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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-

Table 1
The different data sets and the abbreviations used in this study.

Data set	Description	Time period covered	Geographical location	Number of participants	Data resolution
TU-SCB-1996 [20]	Pilot survey of time use (TU) by Statistics Sweden (SCB).	One weekday and one weekend day per household member between August and December 1996.	Not stated explicitly, but a representative spread on different urban and rural areas	431 persons in 169 households.	Mainly 5-min intervals, in some cases 1-min intervals.
TU/EL-SEA-2006 [16]	Survey of time use *and* electricity use by the Swedish Energy Agency (SEA).	Four successive days (two weekdays and two weekend days) in each household in the autumn of 2006.	Three households in Mälardalen region (mid Sweden), one household in Malmö (southern Sweden) and one household in Kiruna (northern Sweden).	13 persons in five households.	Time-use data on 1-min intervals, electricity measurements with 10-min means.
EL-SEA-2007 [1]	Preliminary electricity measurements of household electricity on individual appliance level by the SEA.	Based on yearly and monthly measurements between 2005 and 2007.	Majority of households in the Mälardalen region, a few households in Malmö and Kiruna.	217 households.	1-hour averages based on measurements with 10-min means.
HW-MDH-2006 [17]	Aggregate measured load data for hot water and electricity to be presented for the tenants.	Continuous measurements between 2005 and 2006.	Two multi-family houses situated in Västerås, in the Mälardalen region in Sweden.	40 persons in 24 households	Hourly measurements.
HW-SEA-2007 [18]	Preliminary measurements of water demand at different taps by the SEA and SP Technical Research Institute of Sweden.	Continuously between October 2006 and June 2007, but with different time intervals.	In the area of Stockholm (eight households) and Borås (two households).	29 persons in ten households, six detached houses and four apartments.	Mainly 10-min intervals for shorter periods on 1-min intervals.

geographically inspired visualization of the data (see refs. [20,22]). Subsequent time-use surveys have been conducted after the 1996 study. One set of data from 2000/2001 is currently being imported into the Visual-TimePAcTS software and it is hoped that the model described here can be applied to this data set to determine possible differences in activity patterns between 1996 and 2000/2001.

2.2. Validation and comparison data

The Swedish Energy Agency (SEA) is currently taking a number of actions to improve the Swedish statistics on energy use in the built environment [23]. Two subprojects within this greater framework are of interest for this study. The first one is a measurement survey of household electricity on individual appliance level in a large number of Swedish households. The survey will result in month- or year-long series of 10-min averages of electricity demand for individual appliances in 200 detached houses and 200 apartments [1].

The TU/EL-SEA-2006 data set, which is comprised of data from this measurement survey, contains electricity measurements *and* activity data for five households and therefore provides an opportunity to validate the model against actual measurements

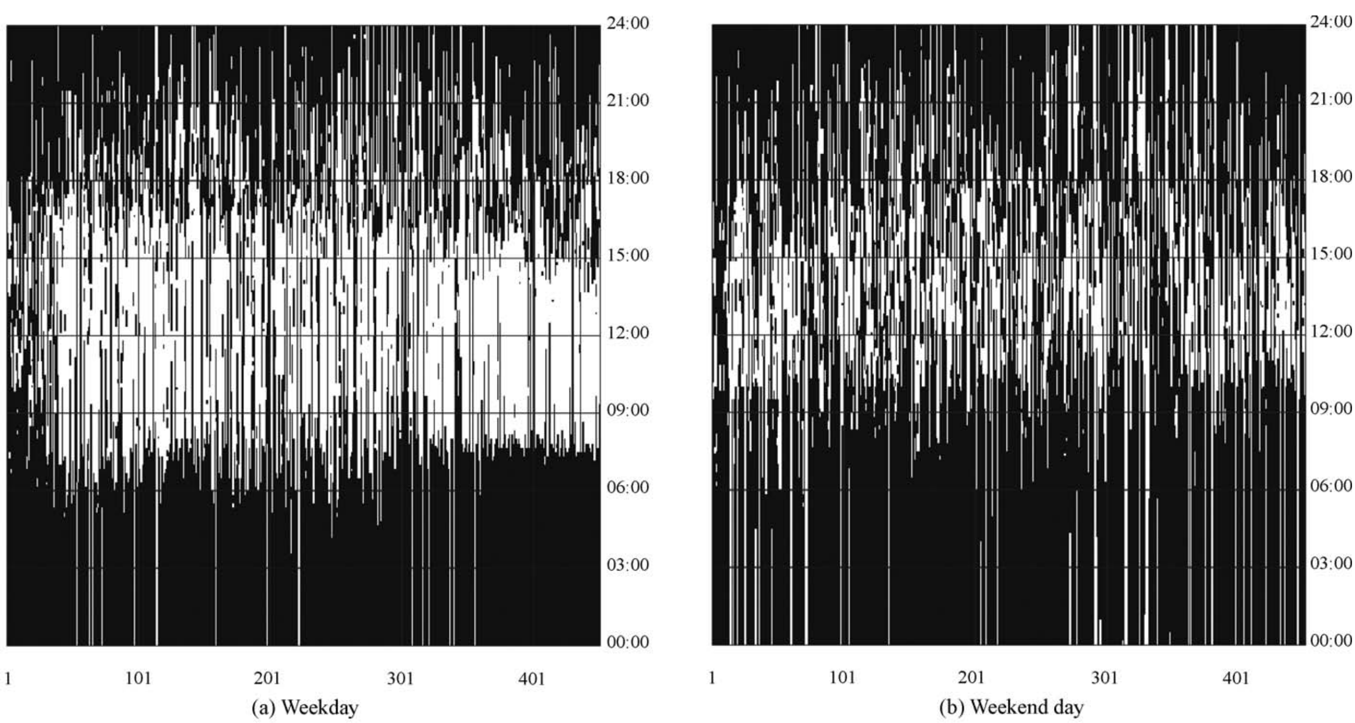

Fig. 1. Activity profiles for all persons in the time-use data set TU-SCB-1996, showing when each person is at home (black lines) and away (white lines). The horizontal axis orders persons by decreasing age from left to right. The vertical axis shows the time of day. The plots were generated with the computer program Visual-TimePAcTS [20,22].

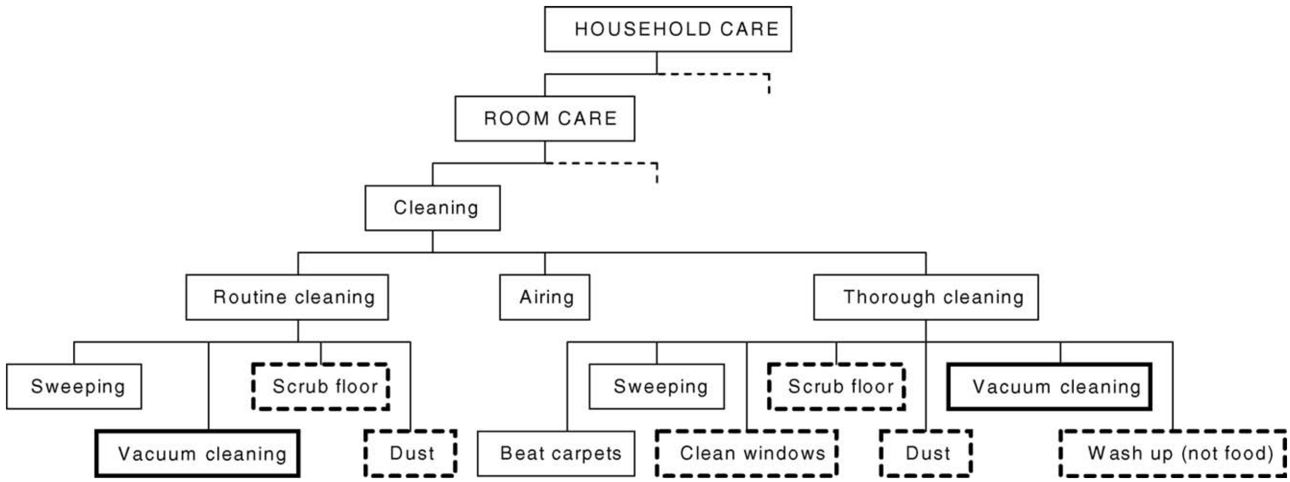

Fig. 2. Activity scheme for cleaning, a section of the complete scheme used for categorization of activity data. 'Cleaning' is a subcategory to 'Room care', which in turn is a subcategory to 'Household care'. Both of these include various subcategories, apart from the ones shown here. Activities that involve use of hot water and electricity are marked with bold broken lines and bold solid lines, respectively.

in individual households. The activity data are organized in the same way as in TU-SCB-1996, so the model can be applied without modifications. The EL-SEA-2007 data set is also based on the SEA's household electricity survey and contains mean load curves for different appliance categories averaged over all the 217 households with finished measurements in late 2007. These data are used for comparing the electricity part of the model with average load curves on population level.

The second SEA subproject of interest for this study is a survey of domestic hot-water use in ten households on the detail of different taps and measurements on total use of hot and cold water in another 60 households. The data set HW-SEA-2007 in Table 1 consists of data from this project, including both detached houses and apartments. The detailed measurements were finished in June 2007, while the more extensive measurements finished in June 2008. The survey results in hot and cold water demand in series of 10-min or 1-min means at different taps [18]. The measurement data has been used to calculate average load curves for comparison to the modelled load profiles.

The HW-MDH-2006 data set in Table 1 comprises hot-water measurements in 24 apartments in two multi-family houses. The total hot-water use for every single household is measured on an hourly basis. The data used for comparison was measured in 2005 and 2006, but the measurements are ongoing [17]. The output from the hot-water part of the model is compared to these data.

