Use of stochastic weather generators in the projection of building energy demand in a changing climate

David R. S. Williams[1, 2,*], Lucia Elghali[1], Russel C. Wheeler[2]

[1] *Centre for Environmental Strategy, Faculty of Engineering and Physical Sciences, University of Surrey, Guildford, Surrey, GU2 7XH, UK*
[2] *Parsons Brinckerhoff, Westbrook Mills, Godalming, Surrey, GU7 2AZ, UK*
* *Corresponding author. Tel: +44 (0)1483 528406, E-mail: williamsdav@pbworld.com*

Abstract: Compliance with building codes in many countries requires energy simulation of designs in local climate conditions. However, over a building's lifespan, weather conditions may alter considerably due to climate change. There is a risk therefore that a future climate may alter lifecycle heating and cooling demands from those experienced today. The development of 'stochastic weather generators' provides an opportunity to produce synthetic weather data representative of a future climate. These models are calibrated against observed data, before being refitted to the climate change projections of global circulation models. The generator's output is thousands of years of weather data for a particular future time period. Theoretically these outputs would be appropriate for building energy demand simulation, although analysis of such a high number of projected years would be impractical. This research has developed a method whereby a unique energy "fingerprint" is created for a building and used to estimate heating and cooling demands without the requirement for hours of computation. Energy demand estimates from the fingerprint have been crosschecked with dynamic simulation, indicating a high degree of correlation. The weather generator utilised in this study has been produced by the UK Climate Impact Programme (UKCIP) and is freely available on-line.

Keywords: *Climate change, building energy demand*

1. Introduction

The 2008 Climate Change Act commits the UK to a challenging 80% reduction in greenhouse gas (GHG) emissions from a 1990 baseline by 2050 [1]. With buildings responsible for almost half of UK emissions [2], the construction industry will play a significant role in achieving this aim.

To drive reductions in GHG emissions, many countries have adopted energy benchmarking processes that require calculation of building energy demand over a single year [3]. For example, the Energy Performance of Buildings Directive (EPBD) in Europe requires member states to develop calculation methodologies to allow building energy demand to be determined [4]. These calculations are required to account for the fabric and systems proposed within a design, as well as the outdoor climate conditions typically found at the location of the building.

Measures such as the EPBD may be effective in reducing GHG emissions assuming steady climate conditions. However, evidence suggests that significant changes to the climate in recent years have already altered the energy performance of buildings. Wright [5] was able to demonstrate changes in heating degree-days over the period 1976-2000 consistent with a warming climate. Similarly Jenkins *et al*. [6] indicated an 18% reduction in heating degree-days, along with a 32% increase in cooling degree-days in London over the period 1961-2006.

Given the long lifespan of many buildings, it is reasonable to assume the climate a building is exposed to over its life could be different to that assumed during the design stage. This could influence the heating and cooling loads of the building, and potentially increase the GHG emissions beyond those expected. To ensure GHG emissions resulting from energy demand are limited across the lifecycle, a method of analysing the possible influences of climate change is required. This paper describes how hourly weather sequences representative of a range of possible future climate alternatives may be produced in a format suitable for routine building energy analysis. The following section outlines work previously completed by others in this field.

1.1. Background

Hundreds of software applications have been developed for the estimation of building energy demands [7]. The most advanced of these tools simulate the performance of designs against hourly (or even sub-hourly) inputs. Weather sequences representative of the proposed building site are therefore required at this hourly resolution. However, there is a lack of data at this level of detail that accounts of the influence of climate change in the future.

1.1.1. Building analysis and climate change

Cole and Kernan [8] first identified the need to consider the influence of a changing climate on building lifecycle energy demands in 1996. However, at the time no suitable weather data were available to undertake such a study. Since then various methods have been developed to address the problem. The most simplistic approach has been to substitute weather data local to the site for that of a remote location that may be representative of a changed future climate. Gatrell and McEvoy [9] used this approach by using weather data from Rome and Milan as an approximation of London's possible future climate. The drawback of this method is that the relative humidity and diurnal temperature range of the substitute location may be quite different to that of the present site, even if the temperatures are similar to those expected for the future. In addition, the hours of sunlight and solar inclination may be unrealistic and would clearly not be subject to variation, even considering climate change.

