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Critique and suggested modifications of the degree day methodology to enable long term electricity consumption assessments; a case study in Birmingham, UK.

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ABSTRACT: Energy consumption and outdoor ambient temperatures are inherently related. Low temperatures increase consumption via space heating, where as high temperatures result in increased demand for refrigeration and air conditioning. A common approach used for investigating this relationship in detail is via the calculation of Heating and Cooling Degree Days. Starting with a critical review of studies in the scientific literature that have used this technique, this paper highlights a range of limitations with the methodology, particularly with respect to standardisation which potentially hinders the utility of the technique in climate change risk assessments. Using an analysis of electricity consumption in Birmingham, UK as an example, this paper calls for a standardisation of the approach via the use of a universal base temperature based on average outdoor air temperatures. Adoption of this measure will not only enable meaningful comparisons to be made across regions, but it will also permit a more robust means to account for acclimatisation in longer term analyses such as that required by climate change risk assessments. This is demonstrated in this paper by coupling the existing degree days methodology with a a temporal analogue.

Key-words: Cooling degree days; heating degree days; climate change risk assessment; acclimatisation; residential electricity consumption; temporal analogues.

1.   Introduction

The onset of climate change will lead to increasingly elevated temperatures over large regions of the world. Higher outdoor ambient temperatures will significantly influence energy consumption by increasing demand for refrigeration and air conditioning (Papakostas *et al.*, 2010). For example, in the United States it has been shown that increases in air temperature can explain 5-10 % of urban peak electric demand, with a typical rise of 2-4 % for every 1 °C rise in daily maximum temperature over 15-20 °C (Akbari, 2005). Air conditioning usage is expected to increase significantly in the short term (Munck *et al.*, 2013), not only because of the increased cooling required by a warming climate, but due to such goods no longer being seen as a luxury item (Cian *et al.*, 2013).

In temperate climates, an increase in energy consumption for cooling in summer will potentially be offset with reduced energy use for winter heating (Santamouris, 2001; McGillian *et al.*, 2011; Li *et al.*, 2012; Golombek *et al.*, 2012; Cian *et al.*, 2013). Although regional climatology will be a key driver in energy use, subtle variations in consumption will also be apparent dependent on energy efficiency measures (Li *et al.*, 2012), availability of passive cooling, building construction (Semmler *et al.*, 2010; Kolokotroni *et al.*, 2012) as well as changes in social attitudes (Semmler *et al.*, 2010). The associated switch of energy requirements from heating to cooling could also be problematic. Oil and gas are traditionally used for heating, where as electricity is more commonly used for cooling. As electricity has a tendency to be less efficient, and therefore more expensive, current estimates indicate additional expenditure of energy on cooling in summer will probably outweigh winter energy savings (McGillian *et al.*, 2011). Furthermore, electricity also has higher CO_2 emissions per unit of consumption, meaning that the switch from heating to cooling, could potentially further exacerbate climate change and global warming (Li *et al.*, 2012; Cian *et al.*, 2013).

Overall, the result will be increasing pressure on electricity networks during times of peak demand (Chapman *et al.*, 2013), which has the potential to be a bigger problem in the longer term if part of the future energy mix is provided by renewables, such as hydropower, which are also vulnerable to climate change (Vine, 2012).

2. Background to Degree Days

Degree days are a climate statistic originally developed by US utility companies in the 1930's for estimating demand for coal and gas based upon typical energy usage. There have been efforts to improve the precision of the technique (e.g. degree hours, used by Tselepidaki *et al.*, 1994; Satman *et al.*, 1999; Kolokotroni *et al.*, 2010; Dimoudi *et al.*, 2013), however the original methodology remains the most common approach used in scientific studies. By definition, degree days are based on the principle that energy balance is achieved when heat inputs in a building are equal to overall heat loss, resulting in no latent load (McGillian *et al.*, 2011). Hence, a Balance Point Temperature (BPT) exists where the outdoor ambient temperature is sufficiently high (or low) enough to ensure that there will be no need for additional heating (or cooling). It is this BPT that is used to define the base temperature which is integral to the degree days methodology (ASHRAE, 2001).

