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Characterizing probability density distributions for household electricity load profiles from high-resolution electricity use data

Joakim Munkhammar [a,*], Jesper Rydén [b], Joakim Widén [a]

[a] Built Environment Energy Systems Group, Department of Engineering Sciences, Uppsala University, SE-751 21 Uppsala, Sweden
[b] Department of Mathematics, Uppsala University, SE-751 06 Uppsala, Sweden

HIGHLIGHTS

- A probability distribution model of household electricity use is presented.
- The distributions are fitted with high-resolution data on household electricity use.
- Both Weibull distribution and lognormal distributions are used.
- Aggregate distribution of multiple uncorrelated households approaches a Gaussian.

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ABSTRACT

This paper presents a high-resolution bottom-up model of electricity use in an average household based on fit to probability distributions of a comprehensive high-resolution household electricity use data set for detached houses in Sweden. The distributions used in this paper are the Weibull distribution and the Log-Normal distribution. These fitted distributions are analyzed in terms of relative variation estimates of electricity use and standard deviation. It is concluded that the distributions have a reasonable overall goodness of fit both in terms of electricity use and standard deviation. A Kolmogorov–Smirnov test of goodness of fit is also provided. In addition to this, the model is extended to multiple households via convolution of individual electricity use profiles. With the use of the central limit theorem this is analytically extended to the general case of a large number of households. Finally a brief comparison with other models of probability distributions is made along with a discussion regarding the model and its applicability.

1. Introduction

Quantifying residential electricity use is valuable for such diverse purposes as devising demand-side management strategies for increased energy efficiency in buildings, integrating distributed renewable energy supply in the built environment and designing electricity distribution grids for urban or rural communities [26,28,29]. However, household electricity use with high time resolution is complex to quantify. Not only are there seasonal and diurnal variations in electricity use from for example heating, lighting, cooking and dishwashing, but the load is also highly stochastic [15].

Based on monitoring data from households it is possible to study electricity use via devising "bottom-up" models based assumptions or data for activity patterns, appliance use and appliances [4,18,20,21,27,29–33]. Here [4,18,27,30,33] make use of detailed information on household appliances and occupancy to model electricity use of any number of households while [20,21,31,32] use data on occupancy and appliances to construct stochastic models [29]. Here bottom-up means calculating the electricity use from individual households and possibly scaling up the results to estimate regional or national electricity use [15,26]. Conversely a "top-down" approach considers only typically the residential sector as an energy sink with no resolution of individual households [15,26]. The top-down models need only aggregate data while the bottom-up models need more detailed data on household level [26].

In both top-down and bottom-up the modeling of electricity use might be either deterministic or stochastic. In both the deterministic and the stochastic approaches measured or estimated data is needed to setup the models along with assumptions regarding model configurations [32]. Stochastic models can be based on methods such as Markov chains and probability distributions [26,31].

* Corresponding author. Tel.: +46 704464271.
E-mail addresses: joakim.munkhammar@angstrom.uu.se (J. Munkhammar), jesper.ryden@math.uu.se (J. Rydén), joakim.widen@angstrom.uu.se (J. Widén).

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The problem of bottom-up quantifying individual household electricity use could be condensed to quantifying three factors: (a) the set of appliances in the household, (b) the electricity use of the appliances and (c) the use patterns of the appliances [31]. The stochastic nature of household electricity use mostly stems from (c); that is mainly human behavior.

The estimation of probability distributions—or probability density functions (PDFs)—for describing electricity use in households have been developed for example for demand forecasting [7]. Such models have also been used for modeling loads in distribution networks [24]. Generally there are several studies on various levels of resolution and detail dealing with different distributions for household load profiles such as Normal, Log-Normal, Gamma, Gumbel, Inverse-Normal, Beta, Exponential, Rayleigh and Weibull [8,9–11,13,16,23,27]. A conclusion which can be drawn from the literature is that there is generally no unique or canonical distribution type suitable for modeling household electricity use [8,24]. However, there are benefits in not using for example the normal distribution, since it extends to negative power use values whereas for example the Weibull distribution and Log-Normal distribution do not [5]. Generally PDF models on electricity use are also frequently used to generate time-series by using Monte Carlo simulations [5,6]. However, the stochastic information and the applicability of PDF models is perhaps most useful in the form of the analytic PDFs, where for example calculations for applications might be done analytically [3]. Generally due to the variability between different regions and countries and the lack of proper measurement data for the electricity use at many of these locations there is a need for stochastic models which have high resolution and are based on high-resolution national or regional data [3, p.185]. Access to high-quality data is crucial for the modeling approach discussed here. If the bottom-up modeling is supposed to aggregate the instantaneous power demand of individual buildings, data from a large set of representative households are needed, with a high sub-hourly time resolution. These data could be available from national monitoring campaigns, or possibly from high-resolution metering of customers by distribution system operators (DSOs). Normally, though, data with this level of detail are not generally available. Therefore, an important aim for electricity use modeling is to find representative models of typical end-users that can be applied for various purposes.

