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SMART METERS ADOPTION: RECENT ADVANCES AND FUTURE TRENDS

ADOPCIÓN DE MEDIDORES INTELIGENTES: AVANCES RECIENTES Y TENDENCIAS FUTURAS

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ABSTRACT: High growth in electricity demand and peaks in the load curve, caused mainly by households, require big investments in infrastructure that are used for short periods. Because of this, it is necessary to look for new developments that allow meeting the needs of users as well as using the electricity system resources efficiently. This is possible through the Smart Grid (SG), which additionally allows users to have autonomy in the electricity supply chain. Our focus of investigation is with households because they can monitor their demand and help to reduce the peaks of the load curve. To do this, users must use Smart Meters, because these devices allow consumers to obtain the information necessary to control their demand. This paper presents a systematic analysis of published literature related to the study of the SG from the demand side, analyses the current situation of this topic and the impact of Smart Meter penetration in households.

KEYWORDS: Demand side management; households; peak demand; Smart Grid; Smart Meters.

RESUMEN: El alto crecimiento en la demanda de electricidad y los picos en la curva de carga, causados principalmente por hogares, hacen necesarias grandes inversiones en infraestructura que solo es usada para periodos cortos. Esto ocasiona la búsqueda de desarrollos que permitan suplir las necesidades de los usuarios y usar los recursos del sistema eficientemente. Esto es posible por medio de las Redes Eléctricas Inteligentes, las cuales adicionalmente brindan a los usuarios autonomía en la cadena de suministro eléctrico. El foco de esta investigación son los hogares, ya que estos pueden monitorear su consumo y ayudar a reducir los picos en la curva de carga, Para esto los usuarios deben usar Medidores Inteligentes, los cuales le permiten obtener información necesaria para controlar su demanda. Este artículo presenta un análisis sistemático de la literatura publicada relacionada con el estudio de las redes eléctricas inteligentes desde el lado de la demanda, analiza la situación actual sobre este tema y el impacto de los medidores inteligentes en los hogares.

PALABRAS CLAVE: Gestión de la demanda; hogares; pico de demanda; Redes Eléctricas Inteligentes; Medidores Inteligentes.

1. INTRODUCTION

Several reasons justify the well-known necessity of reducing daily electricity consumption and flattening the peaks in the daily power curve with the aim of reducing investments and operational costs. First, the power grid constantly needs new investments because the demand for electricity is growing rapidly, and it is necessary to build new generating plants [1] and the infrastructure to connect them; moreover, installed generating capacity grows at a lower rate than electricity consumption, so that it is always necessary to make new investments in generation plants and power grid infrastructure. Second, inefficiency, maintenance and upgrade costs are growing with the size of the grid [2]. Third, growing environmental costs caused by new investments in generating plants and in the expansion of the power grid to connect them; also, it is necessary to account for the environmental impact of greenhouse emissions caused by generating plants, especially for coal-fired plants that are considered to be the major sources of pollution [3]. Fourth, the pronounced peaks and flattened troughs in the hourly load curve causes the inefficient use of generating plants so that it is necessary to install additional capacity just to satisfy the peaks in the power curve during short time periods [4]. Such peaks and low flat regions are illustrated in a typical load curve for the Colombian electricity market in Figure 1. As a consequence, electricity costs are inflated and the technologies in use are less efficient.

In addition, newly installed capacity is required only for attending the daily peak demand.

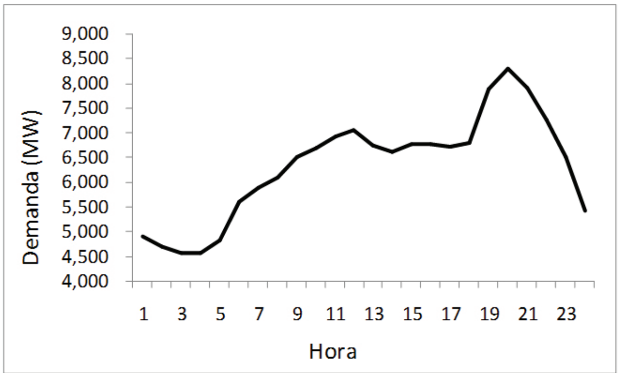

Figure 1. Typical Colombian load curve [5]

The Smart Grid (SG) paradigm is a current and very important technological trend with a strong impact throughout the electricity market affecting it's future development. The Smart Grid (SG) is defined as the full integration of automatic meter reading in the current power grid, and the associated infrastructure, which is conformed by sensors and the proper support software [6]. Additionally, there are many new technologies that are being developed such as controllable appliances, distributed generation, systems to store energy, among others [7].