Two indices are frequently used; Heating Degree Days (HDD), which approximate space heating demand, and Cooling Degree Days (CDD) which approximate demand for refrigeration and air conditioning. HDD are calculated by subtracting the mean daily temperature from a pre-determined base temperature and summing up any positive values over a set time period (1). Similarly, CDD are calculated by subtracting the base temperature

from the mean daily temperature and summing up only positive values over a determined time period (2) (Sivak, 2008).

$$T_{average} = \frac{(T_{max} - T_{min})}{2}$$
$$x = T_{average} - T_{base}$$
$$CDD = \Sigma(x \geq 0) \qquad (1)$$

$$T_{average} = \frac{(T_{max} - T_{min})}{2}$$
$$x = T_{base} - (T_{average})$$
$$HDD = \Sigma(x \geq 0) \qquad (2)$$

Sailor *et al.* (2003) used CDD to demonstrate that a 1 °C increment in temperature corresponded to an average increase in energy consumption of 8 % (with air conditioning being the primary cause of this increase). Other studies have attempted to use the approach to assess the impact of a changing climate on the energy industry. For example, Valor *et al.* (2001) observed a decreasing trend in HDD and a subsequent rise in CDD across Spain over the period of 1983-1998. Similar results were found in Greece by Papakostas *et al.* (2010) who compared HDD and CDD between 2 time periods; 1993–2002 and 1983–1992. Examples of longer term studies include Christenson *et al.* (2006) who noted a significant reduction in HDD, and subsequent increase in CDD, in a number of central European cities over the 20th century and Castaneda *et al.* (2013) who observed local trends in HDD across Argentina over an extended time period of 108 years.

3.   Critique to the use of Degree Days

There are three main criticisms that should be highlighted with the use of CDD and HDD. These are the input data that uses outdoors temperatures in the calculations, the selection of base temperatures and finally the applicability of the methodology over longer time scales.

3.1. Input data: the use of outdoor air temperatures in calculations

Arguably the biggest limitation of the degree days methodology is the use of outdoor ambient temperatures in the calculations. The 'set point' temperature is defined as a comfortable indoor temperature - i.e. the temperature at which air conditioning and space heating are typically switched on by users. Unfortunately, widespread measurements of 'set-point' temperature have not been historically available and as such outdoor air temperatures have to be used instead. McGillian et al. (2011) argues that the way the degree days methodology is calculated, it assumes steady state conditions, where each degree rise would result in an equal indoor temperature rise. Clearly, outdoor ambient temperatures will be quite different from comfort levels experienced in buildings, each with varying levels of insulation and heating/cooling technologies (Kadioglu et al., 2001). This limitation can only realistically be overcome by obtaining detailed indoor temperature data across a large sample of the housing stock. However, this data is slowly becoming available at a high resolution with the advent of smart meters and internet controlled heating and cooling systems.

3.2. Parameterisation: selection of base temperatures

Base temperature is presently the only parameter in the degree days methodology which can be varied to take into account local conditions. Base temperatures are based on BPT and take into account building size, building configuration and available technology for a specific

geographical region (Kadioglu *et al.*, 2001). Hence, in order to compensate for the use of outdoor temperature data in the analysis, base temperatures are often several degrees lower than expected 'set points'. For example, the first adopted base temperature was 18.3 °C (Thom, 1952). This was calculated based on the assumption that 21.1 °C was a typical indoor comfort temperature, of which 2.8 °C could be attributed to solar heat gain, occupants and other internal processes.

The base temperatures used for HDD are frequently different from those used for CDD, as it can be assumed that a range of comfortable temperatures exist between the two (Cian *et al.*, 2013). For example, for uninsulated buildings in the USA, HDD and CDD have traditionally been calculated using a base temperature of 18 °C and 22 °C respectively, thus indicating a non-sensitive 'comfort zone' temperature interval of 4 °C (e.g. Valor *et al.*, 2001). However, base temperatures can often be varied due to both personal preferences (Sailor *et al.*, 2003) and the specific building characteristics controlling BPT. This lack of objectivity means that it is not surprising to find a wide range of base temperatures evident in the literature (Table 1). The result is that standardisation often isn't evident even when the technique is applied in the same country. Whilst this may be appropriate in large countries (e.g. USA), a lack of standardisation in smaller territories (e.g. Greece) is questionable. Overall, the choice of base value (i.e. based on an outline of building standards) is rarely justified in the literature, and highlights a need for improved rigour in the general application of the methodology.

