1. Implications of open access data for low cost KPIs measuring energy efficiency

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Abstract

In response to the Energy Performance of Buildings Directive (EPBD) most EU member states have established a national energy calculation methodology to measure the energy performance of buildings. The EPBD came into effect on 4th January 2003. Its principal objective is to promote the improvement of the energy performance of buildings through cost-effective measures. To achieve this it is obviously necessary to have a way of measuring and comparing the energy performance of buildings.

Each of the European countries has developed a different methodology, tailoring them to the specific characteristics of their country. In the UK the chosen standard was SAP. One common feature of all of these methodologies is that they principally attempt to perform a detailed energy calculation for the house concerned. Doing this requires that considerable quantities of detailed information regarding the house are gathered.

When such information can be gathered with minimal effort, such as for new build housing, these approaches are attractive. However problems arise when assessing large numbers of existing housing. In such cases the basic process of visiting the properties to gather the required data consumes considerable amounts of time and effort.

In practice the effect of this is that large numbers of existing houses are not assigned a rating. This problem is especially prevalent in the UK, where housing stock turnover is low. This brings into question the suitability of detailed energy assessments as key performance indicators (KPIs) for rating the energy efficiency of existing housing.

Recent developments in ICT, and especially the rapid improvement in the availability and quality of freely available street level photography, offer a potential approach which avoids these problems. Namely they have made feasible the idea that it might be possible to assign energy efficiency ratings to houses without ever visiting them in person.

While it is clearly not possible to fully replicate the calculation of the traditional energy efficiency related KPIs in this manner, much of the data traditionally gathered by visits can be derived using these data sources. In addition, the potential cost and time savings derived from avoiding visits are very considerable, thus strongly motivating the development and testing of such KPI's.

In this paper we present a discussion of this including which of the features relevant to measuring the energy efficiency of houses can be measured using such remote data, which can't and the implications of this for the design of KPIs for measuring energy efficiency. We ground this discussion with reference to an example of a KPI derived from simplifying the British standard SAP, which can be calculated purely using freely accessible open access data. This KPI has been tested against the results of traditional manual SAP visits and the results derived from the two found to be closely aligned.

Introduction

In response to the Energy Performance of Buildings Directive (EPBD) (EU 2002) most EU member states have established a national energy calculation methodology to measure the energy performance of buildings (Andaloro, A et al, 2010). The EPBD came into effect on 4th January 2003. Its principal objective is to promote the improvement of the energy performance of buildings through cost-effective measures. To achieve this it is necessary to have a method of measuring and comparing the energy performance of buildings.

The 2002 EPBD does not specify a detailed calculation methodology, leaving it up to Member States to define the details. Although it does specify that the methodology used in each member state should embrace the overall energy performance of the building, inclusive of its services. Specifically the EPBD states that the methodology used shall include at least the following aspects [Anderson, B., 2006]:

- Thermal characteristics of the building (shell and internal partitions, etc.) which may also include air-tightness.

- Heating installation and hot water supply, including their insulation characteristics.
- Air-conditioning installation.
- Ventilation.
- Built-in lighting installation.
- Position and orientation of buildings, including outdoor climate.
- Passive solar systems and solar protection.
- Natural ventilation.
- Indoor climatic conditions, including the designed indoor climate.

In addition the methodology must take account of active solar systems and other heating and electricity systems based on renewable energy sources, electricity produced by CHP, district or block heating and cooling systems, and natural lighting.

The enforcement of the EPBD began in 2006 and by 2010 most of the 27 EU member states had implemented a National Calculation Methodology for measuring the energy performance of buildings (Andaloro, A et al, 2010). The UK implementation of this is SAP (DECC/BRE, 2010,2013).

All of the approaches to national calculation methodologies are based on the principle that the property concerned should be modeled in substantial detail and its expected energy efficiency calculated from this. This 'property' focused calculation procedure is deliberately independent from the variations of occupants and / or property management. In this context, requirements for data are limited to the physical attributes and building geometry.

Approaches requiring detailed modeling are both plausible and desirable when dealing with new build housing. However, when evaluating previously built housing the gathering of the required data for such models imposes a considerable time and cost.

Indeed, the SAP standard recognises this by including a specification for calculating a reduced data version of SAP within the standard, RDSAP (DECC/BRE, 2010,2013). This involves using certain specified approximations to reduce the amount of data that must be gathered when visiting a property. While these measures do speed the overall process, the requirement that someone visit and measure the property remains. The cost and time involved in doing this mean that KPIs such as RDSAP are arguably badly suited to the task of rating large numbers of existing housing.