3. Method

The conversion of activity data to energy load profiles is done by connecting each activity to an end-use category and assuming a basic energy-use pattern for each such end-use category. A number of parameters are defined to describe each use pattern. When developing the model structure, the main aim has been to keep it as simple as possible, while maintaining a realistic performance of the model on an hourly basis. In Section 3.1 the model structure is defined. Estimation of parameters is discussed in Section 3.2. Section 3.3 briefly describes how the model is implemented and what types of data are generated.

3.1. Model structure

Prior to modelling, all activities assumed to involve use of electricity or hot water were examined. Some activities were then excluded, although electricity or hot-water use could be assumed, because of low occurrence in the material in combination with an assumed low contribution to the total energy use of the households where they appeared, for example 'sewing' and 'woodworking'. Furthermore, washing machines and dish washers have not been considered as hot-water-consuming equipment since, at present, most of this equipment is fed with cold water heated by electricity in Swedish households.

Five different modelling schemes were used to describe the energy demand connected to the activities. The applied scheme depends on the type of activity and appliance or water tap involved:

(a) Power demand not defined by activities. This concerns the use of cold appliances, which are modelled as a base load in the form of a constant power. In reality, the power fluctuates, but on the hourly time scale in the output data, these variations largely level out.

(b) Power demand constant during activity. This scheme applies to cooking, ironing, cleaning, use of TV, audio appliances and computer, and to showering, cleaning and scrubbing. The power demand is considered constant during the time given for the activity, as shown in Fig. 3. This is a more severe simplification for certain activities than for others, typically for cooking, which in reality covers a variety of different appliances and patterns of usage not captured by the time-use data.

    This simplification is also necessary for scrubbing, where sub-activities such as changing scrubbing water are not covered in the time-use data. A certain hot-water demand is assumed during the activity, but instead of tapping water at regular intervals (changing scrubbing water) the model is simplified by assuming that water is tapped in smaller amounts continuously throughout the activity.

    To take the possible use of multiple appliances into account, the company data for each person was used. All persons reporting that they were accompanied by another family member while watching TV or using audio appliances and computer are assumed to use one appliance together, while persons reporting that they were on their own are assumed to use one appliance each. This means that explicit assumptions about the number of appliances in the households are avoided.

(c) Power demand constant after activity. This scheme applies to dish-washing, washing and drying. The activities used in the model are of the type 'Fill washing machine', so that the actual appliance use can be assumed to begin after the activity has finished. Power is then demanded until a maximum time has

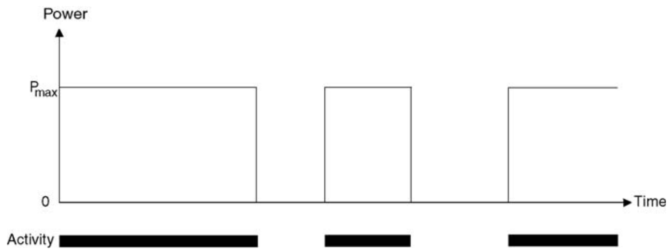

Fig. 3. Modelling scheme for activities where energy is demanded during the entire course of the activity. Throughout the activity, power of level P_{max} is demanded.

elapsed or until the activity starts anew (see Fig. 4). Although the demand for these appliances normally varies during the duty cycle of the appliance, the assumption of constant load is assumed to be sufficiently accurate.

(d) Power demand constant during activity with time constraint. This applies to taking or preparing a bath and do the dishes in the sink. Hot water is in these cases used only in the beginning of the activity. When the bath tub or sink is filled, no more hot water will be used, although the activity itself continues. A constant maximum power P_{max} is in those cases assumed until the total required volume of hot water is tapped (see Fig. 5). A time constraint is also applied to activities such as complementary work after bath as well as washing clothes by hand, since a maximum total hot-water demand is assumed, while the activity can be going on for a long time without more water being tapped.

(e) Activities with time-dependent power demand. This applies to lighting and is similar to scheme (b) above, with the difference that the power varies with time. To make the modelled load curves exhibit realistic daily and seasonal variations in lighting demand, they are made dependent on the daylighting level, e.g. in a certain building or an average daylighting level. All illuminances above a certain limit value (L_{max}) imply minimum demand of lighting power (P_{min}). For illuminances $L(t)$ between the maximum limit value and zero, the power demand $P(t)$ is set to vary according to the following formula, directly relating the lighting power demand to the relative difference between limit and actual illuminance:

$$P(t) = \begin{cases} P_{min}\dfrac{L(t)}{L_{max}} + P_{max}\left(1 - \dfrac{L(t)}{L_{max}}\right), & L \leq L_{max} \\ P_{min}, & L > L_{max} \end{cases} \tag{1}$$

This varying power is demanded throughout activities performed by persons that are at home and awake.

3.2. Parameters

When choosing parameter values, the objective has been to find an 'average' parameter set that gives a realistic mean energy use

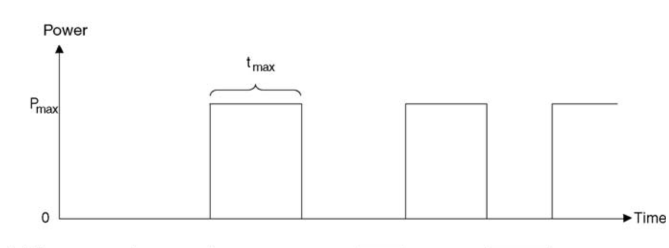

Fig. 4. Modelling scheme for activities where energy is demanded after the entire course of the activity, with a maximum time limit. When the activity is finished, power of level P_{max} is demanded until maximum time t_{max} has elapsed or the activity starts anew.

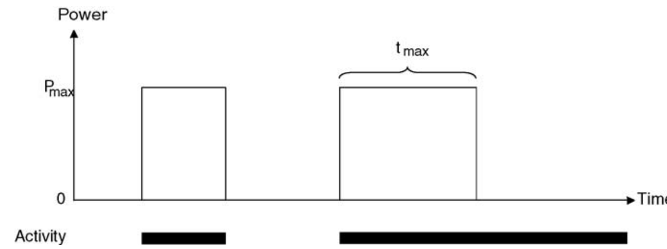

Fig. 5. Modelling scheme for activities where energy is demanded during the activity with a maximum time limit. During the activity, power of level P_{max} is demanded until maximum time t_{max} has elapsed or the activity is finished.

when applied to all households in the time-use data set. Estimates of standard powers and runtime for electrical appliances were obtained through product tests, reflecting the range of appliances available at certain times [24]. To the extent possible, the mean lifetime of appliances was taken into account, so that product tests were chosen from the time when the average appliance was bought. This method has been used previously in ref. [25].

Since it is hard to find reliable data on the actual scope of appliances, the estimates obtained by this method are approximate. In the results reported here, the same appliance set has been applied to all households, but different appliance sets may be defined for each household. The resulting parameters are found in Appendix A. Illuminance values used to determine the lighting power scheme can be obtained as monthly means of hourly values from the online database Satel-Light [26]. In the following simulations, Satel-Light data for a standard building in Stockholm, Sweden, are used. The illuminance limit for minimum power demand is set to 500 lux, a general recommendation for the indoor lighting level (see for example [27]).

Statistics on hot-water use for different activities are not commonly available in the literature. Therefore, values on hot-water demand for shower, bath and dishes, used as rules of thumb by Swedish energy companies, are applied in the first place. When necessary, reasonable assumptions were made about hot-water consumption through empirical estimates, where the hot-water use of a small number of persons was measured during performance of different activities.

The volumes of hot water at 55 °C required to reach usable temperatures when mixed with cold water at 10 °C, as well as the energy required to increase the temperature of the cold water, for all hot-water-demanding activities in the material are found in Appendix A. Most households are considered having traditional taps, both in the shower and at the different washstands.

3.3. Implementation and output format

The model was implemented in Matlab, allowing all modelling routines to be implemented as matrix operations, which speeds up calculation times. The program can also handle subdivision of households on different categories, in this case detached houses and apartments. Prior to the development of this program, a relation database with a graphical user interface was built up to handle in-depth analysis of time-use patterns and their connection to individuals, households and socio-economic background data. This has been extensively reported, together with preliminary versions of the model routines, in ref. [28].

In the following comparisons of model output to measurements, one-hour resolution of the measurements was chosen as model output resolution. Load curves can, however, be generated with different time resolutions down to that of the time-use data. There is obviously a trade-off between model complexity and output resolution, but since hourly intervals are generally needed for applying the model in different simulation programs for small-scale electricity or heating systems (for example PVSYST [29] or Polysun [30]), this seemed to be a reasonable aim for the model accuracy. The general output of the model, when applied to the TU-SCB-1996 dataset, consists of hourly values of demanded household electricity and hot water for the end-uses in the different categories in Appendix A for one weekday and one weekend day in each household. The daylight availability varies with each month, which affects the lighting curves. Thus, the output contains twelve different daily lighting load curves for each person and type of day.

In Fig. 6, three examples of output from the model applied to TU-SCB-1996 are shown, with electricity use per household and hot-water use per average household member. The profiles represent a weekday for three households with different hot-water behaviours, where the six-person household in Fig. 6(a) only uses hot water in the evening, the two-person household in Fig. 6(b) uses hot water during daytime and the four-person household in Fig. 6(c) almost only uses hot water in the morning. The electricity demand is displayed similarly, where differences in peak power demand are clearly seen. Similar profiles can be generated for all persons, individual households or groups of households within the time-use study.