3.3. Acclimatisation: applicability over longer timescales

The simplicity of the degree days methodology remains a key advantage of the approach. However the technique relies on generalised assumptions to approximate BPT as well as

uniform perceptions of thermal comfort independent of age, health and activity levels (Ormandy *et al.*, 2012). For this reason, it is inappropriate to assume that these factors will remain constant over an extended study period. As the impacts of climate change begin to manifest, local temperatures will change and as such, the local population will begin to acclimatise and adapt (Sailor *et al.*, 2003). In a warming climate, people's perception of comfort will change and subsequently so will 'set point' temperatures. As such, when dealing with long-term datasets (especially over large geographical regions, e.g. the USA), there is a need to carefully consider how methodologies can evolve to account for such adaptation. Whilst detailed computer simulations are capable of this at the building scale (e.g. DOE-2, Akbari, 2005), larger scale studies are still reliant on the degree day methodology.

This paper now aims to highlight how these limitations can be overcome by conducting a study into electricity consumption patterns over a 9 year period in the city of Birmingham, UK.

4. Methodology

4.1. Data and Study Area

Birmingham (latitude 52 ° 28 ′ 59 ″ N and longitude 1 °53 ′ 37 ″ W) is the second largest city in the UK, with an estimated population in 2012 of over 1 million (Birmingham City Council, 2014). Ordinary domestic electricity and total domestic gas consumption data was obtained from Department of Energy & Climate Change (DECC), for the city over the time period 2005-2013 (Figure 1).

Upon inspection, gas consumption data was unfortunately not suitable for further analysis in this paper as the data already undergoes a weather correction based on a HDD base temperature of 15.5 °C (DECC, 2011). However, such corrections are not presently applied to electricity consumption data which makes it ideal for sensitivity testing the degree days methodology.

4.2.   Base temperature

In order to demonstrate the methodological sensitivity of the choice of base temperature in the degree day methodology, CDD and HDD were calculated from Equations 1 and 2 for each year of the study period. Hourly temperature data from Coleshill weather station was used (located approx 10km to the east of Birmingham city centre). A range of values between 8-24 °C were then used to test the sensitivity of the technique to a range of base temperatures proposed for the UK in the literature (Table 1). Finally, Spearman Rank correlation co-efficients were calculated between degree days and energy consumption for each of the base temperatures used (Figure 2).

5.   **Results & Discussion**

As Figure 2 shows, regardless of the choice of base temperature, a positive correlation is evident between electricity consumption and CDD in Birmingham. This confirms (as expected) that more electricity is used at higher temperatures due to refrigeration and air conditioning. Subtle differences are apparent in the strength of the relationship at various base temperature values which indicates that some values are perhaps more appropriate than others. UKCP09 uses a base temperature of 22 °C for CDD (Table 1) and based upon this

analysis, this choice appears to be acceptable, since it results in strong correlation. However, higher correlations were obtained using a much lower base temperatures with the strongest relationship between CDD and electricity consumption occurring at 8.5 °C and 10 °C. Interestingly, the choice of 8.5 °C and 10 °C base is close to the average annual temperature of Birmingham which is 9.95 °C (using 1981-2010 as a baseline at Coleshill Weather Station).

Conversely, the relationships between electricity consumption and HDD show a negative correlation indicative of reduced electricity use for air conditioning and refrigeration during colder periods. Again, the strength of the relationship varies depending on the base temperature value used, but the UK base value of 15.5 °C (Table 1: Kolkotroni *et al.*, 2010) together with base values equal to or greater than 21.5 °C outperform all other base temperatures with respect to the strength of the correlation with electricity consumption.

Given the strength of the correlations obtained, it confirms that for simple studies, the use of a wide range of base temperatures is equally acceptable. However, there remains scope to improve the approach by using a base value which also reflects adaptation and acclimatisation of the population to a changing climate. As Table 3 shows, whilst the existing values of 22 °C and 15.5 °C for CDD and HDD respectively, are acceptable for use in the present UK climate, these are likely to change in due course as the impacts of climate change become increasingly apparent. Hence, given the results in Figure 2, it is proposed that the use of universal base temperature values which directly reflect (or are related to) the baseline average temperature experienced in a region could be a significant improvement on the degree days methodology when dealing with extended time periods. By maintaining this link, it becomes possible to take into account adaptation by society in a changing climate.

This would then enable the incorporation of the degree day methodology into climate change risk assessments via the use of weather generators and temporal analogues.

