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Modelling home electricity management for sustainability: The impact of response levels, technological deployment & occupancy

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ABSTRACT

The evolution of electricity grids into a smart grid requires the inclusion of control systems to control load, flatten peaks and ensure the distribution of electricity. In parallel, the building sector will also be incorporating more control technology and put emphasis on sustainability issues such as reducing CO_2 emissions associated with the buildings' electricity consumption. This article aims at modelling the residential sector and assesses the different levels of technology deployment to control the electricity consumption of household appliances. The number of inhabitants and their habits are also considered, and the response levels of users towards control systems are simulated. For this matter, a Markov-chain algorithm was developed for synthesising the electric load and introducing Home Energy Management System (HEMS). The emission levels from electricity consumption were assessed based on hourly CO_2 emission data from electricity production in Finland. Numerous electricity pricing models were also included, to assess the economic impacts of HEMS. The article suggests that a fully deployed HEMS may not be profitable for households with a low number of inhabitants. This is because the power consumption of appliances in stand-by mode offsets the positive impacts of HEMS on the electricity consumption profile.

1. Introduction

The energy sector is under a vast change driven by legislation, aiming at reducing energy use and associated environmental impacts [1]. In the electrical sector, the smart grid represents the future, by allowing the integration of intermittent renewable energy sources into the energy mix [2]. Smart grid integrates a vast amount of disciplines including the communication field, Internet of Things, power engineering, control system engineering, and environmental engineering. Therefore, areas of focus and applications are multiple.

The European Union (EU) has enforced a set of legislations to tackle energy and environmental challenges driven by the change of infrastructure. The Renewable Energy Directive (RED) [3] establishes an overall policy for renewable energy, sets mandatory targets for the share of energy from renewables by 2020 and provides sustainability criteria for biofuels. Further, the objectives for 2020 also include a strategy for smart and sustainable growth, including energy system [4]. The three dimensions of sustainability are environmental, economic and social, which are defined together as the triple bottom line [5]. For firms, the triple bottom line means that they must balance their environmental, and social bottom lines in addition to their financial bottom line [6]. The sustainability of energy production should expand beyond the 2020 targets to all forms of energy [7]. The sustainability framework of RED only considers environmental indicators such as CO_2 emissions and land-use impact. In this research, we included all three aspects of sustainability by considering also economic and social impacts of technology deployment, in addition to CO_2 emissions from electricity production.

The EU building sector consumes 28% of the total primary energy consumption, of which around 30% is for electricity generation [8]. Within the building sector, the residential sector is responsible for 60% of the total energy consumption [8] and has the best potential to impact on peak demand, characterised by the unpredictability of energy usage [9]. Smart buildings are an integral part of smart grids and their full potential is yet to be achieved. Smart buildings integrate a wide span of functions from health assistance, multimedia, everyday-life handling assistance, and energy management. In this research, we focused only on the energy management side, specifically on electricity consumption. In this context, the subject of our