1.1.2. Morphed weather data

In an effort to produce more suitable weather data accounting for future climate change, Belcher [10] developed an approach whereby the weather conditions of a given site are "morphed" inline with the projections of large scale climate models. In this work, Belcher used the Global Circulation Models completed by the United Kingdom Meteorological Office Hadley Centre and presented by the UK Climate Impacts Programme (UKCIP) in 2002 [11]. The process provided an estimate of possible future conditions by "shifting and stretching" hourly recorded weather data. This created a new annual sequence with monthly average conditions equal to those projected by climate models. The morphed data produced by this process have been applied by many researchers [12] [13] [14], although it does suffer from two potential drawbacks. Firstly, only one year of data can be produced for a given time period in the future, so the uncertainty in the projection cannot be satisfactorily addressed. Secondly, the morphing technique relies on the baseline recorded weather being from the same time period as the baseline in the climate model. This is not always possible.

1.1.3. Weather generators

More recently a new method has been made generally available that offers an alternative form of 'future' hourly climate data – stochastic weather generators. In 2009 the UKCIP produced an on-line user interface that allows generation of hourly synthesised weather data for any decade up to 2080 at any location following a 5km grid [15]. A full technical description of the weather generator and reference to the underlying scientific papers is provided by Murphy and Jones [16] [17]. A simplified description of the workings of the weather generator is however now provided by way of introduction.

The main difference between the 2002 and 2009 projections presented by the UKCIP is that a spread of probabilistic climate change is presented rather than one prediction. UKCIP have achieved this by simulating a number of subtly different, but equally plausible, models that all represent the climate in a slightly different way. From each of these models, "change factors" are produced that provide an indication of possible variation in weather variables at a monthly time scale. The weather generator is then used to downscale the monthly projections into a synthesised daily, and finally hourly, time step. Jones *et al*. [17] describe that like most weather generators a stochastic rainfall model is used to synthesise other weather variables based on the rainfall state. To achieve this, the weather generator is first calibrated using observed rainfall data and other weather conditions to produce relationships between the variables. The monthly change factors from the probabilistic models are then used to produce a future rainfall condition, which in turn is used to generate other future weather variables including temperature, humidity and cloud cover. To ensure that a wide range of plausible climate models are applied, a minimum of 100 sequences of data are produced by the weather generator. In addition to this, to ensure that a future climate can be well defined from the synthesised weather, each sequence is 30 years in length. This means that the weather generator produces at least 3,000 years of possible future weather data for any future decade.

The challenge for building energy modelling is how to apply such a vast quantity of data to assess the probabilistic performance of buildings in the future. Some progress has been made by Smith *et al*. [18] in the application of the new data. However in this study all 3,000 years were applied to a specific case study requiring specialised batch simulation and advanced processor power. The work discussed here aims to simplify the process so that analysis can be completed quickly as a routine activity within building design.

2. Methodology

The objective of simulating building energy performance against future weather conditions is to determine the sensitivity of the design against a range of future scenarios. In doing so, the energy required over a lifecycle may be reduced. However, the energy required by one building in the future may be different to that of another. For example, a heated and naturally ventilated building may use less energy in a 'warm future', as no air-conditioning system is present. Conversely, a building with high casual heat gains and a full air-conditioning system may require much more energy in a warmer climate. Many buildings may fall between these extremes. The method adopted therefore first tests a building's response to different weather conditions to define a unique 'fingerprint'. The fingerprint is then used to estimate energy demand (in the form of equivalent carbon dioxide, CO_2eq, emissions) from all 3,000 years of data. The following sections outline how this has been achieved.

2.1. Selection of example weather years

To understand how a building responds to differing climate conditions, a range of example years are required to define a suitable profile. In this analysis, dry-bulb temperature is used to differentiate between the years and indicate the potential energy demand of the building. However, taking a simple average of annual temperature does not indicate how much energy a building may require for heating and cooling. This is because it is the variation of hour-by-hour temperature either side of the average that indicates energy demand. For example, if an annual average temperature is 14°C, it is not known if the temperature spends a long time around this value, therefore requiring little heating or cooling energy in the building, or if wide extremes are experienced over the course of the year leading to high energy loads. Therefore, to indicate the amount of time in a year when temperature is at a particular value, a Cumulative Distribution Function (CDF) is produced for each of the 3,000 years.

