Energy Management Systems: State of the Art and Emerging Trends

Saima Aman, Yogesh Simmhan, and Viktor K. Prasanna, University of Southern California

ABSTRACT

The electric grid is radically evolving and transforming into the smart grid, which is characterized by improved energy efficiency and manageability of available resources. Energy management (EM) systems, often integrated with home automation systems, play an important role in the control of home energy consumption and enable increased consumer participation. These systems provide consumers with information about their energy consumption patterns and help them adopt energy-efficient behavior. The new generation EM systems leverage advanced analytics and communication technologies to offer consumers actionable information and control features, while ensuring ease of use, availability, security, and privacy. In this article, we present a survey of the state of the art in EM systems, applications, and frameworks. We define a set of requirements for EM systems and evaluate several EM systems in this context. We also discuss emerging trends in this area.

INTRODUCTION

There is a growing worldwide interest in the evolution of the smart grid, a modern power grid that supports bidirectional communication between energy providers and consumers for fine-grained metering, control, and feedback. One of the key features of the smart grid is enhanced energy efficiency and manageability of available resources. Energy management (EM) systems, often integrated with home automation systems, play an important role in controlling home energy consumption. These systems provide an infrastructure to the consumers to understand, control, and optimize energy consumption. For example, EM systems can help consumers avoid consumption during peak hours and thus benefit from financial incentives offered by the utility. Widespread adoption of EM systems by consumers will eventually lead to more efficient consumption behavior and will benefit the utility as well. The role of EM systems in a smart grid is illustrated in Fig. 1.

EM systems have been around for a couple of decades, but until recently, they required specialized instrumentation and manual configuration. They also relied on extensive interaction with the customer to be useful. These factors posed an entry barrier, which prevented their large-scale adoption. This scenario is changing rapidly because of several technological advances. First, the growth in non-intrusive load monitoring (NILM) techniques is now making it possible to collect energy consumption data down to the level of appliances. The disaggregated energy data thus collected is more meaningful to the consumers. Second, due to the pervasive availability of sensors, it has become easier to collect different dimensions of data, including ambient temperature, humidity, and lighting, that can be integrated by EM systems to provide more contextual information and thus increase their effectiveness. Third, cloud computing and mobile platforms have made it possible to perform large-scale analytics on sensor data and offer advanced real-time feedback to the consumers. Finally, the growing popularity of social networks, like Facebook, has made it easier to incorporate comparative and persuasive features into EM systems to motivate behavioral changes in consumers.

This article reviews the state of the art in EM systems and identifies emerging trends in this domain. Research into methods for energy consumption management is well established [7], and our article supplements existing work. In 1981, McDougall *et al.* published an extensive review of energy consumption modeling and feedback techniques [3]. More recently, Froehlich *et al.* [6] offered a detailed review of feedback methods for energy management and concluded that providing consumers with detailed feedback on their consumption patterns will help them make more informed decisions about their energy consumption.

REQUIREMENTS FOR EM SYSTEMS

EM systems must provide advanced and versatile functionality while keeping the installation simple and running cost low. The systems should integrate with users' daily activities and offer actionable feedback. We define below the key requirements for EM systems that will facilitate effortless energy monitoring and control.

MONITORING

The system must provide energy consumption information at various temporal granularities such as 15 min, hourly, daily, and weekly. Fisch-