4. Model validation and comparisons with aggregate measurement data

Ideally, the modelling framework presented in Section 3 should be validated against measured electricity and hot-water demand in the same households as where the time-use data were collected. This can be done for the TU/EL-SEA-2006 data set, where both measurements and time-use data were collected in the same households. For the large dataset TU-SCB-1996, however, no such measurements exist. Instead, since these data are supposed to be representative of the Swedish population in general, it is assumed that the average output of the model corresponds to the average national demand of today, under the conditions that (a) the parameters reflect average electrical appliance and hot-water demand of today and (b) no extensive shifts in activity patterns have taken place since 1996. Point (a) is a practical question of finding the right parameters. Point (b) could be more problematic since some activity patterns might have undergone changes during the last decade. If both points hold, the results for electricity load should show the same characteristics as the measurements of the Swedish Energy Agency, since both samples of households are supposed to be representative of the population in general. Similar comparisons can be made to the data sets with hot-water measurements, although the number of households is too low to represent the average Swedish household.

In Section 4.1, sources of error that could influence the model output are briefly described. In the following subsections, validation is done for the electricity part of the model by application of the model to the TU/EL-SEA-2006 dataset, and, as a test of the performance of the model when applied to TU-SCB-1996, aggregate output data are compared to measured electricity and hot-water use on population level.

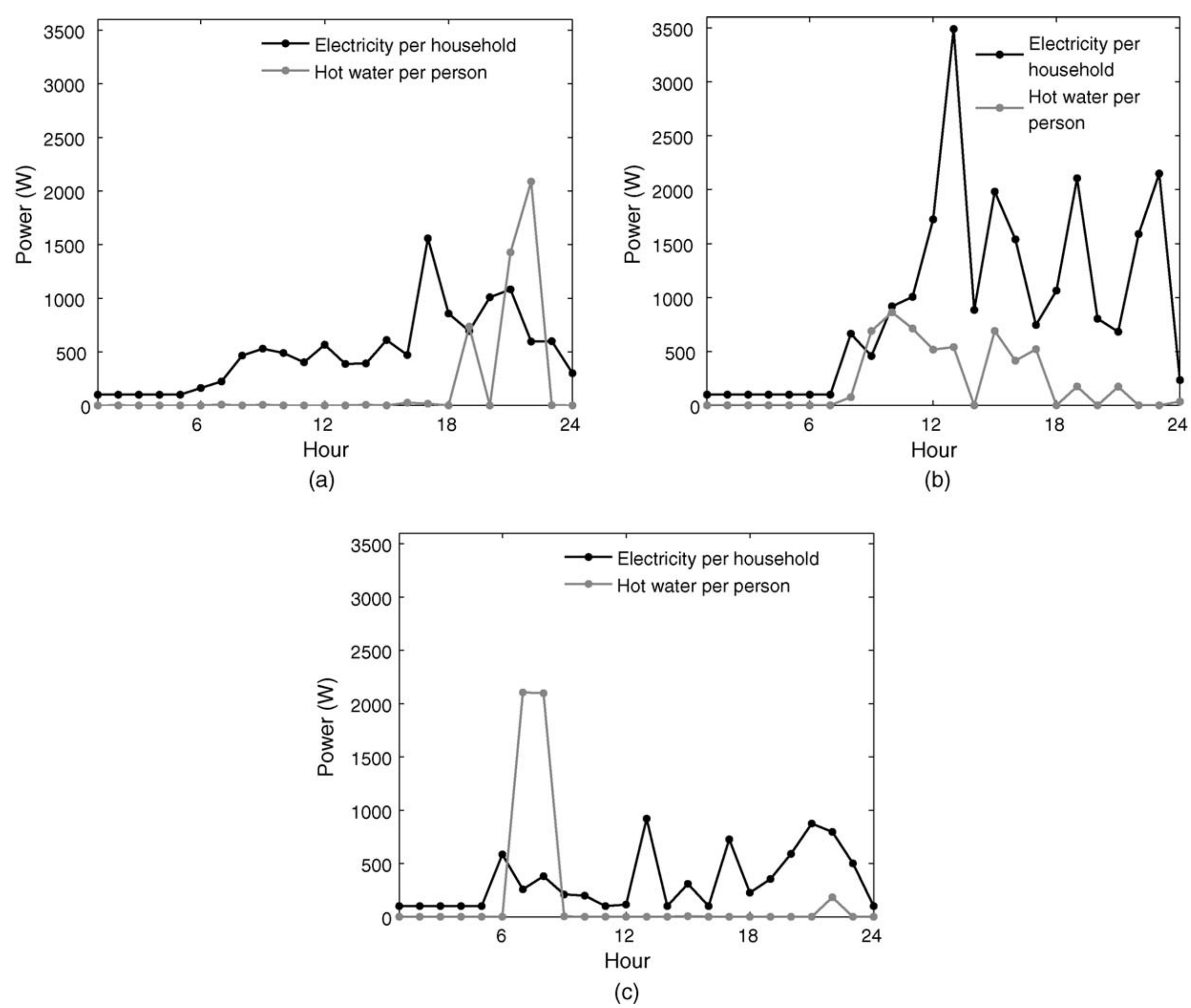

Fig. 6. Examples of load profiles generated by the model when applied to TU-SCB-1996: electricity and hot-water demand on a weekday in three different households. The electricity use is displayed per household and the hot-water demand per average household member. The number of household members is six in (a), two in (b) and four in (c).

4.1. Possible sources of error

The process from the collection of the SCB 1996 time-use data to the validation of the final model output contains a number of possible sources of errors. These are important to identify in order to interpret the validation results correctly. The most important ones are the following:

1. Diary-writers not reporting in accordance with the activities actually performed. Both the timing and descriptions of the activities are reported by the household members themselves. There is thus a possibility of ill-reported data, but the occurrence of such is at the same time hard to determine.
2. Problems with exact interpretation of the diary-writer's notice and applying activity schemes to it. For TU-SCB-1996, this should not be a severe problem, since the data set has undergone a thorough examination and the activities have been carefully classified, as described in Section 2.1.
3. Modelling assumptions. This regards all the steps described in Section 3.1.
4. Estimation of parameters (Section 3.2). Although some of the parameters are problematic to estimate correctly, they are easily adjusted, since the total number of assumptions is kept low.

4.2. Validation of the model for household electricity in individual households

In Fig. 7 the model output for the time-use data in TU/EL-SEA-2006 is compared to separate electricity measurements in the five households. Standard appliance parameters were used and

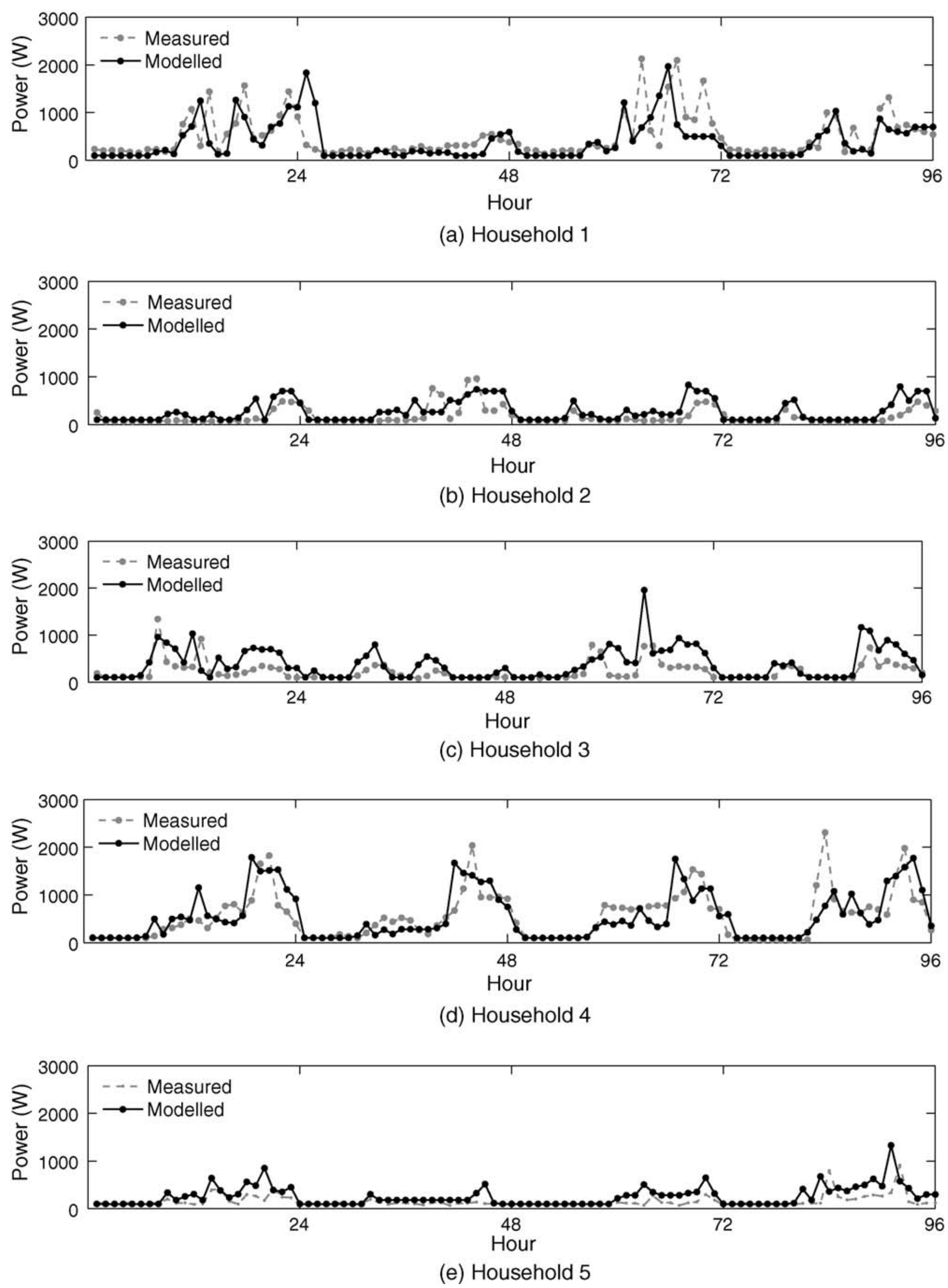

Fig. 7. Modelled and measured household electricity use during four successive days for the five households in TU/EL-SEA-2006. The model is applied to time-use data and compared to measurements in the same households.