This is especially relevant in a context such as the United Kingdom where many existing housings have no energy efficiency rating attached and the building stock renewal rate is only 1-2 per cent[1]. Indeed it was estimated that 75% of the UK domestic stock that existed in 2007 will be still present in 2050 (Boardman 2007).

In recent times alternative electronic data sets have become available. This is open access data accessible over the internet and in particular the recent development of extensive street level photography such as that offered by Google's street view. In this paper we argue that this data can and should be used to create new KPIs which offer a useful measure of energy efficiency but can be applied very much more quickly and cheaply than existing KPIs. These are not proposed as universal replacements for existing KPIs, but rather as filling the role of permitting the efficient gathering of a rough picture of the energy efficiency of the large block of existing housing which has no current rating.

While such measures have potential utility throughout Europe, they have particular importance within the context of the United Kingdom, where the low renewal rate especially motivates the need for such measures. In this paper we illustrate how they might be developed with reference to work (Mhalas, 2012) where such a method was developed from RDSAP and its relative accuracy tested. The paper closes with a discussion of the potential feasibility of fully automating the process of rating housing.

1. Research Context

While the basic principles and methods expressed in this paper have potential applications within any country, the remainder of this paper will focus principally on the context of the United Kingdom. This is done for two main reasons. Firstly the work originally reported in (Mhalas, 2012) was conducted in this context. Secondly, the United Kingdom has a combination of a large number of existing houses with a very low stock renewal rate - the 2008 United Kingdom housing survey (Department for Communities and Local Government , 2008) found that only 12 per cent of the overall housing stock buildings had been constructed since 1990, the lowest

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[1] See either of:
http://www.bis.gov.uk/assets/foresight/docs/energy/energy%20final/ravetz%20paper-section%205.pdf;
http://www.eci.ox.ac.uk/research/energy/downloads/40house/40house.pdf

proportion of new housing and oldest housing stock in Europe. These two factors combine to make the problem of quickly and cheaply assigning a KPI which measures energy efficiency to existing houses especially pressing in the United Kingdom.

One set of techniques which can operate very quickly are those based on building typologies. These have been investigated very prominently in the context of the Tabula and Episcope European research projects[2]. While such approaches can definitely help with evaluating the bulk features of a set of housing, they cannot capture the details of individual houses.

Since the benefits gained from a given retrofit can closely depend on such details, there is a need for fast approaches which can evaluate them. Several energy modelling tools have been developed in the UK over a number of years to estimate the current and future energy consumption of a building. Some of the notable models include Building Research Establishment's Housing Model for Energy Studies (Shorrock et al. 1997); Johnston Energy and CO2 Emission Model (Johnston 2003); DECoRuM (Gupta 2009); and Community Domestic Energy Model (Firth et al. 2010). Finally there is the UK standard methodology, SAP (DECC/BRE 2010, 2013), which is now the UK's National Calculation Methodology, meeting one of the requirements of the Energy Performance of Buildings Directive.

All these models have the same underlying energy calculation engine, namely BREDEM (Building Research Establishment Domestic Energy Model). In order to operate this model requires that many data points be provided for each building that is rated. However, when rating existing housing stock, the cost of sending an engineer to each house to conduct individual measurements quickly becomes prohibitive (Office of National Statistics, 2012) and many organisations have resorted to sampling techniques to generate proxy measure for a larger housing stock.

This suggests the next logical path of investigation might be attempting to gather the information needed to conduct the surveys using some faster method than direct surveys. Such methods trade off a certain degree of the accuracy gained by engineer visits for considerably increased speed and reduced cost of actually conducting the surveys.

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[2] See http://episcope.eu/index.php?id=97 for extensive details.

One early approach to this was seen in (Jones et al. 2007) where drive-by surveys of dwellings were used to gather information. In a similar way, (Gupta 2009) used a combination of walk by surveys and some data sources. However, even using drive by surveys, a survey of 55,000 dwellings in Neath Port Talbot District Borough Council required 18 person months, which is hugely time consuming.

The recent rise of freely available databases, and in particular that of ubiquitous street level photography such as that offered by Google street view, offers the opportunity to greatly improve the efficiency of such indirect methods of assessment. The current paper presents an investigation into the feasibility of such ideas and into how KPIs that properly facilitate them might be developed.

