy PCA variables, described above, but correlations with other proxy and physical variables could be explored within this type of clustering analysis.

Not only may these clusters provide a basis for energy classification, but with an understanding of causation included in the modelling of demand, it could be possible to publish such classifications with basic energy-saving recommendations, as required with current EPCs. There would be a requirement to have data to quantify such savings but, likewise, there is a limitation on a purely theoretical model to only include recommendations that can be modelled within that particular calculation engine.

4. A structure for assessing energy performance of buildings

4.1. Defining the purpose of assessment

The following section sets out a number of criteria (C) around which an energy performance framework might be judged on. Although not an exhaustive list, these are chosen based on the aforementioned research in terms of what is desirable from energy models, but also what is possible. There are clearly elements of subjectivity in the choice, and assessment, of these criteria but their importance is well-documented in studies of energy assessment. The criteria are also designed to be technology-agnostic; or, at least, capable of incorporating a range of different

Table 1
Results of variance from three components of PCA processes.

Proportion of Variance	PC1	PC2	PC3
Cost function related	0.9799	0.01996	0.00017
Load function related	0.5364	0.2752	0.1883

Table 2
Summary statistics of k-means clustering.

	Cluster 1	Cluster 2	Cluster 3	Cluster 4
Size of cluster	21	22	23	14
WCSS	37.22	29.15	39.23	22.18
BCSS	188.19			
Average Si width	0.20	0.34	0.19	0.27

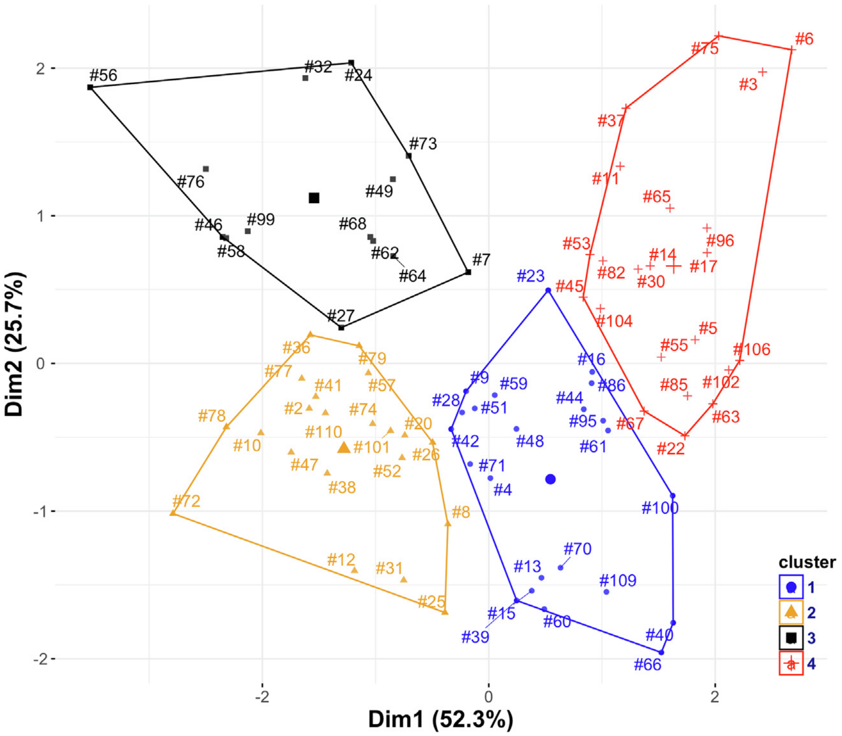

Fig. 1. 56 dwellings organised in four clusters through the application of k-means clustering approach coupled with PCA.

technologies where strengths (and weaknesses) of a diversity of measures may not be currently accommodated comprehensively.

4.1.1. Aligning an energy rating with characteristics of real performance (Criterion 1 (C1))

When defining a measure of success for any energy modelling approach, it is important to recognise the problem of the Performance Gap. Conversely, it should be remembered that a current EPC rating should not be used as a direct proxy for real energy bills, due to the focus on the asset rather than the occupants. However, even accepting that certain models are unlikely to return a high numerical similarity with measured energy data, it is arguably valid to expect characteristics of energy demand from a model to be similar to that of real energy data. For example, a successful model (particularly in relation to some of the potential applications hinted at below) when compared with real data may suggest similar timings of peak demand, similar relative differences between a low and high energy-using home (even if absolute values of model and reality are less well-matched), and similar scales of impact for given technology choices (or refurbishment measures) when applied to a specific building.