In the SG, the behavior of the connected users is integrated in an intelligent way in order to use electricity in an efficient, sustainable, economic and secure manner [8, 10]. Moreover, business processes, objectives, and needs are met efficiently [4]. SG promotes and improves the efficient use of all available resources and provides more information and autonomy to the agents in the electricity supply chain [9].

By using intelligent devices (provided by SG technology), electricity utilities will be able to know the consumption, instantaneous condition of distribution networks, electricity prices and to control the loads with complete control and real-time system status; as a consequence, electricity utilities will be able to optimize the use of the network, to make better decisions, and to control customers consumption [1,11].

Users, by using intelligent devices [1], will be able to have more information about the system, its status, and characteristics [12]; their consumption habits; and electricity costs in real time [13,14]. With this information, they are able to reduce a part of the demand or to shift it to another period when the cost of electricity is cheaper [15] with the aim of mitigating costs and saving on their bills [16,17,18]. This is a financial incentive that encourages changes in consumption habits [1]. These changes in consumption habits due to economic signals are known as Demand Response (DR) [1,19,20].

By promoting investments in SG technology as an alternative to installing more generation capacity to attend the load curve peaks [21], the regulator enables energy price reduction, promoting a more efficient and competitive market, and also allows the system to support the use of renewable energy resources, distributed generation and advanced metering [11].

SG promotes the reduction of the high rates of growth in electricity demand and the flattening of the peaks in the power curve [18]. This is explained by, first, the effects of the electricity utilities decisions in order to optimize network use; and second, by the reduction of peak height and depth of the valleys in the load curve [22]. Several facts support the previous conclusions; according to the Electric Power Research Institute (EPRI), the use of electricity in the residential sector is equivalent to 38% of the total electricity consumption in the USA; thus, changes in consumption habits will modify the load curve. The feedback to users can result in a 9% reduction in household consumption [13,23] and a 10–20% reduction during peak demand periods [24,25]. In the European Union it has been detected that when 80% of the consumers reduce their demand in peak hours because of changes in the price, the reduction in associated capacity and transmission costs would be € 67 billion [26].

These facts explain the penetration of smart meters; previously Capgemini, forecasted that in 2012, from 25 to 40% of European households would have smart meters [27]. Other improvements derived from the use of SG are listed in Table 1.

Despite all the above benefits, SG technology is young and new developments are made rapidly so that for the researcher and practitioner it is very difficult to obtain a complete view of the advances in this area.

Table 1. Smart Grid vs. current system [4].

Current System	Smart Grid
Electromechanical	Digital
One-Way Communication	Two-Way Communication
Centralized Generation	Distributed Generation
Few Sensors	Sensors Throughout
Limited Control	Pervasive Control
Manual Restoration	Self-Healing
Failures and Blackouts	Adaptive and Islanding
Few Customer Choices	Many Customer Choices

Due to the importance of this topic, it is necessary to identify, organize, and evaluate the published manuscripts related to SG technology in order to establish: the current state of development, the current research lines, the main contributions of smart grid technology, the most appropriate research directions to be taken, and the most important new contributions that could be implemented.

The objective of this paper is to answer the following questions by means of an exhaustive literature research using the methodology of Systematic Literature Review:

Q1: Which have been the most influential articles in the area?

Q2: What has been implemented regarding SGs in Colombia?

Q3: How do SGs affect the electricity demand?

Q4: What SG technologies are installed in households?

Q5: How have the SG penetrations been modeled?

Q6: Why is it important to study consumer behavior?

This paper is organized as follows. A description of the research process is described first, followed by the systematic review of results. Then the research questions are answered.

2. REVIEW METHODOLOGY

In our research, we employ the methodology of Systematic Literature Review (SLR) that is rooted originally in the field of evidence-based medicine, and adapted to the fields of software engineering by Kitchenham and others [28,29] and to energy policy by Sorrell [30]. SLR is a scientific research technique characterized by a systematic and ordered procedure for searching, identifying and organizing written evidence with the aim of answering several research questions in an unbiased way.

3. RESEARCH PROTOCOL

In this section, our research protocol, based on the guidelines proposed in [28-30], is described.