2. Evaluation of street view photography as a data source

Before determining the sorts of energy efficiency KPIs that can, and should, be created for use within the context of remote sensing data it is imperative that the foundations are carefully studied. In particular, the following questions stand out:

- Precisely which items of data can be detected using street level photography?
- How accurately can their values be deduced?
- Which can't?

Since each technique for measuring the energy efficiency of houses uses slightly different data inputs, a preliminary to such a discussion is fixing the calculation technique involved. Since this paper works within the UK case, we use the UK Government standard indicator of SAP. The full version of SAP requires the provision of a considerable quantity of information in order for it to operate. Essentially this includes a detailed description of the structural geometry of the house combined with the relevant heat loss parameters for each feature.

The SAP specification however already recognises that in many cases, providing all of this information for existing houses requires the provision of an unfeasible or unobtainable level of information. It therefore provides an alternative specification for use rating existing housing, reduced or RDSAP. We shall start this discussion from this basis.

RDSAP identifies the following categories of information:

- Geometric Data – this includes the basic geometry of the dwelling, such as the floor area and height for each floor in the dwelling, the number of rooms, the exposed perimeter and wall area and the roof area and pitch.

- Details of the basic construction of the dwelling - this includes whether the window area of the dwelling is typical or not, the most common type of window glazing present, the house type, the wall construction, the roof type, the numbers of various sorts of chimneys and the number of sheltered sides.

- Details regarding the fabric and heating system of the dwelling - this includes whether or not any internal or cavity wall insulation has been added, the amount of roof insulation, the efficiency of the primary space/water heating installed in the dwelling, the degree of water tank insulation (if present) and the type of boiler present.

Figure 1: Potential data from historical Google StreetView for a demonstration low energy retrofit property, Newcastle upon Tyne

Figure 1 above highlights the basic information available in Google street view images of a section of housing. This information has in fact recently been expanded on that originally used in (Mhalas, 2012), in that it now offers also historical street view images. The time period between these two sets of images is four years. While this facility is not certain to continue in the future it seems reasonable to expect it to. Potentially this will build up a significant set of snap shots of the state of housing over time.

The question is then which items of the data listed above can be reasonably approximated using the photography. In writing this section, we draw on the experience of doing this within (Mhalas, 2012).

The first set of data is that regarding the basic geometry of the building. While the methods involved would benefit from extensive testing and codification, there is no doubt that much of this data can be reasonably approximated using the photographic data. For example the height can be compared to items of known height in the photographs and the number of floors from the amount of windows.

The floor area of the dwellings concerned is more problematic. Where the physical building only contains one dwelling this can again be approximated from the data by estimating the outline shape of the building.

There is perhaps more potential for errors in doing this than there is for the data types above. More significantly, if a building contains multiple flats then SAP dictates that each must be given an individual rating and there is a much more significant problem. This is addressed in the next section of the paper.

In terms of the data concerning the basic construction of the dwelling, the experience when working on (Mhalas, 2012) was that a combination of the photography with a reasonable level of expert knowledge regarding the area allowed usefully accurate values to be deduced. Thorough systematic testing to determine the degree of accuracy involved, and the consistency as different people did so, would be beneficial.

Finally, the fabric and heating system of the dwelling represent fundamentally obstacles to using purely photographic data to evaluate dwellings. Of them, only the changes in facade appearance – with an example seen in Figure 1 above - arising from external insulation can really be detected and then not the amount of it that was added. These are again addressed in the next section.

3. Non photographic data sources

The above discussion demonstrates that much of the data required to generate RDSAP values can be reasonably derived from freely available photographic data. However several very significant items of data cannot be deduced in this way:

- The internal floor area of buildings and especially those containing multiple distinct dwellings,
- The efficiency of the boilers in a given property,
- The degree of insulation fitted to a given property.

The logical question then arises as to whether these items of data can be gathered from other openly available data sources. Indeed the major purpose of the SEMANCO[3] research project, a three year European research project which funded most of the work reported on in this paper, was to use semantic technologies to permit the interpretation of such data sources in the context of the energy efficiency of housing.

Our experiences arising from investigating this during the project were quite mixed, with genuinely useful data sources proving hard to locate.

One problem encountered can be understood by examining the national Homes Energy Efficiency Database (HEED). This collects detailed information regarding energy efficiency improvement measures fitted to houses in the UK, and has quite substantial coverage. It thus looks to be an ideal candidate for use in measuring the energy efficiency of houses.

