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Methodology for characterising domestic electrical demand by usage categories

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ABSTRACT

Electricity consumption in the United Kingdom is continually growing with demand from the domestic sector a potential/major contribution to this increase in consumption. Although demand is increasing, little information exists on the domestic components that contribute to an increase in domestic energy consumption. Thus, a greater understanding on what is contributing to the increase in domestic energy usage is a pre-requisite to understand how it can be reduced in the future or, if not reduced, contained at its current level.

This article discusses a separation filter designed for disaggregating domestic electrical demand data into different appliance categories. The filter is applied to a real time domestic electrical dataset spanning 1 year, and trends in standby, cold, heating element spikes and residual demand are identified. Several reasons to account for each of the trends are discussed. Additionally, the filter is applied to synthetic data both to confirm the accuracy of the separation filter and to finely adjust the filter for future application. The results indicate an increase in occupancy-related demand consumption during the winter months and an increase in cold consumption during the summer months. Furthermore, the results demonstrate that in contrast to changes observed in occupancy-related demand and cold consumption, there is little variation in standby and heating element spike consumption throughout the year. Finally, the potential advantage of incorporating a tailored separation filter into domestic smart meters is discussed.

1. Introduction

Domestic energy accounts for a significant proportion of total energy consumption both in industrialised and developing countries; estimates suggest that domestic consumption accounts for 31% of UK energy consumption [1]. Homes are where people spend a sizeable portion of their lives, where they eat, sleep and relax. It is therefore not surprising that domestic energy consumption results in a large impact on the national grid of industrialised and developing countries. According to Wood and Newborough [2], the UK's peak power requirement increased from 37.7 GW in 1968 to 50 GW in 2000. Wood argued that domestic energy use was the main driving factor for this rise in power usage. Furthermore, Balaras et al. estimated that building stock in the EU accounted for 40% of total energy consumption, with 63% of that value being associated with residential use [3]. In the UK, electricity consumption of a household can vary from 2000 to 6000 kW h/year [2]. The average domestic electrical energy consumption for a single household in Scotland suggested is to be 4792 kW h/year [1] and the average household consumption in Great Britain is 4628 kW h/year [1]. The UK is one of the top four most energy consuming countries within the EU, in terms of residential and tertiary energy use [3]. Several studies have been undertaken to investigate domestic electricity use within the UK ([4,5] for example) but little information is given on how total domestic energy use is affected by the seasons or occupancy. In addition, interpretation of domestic usage data is complicated by the fact that several methods have been used to analyse energy demand data. Methods used have ranged from computer simulation and analysis programs to basic numeric calculation.

To gain a better insight into electricity demand, it is essential to break energy usage into its contributing components. Few investigations have shown annual trends for domestic buildings, or the annual trends within each of the appliance categories. This lack of basic information makes it difficult to advocate practical measures to reduce energy usage at the individual domestic level which could ultimately have a positive impact on national energy usage.

This study had two primary aims; the first was to design and develop a separation method that was capable of dividing a total energy demand profile into smaller individual energy categories. The second aim was to: (a) use the designed method on real-time data, (b) study the different energy categories, (c) determine how they changed throughout the year, with possible explanations to account for the observed changes. Although the described methodology will be applicable to other industrialised and developing countries this study will focus on the UK. A universal methodology

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is important as it must be able to accommodate specific differences in factors that contribute to domestic energy consumption. Houses in other countries (particularly those with domestic air-conditioning) will have different electrical demand characteristics than those in the UK, where air-conditioning is not normally available in domestic dwellings. In addition, houses with electrical demands that have a weaker relationship with external temperature (i.e. buildings without electrical heating or electrical cooling) are likely to be more suitable for the approach chosen in this study.

1.1. Literature review

Load profile analysis in necessary to understand why energy usage is increasing and where it is being used in the domestic setting. Total energy consumption figures are useful for billing data, but it does not give an insight into how electricity is used, nor how consumer behaviour influences electrical use. To better understand electrical usage (and to analyse load profiles), total electrical demands can be broken down into various categories of usage. Wood and Newborough [2] believed that domestic energy usage could be described in terms of predictable, moderately predictable and non-predictable usage. Firth et al. [4] believed energy usage could be broken down into 'standby', 'continuous', 'cold' and 'active'. It can be argued that both Wood et al. and Firth et al. definitions of energy use are quite similar. 'Continuous' power is the result of appliances being left on throughout the day. Such appliances include alarm clocks and home alarm systems. 'Standby' is very similar to continuous, but is generally associated with the low power mode of the appliance. Thus they consume electricity at a value between zero and the rated power of the appliance. Appliances in the standby category include TVs, Hi-Fis and other home entertainment systems. 'Cold' power includes any appliance that uses a compressor refrigeration system, such as fridges and freezers. 'Active' power is considered to result from appliances being turned on for a period of time. This active component is thought to represent the remainder of the electrical use and can be associated with appliances in operation such as cookers, showers, kettles, TVs and lights. In this study, we have considered, standby and continuous power as one "standby" component.

