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Seasonal variation in household electricity demand: A comparison of monitored and synthetic daily load profiles

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ABSTRACT

This paper examines seasonal variation in household electricity demand through analysis of two sets of half-hourly electricity demand data: a monitored dataset gathered from 58 English households between July and December 2011; and a synthetic dataset generated using a time-of-use-based load modelling tool. Analysis of variance (ANOVA) tests were used to identify statistically significant between-months differences in four metrics describing the shape of household-level daily load profiles: mean electrical load; peak load; load factor; and timing of peak load. For the monitored dataset, all four metrics exhibited significant monthly variation. With the exception of peak load time, significant between-months differences were also present for all metrics calculated for the synthetic dataset. However, monthly variability was generally under-represented in the synthetic data, and the predicted between-months differences in load factors and peak load timing were inconsistent with those exhibited by the monitored data. The study demonstrates that the shapes of household daily electrical load profiles can vary significantly between months, and that limited treatment of seasonal variation in load modelling can lead to inaccurate predictions of its effects.

1. Introduction

In passing the 2008 Climate Change Act, the UK government committed to achieving an 80% reduction in greenhouse gas (GHG) emissions by 2050, compared with a 1990 baseline [19]. The domestic sector is identified as a significant target for emissions reductions, having accounted for 28% of UK final energy use in 2016 [4], and 23% of GHG emissions in 2015 [3]. The UK Carbon Plan identifies the replacement of fossil fuels with low-carbon and renewable generation as key to achieving emissions reductions [20], and the UK Renewable Energy Roadmap sets a target of 15% of UK energy being derived from renewables by 2020 [13].

2017 projections estimate that renewable generation will account for 45% of the UK electricity market by 2035, with nuclear generation accounting for a further 34% [5]. In 2016, solar photovoltaic (PV) and wind generation facilities accounted for 55% of UK renewable energy generation, and represented 48% of the national installed renewable electricity generation capacity [4]. However, the UK solar and wind resources are prone to diurnal and seasonal variability [8,29], while nuclear plants typically run at constant power and therefore provide limited flexibility in comparison with fossil fuels [33].

The changing complexion of the UK electricity supply will present new challenges in demand-supply balancing: mismatches are likely to arise between times of peak renewable generation and peak demand, and the inflexibility of nuclear power renders it unable to efficiently satisfy peak loads. There is therefore a growing need to understand and predict the time-varying behaviour of electricity demand—on diurnal and seasonal timescales—in order to determine the scale and timing of loads that will need to be satisfied by flexible backup generation or energy storage technologies.

Studies exploring relationships between household characteristics and overall electricity demand are widely reported in the academic literature [21]; however, relatively few evidence-based studies have been conducted to establish the factors influencing the shape of daily load profiles [25]. UK studies have tended to be restricted to small samples or limited monitoring periods [10,40], and seasonal variability in diurnal demand patterns has yet to be rigorously analysed.

Previously reported load profile modelling exercises have similarly been lacking in rigorous treatment of seasonal variation in load profile shapes: validation of seasonal variation, for example, has tended to focus only on overall energy demand and superficial comparisons of mean daily load profiles [23,32,36]. However, it has been noted that day of the week and the time of

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year both influence the shape of household-level daily load profiles [16,36], and recently reported appliance-level load-profiling models demonstrate a growing tradition of justifying treatment of seasonal variation through rigorous analyses of monitored electricity demand data [37,39].

The objectives of this paper are: (i) to illustrate the significance of the effects of seasonality on household daily electricity load profiles; and (ii) to examine the representation of those effects in synthetic load data. The analysis focuses on a pair of half-hourly dwelling-level electricity demand datasets, similar to the type expected to be provided by smart meters [14]: the first derived from data gathered in 58 English households during the 2011 Energy Follow-Up Survey (EFUS) [12,15]; the second a set of synthetic load profiles generated using a stochastic load profiling tool developed by Richardson and Thomson [35]. Four electricity demand metrics are used to describe household-level load profiles, and the effects of seasonal variability are investigated through statistical analysis of metrics calculated from monthly data.

2. Materials and methods

2.1. Monitored load profiles: The EFUS dataset

The monitored load profiles analysed for this paper were gathered during the Energy Follow-Up Survey (EFUS) of 2011, commissioned by the Department of Energy and Climate Change (DECC) to collect data on domestic energy use in England [12]. The EFUS sample consisted of 2616 households drawn from participants in the 2010/2011 English Housing Survey (EHS), commissioned by the Department for Communities and Local Government (DCLG) to collect data regarding the condition and energy-efficiency of the UK domestic stock [11].

