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High-resolution stochastic integrated thermal–electrical domestic demand model

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HIGHLIGHTS

- A major new version of CREST's demand model is presented.
- Simulates electrical and thermal domestic demands at high-resolution.
- Integrated structure captures appropriate time-coincidence of variables.
- Suitable for low-voltage network and urban energy analyses.
- Open-source development in Excel VBA freely available for download.

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ABSTRACT

This paper describes the extension of CREST's existing electrical domestic demand model into an integrated thermal–electrical demand model. The principle novelty of the model is its integrated structure such that the timing of thermal and electrical output variables are appropriately correlated. The model has been developed primarily for low-voltage network analysis and the model's ability to account for demand diversity is of critical importance for this application. The model, however, can also serve as a basis for modelling domestic energy demands within the broader field of urban energy systems analysis. The new model includes the previously published components associated with electrical demand and generation (appliances, lighting, and photovoltaics) and integrates these with an updated occupancy model, a solar thermal collector model, and new thermal models including a low-order building thermal model, domestic hot water consumption, thermostat and timer controls and gas boilers. The paper reviews the state-of-the-art in high-resolution domestic demand modelling, describes the model, and compares its output with three independent validation datasets. The integrated model remains an open-source development in Excel VBA and is freely available to download for users to configure and extend, or to incorporate into other models.

1. Introduction

The widespread electrification of heat in the domestic sector, through the replacement of gas boilers with heat pumps, is expected to present a major challenge to the operation of electricity distribution networks, due to the large and potentially undiversified nature of these loads [1]. The cost of having to reinforce existing electricity networks to accommodate these heat pumps and other low-carbon technologies could be very considerable [2] and thus it is vital to make best use of existing network assets, and to ensure that any reinforcement is based on an accurate assessment of need. This assessment is particularly difficult in the case of low-voltage networks (those which connect from the distribution transformers to the individual dwellings through, for example, 400 V three-phase street mains and single-phase 230 V service connections). Conventional low-voltage network design procedures are not well suited to the task, as they typically use rather simple representations of the varying demand and rely heavily on experience, which is not yet available with widespread low-carbon technologies [3]. To address this, high-resolution models of domestic demand are being developed that can provide a suitable basis for future low-carbon network studies. These models are often based on a core representation of occupancy within

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buildings and produce high-resolution stochastic disaggregated end-use energy demand data at the level of the individual dwelling.

CREST's existing high-resolution model of domestic electricity demand was developed for this purpose and was based on a two-state active-occupancy model and accounted for electricity consumption associated with lighting, appliances and generation associated with photovoltaic arrays [4–7]. The model has been widely adopted in academia and industry, for example [8–16].

This paper describes the extension of the existing electrical demand model into an integrated thermal–electrical demand model that can provide a convenient basis for studying future network challenges associated with the electrification of heating. The new model includes the previously published components associated with electrical demand and generation (appliances, lighting, and photovoltaics) and integrates these with an updated occupancy model [17], a solar thermal collector model [18], and new thermal sub-models including a low-order building thermal model, stochastic external temperatures, domestic hot water consumption, thermostat and timer controls and gas boilers. The integrated model remains an open-source development in Excel VBA and is freely downloadable [19].

The following section reviews the requirements for domestic demand modelling for low-voltage network applications and describes the features that characterise the state-of-the-art. The integrated model has been developed to include all of these features, and is described in Section 3. Section 4 demonstrates the model's capture of the appropriate correlation between sub-model outputs through an example of a single day's simulation. To validate the model, Section 5 compares the model output with independent empirical data.

2. Defining the model requirements

The purpose of CREST's demand model is primarily for application in low-voltage network analyses. Other models developed elsewhere of similar structure have been used for similar purposes [20–22]. The fitness of such models should therefore be considered in terms of their ability to produce the type of output that is required for this application.

