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Household electricity demand profiles – A high-resolution load model to facilitate modelling of energy flexible buildings

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ABSTRACT

The objective is to present a high-resolution model of household electricity use developed based upon a combination of measured and statistical data. It is a bottom-up model, which uses the 1-min cycle power use characteristics of a single appliance as the main building block. The effect of parameters, such as the number of occupants and their attitude towards energy use is included in the model. Moreover, the model accounts for phenomena related to unexpected weather conditions and local/national events, e.g. TV shows. The main aim of model is to generate high-resolution household load profiles for investigation of flexibility potential of domestic appliances and network modelling.

The model is validated with two datasets of 1-h and 5-min data from 89 to 16 households, respectively. The comparison between measured and modelled values indicates that model well captures the characteristics of domestic electricity load profiles on a daily as well seasonal basis. For high-resolution data, the model represents well the differences in demand between households of dissimilar size as well as the diversity of demand between households of the same size. For the individual household, the high-end power consumption is under-represented since the timing of peaks is more diverse in the model.

1. Introduction

According to the Danish prognoses, the transition of electricity network towards being fully based on renewable energy sources should be finalized by 2035 [1]. The foreseen large deployment of renewable energy sources can seriously affect the stability of electricity grid; thus, it will be necessary for the energy companies and the national authorities to better control energy consumption in order to match instantaneous energy production. As single family housing accounts for approx. 24% of the Danish final electricity consumption, which corresponds to 75% of the building sector consumption [2], the new control strategies will have to focus on exploiting this potential, and hence significantly alter the characteristic shape of domestic electricity load profile. Therefore in the future, the electricity consumption in single family houses will have to be time-shifted. This can be done by several means i.e. thermal mass, charging of electrical cars and use of appliances. No matter which means are applied, 1-min resolution demand data is required to capture all specifics of household electricity use [3]. This article presents a high-resolution model for generating domestic electricity load profiles used for analysing flexibility potential of household appliances. Other means of shifting or delaying electricity loads will not be further discussed. According to the review by Grandjean et al. [4], there are only 5 models that provide 1-min profiles [5–9]. However, these reflect cultural specifics of the country/region for which they are developed and cannot be directly applied in other circumstances.

The datasets and the literature on Danish electric domestic loads are rather limited. The studies by Gram-Hanssen focus primarily on finding correlations between the electricity consumption and socio-economic factors, such as the size and the year of construction of a house, the number and the age of occupants, the gender, the income level and the education level [10,11]. The analysed datasets are delivered by the electricity supplier and include more than 50,000 residential buildings of different topologies, but only annual values are available. Within the EU (European Union) project EURECO [12], the electricity use of individual appliances in 100 residential buildings was measured in a 10-min time resolution, with the main focus of showing the discrepancy in the electricity use of a single appliance and of indicating the distribution of domestic electricity use. Despite having data in high-resolution, the analysis was done only for the annual values. Using measurements

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of household electricity use from around 20 single family houses, Jensen et al. [13] have developed a simple method for generating 1-h load profiles, which later can be used as the input to dynamic simulation tool – BSim. The method is based on load profiles of a typical weekday and weekend for each season-winter, spring, summer and fall-where each hour is described as a share of the maximum hourly load during the year. The hour with maximum load is set to be on a winter weekday at17:00 h. No discrepancy between households is included in the method.

There is no model available to investigate the flexibility potential within the household electricity use in single family houses in Denmark in a sufficient quality to generate profiles, which can be used as an input for LV (low voltage) network models. Therefore, this paper describes a probabilistic-empirical domestic electricity load model that has been designed to generate 1-min demand profiles that can be used for evaluating the potential and profits of new control strategies to secure stability of the future electricity network in Denmark. The model can also be applied in other domains, e.g. building energy simulations [14] or indoor environmental quality.

The paper is divided into seven sections. Section 2 presents all the data, which has been used as background and validation material for the model. Section 3 describes the model structure, and section 4 presents output example. Section 5 summarises validation results for two datasets, one in 1-h and second in 5-min resolution. Section 6 discusses the results and gives conclusion, and finally section 7 presents further improvements and applications of the model.

