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Residential peak electricity management. A storage and control systems application taking advantages of smart meters

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ABSTRACT

In recent years, technological progress in power electronics and in battery storage systems, along with the introduction of smart meters, have made possible the application of improvements in the control of power peaks for residential customers. The demand charge is an important component in the residential customer's electricity invoice in Spain, which has increased by nearly 100% in the last few years, prompting the consumers to reduce their peak usage. This paper proposes a model which allows residential consumers to save a significant part of their invoice by lowering contracted capacity through the use of a battery energy storage system. Recent academic literature has already studied in-depth the benefits of load-shifting energy throughout the day in the context of time of use (ToU) tariffs, but, regarding power optimization, there is a long way to go; not much research has been conducted in this field. In this article, a model to calculate optimum battery size which reduces contracted power is proposed. The model starts with a given load curve from a typical consumer in Spain in a context of constant energy prices. This system could be financed by the end user directly or by an independent company which participates in the savings.

1. Introduction

Nowadays, 28% of the global electric consumption is related to the residential sector [1]; this fact shows how important it is to find effective methods for the management of energy and power consumption and, consequently, for reducing the costs associated to the energy consumption of customers. In recent years, the electric market has experienced several changes and improvements, prompting the appearance of new, dynamic and flexible electricity tariffs; for instance, those that involve time of use (ToU) or hourly discrimination, in which different time slots are considered to calculate the final electricity price. On the other hand, the rise of the so called 'smart meters' provides the user with more accurate and detailed information and, in addition, generates a large amount of data regarding electricity demand. These changes coexist with the numerous improvements that energy storage technology has undergone in recent decades, reducing its price and becoming economically viable. Because of this, new ways and opportunities arise for household consumers to control their energy demand, which leads to the existence of potential savings. Peak-shaving and load shifting (both linked to the idea of evenly distributed energy throughout the day and reduction of energy and power required) are both significant concepts in this topic and are addressed along this paper.

The first and most natural step to achieve the goals of peak shaving and load shifting would be to change consumers' habits. This consumption modification would be encouraged with the introduction of new ToU tariffs, so that the electricity consumption is shared throughout the day. Going deeper into this matter, it would be possible to schedule all domestic devices and appliances in order that they are not connected simultaneously (by means of a control system), achieving in this way a higher efficiency. Even if consumers' habits are not to be changed, it is possible to achieve lower expenses for customers through the use of batteries and a control system.

Battery energy storage systems (BESS) grant a high level of flexibility and manageability to energy applications, allowing to charge in "valley" hours and discharge in "peak" hours so that demand is more evenly distributed. It is important to note, that it is only possible to produce a net saving if the total storage cost (defined as the sum of installation and operation and maintenance costs) is lower than the electricity invoice saving. There is a broad range of methods to achieve this purpose, such as, thermal storage, compressed air or chemical batteries. Regarding the residential sector, the most feasible option is the one based on battery systems, within which there are also different options like lithium ion or lead acid batteries.

In this article, the key issue under study is the increasing costs associated to the capacity contracted by residential customers in the

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Spanish system of electricity pricing, in which consumers are charged with a fixed cost for the level of power capacity that they freely contract with the utility companies. Instead of a typical application of energy load-shifting or appliance scheduling, this study proposes a model in which a BESS is used to reduce the effects of power peaks on a specific customer's electric invoice, with the final objective of lowering the aforementioned fixed term of the electric invoice. To fulfil this task, the readings from a smart meter of a particular domestic consumer are collected during a one-year period. The proposed model selects the optimum storage size that provides the best saving according to the tier of contracted power by this specific user. In this way, it allows the consumer to save between 6% and 25% of his electricity invoice within the Spanish electricity pricing framework. In addition, unlike demand response applications, BESS does not necessarily involve changes in consumers' habits to produce net savings; hence, it is a more attractive option at first sight from the customers' point of view.

The rest of the paper is structured as follows: first of all, a brief summary of the recent literature regarding energy storage applied to residential customers is displayed in Section 2. Afterwards, the notion of peak demand and how this concept affects a residential customer in Spain are explained in Section 3. A general description of the technologies and devices involved in residential peak electricity management is outlined in Section 4. Once the objective of the study and the technology involved have been shown, the model designed to evaluate the life cycle and the costs of a set of different BESS is described in Section 5. The model is using real readings of the electricity consumption of a specific customer to calculate his power demand. Hereafter, a cost-profit assessment is carried out in Section 6. Finally, according to the results obtained, a set of conclusions are drawn up in Section 7, along with a series of recommendations and some suggestions for further research.