4.1.2. Projecting flexibility of energy demand for different properties (C2)

A steady-state energy model that is not designed to simulate high-resolution energy demand, and is not directly able to account for thermal lag over a period of time, is arguably not suitable for modelling peak energy demand for buildings at either individual or aggregated level. However, other methods mentioned in this paper may be better suited to model demand profiles in such a way that a combination of heating technology, building thermal mass, storage options and heating controls can be directly characterised. This raises the possibility of, in addition to standard energy ratings, the production of a flexibility rating from a standardised model. Applied at scale, this would allow for different building archetypes to be classified in terms of their demand flexibility potential. As well as helping to understand how potential transformation of building stocks could impact issues of energy supply (e.g. changing peak demand on National Grid), this could also help (for example) aggregators identify customers who would be best served by, and be most valuable for, demand management solutions. The use of a separate criterion for demand flexibility reflects this importance.

4.1.3. Accommodates new technologies on market (C3)

There are several technologies that have entered the building sector in recent years, or are projected to do so in the near future. Some of these have arguably tested the ability of our current energy assessment tools. A range of technologies (noted in Section 4.2.3 and elsewhere [50]) are currently being proposed as key markets to expand as we move towards low and zero carbon targets in the housing sector. Combined with the aforementioned importance of understanding the demand-side management impact of energy efficiency measures, there is a danger that the UK ends up with an energy compliance framework that cannot account for some of the more notable transitional technologies for a low-carbon future. More generally, it should not be assumed that a modelling approach that was designed for a housing stock with high space heating demand will necessarily be suitable for a future housing stock that (with improved insulation and climate change) has significantly lower heating demand.

4.1.4. Suitability for taking punitive action on householders (C4)

As already discussed, there is a notable difference between using energy ratings to note generic information, and energy ratings for (potentially compulsory) action particularly when that action is focussed on the responsibility of a homeowner. In the past, a model with a large Performance Gap or, in a subtler way, a model that does not provide the same picture of energy efficiency as real energy data, may offer sub-optimum advice to a householder (e.g. incorrect paybacks of a technology) though that householder may still be given a reasonable idea of what measures may or may not be suitable for their property in a very general sense. Looking to the future, the same models could directly penalise certain house (or household) types over others simply because the chosen model does not compute a certain technology (or architectural feature) particularly well. When transitioning from advising on action to compelling it, there is a clear need to review the modelling approach behind that instruction. How can the risk of unfairness be minimised?

4.1.5. Ability to extrapolate and standardise (C5)

Central to all responses across Europe to the EPBD is the ability to conduct a modelling approach for millions of buildings, in a way that is efficient (in terms of person and time resource) and consistent. Whilst this paper has already documented questions over the consistency of UK EPCs in the past, the philosophy behind the SAP model, and the basis for a replicable, homogeneous energy assessment methodology, is clear and valuable. Any method that requires a greater number of inputs (i.e. more detailed information of the building and/or household), with greater degrees of freedom within those input parameters, and potentially placing greater onus on the assessor to make specific judgements about the property, is likely to become more difficult to standardise thus moving the approach beyond the requirements of the EPBD and making national-level comparisons of building stock less meaningful.

4.1.6. Quality of input information (C6)

It is difficult, for any model that produces questionable outputs, to distinguish whether problems have emanated from a flawed calculation engine or from unrepresentative inputs. The quality of these inputs (defined here as being how representative the model inputs are of the real building) can be impacted by the level of standardisation of the method. For example, the lookup input tables used in RdSAP [8] ensure that all assessed, existing dwellings in the UK are using the same data sources by age group (i.e. enhancing consistency), but do not always allow a modeller to accurately represent the specific in-situ materials of construction (which will have undergone weatherisation and be subject to improvements over time). In other circumstances, an input value may simply be difficult to measure (e.g. actual running efficiency of a heating technology) within the remit of a typical energy assessment. Whilst it might be an over-simplification to say that more standardised approaches take greater compromises on data accuracy, there is a tension between achieving consistency of input data across millions of buildings, and accuracy of input data for a specific building being assessed.

4.2. Suitability of approach towards defined objectives

With the three modelling philosophies documented (including the existing steady-state approach), and criteria proposed for judging their suitability for large-scale energy assessment, Table 3 provides an evaluation on the ability of those modelling approaches to meet these key criteria. The justification for this judgement is provided below.