When these CDFs are plotted and overlaid, a complete 'envelope' is created. Fig. 1 shows a hypothetical example of CDF plots of temperature. Example years are then chosen from across the full range of the envelope to test the building against a wide range of conditions. These are selected by plotting percentile positions across the envelope, then selecting the year which has the closest fit to the percentile points. To achieve this, a "goodness of fit" test is applied in a similar way to that used in the development of Test Reference Years (TRYs) for the UK Chartered Institute of Building Services Engineers (CIBSE) [19] [20].

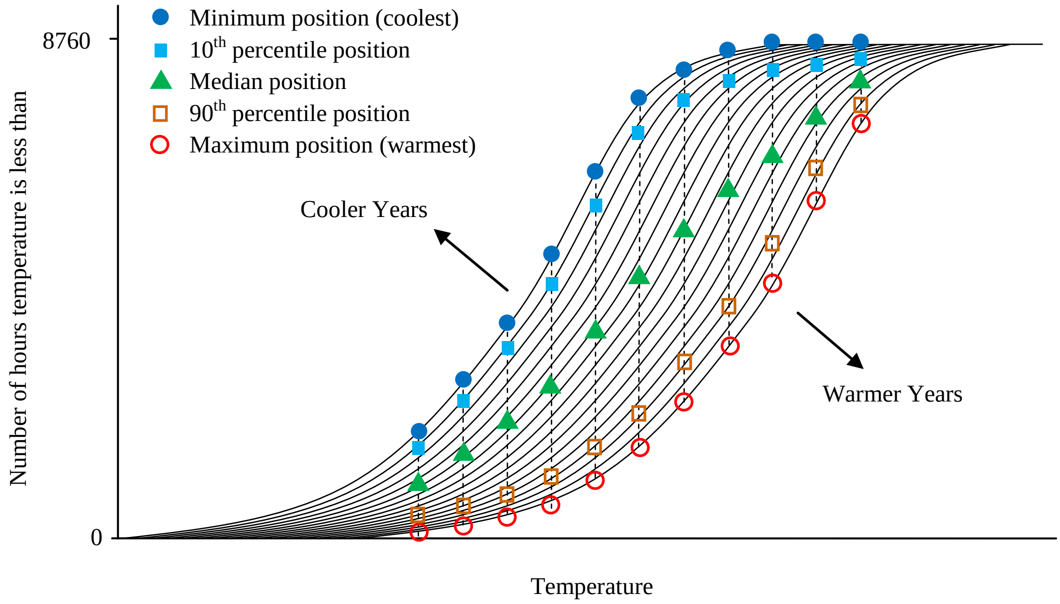

Fig. 1. Hypothetical example of Cumulative Distribution plots from UKCIP Weather Generator output. Each line represents a single synthesised year. In practice the generator would produce at least 3,000 years, each with equal probability of occurring.

In total, nine years are selected from the envelope at a spread of 10 percentile intervals. These years are then used as the external weather conditions in a thermal simulation of a building. To illustrate the process, an example building is described in the next section.

2.2. Testing of building performance

The building used to create an example fingerprint is a small Police Station in the south of the UK. It consists mainly of offices and meeting rooms, but also includes a relatively large computer server room. To complete the dynamic thermal simulation of the nine weather years, Integrated Environmental Solutions[1] (IES) v5.9 has been used. The outputs of heating and cooling energy demand are converted to CO_2eq values using a conversion factor typical to the UK [22] (0.198 kgCO_2eq/kWh for natural gas and 0.517 kgCO_2eq/kWh for grid supplied electricity). The hourly values are then aggregated into daily totals and a corresponding average daily temperature is calculated.

A binned frequency approach is then applied, where frequency of occurrence of daily average temperature in 1°C bins is determined. Using the same bins, the corresponding heating and

[1] The IES software determines annual building energy demands by modelling heat transfer processes at an hourly, or sub-hourly, time step. It is approved for use in building regulations compliance in the UK [21].

cooling energy demand (in CO_2eq) is summated. An example of the output of this process is shown in Fig. 2. Unsurprisingly, most building heating load occurs at low external temperatures and more cooling demand is found at higher temperatures. In addition to this, it is seen that of temperature frequency shows some correlation with the emissions, particularly cooling. This indicates some consistency between average daily dry bulb temperature and total heating and cooling load. The final stage is to use this profile to define a unique building energy fingerprint.