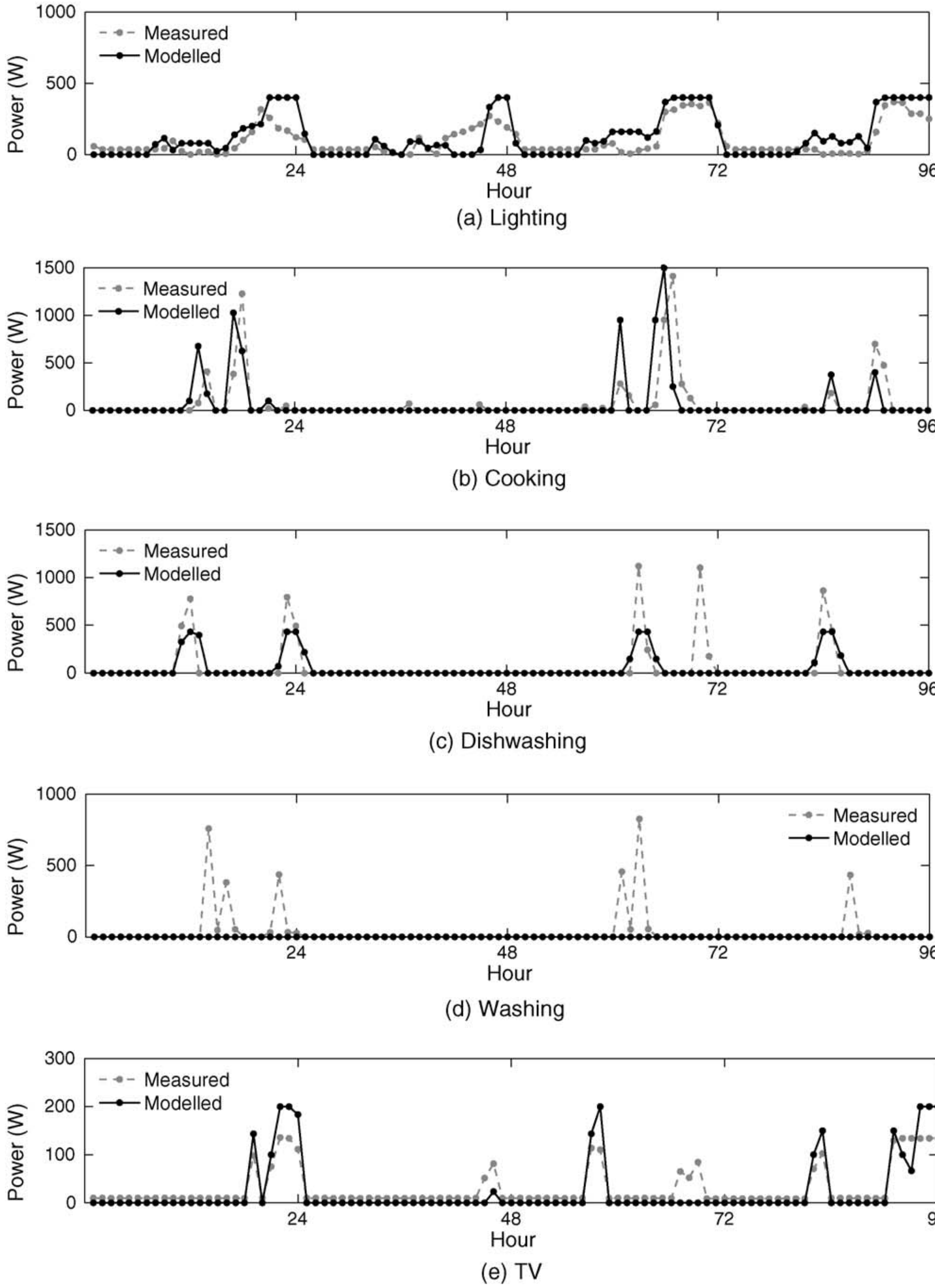

Fig. 8. Examples of modelled and measured end-use specific electricity demand during four successive days for one household in TU/EL-SEA-2006. The model is applied to time-use data and compared to specific measurements in the same household.

daylight availability distributions were chosen from ref. [26] with respect to the data collection period and the site in question. The figures show that there are differences between modelled and measured data, but that general patterns are reproduced by the model, for example higher modelled electricity use in households where the measured electricity use is higher, higher modelled electricity use during days with measured higher electricity use and correspondence regarding the number of power peaks and their magnitudes. Thus, the model does not give an exact reproduction of the electricity use in the households, but the patterns that are generated are realistic and capture important qualitative features.

For further analysis of the discrepancies between modelled and measured data, comparisons for individual end-uses can be made. A few illustrative examples are shown in Fig. 8, for the first household in Fig. 7, showing modelled and measured demand for lighting, cooking, dishwashing, washing and TV. The modelled curves for lighting and cooking correspond well to measurements, despite the simple modelling schemes. A few peaks for dishwasher and TV are missing, either in the modelled or measured curves. An inspection of the time-use data showed that use of TV was recorded without corresponding measurements and that dishwasher use was not recorded at the end of day 3 (error sources 1 and 2). A more severe case of ill-reported data by the households is evident in the curve for washing, due to activities being recorded on a too low level of abstraction in the activity scheme that is not covered by the model. Consequently, no washing is captured by the model, causing

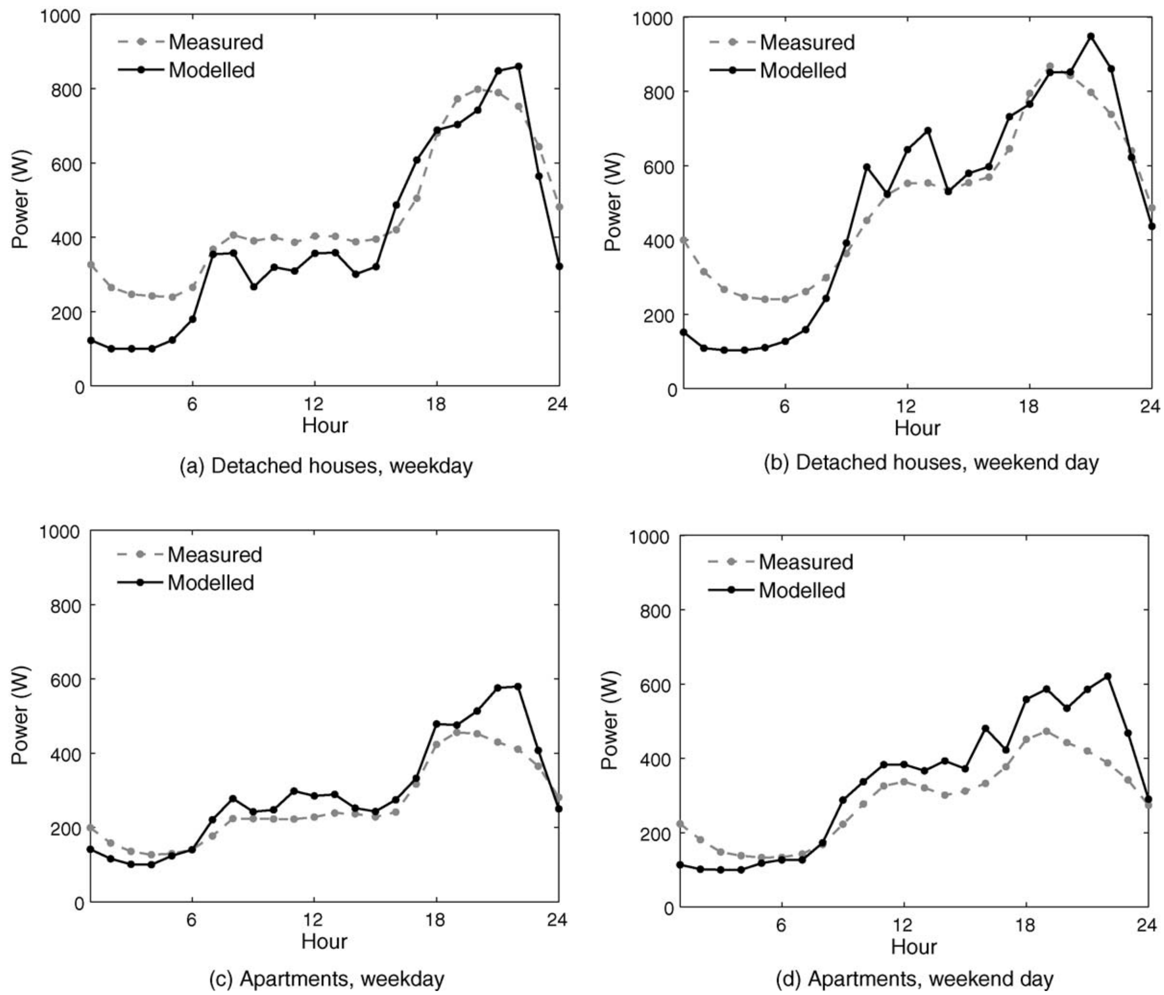

Fig. 9. Modelled and measured average household electricity use per household over the day for detached houses and apartments. The model is applied to TU-SCB-1996 and the measured electricity is from EL-SEA-2007.

most of the missing peaks in Fig. 7. It clearly shows the importance of well-reported activity data on sufficiently high levels of detail.

The same validation of the model output for the other households showed that most discrepancies had similar causes. Generally, the model performs best for end uses where electricity is demanded during the activity, such as TV and computer, and worse for activities where electricity use is not implied unambiguously by the time-use data, such as drying and cooking. Although discrepancies are occurring more frequently for the latter activities, the patterns are generally reproduced. Although standard parameters are used, the model performs adequately. Depending on the desired accuracy level, parameters could be chosen to match appliance sets in individual households to increase the performance of the model.