4.2.1. Alignment with reality

It would be incorrect to suggest that dynamic modelling does not, like steady-state modelling, suffer from a performance gap when comparing with real energy data. However, the fundamental thermal physical processes that occur within a building can be better specified through dynamic models. The transient nature of air flow, heat transfer, thermal mass and occupancy behaviour can only be addressed by steady-state models through considerable simplifications and proxy coefficients. So, whilst the difference in size of performance gap between steady-state and dynamic simulation is difficult to quantify, the ability of dynamic simulation to better model real building physics is clear and hence the suggestion that dynamic simulation satisfies this criteria to a medium level, compared to the low level of steady-state models. Empirical characterisation, by definition, has a stronger relationship with real energy data though this may cause challenges for other criteria that are addressed below.

Table 3
Evaluated ability of different assessment approaches meeting selected criteria.

	Steady-state EPC models	Dynamic simulation	Empirical characterisation
C1 Alignment with reality	Low	Medium	High
C2 Flexible demand rating	Low	Medium	High
C3 Accommodates new technology	Medium	High	Medium
C4 Suitability for punitive action	Low	Medium	High
C5 Extrapolating and standardising	High	Medium	Low
C6 Quality of input information	Low	Medium	High

4.2.2. Flexible demand rating

As discussed, energy system/network modelling requires an enhanced understanding of flexibility of demand. This is a criteria that, arguably, would not have been at the forefront of energy compliance decades ago, but should now be seen alongside energy efficiency as being a fundamental part of a low-carbon system. Steady-state modelling, with its (at best) monthly energy estimates, does not have the ability to model transient, dynamic aspects of energy use and, the authors would suggest, should not be used as an engine for understanding flexibility of demand (and the underlying physical processes that might provide that flexibility) hence the low rating proposed here for meeting this criteria. Dynamic modelling does provide higher resolution demand modelling, and can model key drivers of flexibility such as thermal mass, dynamic thermal storage, and occupancy control/behaviour. The caveat here, and why dynamic modelling is judged as meeting the criteria to a medium but not high level, is that there are challenges to meeting the input requirements for characterising flexibility in a comprehensive manner. This touches partly on C6, but some aspects of flexibility modelling requires a high temporal resolution (e.g. minutely) to understand timings of peak demand. Dynamic modelling, particularly when used within energy compliance frameworks, tends to run at half-hourly to hourly resolution (though less standardised approaches can use greater resolution). The ability to use empirical characterisation to adequately reflect timings of peak demand, and methods of shifting demand for either demand or frequency response, will also depend on the resolution of collected data (e.g. from smart meters), but there is more potential here to comprehensively characterise demand flexibility options.

4.2.3. Accommodates new technology

As a criteria, this can potentially cover a wide range of technologies, some of which have yet to infiltrate a mass market. It could be hypothesised that, providing your underlying calculation approach is robust and comprehensive, any new technology introduced into that methodology could be accommodated. The current approach in the UK does have a procedure for quantifying the impact of new technologies [51], such that they can be accommodated within the existing SAP model. However, as noted in 4.2.1, the underlying calculation methodology must be considered when judging whether specific technologies can be modelled in a reliable way and we should question whether steady-state calibration factors and coefficients of approximation are always appropriate for technologies that are fundamentally dynamic in nature. Such concerns may raise valid questions of the ability of SAP-type approaches to model, for example, district heating, heat pumps, onsite storage (noting the rise of rooftop solar photovoltaics in many countries) and electric vehicles (should the latter become part of residential energy demand more formally through off-street home-charging). Dynamic modelling can operate with calculation time-frames more conducive to modelling some of the above technologies and arguably be more amenable to any technology with a strong diurnal cycle of variation. This justifies a high C3 rating for dynamic modelling, as opposed to the medium rating of steady-state modelling. For empirical data, the judgement revolves around what level of sub-metering is feasible for use with an energy assessment framework for large numbers of buildings. Without sub-metering, pattern recognition techniques [52] can still be used to distinguish specific energy use categories (and even individual appliances) in the home. This suggests some ability to distinguish individual technology performance empirically, but in a way that could compromise C5.

4.2.4. Suitability for punitive action

It is difficult to judge to what extent a model might be suitable for enforcing action from a homeowner, but one way of viewing this is the idea of fairness of an instruction based on our detailed knowledge of a modelling approach, is it fair that an individual will be compelled to carry out some measure based on the output of that modelling approach? Or, faced with some kind of appeal from a homeowner, what evidence might be presented to justify that instruction? For the steady-state approach (and SAP specifically), we are dealing with a model that was primarily designed for generating approximate energy ratings, does not account for the household specifically, and does not accurately predict energy bills. It may therefore be argued that such a model should not be used to enforce action to the level of, for example, restricting the selling/leasing of properties. This is reflected by the chosen low rating for C4. The ability of dynamic modelling to, at least, interrogate why (and when) certain energy uses are higher than desired provides some layer of accountability for justifying a punitive action though only a medium C4 rating is proposed to account that this is still a largely theoretical model. Justifying action on actual energy use (i.e. incontrovertible evidence that energy is high in a property) suggests a higher level of proof and accountability. Even a modified form of this, using generalised energy patterns from an empirical database to match a given property, would provide a stronger platform than theoretical models.