6.   A Future Perspective

2006 was the warmest year in the study period characterised by a heat wave event which, whilst not as severe or prolonged as the much documented 2003 event, extensively covered much of northern Europe. In the UK, the heatwave peaked in July 2006, breaking the previous July temperature record, but falling several degrees short of the of the all-time temperature record attained during the 2003 event (see Rebetz et al. 2009 for a fuller quantification of the two events in Europe)

In this section, a temporal analogue approach is used to set this year in the context of a future climate and to provide a perspective for how the impact of a changing climate can be incorporated into the degree days methodology. The temporal analogue approach is a useful method to identify the possible future impacts of climate change, based on the impacts of real events that have already happened (Giles *et al.*, 1998). The method assumes that a past event is an indicative scenario of the future, and that the probability of an event reoccurring in the future can then determined by using climate change scenario data and a weather generator (e.g. UKCP09). The relative simplicity and versatility of the technique remains a key strength of the approach (Wilby *et al.*, 2004) and as such it has been extensively used in a range of different UK applications including tourism (Giles *et al.*, 1998), road accidents (Andersson *et al.*, 2010) and economic uncertainties (Hallegatte *et al.*, 2007). However, it has not been used in the energy sector to date.

Using UKCP09 probabilistic scenario data, average temperature predictions were derived annually, as well as for summer (June, July and August) and winter (December, January and February), for three different emission scenarios (A1F1: High, A1B: Medium & B1: Low). All projections are relative to the 1961-1990 baseline and were calculated for seven decadal time slices (Table 3). Although the output is probabilistic, the 50th percentile was used in this analysis. Upon inspection of the output, it can be determined that average temperatures of the magnitude experienced in 2006 will become typical by the 2020s (under all emission scenarios). However, the heatwaves experienced in the summer of 2006 will be typical of average conditions that will be experienced in 2040 under the high scenario and 2050 under medium and low scenarios. In contrast, winter average temperatures were representative of current conditions.

The climate change scenario data used in this approach can then be linked to the degree days methodology to help include acclimatisation in the analysis. It is at this point that the advantage of using a standardised base value based on mean temperatures becomes apparent (Figure 2). As the population acclimatises to a warmer climate, it can be assumed that the 'set point' temperature will increase in line with average temperatures and hence, the base temperature used in analyses will also need to increase accordingly. Therefore, in studies over an extended period of time, acclimatisation can now be incorporated into the study by using a base temperature calculated using a moving average of air temperature. This adjustment, when used with a weather generator then becomes a suitable means to approximate electricity consumption at any point in the future.

7.   Conclusions

Following a critical review of the degree days methodology, a number of areas for improvement that could potentially be made to the approach have been identified. Fundamentally, there appears a need to further standardise the method so that it can be used by policy makers and the energy industry to plan and project energy requirements during a changing climate.

As this paper has shown, the calculation of CDD and HDD is sensitive to the choice of base temperature which underlines the caution with which the base must be chosen and justified (Buyukalaca *et al.*, 2001) as well as the manner in which results are interpreted. Currently, it is the difficulty in assessing building standards which leads to most of the subjectivity and this is the cause of substantial inaccuracies (Xu *et al.*, 2012). Hence, there is a strong argument to standardise the approach based purely on climate. Although, there is some evidence of previous attempts for standardisation in the literature, with a consensus on the use of 18 °C as the base temperature for CDD and HDD (as first identified in Thom, 1952), the appropriateness of this value has been frequently challenged. For example, Hekkenberg *et al.* (2009) highlights that for the Netherlands, the daily temperature rarely rises above 18 °C making the use of that value as a base quite limited. This further reinforces the argument made in this paper that the base ideally needs to be linked to localised mean temperatures.

It is accepted that adopting this approach may be too simplistic for all climates, particularly those with a large range in annual temperatures, but the improved objectivity is a considerable benefit. A further advantage is the option to easily adjust the base value when performing comparative studies across different regions or over extended time periods in order to account for acclimatisation as part of a climate change risk assessment. However, as with all long term studies of this nature, the biggest difficulties are caused due to confounding

factors other than temperature such as energy prices, socioeconomic development and adaptation (Kyselý *et al.*, 2012). In a pertinent recent example, Santamouris *et al.* (2013) investigated the relation between economic crisis and energy consumption in Greece which resulted in a 37 % reduction in consumption than expected.

Finally, also evident from this study is a general paucity of data for such analyses. Consumption data often lacks both spatial and temporal resolution and climate data is restricted to outdoor ambient temperatures as opposed to internal building temperatures. However, these problems will be rapidly overcome with the advent of smart metering, ultimately turning analyses of this nature into a 'big data' problem. There is no doubt that with the availability of such high resolution data, the limitations of the existing methodology will become increasingly clear and a new generation of analysis and forecasting techniques will undoubtedly emerge.