- Terms used in the search string: smart grid, adoption, demand peak, modeling, smart houses, smart devices, technologies for home, Demand Side Management (DSM).
- Subject areas: engineering, energy, computer science, business, management and accounting, decision sciences, economics, econometrics and finance.
- Source: Scopus.
- Search period: available information until December of 2012
- Inclusion and exclusion criteria: after obtaining the search results that meet the criteria defined above, a manual filtering process was performed in which the articles that meet any of the research questions proposed are selected. The criteria used are articles that speak about:
    - Changes in the consumer habits due to Smart Meter utilization.
    - Demand Peaks and approaches to solve them.
    - Smart Meters penetration and their improvement of the electricity system.
    - Demand Side Management and household response.
    - The Smart Grid in Colombia.
    - SG technologies implemented in homes.

Other articles related to the topic of study were included at the suggestion of experts.

4. RESULTS

By using the automatic search procedure described in the previous section, we obtained 851 articles; next, inclusion and exclusion criteria were applied and the quantity of selected manuscripts was reduced to 49. In addition, eleven new manuscripts were added at the suggestion of experts. Finally, we obtained 60 articles.

By analyzing the selected articles, we found the following characteristics of the body of knowledge: First, research on smart grid is a young area of rapid development and growth. There are no papers before 2008. Figure 2 presents the number of articles published by year.

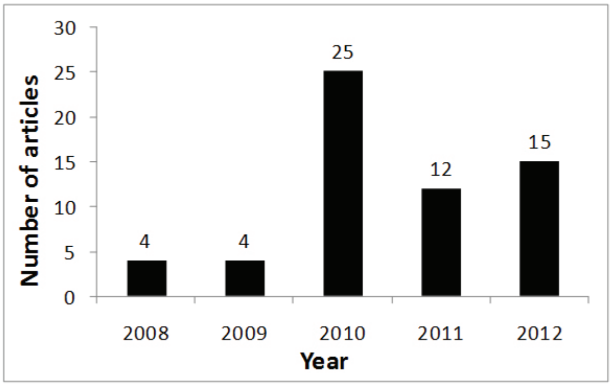

Figure 2. Distribution of articles - inclusion and exclusion criteria and experts suggestions

Second, we found six papers with more than 50 citations; they are presented in Table 2. Note that, all of them are related to methodological aspects of the smart grid.

Three, the most cited article was written by Ipakchi and Albuyeh in 2009 [11] and it is focused on explaining some of the causes of the high investment being made in SG and some possible improvements that are obtained with this approach.

Fourth, in Table 3 we present the conference proceedings and journals where the 60 selected manuscripts were published. The most important journal in the area is the IEEE Power and Energy Magazine with seven published articles and a total of 672 citations, followed by the IEEE Transactions on Smart Grid with 189 citations and seven published articles.

5. DISCUSSION

In this Section, we answer the research questions.

5.1. Q1: Which have been the most influential articles in the area?

Table 2 shows the articles with the highest number of citations (more than 50), so these have been the ones that have influenced research in this area. In Table 3 it can be seen the journals in which the selected articles are published.

5.2. Q2: What has been implemented regarding Smart Grids in Colombia?

We found only three research papers with the aim of studying the Smart Grid in Colombia [3234]. In [32], there is an overview of the technologies that are sought to implement the SG and a study of publications relevant to the development and use of SG technology and current research regarding this topic.

Table 2. Most cited articles.

Author	Title	Year	Research type	References	Citations
Ipakchi & Albuyeh.	Grid of the future. (IEEE Power and Energy Magazine) [11]	2009	Methodology	2	275
Farhangi.	The path of the smart grid (IEEE Power and Energy Magazine) [4]	2010	Methodology	1	206
Vojdani.	Smart integration (IEEE Power and Energy Magazine)[24]	2008	Methodology	1	80
Rahimi & Ipakchi	Demand Response as a Market Resource Under the Smart Grid Paradigm. (IEEE Transactions on Smart Grid)[19]	2010	Methodology	3	70
Conejo, Morales & Baringo.	Real-time demand response model (IEEE Transactions on Smart Grid)[31]	2010	Methodology	26	61
Garrity.	Getting Smart. (IEEE Power and Energy Magazine)[9]	2008	Methodology	1	58

Table 3. Journals and conference proceedings where the selected papers were published.