4.3. Comparison of the model output for household electricity with aggregate measurement data

In Fig. 9 the average modelled electricity use per household is compared to average load curves in EL-SEA-2007. A close overall correspondence can be observed for all four cases, although the modelled load is more variable compared to the measured load curve. This is because the number of surveyed days per household is much greater in the measurement survey (from a couple of months up to one year in the measurement survey and one weekday and one weekend day per household in the time-use survey). General patterns are still clearly captured by the model, for example that the power demand is generally lower in apartments than in detached houses, and that the morning load is shifted towards mid-day on weekend days. One obvious difference is the lower modelled electricity demand during night-time for detached houses. As will be seen later, this is mainly caused by miscellaneous unspecified demand that is not covered by the model. However, this is easily corrected for since it is close to constant.

Comparisons were also made between modelled and measured mean daily demand in each end-use category. For ease of comparison, the model categories were rearranged to match those of the Energy Agency in data set EL-SEA-2007. Fig. 10 shows mean daily demand for each end use in the modelled data and in EL-SEA-2007. Although the exact magnitudes differ, the general patterns correspond, for example that the relative magnitudes of cold appliances, lighting and cooking are roughly the same in both detached houses and apartments. The most obvious difference between measurements and model output is the computer category. This is probably a non-representativity problem, reflecting the increased use of computers since 1996. It could also be due to error source 1, i.e. that household members use computers but define their activity as something else (e.g. 'homework', 'evening work', etc.).

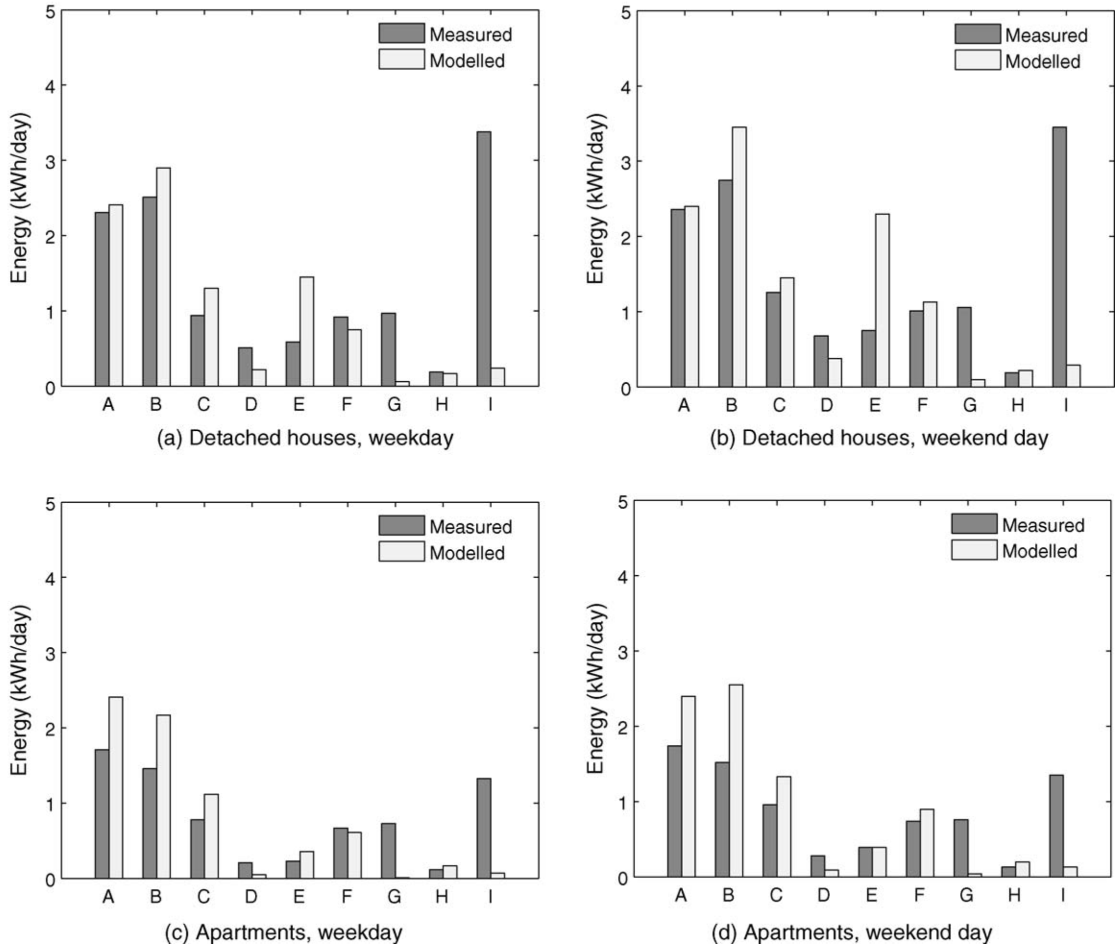

Fig. 10. Comparison between mean daily electricity demand per household from the model when applied to TU-SCB-1996 and measured daily means per household from EL-SEA-2007. Categories are A: cold appliances, B: lighting, C: cooking, D: dishwashing, E: washing and drying, F: TV, VCR, DVD, G: computer, H: audio appliances, I: additional. The 'additional' category includes cleaning and ironing in the modelled data.

The washing and dishwashing categories also differ considerably. These activities are rare, in that they do not commonly occur on a daily basis. Since the activity data cover only two days per household, these activities are more prone to random variations. It should be stressed that certain deviations from the measured data are expected, since the modelled data are based on two daily values per household, while the measured data are based on monthly or annual measurements in every household.

A comparison of daily mean load curves is shown for detached houses on weekdays in Fig. 11. The correspondence is similar for weekend days and for apartments and are not shown explicitly. Instead, the correspondence can be expressed by the Normalized Variation Factor (NVF), also used in ref. [10],

$$\mathrm{NVF} = \frac{\sum_i^n (P_{\mathrm{mod}}(i) - P_{\mathrm{meas}}(i))^2}{n((1/n)\sum_i^n P_{\mathrm{meas}}(i))^2}, \tag{2}$$

where $P_{\mathrm{mod}}(i)$ and $P_{\mathrm{meas}}(i)$ are the modelled and measured demand, respectively, at hour i. The NVF is thus the squared sum of the differences between measured and modelled demand, normalized by the mean squared measured load, in every time step. NVF values for end-use specific load curves in detached houses and apartments on weekdays and weekend days are shown in Table 2.

It is seen from Fig. 11 that modelled and measured curves correspond in most cases, most notably for cold appliances in Fig. 11(a), lighting in Fig. 11(b) and TV, DVD, VCR in Fig. 11(f). The evening peak for the cooking demand in Fig. 11(c) corresponds well in magnitude, but is displaced by one hour, causing the high NVF value shown in Table 2. The biggest difference between modelled and measured values appear for washing and drying, as seen both in Fig. 11(e) and Table 2. This could, as mentioned above, be because of random variation in the data, but also because of an overestimation of the drying demand, since all households are assumed to use an 'average' tumble dryer, while in reality no electric equipment at all might be used in many cases. The power demand for TV and related appliances in Fig. 11(f) is low during daytime, probably since standby power is not included in the model. In contrast to the modelled additional demand, the measured additional category in Fig. 11(i) has a peak in the morning. This is probably due to various appliances such as kettles and water cookers not measured specifically in the SEA's survey.

The model parameters can be adjusted to increase the fit to the measured load curves. However, since the measurement results from the EL-SEA-2007 are preliminary, this has not yet been done. Instead, the comparisons above are intended to show the overall validity of the end-use load profiles produced by the model when applied to TU-SCB-1996, and not to provide exact data for adjustment of the model. Adjusting the parameters in most cases

