Renewable and Sustainable Energy Reviews 80 (2017) 260–275

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Electric energy management in residential areas through coordination of multiple smart homes

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ARTICLE INFO

Keywords:
Smart grid
Demand response
Demand-side management
Multiple households coordination
Rebound peak
Residential energy management

ABSTRACT

Grid modernization through philosophies such as the Smart Grid has the potential to meet increasing demand and integrate new distributed generation resources at the same time. Using advanced communication and computing capabilities, the Smart Grid offers a new avenue of controlling end-user assets, including small units such as home appliances. To enable such evolution, shifting from centralized to decentralized control strategies is required. Effective demand-side management (DSM) and demand response (DR) approaches hold the promise for efficient energy management in homes and neighborhood areas, by enabling the precise control of resources to reduce net demand. However, with such strategies, independently taken decisions can cause undesired effects such as rebound peaks, contingencies, and instabilities in the network. Therefore, the interactions between the energy management actions of multiple households is a challenging issue in the Smart Grid. This paper provides a review of the background of residential load modeling with DR and DSM approaches in a single household and concepts of coordinating mechanisms in a neighborhood area. The objective of this paper is to classify, via comparison, the various coordination structures and techniques from recent research. The results of recent research in the field reveal that the coordination of energy management in multiple households can benefit both the utility (i.e., the service provider) and the customer. The paper concludes with a discussion on the prevalent critical issues in this area.

1. Introduction

Developments in information technologies (IT), control, communication, and associated applications to power engineering have provided the tools for modernizing the traditional electricity grid. The evolution of the Smart Grid heralds a more interactive, distributed, and flexible role for the end-user in the day-to-day operations of the infrastructure [1]. Consumers are provided access to near real-time information and can benefit from technologies such as two-way communication, distributed generation (DG), and schedulable assets, thus changing from passive to active participants in the Smart Grid.

Electricity grid operators respond to the changing demand of consumers by adjusting generation and ensuring the transmission and distribution (T & D) assets are carrying no more than the rated value of power, efficiently and reliably. Historically, generation capacity was built to accommodate consumption peaks, i.e., the highest demand. But such peaks tend to increase over the years, for example due to population increase and the introduction of new consumption habits and devices (such as the personal computer in the 1990s and the projected electric vehicles growth in the coming decades). Although the increased electricity demand can be met by central bulk generation plants, the T & D system must also be upgraded—at high costs—to accommodate these higher capacities. On the other hand, distributed energy resources (DER)—which are located in proximity to end-user loads—provide a promising alternative to building new centralized bulk generation capacity and new or upgraded transmission lines.

DER are relatively smaller rated energy sources, with rated capacity ranging from a few kW in residential buildings to several MW on the distribution grid. DER can also be either conventional (e.g., micro turbines and diesel generators) or renewable energy sources (RES) (e.g., solar photovoltaic, wind turbines and biomass converters). Due to growing concerns of climate change, RES are increasingly preferred to conventional sources.

However, one of the biggest issues of RES integration is their intermittent characteristic [2]. The stochasticity of RES output, combined with the uncertain behavior of the consumer, implies greater difficulties in ensuring a real-time balance between generation and demand for system operators. The uncertainty in availability of generation and demand can be avoided using energy storage, but this solution is currently either prohibitively costly or inefficient at bulk

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http://dx.doi.org/10.1016/j.rser.2017.05.118
Received 22 April 2016; Received in revised form 16 May 2017; Accepted 19 May 2017
1364-0321/

levels or fraught with environmental constraints (such as for pumped hydro storage systems).

Another approach is to increase the flexibility of demand-side resources, i.e., the loads. This may be done by controlling end-user appliances, e.g., through home energy management systems (HEMS). Such approaches require extensive, reliable information on the whole system. This information can be made available through information and communication technologies (ICT), typically using sensors and supervisory control and data acquisition (SCADA) on the T & D system. For example, between end-users and the utility, smart metering and real-time data processing enable bidirectional communication though the advanced metering infrastructure (AMI) [3]. This in turn enables monitoring and control of resources such as DG and storage, which may then result in reverse energy flows, from consumers to the utility. Through such local resources, end-users are thus able to actively participate in electric network operations. This is a major shift from the traditional bulk power generation paradigm, as many more small-scale producers are expected to connect to the grid.

Demand response (DR) is a flexibility mechanism that enables consumer participation to demand modulation in response to a signal from the system operator [4]. Participation is enabled by optimizing the operation of local resources, such as electric appliances. Although HEMS programs propose promising solutions for better and ideally simpler energy management in smart homes, uncoordinated management may cause unexpected results, and may paradoxically lead to unstable operations or higher costs, such as rebound peaks [5,6]. To avoid this situation, efficient and robust coordination mechanisms are key elements in the designed energy management systems. Coordination may here be defined as a process enabling a set of entities (here, smart homes, utilities, aggregators) to organize their actions to work together effectively. This paper therefore primarily focuses on the flexibility of demand and the attached coordination mechanisms in residential neighborhoods—defined as a group of up to several dozen or hundred smart homes.