2. Literature review

Energy storage possesses plenty of applications which have already been illustrated by multiple authors in the literature. Beforehand, the most logical first step to apply the concept of peak shaving would be to encourage the change in consumers' habits regarding electricity demand, or going a step further, the use of automatic appliance scheduling to optimize its consumption; this application is also known as demand response (DR). There are several studies in this specific field such as the one developed in [2], in which the load shifting topic is addressed by modeling a discrete time open-loop control system using the current state of charge (SoC) of the storage as the initial condition, within the framework of a ToU tariff. The calculated savings in this study are greater than 19% compared to the traditional case in which the load would start at the time of request by the consumer. In [3], a stochastic energy consumption scheduling algorithm is developed. The inputs for this algorithm are the time varying prices released by the utility companies; the results of the simulations show that this model can achieve up to 41% cost reduction for the customer. The optimization of a control algorithm with the purpose of scheduling household appliances is also proposed in [4], by using lead acid batteries to reduce the costs of residential customers from south Africa achieving savings in this case near 22%. A peak shaving system is modelled in [5] for a set of residential customers in Toronto, Canada. Different price frameworks are studied, as well as the usage of a price predictor algorithm. It is concluded that the system leads to significant savings in consumers' invoices and encourages the large-scale deployment of smart meters.

In [6], the focus is on the study of individual consumption habits, establishing a relationship among the user location and the energy consumption. By performing short-time predictions, the burden of the algorithm is reduced and it is adapted to each individual residential customer, however, the high costs of energy storage are also discussed. In [7], an innovative DR control system called hierarchical demand response control architecture (HDRA) is discussed. It contains primary, secondary and tertiary control loops to maximize utilization of available DR potentials. The efficiency of this control scheme is later tested, from power and communications point of view, in the scenario of the Danish distribution network. A power and communication co-simulation is carried out, considering electric vehicles as potential DR resources. The results demonstrate that HDRA helps to maximize the utilization of DR potential.

In [8], a case study to optimize demanded energy and capacity for a large house group from the Netherlands and Belgium is developed. During a complete year, the authors study the use of smart appliances in the context of a smart home pilot program. Conclusions drawn from this research are encouraging, since consumers seem to be willing to contribute in the process of shifting energy to hours where electricity is cheaper. This customer willingness makes feasible the rise of energy management systems on a larger scale, as long as the concept of appliance scheduling is compatible with the lifestyle of the population. On the other hand, in [9], a new perspective to model energy consumption of households using energy storage systems is proposed. The issue is faced by proposing an inter-temporal trading economy and by applying peak shaving and appliance scheduling methodologies. The most positive scenario, in respect of cost minimization, is related to a consumption balancing/leveling scheme in which both, utility companies and households, are better off, achieving a 12% reduction in energy costs of the electricity invoice.

In [10], the authors design two types of customer engagement plan, namely CDP and PDP, which describe the key inconvenience parameters of flexible loads in terms of scheduling delays and temperature deviations so as to make the customers easily understand the inconvenience caused by these plans; specifically, thermostat loads of residential households are modelled as power throttling devices. The customer engagement plans which they propose, specify inconvenience parameters for flexible loads. The algorithm developed by the authors helps to identify beneficial plans for both the system operator and the final consumer. They finally conclude that the increase in temperature deviations from thermostat set points results in diminishing returns; Moreover, a set of recommendations for the design of customer engagement plans is outlined. In [11], an uncertainty-aware minority-game based energy management system for a smart building supplied with hybrid power grids is proposed. The system studied consists of a building with multiple rooms supplied with the main grid and one additional solar energy grid. The energy profile classification is applied to form agents based on unique energy profiles of rooms; additionally, uncertainties from energy load profiles are taken into account by the agents. Results show that compared to the traditional static and centralized energy management system, as well as the recent multi-agent energy management system, peak load from the grid can be reduced by 38.5% in summer and by 15.80% in winter.

To face the peak shaving issue, several authors opt for using the load curve of residential customers as the initial input for the research, not taking into consideration changes in consumers' habits. In [12], a linear programming model is applied to residential customers with the purpose of determining the optimal size and economic feasibility of a BESS for households, given their load curve in a ToU pricing environment. According to this research, the optimum battery size with an optimal control system is not economically feasible nowadays due to high Li-ion battery costs, although those costs are expected to decrease in the future. In [13] and [14], the authors also describe in detail a control system strategy to maximize savings. It is also highlighted the need of reducing battery costs and supporting policies to make BESS profitable in load shifting applications, ensuring their feasibility. In [15], the concept of peak shaving is also applied, but combined with the idea of power demand management for several cases regarding medium voltage distribution networks. The main conclusion of the cost-benefit analysis in this study is again the requirement of lower battery prices, in the range of 60–80 €/kWh, for large units to start becoming profitable.

An economic case study for a public building in Italy, is detailed in