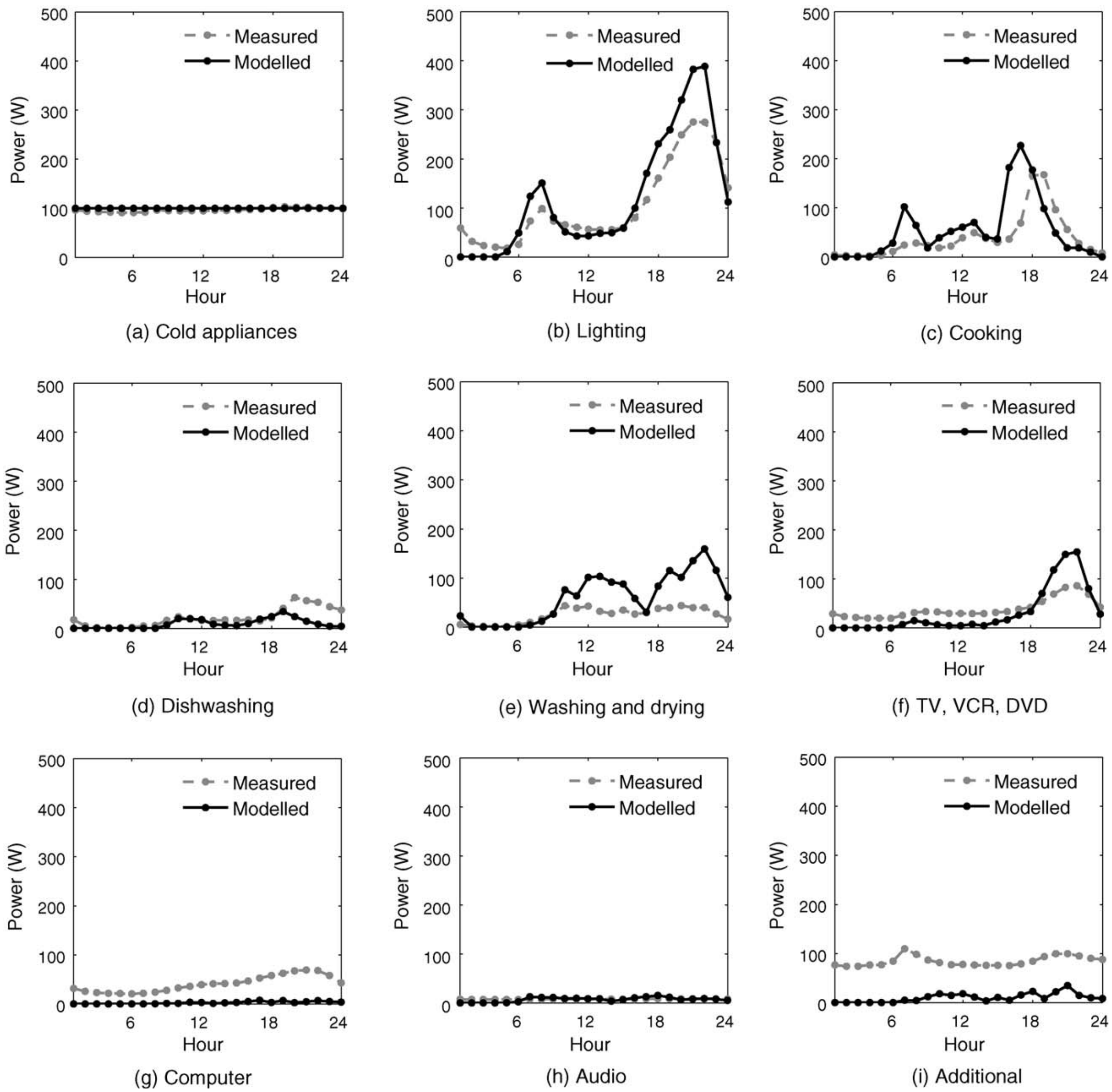

Fig. 11. Measured and modelled average electricity use per household for different end-use categories, detached houses, weekday. The model is applied to TU-SCB-1996 and the measured electricity is from EL-SEA-2007.

means adjusting the power demand level for different appliances/activities. This adjustment lowers or raises the total use in Fig. 10 and the magnitude of the load curve variations in Fig. 11, while the implicit variations in the input time-use data cause the spread of demand over the day.

4.4. Comparison of the model output for hot water with measurement data

For the hot-water part of the model, no detailed validation can be done since hot-water and activity data are not available in the same

Table 2
Normalized Variation Factor for end-use specific household electricity load curves.

End-use category	Detached houses, weekday	Detached houses, weekend day	Apartments, weekday	Apartments, weekend day
Cold appliances	0.00	0.00	0.17	0.15
Lighting	0.21	0.29	0.79	1.31
Cooking	1.78	0.72	0.81	0.83
Dish-washing	0.82	0.35	0.95	0.64
Washing and drying	4.42	7.69	2.57	0.98
TV, VCR, DVD	0.57	0.76	0.70	1.05
Computer	1.00	0.91	1.08	0.96
Audio	0.30	0.51	1.18	2.11
Additional	0.89	0.87	0.91	0.84

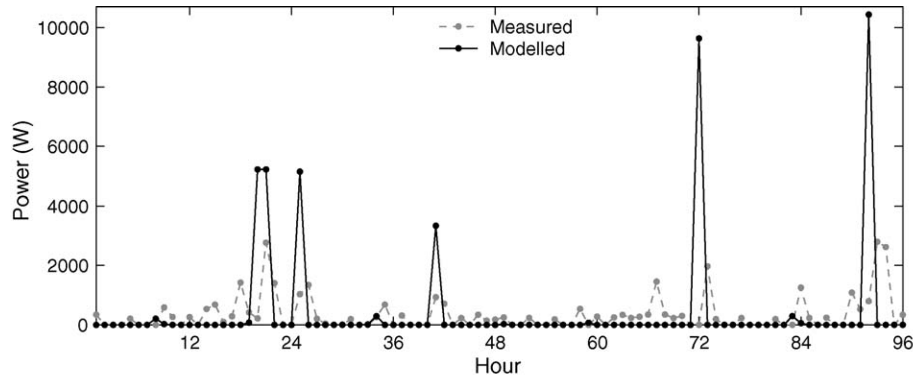

Fig. 12. Comparison between measured electricity to the electric water heater and the modelled hot-water use for a single household where both electricity use and activities were followed during four successive days. Electricity measurements and the activity data, which the model is applied to, are both from TU/EL-SEA-2007.

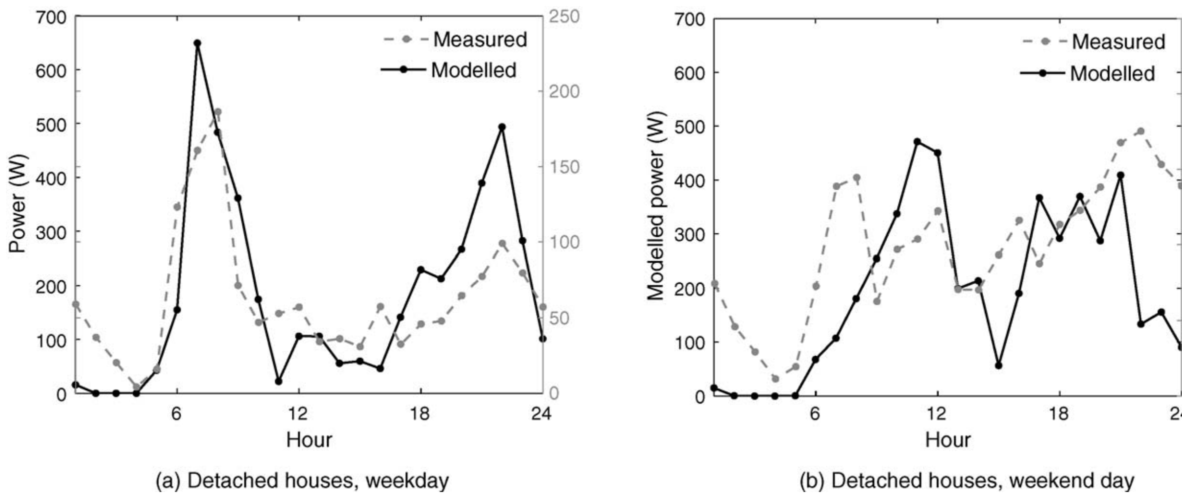

Fig. 13. Modelled and measured average hot-water use per person over the day for detached houses. The model is applied to TU-SCB-1996 and the measurements on hot-water use are from HW-SEA-2007. The left *y*-axis is for modelled data and the right for measured.

households. However, the first household in Fig. 7 uses an electrical hot-water heater, for which the electricity demand is recorded. A comparison between the modelled load curve and measurements from TU/EL-SEA-2007 for the four days is shown in Fig. 12. Electricity used by an electrical water heater does not exactly correspond to the energy required for hot water. The losses from water heaters can be significant, but energy is also continuously supplied to the tank to keep a certain set temperature (seen as "noise" or small recurring peaks in the figure), which means that energy will not only be supplied when hot water is used.

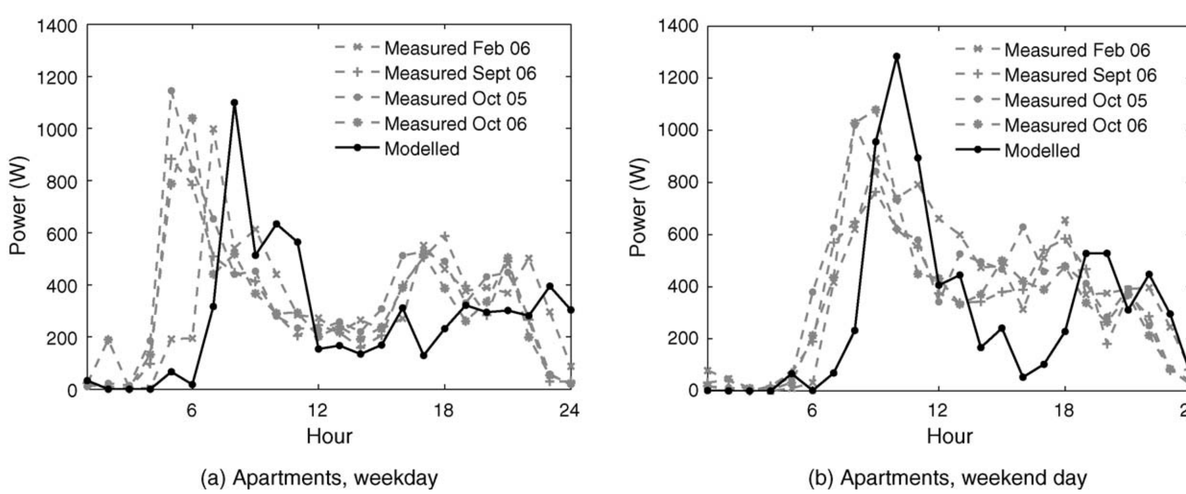

Fig. 14. Modelled and measured average hot-water use per person over the day for apartments. The model is applied to TU-SCB-1996 and the measurements on hot-water use are from HW-MDH-2006 for February, September, October 2006 as well as October 2005.