However as noted in (Foulds and Powell 2014), "Although the HEED records information on a dwelling level to avoid double counting, such information is unavailable for research due to confidentiality and data protection.". This data, as with fuel poverty and energy consumption data, can therefore only be accessed as aggregated data[4]. Similar data sources include the UK housing conditions survey (Department for Communities and Local Government, 2008) and the Europe wide survey in (BPIE, 2011).

[3] http://semanco-project.eu/
[4] The UK data is typically given for a lower level super output area of between 400 and 1200 houses.

While such aggregated data cannot be used for directly rating individual houses, it retains some utility. In particular it can be used for targeting attention to those areas in most need. The SEMANCO prototype software uses aggregate level fuel poverty data to highlight areas of interest, and (Foulds and Powell 2014, Hamilton et al. 2013) both examine the use of the HEED in this context.

The other potential use of such data is to provide a basis for intelligent estimates. For instance the approach taken to estimating boiler efficiency and overall insulation levels in (Mhalas, 2012) was to use such area level data combined with the appearance of the property to make an intelligent estimate. Unless data protection regulations change, this is likely to be the best that can be done without detailed inspections of the dwellings concerned.

The other potential data source regarding dwellings is if the organisation owning the dwellings has kept such data concerning them. For instance one might reasonable expect a housing association to keep data regarding any refits they have had made to their dwellings.

However, our experiences with dealing with such data in the SEMANCO project indicated that, even where such data does exist, it is often less useful than might be expected. Firstly it is typically stored in formats which require substantial human processing to be applied before they are usable. Secondly, the coverage and quality are such that only a small subset of it can be directly reused for energy assessments. The situation with such data might be more positive in other European countries but it cannot be expected to provide a major part of any solution in the UK.

A final option is non free data sources. In (Mhalas, 2012), the basic approach to deducing the internal floor areas of buildings containing just one dwelling made use of available ordnance survey outline maps (Ordnance Survey, 2010). While this data can be deduced from photographic evidence, this is a more reliable option with the drawback of being quite expensive for commercial organisations.

The main problems with floor plans arise when there are multiple flats within a single building. Indeed, and especially with converted buildings, even the number of flats is sometimes not known. This makes even generating sensible approximations difficult. Unless floor plans for the buildings have been stored by some organisation who are prepared to make them available, resolving this problem is in general not possible without visiting at least some of the buildings in question.

Indeed, in (Mhalas, 2012) the decision was taken to simply not attempt to rate such dwellings. While this is clearly a limitation of such approaches, the English house conditions survey (Department for Communities and Local Government , 2008) found that such flats comprised only nineteen per cent of the overall United Kingdom housing stock, meaning that the approaches remain of considerable interest.

4. The development of KPIs for quickly rating existing housing

Having examined the extant data sources, the next question is how KPIs which used purely these openly available sources of data might be developed, whether they can be used to develop approaches for guiding decisions as to where to apply refits when faced with very large[5] amounts of unrated housing.

When considering a KPI for guiding the bulk refit of housing, the crucial factors are the following:

- That the approach provides useful guidance,
- That it is cheap and fast enough to conduct on such a scale,
- That the results are consistently reproducible and comparable with each other.

The primary source of evidence for the potential accuracy of KPIs using photography is presented in (Mhalas, 2012). Here the approach was to use the data sources described in the two sections above to derive values and to insert those values directly into the RDSAP calculation methodology. In addition certain factors which had a small overall impact on the calculations, such as the percentage of low energy lighting in the house, were assigned fixed approximations.[6]

The 'SAP' values produced in this manner were cross checked against values previously obtained by people visiting the properties in question. The values resulting were normally within ten per cent of each other and there was no source of systemic error in the methodology using photography.

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[5] Thousands

[6] 50/50 in this specific case.

While extensive further testing – especially in terms of consistency when applied by multiple different people – and codification would be required before making such an approach any form of standard, these results form a strong vindication of the principle that it is possible to usefully measure energy efficiency using remote data.

The second criteria is where existing techniques such as SAP or more complex models fail. While such approaches are unarguably superior for new build housing, or extensive refits of individual buildings, they are simply too complex to possibly calculate on this scale. In consequence many buildings are either not rated at all, or various ad hoc methods are used. A reliable method of obtaining reasonable data in a feasible time scale would be a major benefit.

