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Constructing load profiles for household electricity and hot water from time-use data—Modelling approach and validation

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ABSTRACT

Time-use data, describing in detail the everyday life of household members as high-resolved activity sequences, have a largely unrealized potential of contributing to domestic energy demand modelling. A model for computation of daily electricity and hot-water demand profiles from time-use data was developed, using simple conversion schemes, mean appliance and water-tap data and general daylight availability distributions. Validation against detailed, end-use specific electricity measurements in a small sample of households reveals that the model for household electricity reproduces hourly load patterns with preservation of important qualitative features. The output from the model, when applied to a large data set of time use in Sweden, also shows correspondence to aggregate profiles for both household electricity and hot water from recent Swedish measurement surveys. Deviations on individual household level are predominantly due to occasionally ill-reported time-use data and on aggregate population level due to slightly non-representative samples. Future uses and developments are identified and it is suggested that modelling energy use from time-use data could be an alternative, or a complement, to energy demand measurements in households.

1. Introduction

Detailed load profiles for domestic energy use are important as input to simulations of small-scale energy systems such as distributed electricity generation and solar heating. Direct, high-resolved measurements of the energy use in households can provide such data, but in order to determine energy end-use, for example for individual appliances or water taps, the number of devices required make the measurements complex and costly. Surveys on this level of detail are seldom performed, although the measurement study by the Swedish Energy Agency, finished in 2008, is a counter-example [1]. Similar monitoring studies with different degrees of detail have been performed in Europe [2–4] and elsewhere in the world [5]. In lack of detailed measurements, but also to reduce expenses, load modelling is an alternative.

Models of domestic energy use can be classified on the basis of their resolution. Load forecast models, describing the electric power demand for a cluster of households, typically within a power utility's area of supply, often have a high time resolution but a low spatial resolution, i.e. short time-scale variations are covered by the model, but it is not possible to subdivide the electricity demand on individual households or end-uses. In these cases, maintaining a low spatial resolution is a way to simplify the model structure. For example, variations in power demand between large numbers of households can be modelled as noise or implicit variations in time series [6].

Examples of the opposite are also common. In econometric models, for example, total annual energy use can be subdivided into use per appliance or end-use category, e.g. by use of statistics on appliance ownership or sales figures for appliances. Thus, spatial resolution is high but time resolution is low. Examples include refs. [7–9].

Models with both high time resolution and high spatial resolution tend to be complex because they need large amounts of data, and are therefore not commonly used. An example is bottom-up modelling, which, starting from the smallest possible units of a system, successively aggregates these units to reach higher system levels. The load model of Capasso et al. [10] constructs load curves for large numbers of households by adding the power demand of individual appliances together, using detailed data on demography, socio-economical status and life-style collected from a variety of sources. In a similar approach,

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Paatero and Lund use statistical mean values and general statistical distributions to lower the amount of input data [11].

In the same way, hot-water load profiles are modelled with a 1-min time resolution in Jordan and Vajen [12] by starting from the hot-water flow rate, duration time and mean number of draw-offs during a day. The flow rates and draw-off durations are based on statistical means, while a probability function describes the seasonal variation in load. Assumptions are based on studies of hot-water use in Germany and Switzerland. Models for predicting domestic hot-water use have previously been developed for Swedish conditions as well. For example, Wollerstrand [13] describes a statistical model based on the empirical work and probabilistic model developed in Holmberg [14]. The models are developed to enable simulation of hot-water loads in different types of residential buildings, where stochastic variables are derived based on measurements. These models, however, focus on peak hot-water load to enable sizing of components for district heating and do not take the actual hot-water-consuming activities in a household into account.

Time-use data, empirical sequences of activities in households, are normally collected with time diaries where household members write down their daily activity sequences, providing a rich and multi-faceted material. Time geography, an interdisciplinary field based in human geography, makes use of the information about the sequences in the diaries. In time geography, everyday life of individuals is seen as a series of activities with an inherent logical structure. There are few recent examples of time-use data being used for energy-modelling purposes (one is ref. [15]) and time-use studies are a rather unutilized resource in the energy field. Nonetheless, it could provide to better modelling of the behaviour component in domestic energy use and could also be a complement, or even an alternative, to measurements.