Journal or conference	Number of articles	Citations
IEEE Power and Energy Magazine	7	672
IEEE Transactions on Smart Grid	7	189
Energy Policy	4	41
Applied Energy	3	5
IEEE PES Innovative Smart Grid Technologies Conference Europe	3	1
Energy	2	13
IEEE Innovative Technologies for an Efficient and Reliable Electricity Supply	2	5
Power and Energy Engineering Conference, Asia-Pacific, 2010	2	1
The Electricity Journal	2	4
IEEE Transactions on Industrial Informatics	1	46
IEEE Transactions on Industrial Electronics	1	22
IEEE Transactions on Consumer Electronics	1	17
Annual Conference - Rural Electric Power Conference	1	10
IEEE Network	1	8
36th Annual Conference on IEEE Industrial Electronics Society, 2010	1	7
3rd European Modelling Symposium on Computer Modelling and Simulation, 2009	1	7
International Journal of Electrical Power and Energy Systems	1	6
Energy and Buildings	1	6
ACM Transactions on Intelligent Systems and Technology	1	6
IEEE/IFIP Network Operations and Management Symposium Workshops, 2010	1	4
International Journal of Energy Sector Management	1	4
IEEE Potentials	1	2
ABB Review	1	1
E-Energy 2010 - 1st Conference on Energy-Efficient Computing and Networking	1	1
Engineering & Technology	1	1
Electric Power Systems Research	1	1

Table 3. Continuation.

Journal or conference	Number of articles	Citations
IEEE/PES Transmission and Distribution Conference and Exposition: Latin America, 2008	1	0
Energy, Utilities & Chemicals	1	0
IEEE PES Innovative Smart Grid Technologies Conference Latin America, 2011	1	0
IEEE Innovative Smart Grid Technologies Conference, 2010	1	0
National Energy Technology Laboratory	1	0
2nd International Conference on Computational Intelligence, Modelling and Simulation, 2010	1	0
9th Conference Telecommunications Internet and Media Techno Economics, 2010	1	0
Tesis, Universidad Nacional de Colombia	1	0
45th International Universities Power Engineering Conference, 2010	1	0
Asia-Pacific Power and Energy Engineering Conference, APPEEC	1	0
Colombia Inteligente - http://www.colombiainteligente.org	1	0

In [33], a study was made by electricity utilities with the aim of determining the current state of the SG in Colombia and to build a reference based on the knowledge of the participants. In this work a reference map of the SG implementation in the Colombian electricity sector was defined. This study concludes that there is no specialized commercial network of Smart Grids in Colombia and that all research and development in this area focuses on the U.S. and Europe.

In [34], "Colombia Inteligente" was defined as a strategic framework that defines the guidelines and metrics toward a sustainable and efficient energy sector. The aim of this project is to establish guidelines, policies and strategies for the implementation of the REI in Colombia and to allow the country to have good practices in energy efficiency.

5.3. Q3: How do SGs affect the electricity demand?

SGs allow consumers to receive information about their consumption habits [15] and the associated electricity prices [35,36]. With this information, they can modify their consumption patterns by load shifting, shaping or cutting [37,38], consuming electricity in time periods with lower prices [1,3,15,21,39,40] in order to mitigate costs, save on their bills [16,17,38] or receive incentives [3,8,41,42].

As a consequence of changes in the consumption patterns, it is expected the following improvements are expected: more efficient use of energy [36], reduction of the peak demand [42,43], and increase of the grid sustainability by reducing the overall cost and carbon emissions [44,40,8]. With these improvements it is expected to reduce electricity demand between 10% and 20% during peak hours [1,20,24,25,26] and to reduce the depth of the valleys in the demand profiles [22]. The reduction of demand during peaks can result in a 9% reduction in household consumption [23,13]. In addition, the European Smart Metering Industry Group (ESMIG) believes that the greenhouse gas emissions for 2020 can be reduced by 20% [27].

5.4. Q4: What SG technologies are installed in households?

SG technologies installed in homes are:

- Smart meters for managing household electricity usage [16,45]. They are a key part of the communication infrastructure with the aim of making the users aware of their consumption [46,8] and receiving signals to help in the decision process [47,48]. With smart metering and home-based micro-storage, the demand will be more flexible to changes and will react to signals from the grid [49].
- Intelligent controllers and devices that cooperate in an intelligent way and that allow any appliance to be configured [50], so that when energy price is at some level (usually off-peak) they start working automatically [16,23,13]. These devices can administrate the consumer's demand based on the electricity market price[22].
- Advanced measurement systems, so called AMI (Advanced Metering Infrastructure), which are systems for the measurement, collection, storage, analysis and application of information from users [51].
- Online services like Google PowerMeter and Microsoft Hohm, which show the total consumption of a house using a friendly web interface and Smart Sockets, which control the energy consumption of the appliance [52]. However, Google PowerMeter and Hohm services were retired on September 2011 and May 2012 respectively.
- Smart sensors that offer a variety of technological functions like electricity controls, home interfaces, web interfaces, fire monitors, control appliances, gas leak monitors among others [53].