One major theoretical objection remains – namely that, for any approach using purely external data, it is possible to totally refit the inside of a property without changing the value that is assigned to it.

In fact though, this objection is only a serious problem when the KPI is viewed as predicting actual energy usage in some sense, rather than a more abstract measure of the quality of the housing.

Indeed, even more thorough approaches such as SAP do not consistently predict the actual energy use within occupied properties, with the actual energy performance having a strong correlation with the behaviour and characteristics of occupiers rather than the building fabric and energy systems (Clark 2013).

One further critique is offered in (Kelly et al, 2012). This addresses SAP and in particular contains a discussion regarding precisely what SAP measures showing how the way that it mixes considerations of cost, energy use and the types of fuel burnt means that it does not have a simple real world interpretation and can potentially incentivise otherwise suboptimal behaviour.

A final critique is offered in (Majcen, 2013). This paper reports on a very large survey of Dutch housing, comparing the ratings of around 200,000 buildings with energy certificates with their measured energy consumption in terms of both gas and electricity. They found only a weak relationship between the predicted and actual values. In addition they report on other surveys which retested the values previously assigned to housing by visits and found considerable differences.

Hence, so long as the baseline indicators generated by any such method are useful for guiding basic refit decisions, the overall approach would also have considerable potential utility. Indeed one potential solution to this objection would be the consideration of KPIs which measure only 'external' energy efficiency - i.e. that omit any consideration of the efficiency of the boilers in the dwellings rated and any internal insulation. This is a potentially very valid approach, alternatively approximations could be used and the inevitable mistakes accepted.

While there are undoubted problems to be addressed, approaches using the sort of openly available data discussed in this paper offer significant promise in being able to provide useful baseline indicators when considering refits of large numbers of houses.

5. Further Automation

Once the idea of doing fast evaluations using electronically available photography is introduced it is very natural to consider if the process can be made even faster by using systems such as image recognition and photogrammetry in order to perform the evaluations in a fully automated manner. The current section considers the potential feasibility of such an approach and attempts to highlight the likely obstacles to achieving it.

In order to do this, we shall consider the types of data identified above in order. First are the geometric elements of a property. Essentially for fully automated processing to make sense, the grid of floor plans must be taken as an input. In practice this would be very likely to derive from the Ordnance survey mapping, although it could also be generated by hand. Either this grid might be used in conjunction with a two dimensional map in GIS software, or somehow automatically overlain on a three dimensional map such as that generated by a LiDAR survey or sometimes available from sources such as Google earth.

The heights of the buildings could be either automatically approximated from street view images or, where three dimensional imagery is available, taken directly from this source.

Figure 3 below contains a screen shot taken from Google Earth's current three dimensional mapping of Newcastle. As can be seen each house has a fairly detailed geometry attached within the model.