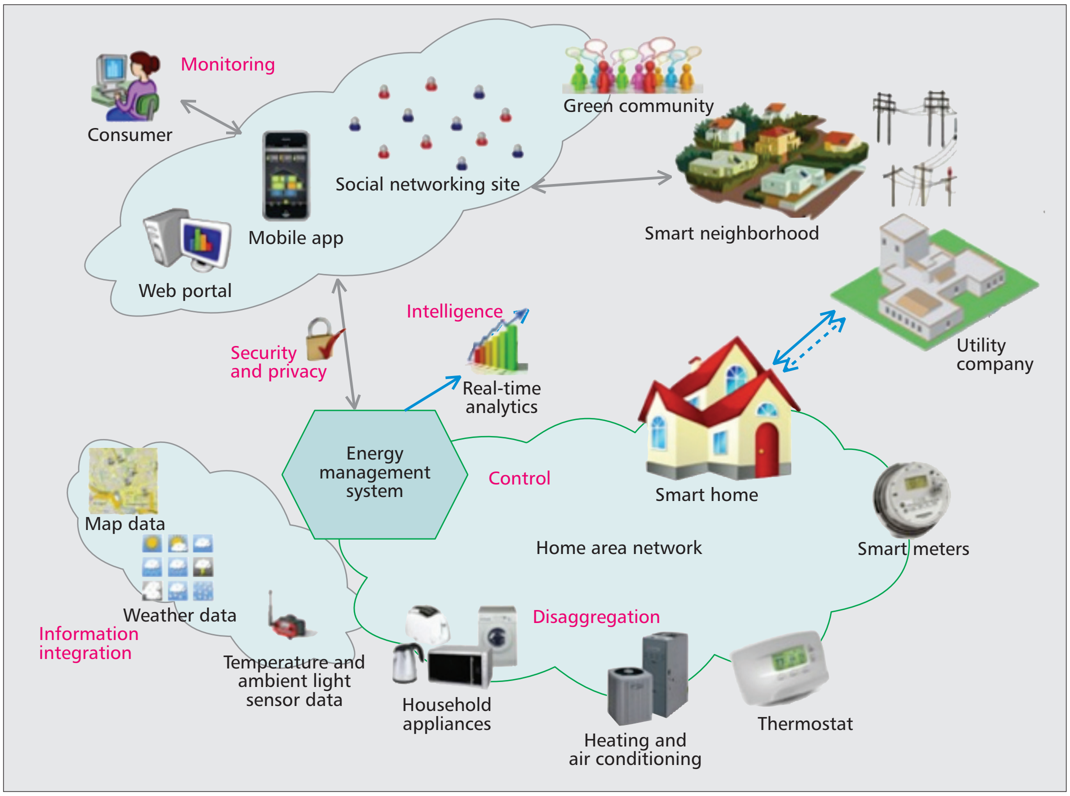

Figure 1. *Energy management system in a smart grid.*

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er [4] noted that the feedback is most successful when it is provided frequently and over a long period of time. Consumers can then directly relate near-real-time information with their energy use actions [14].

Disaggregation

Often, consumers have a misperception about the energy consumed by individual appliances [6], which can be corrected by providing disaggregated data for different appliances. Consumers can also benefit greatly from information about the real-time impact of specific appliances being powered on or off [5]. The disaggregated data also highlights the impact of long-term changes such as switching to an energy-efficient appliance. Many EM systems use indirect load sensing methods to provide disaggregated information based on specific current and voltage waveform "signatures" of individual appliances [9].

Availability and Accessibility

The system must make the information available to the consumer at all times through an easy-to-use interface, either in the form of a physical device, or through a web or mobile portal that also gives remote access to the information. EM systems may also use push technology to send urgent notifications to consumers' smart phones or system screens.

Information Integration

Besides current energy consumption, EM systems must also integrate other types of information such as indoor temperature, humidity, acoustics, and light; and consumers' historical data, usage data related to different appliances, as well as peers' consumption data. This type of data is collected at different timestamps, and needs interpolation before being presented to the consumer. Semantic web technologies have been used for this purpose [17].

Affordability

The system should allow easy installation without professional help. Its configuration and maintenance should be simple. It should consume minimal energy with a low running cost. These factors help reduce the entry barrier of the system and facilitate widespread adoption.

Control

The system should be able to provide remote, programmable, and automatic control of devices. Generally, the consumer is expected to perform necessary control operations manually. However, a digital control option or automated actions are more effective.

Cyber-Security and Privacy

The communication of data and control signals by EM systems poses security challenges. There are also privacy issues related to disclosing personal consumption profiles of consumers. The system must authenticate all transactions to ensure that consumers' data and control operations are secure, and not accessible to third parties without explicit consent.

Intelligence and Analytics

A desirable feature in new generation EM systems is that of intelligence. Consumers often lack a deep understanding of electrical systems and have limited time to make energy-related decisions [1].