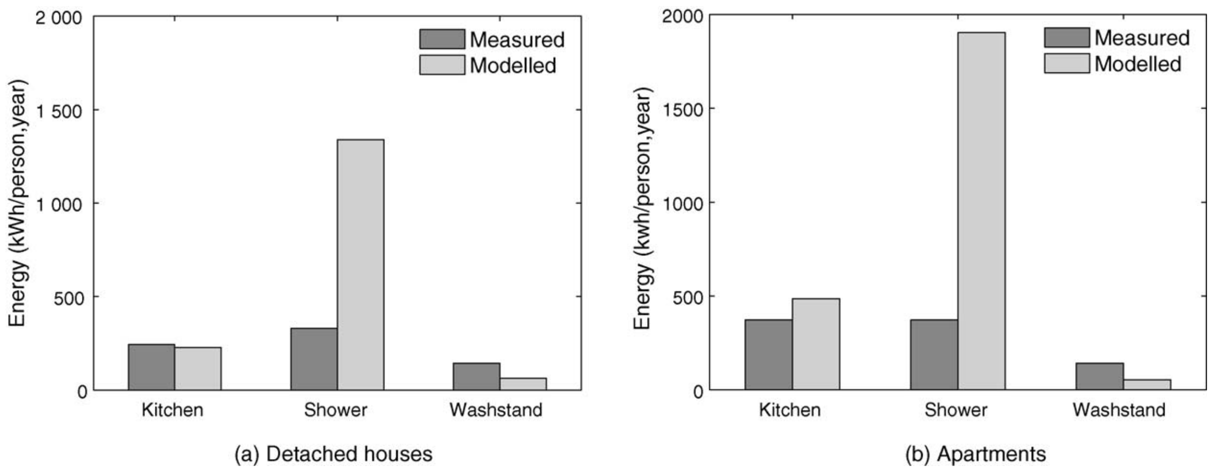

Fig. 15. Comparison between predicted annual hot-water demand per person from the model and measured annual means from HW-SEA-2007 for different tap categories.

Nonetheless, the comparison shows that the modelled and measured peaks are correlated, with the modelled peaks occurring slightly before the measured ones. This follows the time delay in required energy supply to the water heater after the hot-water draw-off. There are, however, differences in peak power between measured and modelled demand, which may have two reasons. First, it is influenced by the behaviour of the household in question. For example, double baths were recorded by the model, although the parents rather relieved each other while bathing the children. Furthermore, the model is based on average use and equipment, which may not be representative for this household (error sources 3 and 4). The difference may also come down to the electrical hot-water heater, which is supplied by heat for a longer period after the activity, causing lower peaks, but extended in time. The agreement in time of the peaks is however of higher importance than the magnitude when studying an individual household. The reliability of the assumptions on energy use is rather shown when comparison is made to a large group of households, representing the average.

Comparison was also made to measurement data, although they are less representative than in the case of electricity, due to the low number of measured households. It should be noted that the hot-water measurements in HW-SEA-2007 are the most detailed available in Sweden at present. Agreement between modelled hot-water use and measured data from HW-SEA-2007 and HW-MDH-2006 is shown in Figs. 13 and 14 respectively. Features of the modelled pattern, such as the time of the morning peak, the mid-day peak, but also to some extent the evening peak, recur in the measured data. For apartments the peaks appear more or less at the same time of the day and the magnitudes of the peaks correspond well. The displacement of the measured load curve compared to the model for apartments in Fig. 14 is most likely due to that most residents in those apartment buildings commute quite far. There is, on the other hand, a clear disagreement in amplitude for detached houses, which is most likely due to the low number of measured households; six detached houses as compared to the 24 apartments.

A comparison between measured annual hot-water use from HW-SEA-2007 and estimated annual use from the model at different taps can be found in Fig. 15. The most obvious difference between measurements and modelled use is for showers. It should be noted that the measured results from the SEA survey are surprisingly low compared to previous studies and that further deviations are expected since the annual hot-water use was extrapolated from a five months measurement period. Only six detached houses and four apartments were measured, which is too few to be considered statistically significant and representative for the average Swedish household [18]. As shown in Fig. 16, the modelled data is closer to the HW-MDH-2006 data, which are based on a larger number of households and is more statistically reliable, suggesting that the HW-SEA-2007 data are biased rather than the model.

Figs. 17 and 18 show the comparison between modelled and measured daily load curves from HW-SEA-2007 for the different tap categories in detached houses and apartments, respectively. The main overall measured load pattern is in most cases captured by the model, although the magnitude diverges, as was also seen in Fig. 16. The main reason for the disagreement between the peaks for showers in Figs. 17(a) and 18(a) is again most likely the low number of measured households, where the behaviour of a single household influences the results considerably.

5. Discussion

An important aim of this study has been to test the usefulness of time-use data for modelling energy use in households. As the validation has shown, realistic load curves are generated when the model is applied and compared to data from individual households. Most importantly, qualitative

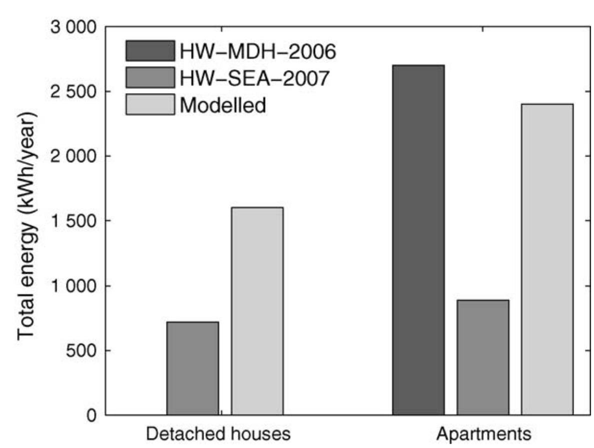

Fig. 16. The total annual hot-water demand per average person according to measurements in HW-MDH-2007, HW-SEA-2006 and modelled data respectively.

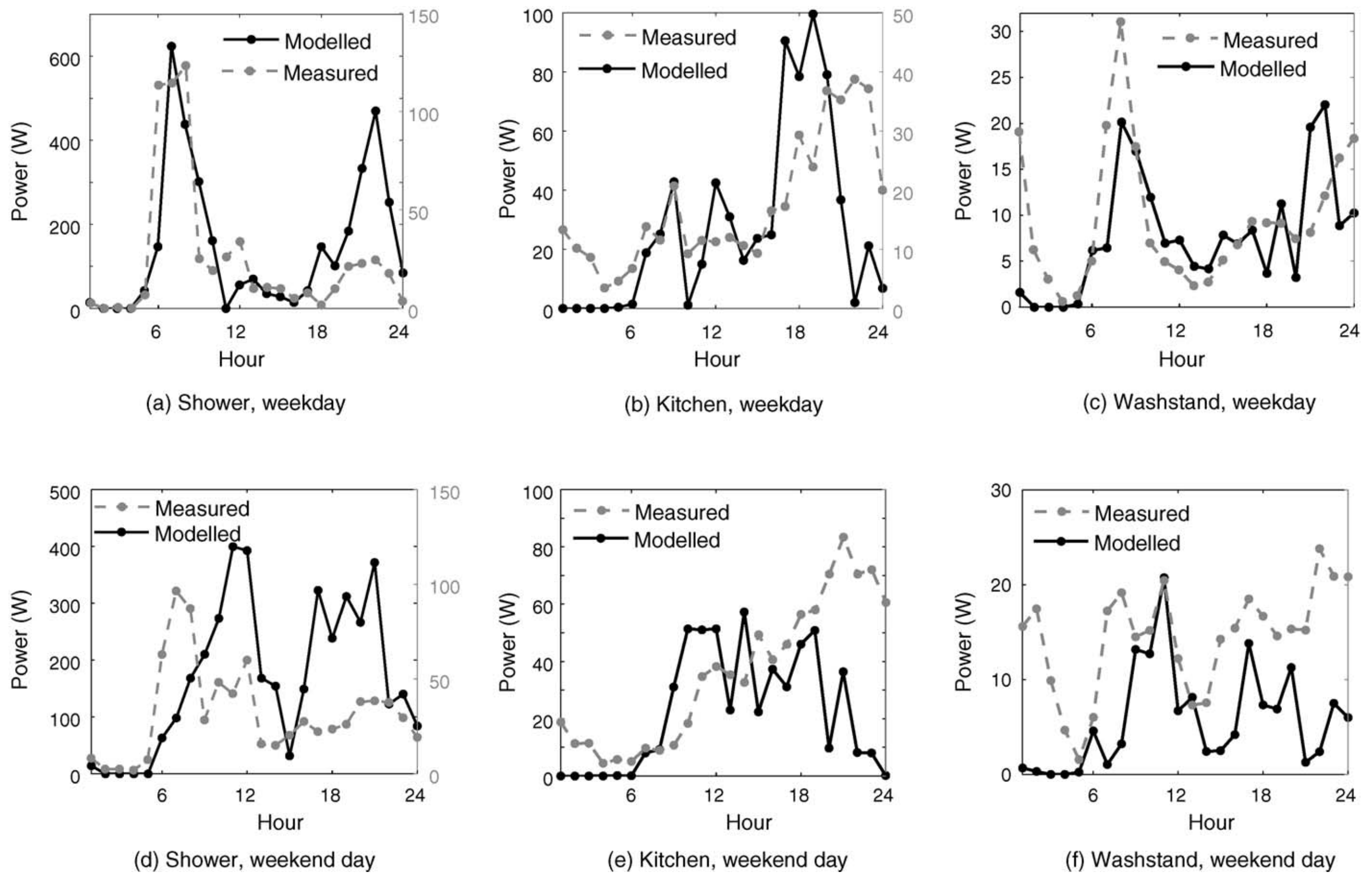

Fig. 17. Measured and modelled average hot-water use per person for different taps on weekdays and weekend days in detached houses. The model is applied to TU-SEA-1996 and the measured hot-water use is from HW-SEA-2007. When the magnitudes differ, the left *y*-axis is for modelled data and the right for measured.

features such as the overall differences between different days and between different households are reproduced, and the number of peaks and their magnitudes in measured and modelled data are the same. The average load curves generated by the model correspond well to measured average load curves, particularly in the case of household electricity, since sufficient data have been available. This shows that energy use can be generated from time-use data with reasonable accuracy for both populations and individual households. Although there are deviances, these can in most cases be corrected for by introducing a constant correction for additional demand that is not covered by the time-use data, or by scaling of the model parameters. The agreement for hot-water use in detached houses is not as close, which is most likely due to non-representative measurement data.