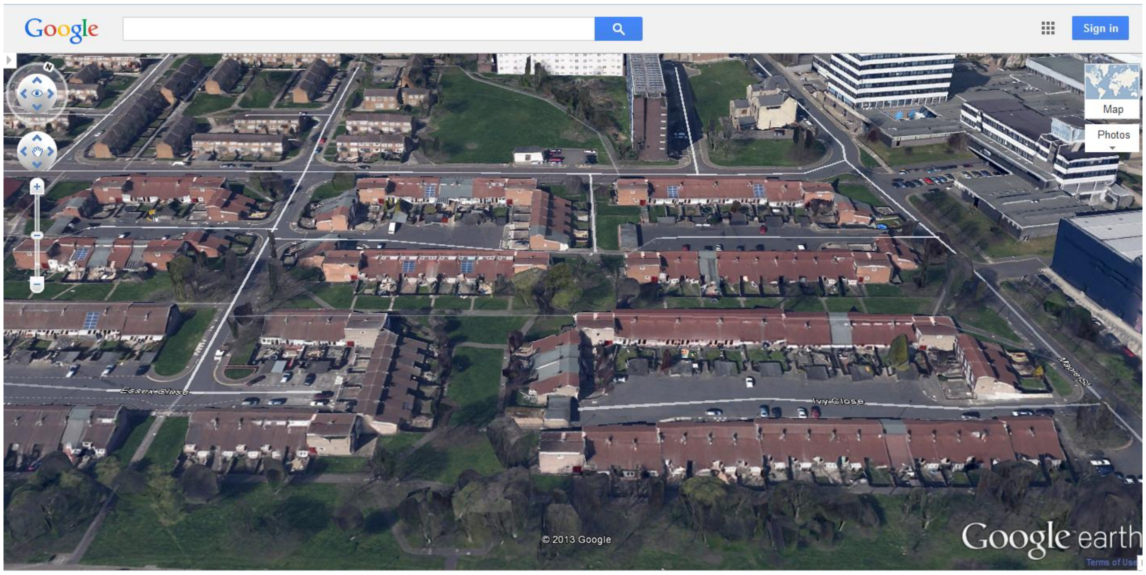

Figure 3: Screen shot of Google Earth 3D model of Newcastle

The roof area and pitch could clearly be deduced from such a model. The number of rooms remains somewhat harder to derive from external data. A potential approximation of this value might be made more accurate by counting the numbers of windows on the dwelling or by comparison against standard property sizes and ranges. This can be done manually or potentially by automatic image recognition techniques.

Mention of such techniques brings us on to the second group of data to be addressed, that of the externally available data types. For each of these data types sensible values can be gained by knowledgeable users conducting a manual inspection of street level photography such as that provided by Google street view.

Wherever human inspection of photography is involved, the potential for the application of automatic image recognition techniques is present. Indeed these techniques have been applied to identifying features of housing from street level photography. Papers mentioning this include (Recky et al., 2011) which deals with the problem of isolating the facade from street level photography, (Recky & Leberl, 2010) which deals with the identification of windows in those facades and (Zamir & Shah, 2010) who used image recognition and pattern matching to determine which city a Google street view image came from.

In general the application of such techniques to the identification of the sorts of features involved here would require the following steps:

1. Identifying the broad area of the street level photography which contains the dwelling in question,
2. Identifying which parts of this photography actually directly correspond to the facade of the dwelling,
3. Identifying the features of interest on this photography.

None of the stages of this problem are straightforward, but it is very relevant to note that the production of the Google Earth model in figure 3 involved the solution of the first two of these. Indeed, were that model to be combined with an appropriate floor plan mesh, it would be possible to directly select the textures that were mapped to each wall of the dwellings and process them.

The final stage of processing is also not straightforward. In general it would involve extensive tuning of image recognition and machine learning algorithms with hand labelled/processed result sets. None the less, achieving such results as identifying the construction type of a house seems to be very possible in principle and this is a promising area for future research.

In general there seems to be no fundamental obstacles in the path of automatically determining sensible values for all of the attributes for which a human could extract values from photography. Finally there are the internal features. Similar problems to those faced by humans trying to interpret such data would be faced here and there is again no clear cut solution to them.

6. Conclusions

While current methods of calculating energy efficiency for housing stock, and the KPIs associated with them, are suitable for use with newly constructed housing the cost and time involved in calculating them makes them unsuitable for dealing with large stocks of existing houses. This motivates the development of new KPIs, the need for which is especially urgent in the context of the UK where the housing renewal rate is very low.

The recent development of extensive, free, street level photography offers a potential route to the production of much cheaper and faster KPIs which use only remote viewing to derive their values. This paper has explored the feasibility, and potential limitations, of such approaches with particular reference to the case of the United Kingdom. The potential cost and time benefits from such approaches are unquestionable, and the example of the approach developed in (Mhalas, 2012) suggests that the results from such approaches can be useful, and indeed even closely approximate the results arising from site visits. They therefore represent a highly promising direction for future research.

Indeed, as described in Section 5, it seems entirely plausible that it might ultimately be possible to develop a fully automated method for producing measures of energy efficiency. We highly commend future investigation into this area.

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References

1. European Union. (2002) Directive 2002/91/EC of the European Parliament and of the Council. *Official Journal of the European Union*.
2. Andaloro, A. P. F., Salomone, R., Ioppolo, G., & Andaloro, L. (2010) Energy certification of buildings: A comparative analysis of progress towards implementation in European countries. *Energy Policy* 38, 5840–5866.
3. Anderson, B. (2006) Energy Performance of Buildings Directive. Building Research Establishment. Available from: http://www.bre.co.uk/filelibrary/Scotland/Energy_Performance_of_Buildings_Directive_%28EPBD%29.pdf.[Accessed July 19th 2012]
4. DECC/BRE, 2010, 2013. The Government's Standard Assessment Procedure for Energy Rating of Dwellings. 2009 Specification Available from : http://www.bre.co.uk/sap2009/page.jsp?id=1642 2012

   Specification published in late 2013: http://www.bre.co.uk/sap2012/page.jsp?id=2759
5. Boardman, B. (2007). Examining the carbon agenda via the 40% house scenario. Building Research and Information, 35(4), 363-378.
6. Mhalas, A., Crosbie, T. & Dawood, N. (2012) Development of a Visual Domestic Energy Assessment Tool. In CONVR2012, the twelfth international conference of construction applications of virtual reality, November 1/2, 2012.

