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Stochastic model for lighting's electricity consumption in the residential sector. Impact of energy saving actions

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ABSTRACT

The residential sector represents about 30% of the total energy demand in Europe. Included in this percentage, lighting consumption is one of the basic end uses in all households and it may come to represents 15–20% of the total electricity bill. This figure can be reduced using advanced control techniques or more efficient lighting technologies, requiring previous detailed information about current consumption patterns. In this context, bottom-up stochastic models are established as the main tools to study new energy savings. In this paper, a high-resolution stochastic model for simulating lighting consumption profiles was developed, obtaining both daily active and reactive instantaneous power demand profiles, with a 1-min resolution. The model takes into account the number of household residents and differentiates between weekdays and weekends. Moreover, the monthly and annual amounts of electricity demanded by lighting in Spanish households were simulated. The proposed model was also used to quantify the impact of LED technology's penetration into domestic lighting systems on consumption patterns. Research has revealed the existence of two consumption peaks matching with morning and evening. Although these peaks are hard to shift since they are due to human behavior, they are easy to reduce through the improvement of lighting systems.

1. Introduction

In the current energy context the residential sector, with an average worldwide energy consumption of around 30% of total consumption [1,2], represents a key factor in terms of energy supply needs. In Spain, this sector represents 17% of the end energy consumption and 25% of total electricity demand [3]. In addition, this electricity consumption has a broadly upward trend due to the increasing number of households, the higher comfort of occupants and the greater number of appliances at home, with a widespread utilization of new types of electricity loads [4].

Against a backdrop of increasing electricity demand, new policies and measures, focused on optimizing users' consumption, are being studied by researchers and governments. The aim is to achieve a significant impact on aggregate energy saving and to establish a way of meeting the environmental requirements for CO_2 reductions [5]. Along with this environmental factor, higher demand may involve a grid overload. In this situation the ability to withstand the demand peaks could mean the full resizing of the current system which would, in turn, require heavy investment. Thus, not only is the goal to reduce consumption, but also to stimulate the development of strategies for demand response (DR) solutions which would lead to peak shifting and to a better equilibrium between generation and consumption [6,7], while looking toward a future scenario of smart grids and smart homes [8].

In order to reduce consumption and to achieve load control it is fundamental to know the demand profiles of individual electrical devices in dwellings, instead of merely the total household electricity consumption [8]. Among all domestic appliances, one of the potential devices for focusing the means of action are household lighting systems, whose consumption in some European countries such as Sweden or UK, and in Canada, could amount from 15% to 20% of the total electricity bill [4,9–12]. Based on these considerations, the first objective of this work was to develop a model which would enable us to deliver a reliable measurement, with high temporal resolution, of the consumption patterns related to the electrical energy demanded, associated with lighting, in the Spanish residential sector, data which were unavailable for this country.

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At present, the global estimations of electrical consumption for lighting in Spanish households were supplied by IDAE [3]. In addition, Gago et al. [13] have previously developed a lighting consumption model for the residential sector in Andalusia, Spain. However, the demand load profiles provided by these authors, gives only a 1-h resolution. Using the model proposed in this paper, 1-min resolution load profiles can be achieved, differentiating between the number of residents in the household, the type of day (weekdays and weekends) and the month. This higher resolution in the results are justified since most DSM (Demand Side Management) programs require a level of granularity in time-related data of between 5 and 30 min [14]. Information on lighting consumption patterns in the residential sector already exists for other EU countries [10,15], some of them within the European REMODECE (Residential Monitoring to Decrease Energy Use and Carbon Emissions in Europe) project [4] framework. Nevertheless, Spain was not included in these studies and the different schedule distributions, lifestyles and routines of Spain versus its neighboring countries indicate the importance of this present analysis [16].

Once consumption patterns were modeled and analyzed, the second objective of this paper was to make use of the model developed in order to assess the impact associated with saving policies in domestic lighting systems with regard to the current situation. The use of electric lighting at home, related to the basic comfort of its residents, takes place mainly in the hours associated with higher occupancy and with lower solar irradiance levels. Changing these schedules, by means of implementing demand management techniques, might not be the most suitable solution for this type of loads at home. In contrast, other energy saving measures, such as using regulated lamps [17] or installing more efficient technologies, with a higher lumen per Watt rate, may be more appropriated for this goal. Some European and National policies are focused on this latter proposal to use more efficient lamp technologies [18]. This was the measure analyzed in this paper due to its effectiveness to reduce electricity consumption. Implementing this saving measure through the use of the proposed model enabled to obtain a detailed environmental impact analysis and a reliable economic study.