Evaluation criteria →	Monitoring	Dis-aggregation	Availability and accessibility	Information integration	Affordability	Control	Security & privacy	Intelligence
PERSON (Yang and Li, 2010)	Yes	Yes	Monitor and control center available at user premises; no web or mobile interface	Aggregates others' usage information; integrates temp, humidity, luminance, and motion sensor data	Low cost and low power consumption	Manual remote control of the switches and dimmers in the home.	No	Context-aware intelligent algorithm
WattDepot (Brewer and Johnson, 2010)	Yes	Possible to implement, separate sensors present	Web-based interface	Automatic interpolation	Open source, freely available	No	Limited privacy model	No
ViridiScope (Kim *et al.*, 2009)	Yes	Yes	Not discussed	Aggregates magnetic, acoustic, and light info	Requires indirect sensors; no in-line installation required	No	No	No
Mobile feedback (Weiss, *et al.*, 2009	Yes	Yes	Interactive; readily available feedback on smartphone	Integrates historical information	High availability through mobile phone app	No	No	No
DEHEMS (Sundramoorthy, *et al.*, 2011)	Yes	Yes	Web-based UI, real-time display unit	Integrates info from sensors, electric supply and gas supply lines	Requires sensors	No	No	Not yet (planned for 3rd phase)
EnergyWiz (Petkov, *et al.*, 2011)	Yes	No	Mobile phone app	Integrates historical usage, and user info from peers, social network friends, and EnergyWiz users	Requires mobile app installation	No	No	No
NOBEL (Karnouskos, 2011)	Yes	Yes	Mobile phone app	No	Requires mobile app installation	No	Yes	Limited (user behavior analytics)
ALIS (Bartram, *et al.*, 2010)	Yes	No	Web, smartphone, touch panel, art display	Integrates historical use, community usage data	Requires extensive installations; less affordable	Yes	No	No

Table 1. *Evaluation of various energy management systems.*

Thus, it is desirable to have the system perform intelligent actions that balance energy consumption and consumer comfort. This can require techniques from machine learning, human–computer interaction, and "big data" analytics to discern usage patterns and predictive actions. This reduces the onus on the consumer to directly control and manipulate all appliances all the time [11].

State of the Art in EM Systems

In this section, we review several EM systems and evaluate their features with respect to the requirements presented above. A summary of the results is presented in Table 1.

PERSON

Yang and Li [15] implemented an EM system based on the Pervasive Service-Oriented Networks (PERSON) framework. The framework has three layers: a heterogeneous network platform that provides application programming interfaces (APIs) for information exchange to the upper layers; a service-oriented network that abstracts the functionality in the form of services, and thus supports modularity and inter-operability; and a context-aware intelligent algorithm, which incorporates intelligence for dynamic control and system optimization. The EM system is based on a heterogeneous home area network (HHAN) comprising energy meter, power outlets, sensors, display, remote controller, switch, and dimmer, and uses a ZigBee wireless sensor network for communication. The energy meter uses indirect non-intrusive sensors for measuring the total energy flow in a home. The sensors measure temperature, humidity, luminance, and motion. The system can aggregate information from various sources, and supports remote control of devices through switches and dimmers. The system has a home gateway and control center (HGCC) that handles collection, storage, and transmission of data, supports monitoring and control, and allows intelligent analysis and decision-making. The data and service center (DSC) is a system component that can be used by consumers to get energy related information such as the average consumption of the community. The system offers several useful features such as low cost, low energy consumption, monitoring, and control, but lacks in providing security and privacy.

WattDepot

Brewer and Johnson [2] implemented an open source service-oriented framework for energy management called WattDepot. It comprises sensors, services, and clients. Sensors are software processes that request data from different energy meters; servers collect data from the sensors over the Internet; and the clients request data from the servers for display or for use by higher-level services. WattDepot provides services for collection, aggregation, analysis, and visualization of energy data. The consumers can configure the source to be monitored and the type of data displayed, and can get near-real-time feedback. It uses a simple privacy model. All sensors that transmit data for a particular source share the same access information corresponding to that source's owner. All data requests are authenticated before being stored on the server. Each source can be labeled as public or private. Anyone can access data from a public source, while only the source's owner can access data from a private source. The main limitations of WattDepot are lack of intelligence and absence of any programmable or automatic control.

