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Application-oriented modelling of domestic energy demand

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ABSTRACT

Detailed residential energy consumption data can be used to offer advanced services and provide new business opportunities to all participants in the energy supply chain, including utilities, distributors and customers. The increasing interest in the residential consumption data is behind the roll-out of smart meters in large areas and led to intensified research efforts in new data acquisition technologies for the energy sector. This paper introduces a novel model for generation of residential energy consumption profiles based on the energy demand contribution of each household appliance and calculated by using a probabilistic approach. The model takes into consideration a wide range of household appliances and its modular structure provides a high degree of flexibility. Residential consumption data generated by the proposed model are suitable for development of new services and applications such as residential real-time pricing schemes or tools for energy demand prediction. To demonstrate the main features of the model, an individual household consumption was created and the effects of a possible change in the user behaviour and the appliance configuration presented. In order to show the flexibility offered in creation of the aggregated demand, the detailed simulation results of an energy demand management algorithm applied to an aggregated user group are used.

Introduction

In recent years the research in the field of residential energy consumption has been intensified both by the scientific community and the industrial sector. This interest is a result of several factors, including the massive integration of intermittent renewable energy sources, the continuously increasing energy demand of the residential sector [1,2] in combination with the limitations of the current infrastructure for energy production and distribution as well as the idea to create new services with an added value for companies and customers. The availability of affordable smart meters and the establishment of appropriate legal frameworks in many countries enforced the deployment of smart meters in large areas. These smart meters collect measurements of the electric and gas consumption with a relatively low sampling time and give a good idea on the demand of a household.

Detailed smart meter data can be used to offer a wide range of applications and services such as demand optimisation, fault detection and network management. Possible positive effects range from higher economic profits to technical improvements including better power quality and grid stability in electric networks and optimised infrastructure for the gas supply. Both customers and companies from the energy sector benefit from the implementation of advanced services based on residential energy consumption data. However, unresolved privacy issues and quality problems of the collected measurements complicate or even impede the development and validation of new services and applications. These adverse conditions when dealing with residential energy consumption data can be avoided, at least to some extent, by using artificial data generated with the help of mathematical models. Consequently, suitable consumer energy demand models for the generation of realistic domestic energy demand data play an important role in the design of value-added services for the energy sector.

Research aim

The main objective of this paper is the development of an appropriate consumer energy demand model for the generation of detailed energy demand profiles. In the case of a deficiency or a complete lack of useful measurements, synthetic residential consumption data can be used in the design of advanced services for customers, utilities, network operators and retailers. With the objective to employ the artificial data in the development of a wide range of different applications such a consumer energy demand model has to provide a high degree of flexibility. An

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application-oriented model needs to allow the generation of consumption data of one or several households over a freely selectable period of time with reasonable detail. Besides, such a model has to offer the possibility to consider local or regional peculiarities, e.g. more frequent use of heating devices in colder climates. It is important to emphasise that the development of a high precision model, e.g. for dynamic thermal simulation, material testing or building design optimisation, is not in the scope of this work.

Another aim of this work is the analysis of typical applications based on detailed residential consumption data and the resulting benefits for utilities, network operators, retailers and customers. The importance of a suitable consumer energy demand model is underlines with the help of several application examples.

Paper overview

This paper proposes a consumer energy demand model based on the contribution of a wide range of common household appliances and under consideration of photovoltaic installations. The artificial consumption data generated by this model allow the development of new services and applications for customers and companies. The paper is organised at follows: Section 'Research background' reviews different modelling approaches for residential energy consumption and provides the general research background of this paper. A description of possible services and applications based on residential energy consumption data is given in Section 'Applications and requirements'. Section 'Consumer energy model' proposes an application-oriented model for the generation of artificial domestic energy demand data. Then, Section 'Application examples' presents simulation results of the applications based on the consumption data generated with the proposed model. Finally, in Section 'Conclusions' the most important conclusions are drawn.

Research background

In the last years, energy consumption modelling gains an increasing interest from the industry and the scientific community. Special attention is paid to the modelling of the residential sector due to the high ratio of primary energy consumption. The understanding of the consumption and prediction of the future demand provides the opportunity to solve, at least partially, energy related problems such as power supply, environmental issues and economic questions. Generally, residential energy consumption models describe the energy needs in function of a certain set of parameters.

The review presented in [3] divides the different modelling techniques for the residential sector in top-down and bottom-up approaches. In the case of top-down models, the residential energy sector is regarded in its entirety without considering the energy consumption of individual customers. This type of model is especially useful to estimate price and income elasticities of the energy demand [4] and to study long-term macroeconomic trends [5]. In contrast, bottom-up models work on a disaggregated level with detailed data of energy end-uses like heating and lighting [6]. The bottom-up models for the energy consumption of the residential sector are frequently classified into two main categories: statistical methods and engineering techniques [3].

Statistical methods

Statistical methods are based on historical data and regression techniques which determine the relation between the end-uses and the energy consumption. This type of model takes into account the influence of different sets of socio-economic and environmental indicators such as dwelling type, location, family size and type, earnings, social class and appliance ownership. The common statistical methods in residential energy consumption modelling are regression techniques, conditional demand analysis and neural networks [3]. One of the most important benefits of statistical models is the ability to perceive the effect of occupant behaviour. Besides, these models can be developed without detailed consumption data and without a deep knowledge of the underlying processes. The fundamental disadvantages include the often low significance of the estimated parameters, the required large samples, the low flexibility and the common regression problems such as multicollinearity, heteroscedasticity and autocorrelation. An overview of the benefits and limitations of statistical models can be found in [5].

Statistical methods have been employed in [7] to develop linear regression models for the yearly and monthly household energy consumption using setpoint temperature, electricity usage of appliances and lighting, airflow gains and occupant sensible heat gains as independent variables. A regression analysis was carried out in [8] in order to quantify the influence of window opening, lighting, heating and solar shading on occupant behaviour. The model proposed in [9] estimates the building sector energy end-use intensity for New York City as a function of the ZIP codes.

Engineering techniques

Engineering techniques use physical principles to determine the residential energy consumption on building level or for sub-level components [10]. Models based on engineering techniques can be developed without historical data and the scope ranges from very simple designs to extremely complex structures. A common approach makes use of appliance ownership, use, rating and efficiency as well as cycle lengths to compute the residential energy consumption [3]. The possibility to consider physical concepts such as heat and mass transfer, thermodynamics and fluid mechanics allows the development of highly precise models. However, the required parameters for such a model are often unavailable or hard to obtain leading to a less accurate estimation of the residential energy consumption. Other disadvantages of engineering techniques are the nearly impossible integration of the effect of macroeconomic changes and the difficulty to consider user behaviour. In contrast, models based on engineering techniques can be easily modified to include technological progress and use physically measurable data. Further information of advantages and drawbacks of engineering techniques for residential energy consumption modelling is given in [5].

An example for engineering techniques is the model for the electric demand in an individual household presented in [11] which combines the active occupancy and daily activity profiles of the occupants to determine the residential energy consumption. The model proposed in [12] considers both appliance characteristics (e.g. operation mode, appliance penetration, power consumption, frequency of use and turn-on times) and socially influenced factors such as number of residents, occupancy pattern and customer classification. The prediction method in [13] uses a dynamic thermal model to determine domestic space heating profiles. The detailed dynamic simulation models of different types of dwellings developed in [14] can be used for a sensitivity analysis of different variables with respect to the thermal demand. Other models developed with engineering techniques are used for the computation of load profiles of a residential area [15], testing of a residential cogeneration system [16] or validation of demand side management (DSM) strategies [17].