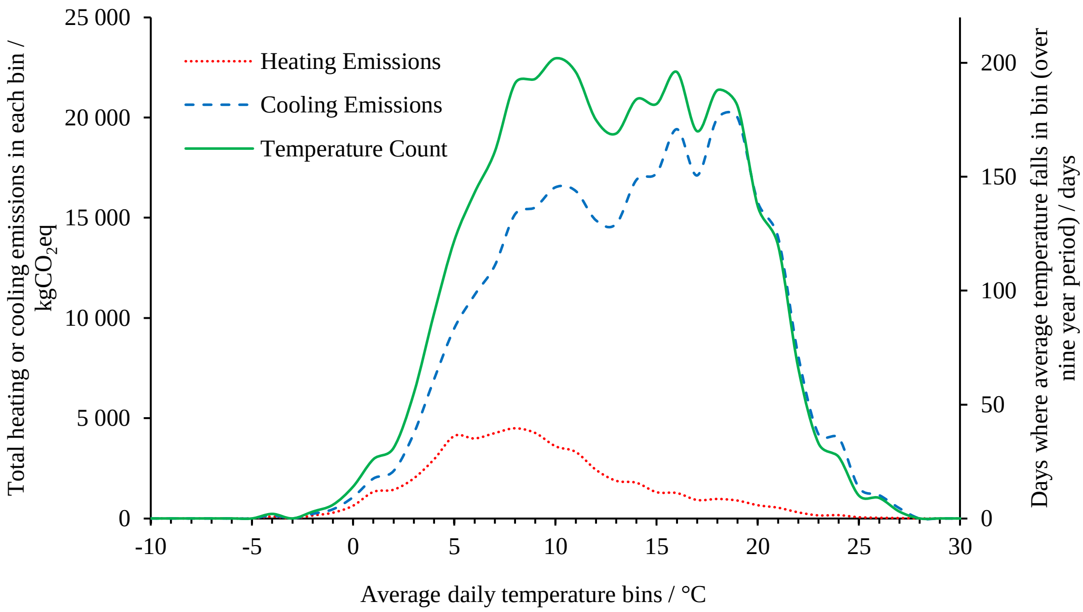

Fig. 2. Total CO_2eq emissions from example building heating and cooling demands and temperature frequency of occurrence in daily average temperature bins of 1°C

2.3. Production of unique fingerprint

To produce the fingerprint, the heating and cooling emissions are simply divided by the frequency of temperature occurrence. This gives a varying heating and cooling coefficient at each of the temperature bins with units of kgCO_2eq/day. Fig. 3 shows the unique fingerprint for the example police station building. In this particular case a minimal year round heating demand can be seen regardless of external temperature. This is due to a continual requirement for domestic hot water. Similarly a continual baseline load is also present for cooling as a result of the computer server room air conditioning equipment. In this case CO_2eq emissions are clearly dominated by cooling demand.

Once the fingerprint is created, annual CO_2eq emissions can be determined for any year with no need for further dynamic thermal simulation. This is achieved by simply multiplying the coefficient by the frequency of temperature occurrence for a given year, which can be readily achieved using a spreadsheet application.

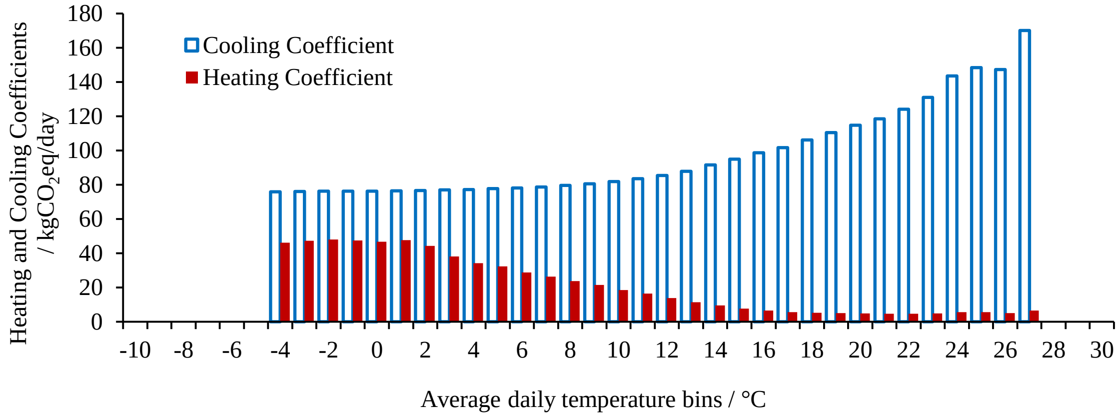

Fig. 3. Unique fingerprint of example building built from heating and cooling coefficients