ViridiScope

Kim *et al.* [9] developed ViridiScope for fine-grained monitoring of domestic energy consumption. It provides real-time appliance-level energy use estimation without the need for external calibration. It does this by means of indirect magnetic, acoustic, or light sensors placed near each appliance. Data is collected from heterogeneous sensors, and a machine-learning algorithm is used to learn and estimate the energy consumption of every appliance. This is a self-calibrating method that requires little human intervention, but it does require a sensor to be deployed with each and every device. The system is easy to install and run long-term and supports information integration from various sources. However, it does not provide manual, programmable, or intelligent control of devices, and also offers no security feature.

Mobile-Based Feedback System

Weiss *et al.* [14] implemented a mobile phone application to monitor and measure appliance-specific energy consumption based on the data collected by a smart meter. The application can be downloaded from the Internet, and requires no further configuration. It provides current energy usage, historical usage, device inventory, and measurement. The consumer can perform remote measurement and control of any appliance, and get results in near real time. The application is linked to the smart meter through an information gateway that gets data from the smart meter every second, and parses and stores it in an SQL database. The gateway's functionality can be accessed through a web server, and the meter readings can be accessed through URLs. A device's consumption is measured by turning the device on and observing the change in consumption data collected in real time by the smart meter. The information is then added to the device inventory, which maintains information about all previously measured devices. The main limitations of the system are lack of a security mechanism without any user authentication, no support for remotely controlling or programming the devices, and no embedded intelligence for automatic operation.

Dehems

Sundramoorthy *et al.* [12] proposed a Digital Home Energy Management System (Dehems) that collects user experiences and preferences, and provides useful feedback to consumers. Dehems senses data from electrical and gas supply lines, individual appliances, and ambient sensors. The data is then aggregated by means of the Dehems gateway and communicated to the server, which sends it to the web service. Dehems supports display of real-time of energy use, historical use, energy-saving tips, and comparison with average use of all system users. The system development involves three cycles of requirement gathering, design, implementation, deployment, and behavior assessment. Currently, it is in the second cycle. Repeated cycles would allow the system to understand energy use behavior and evaluate the efficacy of various persuasive techniques, and make corresponding improvements in the next phase. The main features of the current cycle are relative comparisons with similar households, disaggregated appliance-specific feedback, support for setting goals and targets for the consumer, provision of energy-saving tips and environmental facts, and a Facebook account for information sharing. An intelligent reasoning tool is planned for the third cycle that will automatically detect energy use patterns and generate corresponding personalized energy-saving tips. The system does not currently provide any kind of security and privacy, or control for individual devices.

EnergyWiz

Petkov *et al.* [10] introduced EnergyWiz, a mobile application that provides information about energy use and comparison with other individuals, including neighbors, social network friends, and other EnergyWiz users. The main goal of the system is to provide different kinds of comparisons to the consumer and motivate behavior change. It provides five types of comparative feedback: live data, historical data, neighbor data, challenge, and ranking. The feedback is available in different energy consumption units (kilowatts per hour, kilograms of CO_2, and money). EnergyWiz is Facebook-enabled, and allows monitoring and sharing of energy information in a social context. Consumers can challenge friends on Facebook in energy saving competitions and get a ranking among friends on Facebook who use EnergyWiz. The system uses a distributed architecture that facilitates information collection, management, and consumption at different sites. The energy consumption data is collected by an application/manager interface (AMI) and is stored on the server in a relational database server. The main limitation of the system is lack of support for privacy and security, especially when the data is shared on social networking sites. The system does not provides device-specific disaggregated information or control of devices. Also, no intelligence is embedded in the system for any kind of automatic operation.