1.1. Aim of the study

In this study, a method to generate load profiles for household electricity and domestic hot water from time-use data is proposed. The aim has been to develop a model that can be used for determination of households' energy use through collection of time-use data and for prediction of changes in future energy use through behavioural change and improvement of the energy efficiency of household appliances.

Profiles are generated from a detailed data set on the time use for everyday activities in Swedish households and the results are compared to electricity and hot-water profiles from recently performed measurement studies. Validation is done by application of the model to a small data set containing both recorded time use and electricity demand. Since the potential of time-use data to contribute to energy demand modelling has not yet been studied in any detail, this study will give some first insights into this approach.

An advantage of the model is that the time-use profiles for individual household members allow load profiles to be individual-based rather than using the household as the smallest unit of analysis. This enables determination of the contribution of each household member to the total energy use of the household. Additionally, various types of activity patterns can be identified and connected to different household categories. Contrary to many measurement studies the model also covers electricity use and hot-water use in the same households, allowing possible correlations between hot-water use and electricity use to be taken into account when applying the model.

1.2. Outline of the paper

The time-use study constituting the background material for the model is described in Section 2, while the following section covers model structure, parameter estimates and model implementation. Validation results and comparisons with aggregate measurement data are presented and analysed, both for apartments and detached houses and for different end-uses, in Section 4. Finally, in the last section, future developments and applications of the model are discussed.

2. Material

Five sets of time-use data and energy measurements are used in this study, for input to the model, validation of the model and comparison with aggregate measurements. An overview of the scope and other characteristics of the data sets is shown in Table 1. The data set TU-SCB-1996 is used as the main input to the model while TU/EL-SEA-2006 is used for validation. The other three data sets provide data for comparison of model output and energy measurements on population level. Further descriptions of how the data sets are used follow below.

2.1. Time-use data for model input

The TU-SCB-1996 data set, which is used as the main input to the model, contains data on the time use for different daily household activities in a large number of Swedish households. The study was performed as a pilot survey of time use by Statistics Sweden (SCB) in the autumn of 1996. Each person in the participating households being ten years or older was instructed to write a diary reporting the timing of activities and a description of the activities performed, together with information about geographic location, means of transport, and by whom they were accompanied while performing the activity [19].

Most diaries were written on one weekday and one weekend day per household, on dates defined by Statistics Sweden. The sample of households covers individuals aged between ten and 97 years, in different family constellations, such as couples, singles, etc., and different rural and urban settings [20]. Household members younger than ten years are mentioned in the background data, but are not directly included in the time-use study.

The time-use data originally included 464 individuals in 179 households, but in this study a few households were excluded because of incomplete data for some persons and because two weekend days were reported instead of one weekday and one weekend day in one household. In order to maintain a high data quality, all households where data were missing for at least one person were excluded. The subset finally contained 431 persons in 169 households. For the modelling, only activities performed at home are considered. As an example of time-use data in the data set, Fig. 1 shows the availability at home of all persons in the time-use material on a weekday and a weekend day.

The time-use data are recorded on 5-min intervals (although a few households have reported on a 1-min basis) and the activities are organized in a detailed hierarchic activity code scheme, defining activities at different levels of abstraction [21]. This code scheme is constructed by interpretation of the diary-writers' descriptions of the activities performed and classifies activities into different categories, as depicted in Fig. 2 for the case of 'Cleaning'. The figure shows the different activities involved in cleaning as subcategories of 'Room care', which in turn is a subcategory of 'Household care'. The subdivision of 'Cleaning' is done on two levels of detail. Considering energy-demanding activities, 'Vacuum cleaning' (marked with solid bold lines in Fig. 2) is the only activity in direct need of electricity, while use of hot water can be assumed for 'Scrub floor', 'Wash up' and 'Clean windows' (marked with bold broken lines in Fig. 2). The figure gives an impression of how energy use is embedded in larger activity schemes.

Previous research on this time-use data set has resulted in the creation of a computer program (Visual-TimePAcTS) for time-