4.2.5. Extrapolating and standardising

The advantage of a relatively simple calculation method with a well-established framework is that, evidently, this can be extrapolated and standardised (subject to concerns addressed above for SAP specifically). The current method (rated high for C5) will therefore not necessarily have the same level of challenge experienced by a dynamic model (rated medium) with more complex inputs and (potentially) a higher level of training required for the assessors. However, there is enough research (some documented above) to suggest that we have not adequately explored the potential for dynamic modelling in the residential sector noting that the UK already uses dynamic modelling for some non-domestic EPCs. Empirical data could place a greater challenge on standardisation; even with the suggested clustering and template approach of Section 3.2, empirical data betrays the role of the householder within the signals generated, in a way that asset-based theoretical models do not. There may therefore be a compromise required on either the level of standardisation, or a new approach to rating buildings that are linked to different household (as well as building) categories.

4.2.6. Quality of input information

Previously documented research on current EPCs draw attention to issues around data quality, with different assessors using different input parameters for the same house. However, even ignoring that problem, a heavily standardised approach will (by design) attempt to simplify modelling inputs into a finite number of options. This raises the prospect of giving misleading information about how a specific dwelling may perform which, depending on the application of an EPC, may become a problem. Dynamic simulation gives more scope for building-specific information to be collated, and the data collection method proposed in Section 3.1 suggests that this can be achievable at scale whilst still noting the limitations of collecting data for a theoretical model. A Big Data approach to building and energy classification implies a higher degree of representation of individual buildings and their energy characteristics for the Empirical Characterisation method. However, this would have to be paired with a wide-ranging clustering method for categorisation, and causal factors, that would require the method of Section 3.2 to be extended somewhat.

In the way defined here, C6 essentially counterbalances C5; the ability to get reliable input information for individual dwellings can cause challenges for standardisation.

5. Conclusions

This paper has attempted to demonstrate new approaches to large-scale energy assessment in buildings, alongside a criteria-based evaluation framework for judging new methods. The study draws a contrast between currently accredited approaches to energy assessment and the advances being made in this field within academic research. There is clearly a philosophical difference between some of the traditional forms of building energy assessment used under the EPBD, and some of the less established techniques described in this paper. Going forward, if the only intention of energy assessment frameworks was to maintain a very approximate basis for calculating energy ratings of buildings, then there would be a reasonably strong argument to maintain status quo albeit with considerable updates to methodologies, and more best-practice sharing across EU member states. There is also an unavoidable discordancy between relatively complex technologies and design features (e.g. solar passive design, control of onsite generation technologies) and, by design, simple energy compliance frameworks.

However, as argued in the paper, on both a technical and policy level, there are several examples of EPCs being asked to provide guidance in areas that they are ill-suited to do so. Furthermore, even some of the perceived strengths of current EPC approaches, particularly relating to standardisation and consistency, should be questioned; in particular, new methods of energy assessment could enhance aspects of standardisation, rather than dilute this.

The alternative methods proposed in this paper are not exhaustive, and are not presented as complete and fully-formed alternatives to current EPC methodologies. However, they do demonstrate that there are now substantial bodies of research that point to a new way of assessing energy use in buildings that are replicable, scalable, and adaptable to the vagaries of a non-homogeneous building stock.

As energy policy relating to buildings enters a new phase, where new technologies and interactions with those technologies are fundamentally different to previous decades, it is vital to have adequate tools to design these energy systems, plan ahead for new building and large-scale retrofit projects, and reflect that our description and characterisation of energy demand needs to change to maximise effectiveness of these energy systems. In addition to the above, this paper has proposed a series of criteria that may be used to critique any new form of building energy assessment, where these criteria are based on current and future challenges impacting energy policy, rather than looking backwards at criteria from yesteryear. The next step will be to ensure that the considerable number of options available to meet these criteria are morphed towards a practical approach to standardising and characterising energy performance of our building stock, with a modelling architecture that is future-proofed for key challenges in the coming decades.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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