Various DR methodologies and programs were reviewed in the literature. In [7], HEMS and DR programs are reviewed for the single household environment. In [8], the psychological and economic behaviors of consumers for residential DR are analyzed. In [9], the impact of technological developments in the smart home area and on consumer behavior are investigated. In [10], household appliances are categorized to investigate their effect on DR programs. In [11], building energy modeling is reviewed by investigating optimal control models for single and multiple smart houses. In [12], a comprehensive survey reviews and classifies DR algorithms for the residential, commercial and industrial sectors according to the utilized pricing and optimization methods. The structure (centralized and distributed approaches) of the proposed methods is also considered; however the coordination of groups of houses is not discussed. In [13], DR algorithms for the residential sector are presented with a review of the latest scheduling methods and communication techniques. Finally, in [14], multiple DR programs are reviewed with a focus on their interactions with RES.

The above literature survey shows that although numerous management systems and techniques have been proposed and investigated, literature on coordination mechanisms at the smart neighborhood level has not yet been studied in details. This paper aims to fill this gap and provides a review and analysis of coordination mechanisms for energy management of multiple households. Several aspects are considered in the survey, including coordination structures (which entities interact with each other and how) and techniques (how decisions are taken). Through this paper, the authors aim to provide the reader with an overview of the state-of-the-art of such coordination mechanisms. Trends in research activities are then identified, as well as a series of proposed next steps to tackle current issues and challenges. Selected papers from the literature are thus reviewed, with a focus on journal papers published between 2010 and 2016. The breakdown of publication years for the reviewed papers is shown in Fig. 1. Figures show that the topic significantly grew in popularity from 2012. It should however be noted that not all published papers were included in this survey, and this graph does therefore not represent a precise description of the existing literature.

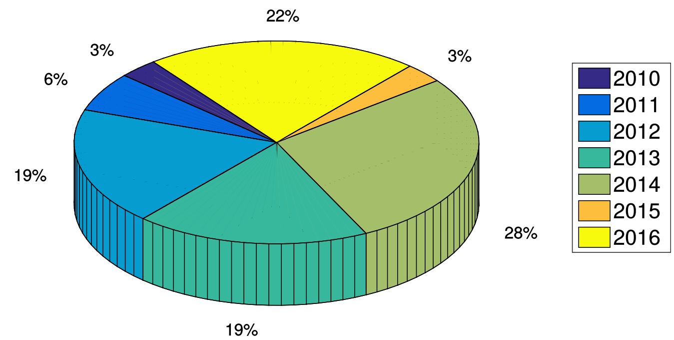

Fig. 1. Breakdown of publication years of reviewed studies related to multiple smart homes electric energy management.

The remainder of this paper is organized as follows: Section 2 introduces load modeling techniques; Section 3 presents the smart home concept and gives a short review of single residential house energy management; Section 4 explains the neighborhood concept, introduces the role of neighborhood entities, and reviews studies with a focus on coordination structures and techniques; Section 5 presents an overview of the state-of-the-art and proposes future steps; and Section 6 concludes the paper.

2. Load modeling techniques

Designing efficient and reliable HEMS usually requires load models to estimate the impact of control strategies on home energy consumption. In the literature, two main approaches are followed for modeling residential loads: top-down and bottom-up approaches. While top-down approaches model each home or the whole residential area as a single unit, bottom-up approaches investigate the energy consumption of each individual load (or group of loads), and aggregate these to obtain the consumption of the whole area or house. A comparison between both approaches is given in Table 1. A comparative review of such models for the residential sector may also be found in [15].

2.1. Top-down approaches

The principle of the top-down approach is to aggregate all energy consumption units in one spot (e.g., a home or several ones); thus, only the total energy consumption of a house or a residential area is known [16]. Top-down models often rely on historical data to model the energy consumption of an area, and are typically used to investigate the effect of long term changes (five years or more) on load profiles. The main advantage of this approach is simplicity, as aggregated data is commonly available, for example from distribution transformers. On the other hand, the main drawback of this method is that information about individual peaks, types of loads, load factors and customer behavior are overlooked. As a consequence, precise control strategies

Table 1
Residential energy consumption modeling approaches [15].

	Advantages	Disadvantages	Typical scale
Top-down	Simplicity, easy access to data.	Limited information on individual behaviors.	Neighborhood, city, region, or nation.
Bottom-up	Detailed information on individual behaviors.	High model complexity, difficult of data acquisition.	Individual or groups of residences.