The aim of this paper is to develop a PDF-model by estimating parameters for Weibull distributions and Log-Normal distributions of average household electricity use from a unique high-resolution monitoring campaign of household electricity use in 400 detached houses in Sweden provided in [34]. The PDF model for an average household electricity use is then extended to the scenario of multiple households via convolution of distributions from the sum of stochastic variables for N households. The distributions are analyzed in comparison with data in terms of relative variation of electricity use and standard deviation. A Kolmogorov–Smirnov test of goodness of fit is also provided. As a first study of its kind on Swedish data it will provide information on the fit to distribution for Swedish electricity use from detached houses and have applications for grid power calculations and coincidence estimates between load and intermittent power sources.

In Section 2 the model and the statistical tools are described. In Section 3 the data which was used to fit the distributions of the model is presented. In Section 4 the statistical properties and simulations of the model are given. In Section 5 the results are discussed.

2. Methodology

The model in this paper is defined by a set of PDFs which have been fitted with a recent large data set for household electricity use for a representative sample of detached houses in Sweden [34]. The investigation in this paper was restricted to two typical PDFs which can be used for modeling household electricity use and which have appeared in the previous literature, but for different data resolution and region [5,6,11,23]: Weibull distribution and Log-Normal distribution. The technical part of the parameter estimation was made with software developed in Matlab. In the following subsections we will describe the mathematical details of the distributions, the statistical analysis tools and describe the data which was used to estimate the fit to distributions.

2.1. Model framework

The model in this paper is based on two assumptions:

(I) At any time, the magnitude of power demand for a household is a random outcome.
(II) The probabilities for all possible magnitudes of electricity use can be approximated by a continuous PDF.

Assumption (I) includes the stochastic aspect of household electricity use which together with the assumption of approximate equivalence of probability for household electricity use with continuous PDFs (II) directs the model developed in this paper: The fitting of PDFs to data. The model is developed according to the flow-chart in Fig. 1. The basic assumptions of the model are illustrated in Fig. 2; a fictive data set represented by a histogram and a fictive PDF fitted to the data for one time interval.

Upon inspection the histograms of the data sets appeared to be similar to Log-Normal and Weibull distributions, which were chosen since they appeared to capture the essential random features of the data sets. In order to include most of the diurnal and seasonal variation while keeping the number of distributions within a reasonable limit in the model, both the distributions Weibull and Log-Normal have been estimated for the following categories:

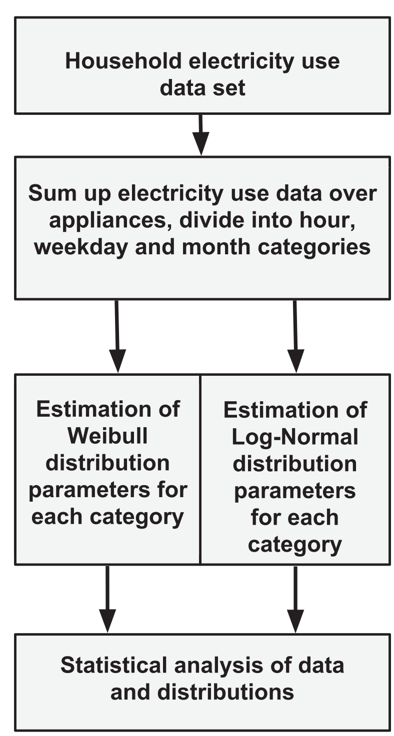

Fig. 1. A flow chart of the process for developing the model in this paper.