Household-level electricity demand data, recorded at 10-second intervals using digital voltage loggers, were available for 79 of the EFUS households. Prior to the installation of monitoring equipment, householders were interviewed on a range of topics, including household make-up, dwelling characteristics and appliance ownership. Sampling of households was structured to ensure geographic spread of monitor placement across England, with households excluded on the basis of the following criteria [12]:

1. Households in flats;
2. Use of electric mains heating and/or supplementary electric heating;
3. Use of electric water heating;
4. Use of electric heating in conservatories;
5. Absence of mains electricity;
6. Presence of antiquated power sockets and/or consumer units;
7. Inaccessible meter cupboards and/or electrical hazards identified.

Individual household monitoring periods commenced between March and August 2011, and concluded in January 2012. For this paper, the sample was reduced to 62 households—all living in houses—monitored continuously between 1 July and 31 December 2011, such as to allow investigation of monthly variation in a consistent set of households. This was further reduced to 58 households—hereafter referred to as the EFUS58 sample—following the removal of households presenting anomalous load profiles, such as abnormally high overnight loads in summer (perhaps indicating air-conditioning) or long periods of near-zero electricity demand (perhaps indicating an unoccupied dwelling or prolonged monitoring error).

To enable investigation of seasonal variation, this study initially sought publicly available half-hourly electricity demand data gathered over periods of a year or more; however, suitable datasets were sparse. Data from the Energy Demand Research Project (EDRP)—gathered over a period of 2.5 years during early smart metering trials in the UK [1]—were considered; however, the EDRP dataset lacked sufficiently detailed household appliance data required for the definition of synthetic households in the load profile generation exercise described in Section 2.2, and thus the EFUS dataset was preferred.

2.2. Synthetic load profiles: The CREST dataset

The synthetic load profiles analysed for this paper were generated using a bottom-up household electricity demand modelling tool developed by Richardson and Thomson [35] at the Loughborough University Centre for Renewable Energy Systems Technology (CREST)—hereafter referred to as the CREST model—and accessed through the Loughborough University institutional repository [34]. The model provides simulation of household-level demand at a 1-minute resolution, with simulation of occupant activity and appliance use based on data from the 2000 UK Time Use Survey (TUS) [36].

Occupancy modelling in Richardson and Thomson's model is governed by a set of activity profiles, which account for the number of occupants and whether a weekday or weekend day is being simulated. However, the same activity profiles are used regardless of the month being simulated: seasonal variation is accounted for only in modelling of lighting demands, a process dependent on simulation of daily outdoor irradiance profiles. Subsequent comparison of seasonal variations in the monitored and synthetic datasets was therefore expected to indicate potential shortcomings of this limited treatment of seasonality.

Generation of a set of synthetic load profiles comparable with the monitored profiles required the definition of 58 synthetic households matched against the EFUS58 households where possible:

1. Household size was estimated on the basis of EHS-derived statistics associating number of bedrooms with number of occupants [11] (as the EFUS interview data did not include the number of occupants in each household);
2. EFUS interview data [15] were used to match cold appliances, televisions, wet appliances and electric cooking appliances (ovens, hobs, microwaves);
3. Consumer electronics and ITC appliances—data for which were unavailable—were randomly assigned by the CREST model, as were lighting configurations;
4. Simulation of electric water and space heating—which were reported absent across the EFUS58 sample in the EFUS interview data—was disabled.

For each synthetic household, daily load profiles were then generated for the 184 days from 1 July to 31 December 2011, matching the monitoring period of the EFUS58 dataset.

With the exception of televisions, the EFUS interview data did not record numbers of appliances found in each household, only whether each appliance type was present. In defining synthetic dwellings for this study, it was assumed that no household owned more than one of each type of electrical appliance modelled, with the exception of an allowance for up to three televisions per household. Furthermore, as the CREST tool had an upper limit of 5 occupants per dwelling, this was the maximum occupancy modelled.

2.3. Electricity demand metrics

This paper reports on the monthly variability of four per-household electricity demand metrics selected to describe the shapes of household daily load profiles:

1. Mean electrical load L_M;