To quantify the impact of these proposed policies, or other future possibilities, the developed model should exhibit a high degree of flexibility in order to work with low-level individual household data, in order to establish the correct modification that these saving measures would involve in their characteristics. As shown in the Swan and Ugursal classification [2], named bottom-up models are the most suitable tools to perform these studies. This type of energy demand models yield accurate results with high time and spatial resolutions, without any great complexity. These models start with the individual households or just an appliance as a basic consumption unit, and make use of statistical data relative to household characteristics, types of appliances or installed systems, as well as information on their occupants' behavior, highlighting the active occupation patterns of different household types [19–21]. The global consumption in this type of model is then obtained by the aggregation of each individual unit. However, one of the principal issues is to obtain all of the input data required by the model, data which are not always easily available. In addition to other sources, this paper used information from national Time Use Surveys (TUS), conducted in 2009–2010 by the National Statistical Institute in Spain for an annual period, following the EUROSTAT guidelines for harmonizing time use data [22]. Despite the disadvantage of requiring an extensive database of empirical data, this type of model enables us to simulate changes in consumption habits and installed technologies. By comparing the results with the previously existing data, this enables us to analyze the load profile alteration as a consequence of the energy saving policies employed.

For lighting systems, different energy saving options could be the use of regulation in lamps [17], the implementation of demand management techniques, or the installation of more efficient technologies with a higher lumen per Watt rate. European and National policies are focused on this latter proposal (efficient lamp technologies) [18], so the second objective of this paper concentrates on analyzing the economic and environmental impact of applying of this particular energy saving measure.

The structure of the ideas described in this paper is the following: in Section 2, the modeling procedure and applied saving policies will be defined. Section 3 will present the results obtained with the current scenario and later, the improvement load profiles after applying the proposed saving will be presented. Finally, the conclusions of this work will be discussed in Section 4.

2. Methods

In order for it to be implemented, the bottom-up model developed required, in the first stage, a number of input parameters to be entered. After that, an algorithmic process to determine the electricity demand profiles automatically was applied. A Graphical User Interface (GUI) was developed to facilitate its implementation. Each of these parameters and the processes for result calculation are described below.

2.1. Input parameters

The parameters to be entered into the model using the graphical interface were the number of occupants of the dwellings, their geographic location, the date and the type of day (weekday or weekend). These parameters are not directly introduced in the calculus algorithm of the model, but the application uses them to generate the necessary input information required to determine lighting consumption profiles. This information is the daily active occupancy profiles of houses, the global daily external irradiance profiles and the type and the number of existing lighting points in the households. The procedure to calculate them from user input parameters is detailed below.

2.1.1. Active occupancy in households

Active household occupancy is taken to be the number of residents at home and not sleeping at each instant of time. Active occupancy profiles are one of the most influential factors in domestic energy consumption, and therefore constitute the principal input in electricity consumption simulation models. These profiles were synthetically generated by simulating a stochastic model, grounded in Markov Chain probability theory and Monte-Carlo techniques [23,24], included inside the general lighting consumption model proposed in this paper. This stochastic model was implemented and validated for Spain by Lopez et al. and its bases are described in detail in previous publications [16,19–21]. It is also based on data extracted from Time Use Surveys (TUS) [22], conducted in Spain of 19,295 people who were at least 10 years old and living in a total of 9541 homes. To obtain occupancy profiles by using the model, it was established that the number of active occupants for each time step depended on the number of occupants in the previous time instant. The evolution between two states was conditioned by the transition matrices. Due to it being a non-homogeneous Markov Chain process, these matrices were calculated or each of the 144 time instants considered over a whole day, based on TUS information. In TUS surveys the interviewees noted down in a diary, at 10-min intervals, data concerning the activities that they performed over 24 h during one random day; the place where the activities took place and whether someone accompanied them. Initial states of the model, corresponding to