Several methods exist for analysing and disaggregating demand data. One method is a software based system discussed by Farinaccio and Zmeureanu [6]. This approach is a 'top-down' method that uses previous data or assumptions to derive energy profiles for individual types of energy demand. The Farinaccio method has several stages to separate out energy data. It uses pre-existing knowledge, gained during a training phase, to create a hypothesis about the appliance or profile. The change in electric demand due to the appliance being turned on or off, the Herin 'initial signal', can be used to recognise appliances within the total load profile. This method effectively uses predetermined appliance signatures and attempts to identify them with signatures in the profiles. A more statistical approach was discussed in Aydinalp et al. [7], and involved taking into account the dwelling, number of occupants, number of children and whether the dwelling is owned or rented.

A calculative approach, using numerical calculations to determine the individual components of energy usage was described by Firth et al. [4]. This method involves multiplying the power usage with the time intervals to obtain the energy use. The total power consumed, P_{TOTAL}, is determined by the summation of cold, active and continuous and standby (C&S) power components.

If P_{TOTAL} is defined, it is then possible to calculate the other power values contributing to P_{TOTAL}. The first calculation is determining the C&S power component. Firth assumes that the minimum value on the total load profile will represent the standby/continuous component.

The cold appliance consumption is more complicated to define, due to the nature of the cycling pattern in energy consumption. In this study we have assumed a constant minimum value, a constant maximum value, and that the pattern does not change throughout the day. Firth et al. [4] suggest that taking data from 1 am to 4 am will ensure an indicative cold power activity profile, as it is assumed that there will be no other activity than the refrigeration contributing to energy usage. It should be noted that this also assumes that there is no home security lighting or courtesy lighting that would affect the outcome of the monitoring period.

The last step is to determine the active portion of the energy consumption. This portion accounts for the active appliances and the active standby appliances (TVs or DVD players). If the standby/continuous and the cold power components have been calculated, they can then be subtracted from the total power consumption to give an indication of active power. The definitions of power, energy and duration for each of the different power categories used in Firth et al.'s investigation can be found in Table 1.

Further research into domestic electricity consumption was carried out by Sidler [8]. As part of the ECODROME project, 20 households were studied over a 2 year period. Each plugged load and lighting system was monitored with plug in meters that sent data automatically to a storage PC. The system was designed to be a 'install and forget' system that requires no input or attention from the house occupants. The study provided detailed electricity demand data of each household's plugged load and lighting, that was able to create a total electricity demand profile.

Constructing an algorithm that can disaggregate loads would have a clear application in the area of smart metering of domestic energy usage. There has been an increase in legislation across Europe, regarding the importance of smart metering [9] and how it should be used. In particular, it is often suggested that smart meters will be more effective if they provide the user with some graphical interface showing how much energy they are using [10]. The methodology described in this study aims not just to present the energy used by the occupant, but also to provide a visual method of displaying the type of energy being consumed by the occupant. It is suggested that information of this type indicating, for example, whether standby loads are too high or energy use during occupancy is excessive, will provide the user with an extra level of information on which they can modify their behaviour in relation to activities that consume energy.

The methodology discussed in this paper aims to extend observations made in previous research. The methodology discussed in Farinaccio et al. aimed at breaking down recorded energy data into individual appliance usage, based on their unique energy signature. There is one important point highlighted in this work: the 'initial signal', used to identify appliances, can be confused by two or more appliances that have a similar 'initial signal'. Equally the system can be confused with two appliances being turned on at the same time, a problem that is evident with any load recognition software [6]. It appears that this method is designed to separate demand data into the contributing appliances, rather than divide the demand data into standby, cold and active.

The methodology and results discussed in Firth et al. [4] appeared to be more focused on producing an understanding of annual energy consumption. A calculative approach was used to determine annual active, standby and cold energy consumption, and could be used to determine daily standby, active and active energy consumption. It does not appear that this method could be applied to daily demand data to produce separate energy use profiles. The methodology discussed in Sidler [8] was a different approach to the previously discussed research. Individual appliances were monitored to create demand profiles. This method was based on a "bottom-up" approach rather than a "top-down" approach. The method discussed in [8] provided accurate demand