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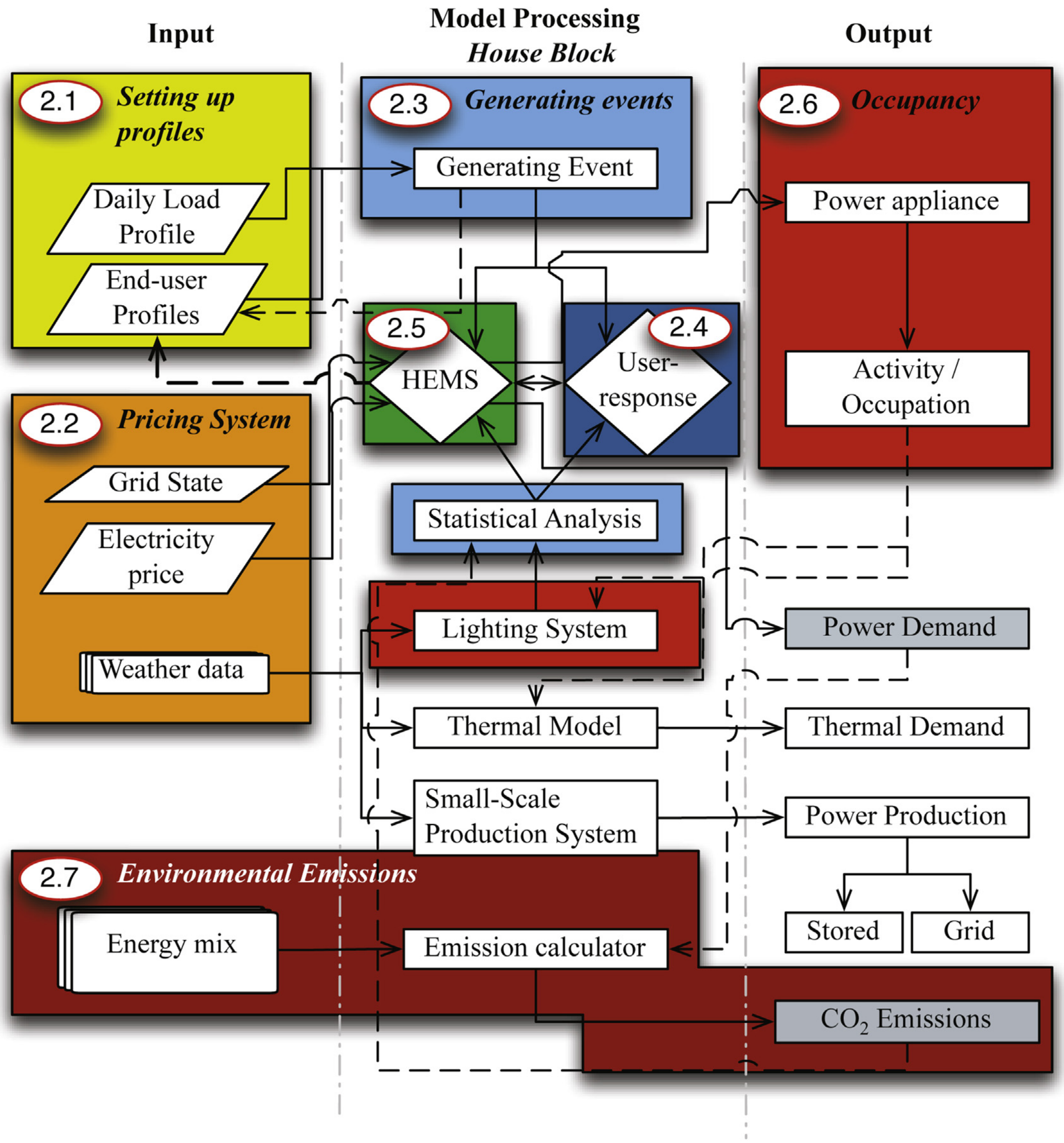

Fig. 1. Box diagram of the model steps for simulating residential homes.

study is the Home Energy Management System (HEMS), comprised of sensors, computing systems, and a communication network. Whilst smart buildings can tackle energy consumption and peak shifting [10], the issue of concern is the impact of demand-side management and the response of end-users [11]. Modelling and pilot tests have earlier focused mainly on the benefits of automation technologies in homes, whilst the energy used to run the system was disregarded. Research has recently been carried out to evaluate the impact of the automation system by extending the scope of studies and including the electricity consumption required by the system [12]. Van Dam et al. [12] have found that energy management devices must reduce their energy consumption before they become economically and environmentally viable. However, their evaluation has been carried out in a static manner. There is need to carry out dynamic modelling, which integrates user specificities, different household sizes and levels of technology deployment.

For the modelling of the electrical demand profiles of dwellings, two distinct modelling techniques exist: the top-down and the bottom-up approach [13]. The top-down approach is more suitable for studying the general behaviour on a country level, whilst the bottom-up approach allows for a more detailed and flexible way of modelling the electricity consumption of individual users. The latter approach was used to model multiple dwellings where individual appliances were first aggregated to produce individual profiles, followed by an aggregation of the generated profiles to a large sample of electrical load under one node [14]. Appliance usage models rely either on the aggregation of measured data from multiple dwellings [15,16], or on databases compiled for a specific country representing the overall market [17–19]. The advantage of using a database is that it bypasses the need for an extensive and exhaustive work of data collection. Once a database is compiled, statistical information are extracted and will serve as a basis to build the electrical demand profile of the system. Further, these statistics are traditionally used in probability distribution function, in support of stochastic methods for generating electricity load profiles [20,21].

The end-use of the models lie in the technological influence on the electric load [22], and in the development of pricing models to enhance demand-side management (DSM) [23]. In addition, the environmental impacts associated with electricity consumption of the residential sector have been studied [24–27], and the CO_2 emissions due to electrical appliance usage evaluated [28]. The limiting