   Available from: http://convr2012.com/download/CONVR2012-Proceedings.pdf [Accessed June 2013]
7. Department for Communities and Local Government , 2008. English Housing Survey Housing stock report 2008.
   Available at:
   https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/6703/1750754.pdf

8. Shorrock, L. D., & Dunster, J. E. (1997). The physically-based model BREHOMES and its use in deriving scenarios for the energy use and carbon dioxide emissions of the UK housing stock.
Energy Policy, 25 (12), 1027–1037

9. Johnston, D. (2003). A physically based energy and carbon dioxide emission model of the UK housing stock, Leeds, UK: Leeds Metropolitan University

10. Gupta, R (2009). Moving towards low-carbon buildings and cities: experiences from Oxford, UK. *International Journal of Low-Carbon Technologies*, *4*, 159–168.

11. Firth, SK, Lomas, KJ, Wright, AJ (2010). Targeting household energy-efficiency measures using sensitivity analysis. *Building Research and Information*, *38*(1), 24–41

12. Office of National Statistics, 2012. Neighbourhood Statistics Topics. [Online] Available at:
http://www.neighbourhood.statistics.gov.uk/dissemination/LeadHome.do
[Accessed 15 June 2012].

13. Jones, P, Patterson, J, Lannon, S (2007). Modelling the built environment at an urban scale - energy and health impacts in relation to housing. *Landscape and Urban Planning*, *83*, 39–49.

14. Foulds, C., & Powell, J. (2014) Using the Homes Energy Efficiency Database for residential insulation improvements. *Energy Policy* **69**, 57-72.

15. Hamilton, I. G., Steadman, P. J., Bruhns, H., Summerfield, A. J., Lowe, R. (2013) Energy efficiency in the British housing stock: Energy demand and the Homes Energy Efficiency Database. *Energy Policy* **60**, 462-480.

16. Buildings Performance Institute Europe (BPIE), 2011. Europe's buildings under the microscope.
Available at:
http://www.institutebe.com/InstituteBE/media/Library/Resources/Existing%20Building%20Retrofits/Europes-Buildings-Under-the-Microscope-BPIE.pdf.

17. Ordnance Survey, 2010. OS MasterMap Topography Layer User Guide and Technical Specifications. s.l.:Ordnance Survey.

18. Clark, D (2013) *What Colour is your Building?: Measuring and reducing the energy and carbon footprint of buildings*. RIBA Publishing, London.

19. Scott Kelly, Doug Crawford-Brown, Michael G. Pollitt, Building performance evaluation and certification in the UK: Is SAP fit for purpose?, Renewable and Sustainable Energy Reviews, Volume 16, Issue 9, December 2012, Pages 6861-6878,

Available at:
http://www.sciencedirect.com/science/article/pii/S1364032112004595

20. D. Majcen, L.C.M. Itard, H. Visscher, Theoretical vs. actual energy consumption of labelled dwellings in the Netherlands: Discrepancies and policy implications, Energy Policy, Volume 54, March 2013, Pages 125-136, ISSN 0301-4215,

Available at:
http://www.sciencedirect.com/science/article/pii/S0301421512009731

21. Recky, M., Wendel, A. & Leberl. F. (2011) Façade Segmentation in a Multi-view Scenario. In Proceedings of the 2011 International Conference on 3D Imaging, Modelling, Processing, Visualization and Transmission (3DIMPVT '11). IEEE Computer Society, Washington, DC, USA, 358-365. Available from: http://dx.doi.org/10.1109/3DIMPVT.2011.52 [Accessed July 31, 2013]
22. Recky, M. & Leberl, F. (2010) Windows Detection Using K-means in CIE-Lab Color Space, 20th International Conference on Pattern Recognition (ICPR), pp.356-359.
23. Zamir, A. R. & Shah, M. (2010) Accurate Image Localization Based on Google Maps Street View, Computer Vision – ECCV 2010, Lecture Notes in Computer Science Volume 6314, pp 255-268.