5.5. Q5: How have the Smart Grid penetrations been modeled?

Smart Grid penetration has been modeled from different points of view and different objectives:

- In [16], the authors develop a system to support users' intelligent decisions to increase the efficiency of energy use in the Smart Grid.
- In [20], an agent-based model is developed to simulate an electricity market with DR from different types of commercial buildings.
- In [31], an optimization model is developed to allow consumers to adjust their electricity demand level in response to the electricity price.
- In [54], the authors develop a methodology for modeling the prosumers' behavior (prosumers are the consumers who are themselves producers) with the aim of supporting policy makers decisions.
- In [55], an agent-based model is developed for simulating the behavior of a dynamic smart city in the future infrastructure of SG.
- In [56], an agent-based model is developed for simulating restructured electricity markets and exploring the impact of the price elasticity of consumer demand.
- In [57], a benchmark is proposed for evaluating management methodologies of domestic energy using different criteria in order to compare SG management solutions.

- In [20], an AHP (Analytic Hierarchy Process) methodology is developed for quantifying consumer preferences related to the use of appliances in peak periods when the price is higher. Then, a dynamic programming approach is used to achieve the optimal solution for managing appliances.
- In [58], a tool is designed to simulate a smart home, show the operation of DSM for customers, and estimate the home electricity consumption minimizing the customer cost.
- In [59], a model that simulates the response of consumers to dynamic pricing is developed. This model is integrated with an agent model that simulates deregulated markets.
- In [12], the authors design an in-home energy management (iHEM) application that uses a wireless sensor home area network to communicate all the appliances and the grid. This application accommodates consumers demand depending on the electricity price.
- In [43], a convex programming (CP) DR optimization framework is proposed for the automatic load management of different appliances in a smart home.
- In [7], the authors propose a model for energy use planning to optimize the consumption, generation and storage of residential electricity in a dynamic pricing environment.
- In [42], a model for demand response is developed; this work models consumer behavior in different scenarios and levels of consumers' rationality considering real time pricing.

5.6. Q6: Why is it important to study consumer behavior?

It is important to study consumer behavior because:

- It is necessary for consumers to modify their consumption patterns in order to reduce electricity costs and investments, to avoid price spikes [22] and to use appliances and energy more efficiently [14,26,60,23,13,54].
- Consumers can bring energy saving, energy efficiency and peak load shifts by using smart meters and information about the system [61].
- It is necessary to analyze and understand how consumers decide how much and how they want to consume energy [1,62].
- It is necessary to understand how to encourage the reduction of consumption or how to transfer it to periods with lower demand [63].
- It is necessary to determine how the most relevant information would be presented to the consumers in order to achieve changes in the consumption profile [3,64].
- It is necessary to understand how to encourage the use of advanced technology such as smart meters and other smart devices [47,65].
- In a scheme where consumers can directly participate in demand management it is necessary to find the best way to forecast the electric loads of individual consumers [66].
- Demand Response can provide competitive pressure to reduce energy prices, increasing awareness of energy use and providing a more efficient functioning of markets [11,19].
- With Demand Response, consumers can make the system more efficient, and with a 5% increase in network efficiency the equivalent of 42 coal thermal plants in the U.S. would not be needed, which would bring benefits to the system and the community [67].

6. CONCLUSIONS

Through the above study and the selected publications, the state of the art in Smart Grid and user behavior has been shown.

The publications of Kitchenham [28], Software Engineering Group [29] and Sorrell [30], propose the methodology of the systematic literature review, which was performed. These methodologies give as a result an analysis of the studies that some authors have made about the investigation subject, which allows further research into the area and will complement the work done.

The study of consumer behavior regarding SG is important because these users will become active entities in the electricity supply chain and their behavior can influence the improvement of the system.

Finally it can be said that in the literature there is no methodology to model and define policies for the entry of a SG and the Smart meters in an electricity system.

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