3. Results of validation

To check the validity of the developed approach, the accuracy of the fingerprint at estimating building energy demand has been crosschecked using dynamic thermal simulation. To complete this, a number of years have been selected from the UKCIP weather generator and energy demand for heating and cooling has been determined in the example building using both methods. The years chosen for this process did not include those used to produce the fingerprint. Figure 4 shows the correlation between total (heating plus cooling) CO_2eq emissions for the example building against fourteen different years of weather.

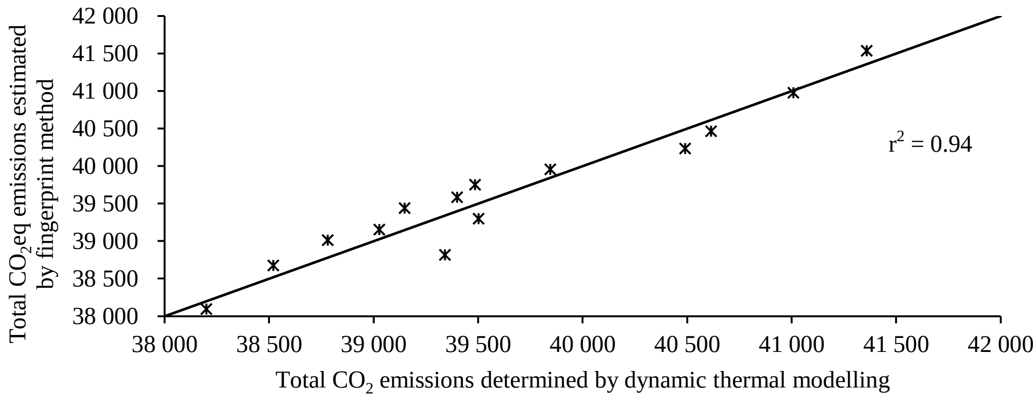

Fig. 4. Comparison of CO_2eq emissions between estimated figures using fingerprint method and dynamic thermal simulation

An r^2 value of 0.94 has been found between the two methods, indicating a high degree of correlation. This would suggest that for the case study examined, the fingerprint method is an acceptable way of estimating building energy demand for multiple years of data without requiring thermal simulation of each year.

4. Discussion and conclusions

The process developed here allows building CO_2eq emissions to be estimated directly from probabilistic climate change projections with minimal computation. The degree of correlation of the 'fingerprint' estimate to that determined by dynamic thermal simulation is very high, and greater than anticipated. It was previously assumed that a lower correlation may have been found, as the fingerprint method does not consider varying solar radiation and (de)humidification requirements, focusing instead only on external dry-bulb temperature. It is however well known that these weather variables may affect building energy demand separately form dry-bulb temperature. It is assumed that as the weather data are produced by a 'generator', there may be a stronger link between the variables than experienced in reality. For example, in the generator it may be that warm days are generally also sunny and that cool days are frequently cloudy. This is not always true in reality. It may therefore be that the Weather Generator produces weather sequences where the variables are more correlated than reality (due to the known link to the stochastic rainfall state) and therefore particularly suitable for building energy estimation. However, as the method described in this paper is only applicable to generated weather sequences, this limitation is not a primary concern. Despite this, the issue is recommended for investigation in future work.

The method developed in this study allows any building design to be tested against possible future climate conditions. The advantage of using a weather generator as the basis of this work is that a wider range of climate conditions can be investigated than previous methods allowed. This will allow a design to be checked in multiple scenarios, allowing poor performing systems to be focused on for improvement. The main benefit of the approach is that a wide range of weather conditions can be explored without excessive levels of thermal simulation. It is hoped that this approach will be applicable to the routine thermal analysis of buildings. Further work is however required to investigate the accuracy of the fingerprint method in different building types in different locations to fully validate the method.

Ultimately, by investigating building energy demand performance over a range of possible weather conditions a better insight is provided into possible CO_2eq emissions that may be released as a result of heating and cooling a building over its operational lifecycle. The situation to be avoided is one where emissions in the future increase as a result of increases in cooling demand due to a warmer climate. This would be counterproductive to the UK achieving its target reduction of 80%.