A critical aspect of demand modelling for this purpose is the appropriate representation of the timing of that demand. It is natural that the electricity consumption of an individual dwelling can vary greatly from one moment to the next as appliances within that dwelling are switched on or off by the occupants or automatically. This behaviour is to a large extent random and unpredictable, but it must be taken into account in the design of electricity networks and in particular when considering the low-voltage network. Similar considerations are relevant to the design of gas distribution networks, water supply, sewage and local transport systems, and so there is some overlap of interest in models for these purposes, which we will come back to in Section 2.9.

Recognising that it is not possible to predict the exact behaviour of individual occupants or appliances, the aim of stochastic demand modelling is to provide simulated data that has the right statistics overall, so that it is suitable for the task in hand – in our case, low-voltage network design. A critical precursor to the modelling therefore is the careful consideration of exactly which statistics need to be got right, and, equally important, which aspects may safely be approximated. There is a considerable risk in this type of modelling of attempting to include too much detail in some areas and so creating a model that is too computationally intensive or that requires input data that is simply not available. The choices of what should be included in a model are largely a matter of judgement and the following sections describe the perceived priority requirements that have guided the development of the model presented in this paper.

2.1. High temporal resolution

Electricity demand of individual dwellings is typically characterised by long periods of low to medium demand when multiple small appliances are in use, and occasional spikes of high demand due to kettles and the like. Looking to the future, heat pumps and electric vehicles will likely make these spikes much broader (longer duration) and it is the cumulative effect of this (rather than a big increase in peak demands of the individual dwellings) that presents the main challenge for distribution networks. For the moment however, our focus is on the modelling techniques that can be used to simulate this spikiness. It is important that it is duly represented because it has significant effect on actual customer voltages and network losses (particularly in service cables).

In order to duly represent this 'spikiness' it is necessary to use a sufficiently high temporal resolution. The voltage drops and energy losses in electricity networks are all dependent on the instantaneous power flows and can be significantly underestimated if, for example, half-hourly average demand values are used in their calculation [23]. The required temporal resolution to minimise such errors is dependent on the typical switching rate of appliances within dwellings and the desire for modelling precision has to be balanced with the practicality of dealing with large amounts of data. As a compromise, a time resolution of one minute is often used [15,20] and is selected for the model presented in this paper. It should be noted, however, that in practice there may be a limit on the resolution of input data e.g. occupancy data based on time-use surveys is often of 10 min resolution [17]. Readers are referred to [24,25] for analyses of the impact of data averaging on domestic energy demand modelling at the low-voltage distribution network level.

2.2. Demand diversity

Low-voltage network analyses are typically conducted on individual low-voltage network feeders serving up to about 100 dwellings [26]. While there is a need to simulate individual dwellings at high-temporal resolution, the aim is not for the exact prediction of any one specific dwelling, but rather the statistical accuracy of the group.

Network planners often base the design of electricity distribution networks on the 'after diversity maximum demand' [26] – the maximum demand, per dwelling, as the number of dwellings connected to the network approaches infinity. While a single dwelling might have a maximum demand in excess of 10 kW, as the number of dwellings is increased the time-coincident maximum per dwelling rapidly approaches the after diversity maximum demand, typically around 2 kW for non-electrically heated dwellings in the UK.

Of the statistics that should be accurately represented, therefore 'diversity' is particularly important. We note, however, that the term is ambiguous and deserves clarification. Diversity can refer to the timing of individual demands, i.e. whether they are coincident or correlated in time. Diversity can, however, also refer more generally to the presence of a 'spread' or probability distribution of another property of interest, such as magnitude or duration. To be clear, therefore, when we need to be specific we will explicitly mention the type of diversity referred to e.g. 'time-diversity'. We note also that by 'demand' we can be referring to individual dwellings, as well as to the individual appliances or fixtures within a dwelling. To be clear, when it is important to distinguish between these, we will refer to the former explicitly as dwellings and the latter as 'loads'.