NOBEL

Karnouskos [8] proposed a system to crowd source high-quality energy use data and context information from mobile phone consumers. This data can then be utilized in building decision support systems, and for profile analytics and prediction. The prototype energy crowdsourcing system (part of the NOBEL project for smart city neighborhoods) provides detailed consumption data as well as device-specific disaggregated information. The data is stored locally and par-

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tially synchronized with a backend system. It connects the mobile user to Internet hosted services coupled with an enterprise system. The Internet hosted services include an energy service manager, notification, billing, analytics, and metering. The enterprise system consists of a device manager, a business data manager, trusted third party interaction, as well as a security manager that performs authentication for all transactions. However, with individual user profiles being contributed by different consumers, there is a need to provide support for privacy. The system lacks information integration from various sources and relies entirely on the consumer for sourcing information.

ALIS

Bartram *et al.* [1] developed an Adaptive Living Interface System (ALIS) to serve as an information backbone for their net-zero solar powered home. ALIS is a distributed system that consists of energy dashboards, monitoring and awareness tools, device controls, and a feedback system. The consumer is provided both historical and predicted usage information. The system is made available through personal computers, smartphones, embedded touch panels, and a light-based informative art display. On a personal computer, the consumer has access to a high-level house dashboard for detailed consumption information, an analytical resource usage interface, and a neighborhood bulletin for sharing and comparing their energy conservation techniques with others in the local community. On a smartphone, the consumer has access to simplified versions of what is available on a personal computer, and additional alerts about energy consumption status and thresholds. Three touch panels are embedded in the house to serve as control panels as well as dynamic feedback displays. Finally, an aesthetically motivated Ambient Canvas provides feedback on net-zero performance, water consumption, and progress toward a performance goal. The system uses several units for display (kilowatts per hour, dollars, and grams of CO_2), different display methods (numerical and graphical), time scales, and usage types. It also has added support for motivational factors including social interaction, personal milestones, and community involvement. The main limitation of the system is that it requires extensive installation, which makes it less affordable. It also lacks intelligence and support for security and privacy.

Emerging Trends

We are witnessing rapid advances in technology that will significantly impact the design and implementation of future EM systems. The home automation infrastructure is increasingly becoming complex and enabling several functions such as information acquisition, decision-making, and actuation. Future EM systems need to be fully integrated with the home automation system, support control of appliances, and offer advanced features such as security surveillance using sensors such as thermostats and motion detectors. The main challenges in this regard are interoperability and security. The EM system would in essence serve as a *central control system* in a digital home. The system would communicate with other devices and sensors through wireless protocols such as ZigBee without requiring physical wiring.

Mobility is an important issue in EM systems. Future EM systems are expected to provide versatile mobile functionalities. In the EM domain, mobile devices can serve as a tool for real-time communication with consumers, whose behavior adjusts to near-real-time impulses received about their energy consumption, carbon footprint, and current energy tariffs. A mobile device can provide value-added services such as recommendation for an energy-efficient appliance, selected based on analytics performed on fine-grained appliance-specific consumption profiles. Mobile devices can also be used for *crowdsourcing* user-collected information. The information may be measured directly by the user or passively collected from the user's context such as location. This information can be used intelligently for several goals. For example, the sensory information such as a user's location and activity can be correlated with their behavior, and aggregated on a large scale for insight into a neighborhood's energy usage trends.

EM systems can serve as a useful tool toward active *demand side energy management*, one of the fundamental goals of smart grid [16]. It involves influencing the consumers' energy use behavior, to either turn on/off or reschedule appliances. This requires better understanding of energy use within homes and their impact on overall consumption in the smart grid. The utility can send real-time curtailment notifications to the EM system on which the users are expected to act. Future EM systems may have embedded intelligence that could automate decision making and control of household appliances in response to demand response or price signals from the utility. The direct communication channel present through the EM system may also be used by other entities besides the utility such as by a social network provider for communicating social and comparative messages.

The user interface is another important factor that would govern the success of an EM system. Weiser's [13] vision is that of a *pervasive* future computing environment where sensing, computing, and response are carried out without consumer intervention and in a non-intrusive way. For EM systems to be effective, they should increasingly conform to this paradigm. One way to implement this is to embed learning and intelligence into EM systems so that they absorb a user's preferences and comfort level, and use this to perform automatic control of devices. System developers will also benefit from the interface guidelines regarding persuasiveness being developed by Medland *et al.* [10].