2. Material

Three sets of electricity measurements are used as input to the model and two for the validation of the model. Tables 1–3 summarise the overview of scope and characteristics of various datasets. More detailed description of datasets and how they are used follows below. The system for naming the datasets is following: IN – background material, VAL – material used for validation, EL – electricity, TOT – total electricity use of a house, APP – electricity use of individual appliances, LIGHT – electricity use for lighting, 201X – year of data collection. It should be noted that at the period of model development only IN-EL-TOT-2012, IN-EL-APP-2000, IN-EL-LIGHT-2010 datasets were available. Therefore, they were used as background information for the model, and VAL-EL-TOT-2012 and VAL-EL-TOT-2014 were used for validation.

2.1. Input data for model development

The following section describes the datasets used as background information for the model.

Table 2
Distribution of occupants in single family houses in Denmark and IN-EL-TOT-2012.

	Dataset	Statistics Denmark Mean for years 2010–2015
1 person	11% (3)	7% (5)
2 persons	43% (1)	31% (1)
3 persons	9% (5)	17% (3)
4 persons	20% (2)	28% (2)
5 persons	9% (4)	13% (4)
6 persons	3% (6)	3% (6)

*number in brackets indicates ranking place.

2.1.1. Household electricity use measurements for model input (IN-EL-TOT-2012)

The IN-EL-TOT-2012 dataset, which is the main input to the model, comprises hourly data from 35 single family houses. The data is an indirect output of 'Styr din varmepumpe' project [15]. The household electricity profiles are obtained as the difference between the measured total electricity use of the house and the heat pump electricity use. The measurements of electricity used by the heat pump are recorded in 5-min intervals; however, the readings of total electricity use are delivered by the electricity supply companies in 1-h resolution. Hence, the electricity used solely by occupants must be in 1-h resolution. The sample of households covers different family types, such like singles, couples with and without kids (with differentiation between kids and teenagers) and different rural and urban settings. The configurations of appliances in the households are unknown. Additionally, but not used as input for the model, the size and age of houses are also available.

The sample consists of only 35 houses; however, the distribution of households between number of occupants mirrors quite well the distribution of occupants in single family housing given by Statistics Denmark for the years 2010–2015, see Table 2. Therefore, it can be expected that the observations and hypothesis about the load profiles are of sufficient quality and, therefore, can be used as the background material for the model.

The IN-EL-TOT-2012 dataset was used to understand the main characteristics of household load curves. When looking on the electricity consumption pattern of the households during a year presented in Fig. 1(left), it has a clear sinusoidal trend. This is typical for the high latitude locations as a consequence of significant variation in the sun's altitude between summer and winter season, e.g. for Copenhagen 55.6°N – summer maximum of 57.5° (17.5 h with daylight) and winter minimum of 10.5° (7 h with daylight), hence many hours with artificial lighting during the winter period [16]. The sinusoidal pattern is used to model the seasonal variations in household electricity use - $P_{seasonal}$.

Further analysis of the IN-EL-TOT-2012 dataset indicated that there is a variation in daily electricity profile between an average weekday and weekend, see Fig. 1(right). It is a consequence of the

Table 1
Details of background material.

Data-set	Description	Time period covered	Geographical location	Number of houses	Data resolution
IN-EL-TOT-2012	Measurements of the total house and heat pump electricity use	From 2 to 12 months in 2012	Not stated explicitly where in Denmark	35 single family houses	1-h-averages based on measurements with 5-min and 1-h intervals
IN-EL-APP-2000	Measurements of household electricity use on individual appliances level	1 month measurements between 1999 and 2000	Odense/ Denmark	100 houses, out of which 90 single family houses	1-h-averages based on measurements with 10-min intervals
IN-EL-LIGHT-2010	Measurements of household electricity use split into different appliances groups	12 months continuous data for 2010	Taastrup/Denmark	1 single family house	Hourly measurements