A number of developments and applications of the model, and future uses of time-use data in energy research, can be identified. One point for development is generalization of the model. This concerns for example creation of data time series longer than the exact ones in the input time-use data, and the possibility to lower the amount of input data needed. Longer time series can be generated by simply adding the same daily patterns in series, which is a reasonable approach for aggregate use, but becomes too rough for individual households. Another approach is to generate synthetic activity data with time-dependent Markov chains, similar to the model of [15], that preserve the important diurnal variations in the time-use data and keeps the amount of input data down to the number of transition probabilities of the Markov chain state changes. Extensive time-use data sets are then used only to calibrate the model parameters. A stochastic Markov-chain based model for household electricity is currently being developed [31].

Another possibility to generate annual load profiles from the daily distribution is to use probability methods, such as the cumulated frequency method in ref. [12]. The energy distribution for an individual household can then be varied to generate more realistic long-term variations in behaviour, without losing the rough household-specific use pattern.

One application of the model is visualization of energy use connected to everyday activities. The visualization program Visual-TimePAcTS [20,22], developed for analysis of activity patterns, can be extended to include graphical representation of energy use with visualization of activity patterns. This will potentially give households and researchers insight into how everyday activities contribute to energy use and is a way to integrate qualitative research on households' behaviour and habits with modelling and quantitative analysis of energy demand.

The method for collecting time-use data, usually through hand-written time diaries, can also be improved in various ways, if the time-use data are intended to be used for energy demand modelling. With improvements in the data collection phase, time-use data could be an alternative to end-use specific measurements, which are often costly and involve a large number of measurement devices. Time-use data could also be a complement to measurements, providing additional information on individual energy use. This approach has been used in a combined measurement and behavioural study connected to the Swedish Energy Agency's measurement survey [32], but could be developed even further.

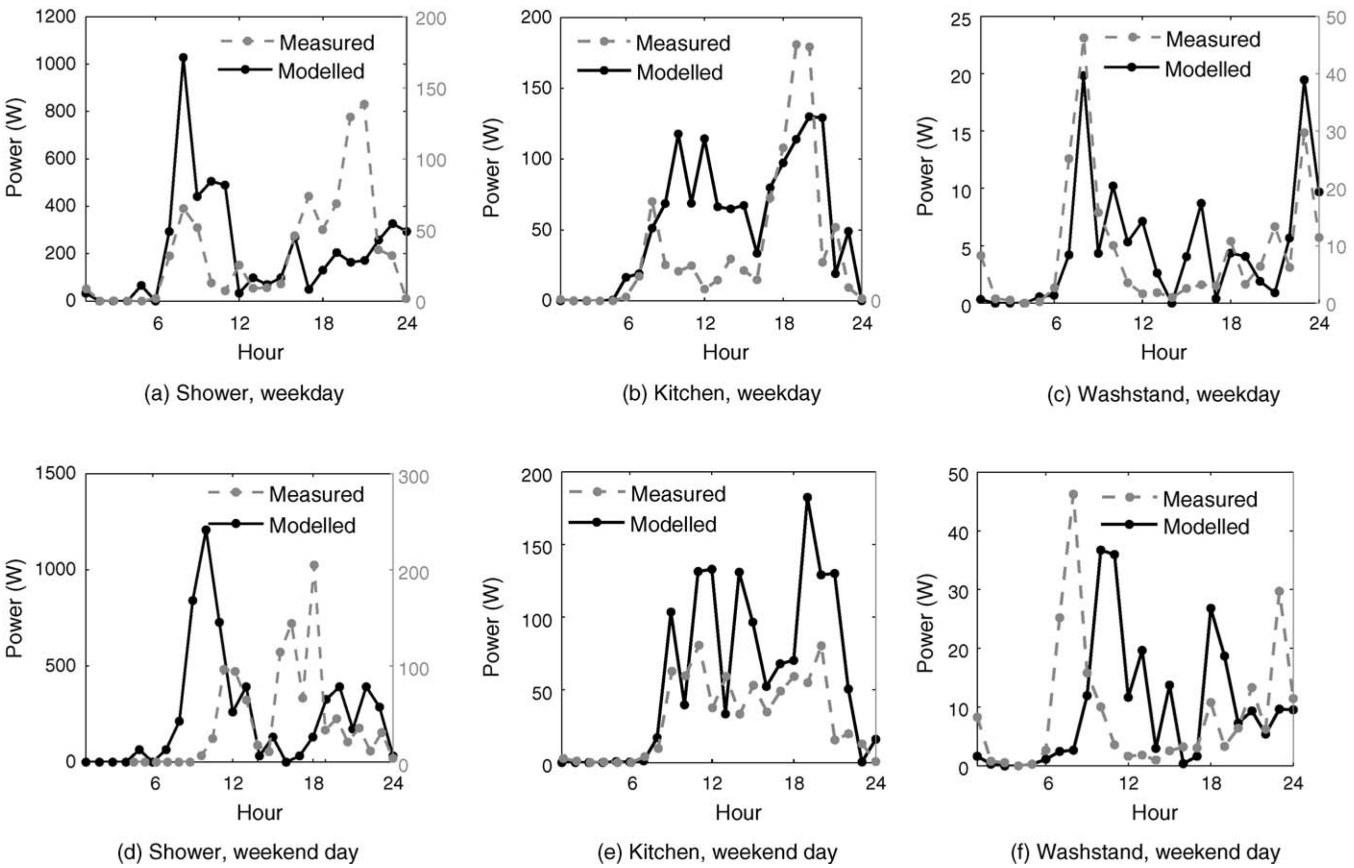

Fig. 18. Measured and modelled average hot-water use per person for different taps on weekdays and weekend days in apartments. The model is applied to TU-SEA-1996 and the measured hot-water use is from HW-SEA-2007. When the magnitudes differ, the left *y*-axis is for modelled data and the right for measured.

6. Conclusions

A model for generating residential electricity and hot-water load profiles from time-use data has been developed and validated. The model is shown to make realistic reproductions of electricity demand for individual households and to generate well-corresponding load distributions when compared to available measurement data. The agreement between modelled and measured electricity demand is in general better than for hot water, mainly due to the low number of measurements of detailed residential hot-water use.

Some model functions reflect measured load better than others. The overall energy-use pattern found in measured data is well-described by the model, while magnitudes sometimes deviate. Additionally, for some end uses the energy use is believed to have changed considerably compared to 1996 when the time-use data were collected. To some extent, this is due to activity-pattern changes, regarding for example computer use, which influence the agreement with measurements in a few cases. Since the model is heavily dependent on the time-use data, more up-to-date data might improve the model output for contemporary conditions. Furthermore, the energy use for hot water is highly influenced by showering habits and appliances. The model however allows the parameters to be easily varied to suit the purpose of a study and to agree with known conditions, such as the energy performance of appliances.

Modelling energy use from time-use data appears to be a well-functioning method for generating electricity and hot-water load profiles for households. It is a cheap and straightforward method, avoiding severe interference in the households, and has potential for development and further uses.

Acknowledgements

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Appendix A

The values of all parameters used to generate electricity and hot-water load profiles in the model are found below. In Table A.1 the power and maximum runtime for electricity consuming

Table A.1
Parameters used for modelling electricity demand: power demand for activities/appliances and maximum runtimes when applicable.

Appliance/activity	Power (W)	Maximum runtime (min)
Cold appliances	100	–
Lighting (min/max)	80/200	–
Cooking	1500	–
Dishwashing	430	160
Washing	490	130
Drying	1650	90
Ironing	1000	–
Cleaning	1000	–
TV	200	–
Computer	100	–
Audio	100	–

Table A.2
Parameters used for modelling hot-water demand assuming 55 °C water temperature expressed both in volume and energy.

Activity	Volume	Energy
Shower	40 l/5 min	2.1 kWh/5 min
Bath	100 l	5.2 kWh
Wash hands/go to toilet	0.67 l	0.035 kWh
Dishes, by hand, in tub	16 l	0.8 kWh
Dishes, cross between tub and running water	39 l	2.0 kWh
Dishes after baking or preservation	7.8 l/5 min	0.41 kWh
Hand wash	0.7 l	0.04 kWh
Cooking/baking	0.45 l/5 min	0.02 kwh/5 min
Cleaning, scrubbing	3.3 l/5 min	0.2 kWh/5 min
Wash clothes by hand	6.7 l/5 min	0.35 kWh/5 min
Brush teeth	0.27 l	0.014 kWh
Wash oneself	0.37 l	0.019 kWh
Wash hair	10 l	0.52 kWh
Shaving	4 l	0.21 kWh
Wash face	1.3 l	0.068 kWh
Wash feet	2 l	0.10 kWh
Change napkin, clean chamber pot	0.67 l	0.35 kWh
Complementary work, bath	10 l	0.52 kWh
Foot bath	7.8 l	0.41 kWh
Wash up things (not food)	6.7 l	0.35 kWh
Dust	1.7 l/5 min	0.89 kWh/5 min
Clean windows	1.1 l/5 min	0.057 kWh/5 min
Car wash	2.2 l	0.11 kWh
Work on the car	3.3 l	0.17 kWh
Wash bike or moped	6.6 l	0.34 kWh

appliances are shown and in Table A.2 the hot-water volumes and energy use for increasing the temperature of the water from 10 °C (cold water) to 55 °C (hot water) are found.

One assumption made is that cooking or baking requires on average two hand washes or rinsing of household goods every 15 min. Moreover, for washing clothes by hand washing up once and rinsing three times at a temperature of 40 °C was assumed. The flow in a traditional shower tap could be as high as 35 l/min, while in a modern tap it is about 12 l/min [33].

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