EM systems may also integrate information about gas and water consumption along with electricity consumption. Many of the EM systems may be adopted by local utility companies and offered to customers at subsidized prices to make them more affordable. The utilities may also offer energy efficiency tips to the consumers through the EM system. In the long term, this helps the utilities meet their sustainability and energy efficiency goals, while making their operations more reliable and cost effective.

EM systems can also be used to assess *what-if* scenarios, where the consumers can evaluate fine-grained effects of behavior changes, such as rescheduling an appliance's running time. EM systems should also provide a framework for goal setting and allow consumers to track their progress toward their self-specified goals related to behavior change.

Security and privacy will potentially be a critical challenge for future EM systems since the data collected and analyzed by EM systems can now be used to monitor, infer, and devise user actions. Since the data will also be shared among peers through social networking sites and other communication means, extra precautions are required to tackle attacks.

CONCLUSIONS

There is a high level of heterogeneity in modern home infrastructures, which poses several challenges to developing approaches for smart energy management in homes. Current EM systems are fundamentally different in design and operation from before, even as they share the common goal of optimizing home energy usage. Smart EM systems are able to communicate and interact with both customers and energy devices to help adapt the home energy consumption to the available energy supply. Here, we present the state of the art in EM systems whose main thrust is to motivate behavior change in consumers, through either real-time consumption monitoring, ubiquitous sensing, or contextual comparisons with neighbors, social network friends, and other similar users. Future EM systems will need to more carefully address security and privacy issues, which are currently inadequately handled. There is also a need to offer built-in intelligence based on analytics and learning for providing more insight into consumer behavior and for automatic operation. Smart EM systems integrated with home automation systems are a key component of the smart grid cyber-physical system, and are essential to bring its multitude of benefits to fruition. Emerging trends point to a future beyond isolated consumer engagement toward dynamic communities that smartly and collectively manage their energy consumption and share information with each other to achieve a mutual goal of energy sustainability.

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BIOGRAPHIES

SAIMA AMAN [M] (saman@usc.edu) is a Ph.D. student in computer science and research assistant at the Center for Energy Informatics, University of Southern California, Los Angeles. Her current research is focused on applying data analytics to the problem of dynamic demand response in smart grids, including both direct building controls and voluntary curtailment by consumers, to achieve reliable and efficient grid operations. She received her M.S. in computer science from the University of Ottawa, Canada, and B.Tech. in computer engineering from Aligarh Muslim University, India. She is a member of AAAI.

YOGESH SIMMHAN [M] (simmhan@usc.edu) is a research assistant professor at the Electrical Engineering Department and associate director of the Center for Energy Informatics, University of Southern California, Los Angeles. His research area is on distributed data and computing systems that spans cloud and distributed computing, high-performance computing, distributed data and metadata management, and software architectures for large-scale applications in eScience and eEngineering. His current research is on distributed and adaptive software infrastructure for the energy informatics domain, and he serves as a project manager in the Los Angeles Smart Grid Project. He has a Ph.D. in computer science from Indiana University and was previously with Microsoft Research. He is an ACM member.

VIKTOR K. PRASANNA (prasanna@usc.edu) is Charles Lee Powell Chair in Engineering, and a professor of electrical engineering and Computer Science at the University of Southern California, Los Angeles, and serves as the director of the Center for Energy Informatics. He is the executive director of the USC-Infosys Center for Advanced Software Technologies (CAST). He is an associate member of the Center for Applied Mathematical Sciences (CAMS). He also serves as an associate director of the USC-Chevron Center of Excellence for Research and Academic Training on Interactive Smart Oilfield Technologies (CiSoft) at USC. His research interests include high-performance computing, parallel and distributed systems, reconfigurable computing, cloud computing, and embedded systems. He received his B.S. in electronics engineering from Bangalore University, his M.S. from the School of Automation, Indian Institute of Science, and his Ph.D. in computer science from Pennsylvania State University.

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