5. Acknowledgements

The authors gratefully acknowledge the support of the UK Engineering and Physical Sciences Research Council (EPSRC) for this research, which forms part of the University of Surrey / Brunel University Engineering Doctorate Programme in Environmental Technology. They would also like to thank Parsons Brinckerhoff for their continued support of the programme.

References

[1] United Kingdom. Climate Change Act 2008 (c. 27). London: HMSO

[2] BERR (2008) Strategy for Sustainable Construction, Department for Business, Enterprise and Regulatory Reform (BERR) [online] Available at: http://www.berr.gov.uk/files/file46535.pdf (accessed December 2010)

[3] W. Lee and J. Burnett, Benchmarking energy use assessment of HK-Beam, BREEAM and LEED, Building and Environment, 43, 2008, pp. 1882-1891

[4] European Union, On the energy performance of buildings, Directive 2010/31/EU of the European parliament and of the council of 19 May 2020, Official Journal of the European Union, 2010, Brussels

[5] A. J. Wright, Evidence for climate change relevant to building design in the UK, 1976-2000, Building Services Engineering Research and Technology 23 (4), 2002, pp. 279-285

[6] G. J. Jenkins, M. C. Perry and M. J. Prior, The climate of the United Kingdom and recent trends, Met Office Hadley Centre, Exeter, UK

[7] D. Crawley, J. Hand, M. Kummert and B. Griffith, Contrasting the capabilities of building energy performance simulation programs, Building and Environment, 43, 2008, pp. 661-673

[8] R. Cole and P. Kennan, Life-Cycle Energy Use in Office Buildings, Building and Environment 31 (4), 1996, pp. 307-317

[9] M. Gaterell and M. McEvoy, The impact of climate change uncertainties on the performance of energy efficiency measures applied to dwellings, Energy and Buildings, 37, 2005, pp. 982-995

[10] S. Belcher, J. Hacker, S. Powell, Constructing design weather data for future climates, Building Services Engineering Research and Technology, 26 (1), 2005, pp. 49-61

[11] M. Hulme *et al*., Climate Change Scenarios for the United Kingdom: The UKCIP02 Scientific Report, Tyndall Centre for Climate Change Research, School of Environmental Sciences, University of East Anglia, 2002

[12] D. Coley and T. Kershaw, Changes in internal temperature within the built environment as a response to changing climate, Building and Environment, 45, 2010, pp. 89-93

[13] D. Jenkins, Y. Liu and A. Peacock, Climate and internal factors affecting future UK office heating and cooling energy consumptions, Energy and Buildings, 40 (5), 2008, pp. 874-881.

[14] M. Jentsch, A. Bahaj and P. James, Climate change future proofing of buildings – Generation and assessment of building simulation weather files, Energy and Buildings, 40, 2008, pp. 2148-2168

[15] UKCIP, UK Climate Projections: Login Page, [online] Available at: http://ukclimateprojections.defra.gov.uk/ (accessed December 2010)

[16] M. Murphy et al. UK Climate Projections Science Report: Climate change projections. Met Office Hadley Centre, 2009, Exeter

[17] P. Jones, C. Kilsby, C. Harpham, V. Glenis and A. Burton, UK Climate Projections science report: Projections of future daily climate for the UK from the Weather Generator. University of Newcastle, 2009, UK

[18] S. Smith, V. Hanby and C. Harpham, A probabilistic analysis of the future potential of evaporative cooling systems in a temperate climate, Energy and Buildings, 2010, in press. doi:10.1016/j.enbuild.2010.10.016

[19] J. Finkelstein and R. Schafer, Improved goodness-of-fit tests, Biometrika, 58 (3), 1971, pp. 641-645

[20] G. Levermore and J. Parkinson, Analysis and algorithms for new Test Reference Years and Design Summer Years for the UK, Building Services Engineering Research and Technology, 27 (4), 2006, pp. 311-325

[21] Integrated Environmental Solutions, Available at: http://www.iesve.com/ (accessed December 2010)

[22] The Government's Standard Assessment Procedure for Energy Rating of Dwellings, Building Research Establishment on behalf of the Department for Energy and Climate Change, Available at: http:// www.bre.co.uk/sap2009/ (accessed December 2010)