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Smart home energy management systems: Concept, configurations, and scheduling strategies

Bin Zhou [a,*], Wentao Li [a], Ka Wing Chan [b], Yijia Cao [a], Yonghong Kuang [a], Xi Liu [a], Xiong Wang [a]

[a] College of Electrical and Information Engineering, Hunan University, Changsha 410082, China
[b] Department of Electrical Engineering, The Hong Kong Polytechnic University, Hong Kong

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ABSTRACT

With the arrival of smart grid era and the advent of advanced communication and information infrastructures, bidirectional communication, advanced metering infrastructure, energy storage systems and home area networks would revolutionize the patterns of electricity usage and energy conservation at the consumption premises. Coupled with the emergence of vehicle-to-grid technologies and massive distributed renewable energy, there is a profound transition for the energy management pattern from the conventional centralized infrastructure towards the autonomous responsive demand and cyber-physical energy systems with renewable and stored energy sources. Under the sustainable smart grid paradigm, the smart house with its home energy management system (HEMS) plays an important role to improve the efficiency, economics, reliability, and energy conservation for distribution systems. In this paper, a brief overview on the architecture and functional modules of smart HEMS is presented. Then, the advanced HEMS infrastructures and home appliances in smart houses are thoroughly analyzed and reviewed. Furthermore, the utilization of various building renewable energy resources in HEMS, including solar, wind, biomass and geothermal energies, is surveyed. Lastly, various home appliance scheduling strategies to reduce the residential electricity cost and improve the energy efficiency from power generation utilities are also investigated.

Contents

* Corresponding author. Tel.: +86 731 8388 9677; fax: +86 731 88664197.
E-mail addresses: binzhou@hnu.edu.cn (B. Zhou), yjcao@hnu.edu.cn (Y. Cao).

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1. Introduction

In 1998, Electrical Power Research Institute (EPRI) carried out a research of "complex interactive network/ system" to develop a highly reliable and fully automated grid in the United States, which is the prototype of the U.S. smart grid [1]. Since the EPRI formally proposed the term "Intelli-Grid" in 2002, the concept of smart grid has been widely accepted to indicate the future development trend of power grids [2,3]. With the use of the term "Smart Grid", European countries founded the "European Smart-Grids Technology Platform" in 2005, and then launched a research report in 2006 to comprehensively formulate the concepts and framework for the European smart grid [4]. Later, the U.S. Department of Energy released a report "The Smart Grid" in December 2007, and it integrated the European ideas and concepts into the U.S. smart grid to support the trend towards a more reliable and sustainable green energy supply [5,6]. In recent years, developing a modernized smart city infrastructure has become a global common priority in most countries because of the tremendous environmental, economic, and societal benefits that it could offer. In particular, smart electricity usage in demand side plays an important role in improving the sustainability and energy conservation for the home end-users, and will also affect the electricity consumption pattern of human daily behaviors [7,8]. Recent advancements on information and communication technologies, such as advanced metering infrastructure (AMI), smart sensor technologies, bidirectional communication, smart home appliances, home area network (HAN) and home energy storage system (HESS), etc. have been developed. Therefore, this growing trend provides the technical foundation and infrastructures for the smart house with home energy management system (HEMS) [9].

Smart HEMS is an essential home system for the successful demand-side management of smart grids [10]. It monitors and arranges various home appliances in real-time, based on user's preferences via the human–machine interface in smart houses, in order to conserve electricity cost and improve energy utilization efficiency [11–13]. With the growing concerns on global energy security and environmental emissions, more and more distributed renewable generations, such as wind turbines, solar panels, and plug-in electric vehicles (PEVs), etc., would be gird-integrated into the active distribution networks with gradually increasing penetration [14,15]. Coupled with the rapid development in advanced power electronics and alternative energy technologies, building renewable and stored energy sources installed at the residential premises can be incorporated in smart HEMS to improve the in-home efficiency of energy conversion and utilization [16]. Consequently, this leads to a fundamental transition for modern energy management systems from traditional centralized infrastructure towards the cyber-physical HEMSs and autonomous responsive demand with large geographical regions of renewable and stored energy sources throughout smart power systems [17,18].

With the two-way information flow between electricity providers and consumers in smart grid, the massive HEMSs are encouraged to participate in demand response mechanism for energy savings and cooperation. The demand response is defined as the changes in electricity usage by the end-use customers from their normal consumption patterns in response to changes in the time-dependent electricity price [19], and it offers incentives for the demand-side consumers to urge lower electricity usage over periods with higher prices or when power supply reliability is jeopardized [20]. Furthermore, in response to the real-time electricity price from smart meters, the home consumers with HEMS can shift their demand consumptions of appliances automatically or manually into off-peak hours in order to minimize the electricity payment [21]. In a typical smart house, the thermostatically controlled appliances, including heating, ventilation, and air-conditioning system, electric water heater and refrigerator, usually account for most of residential energy consumption [22]. The ever-increasing load demand and energy crisis issue have made the use of smart HEMS more attractive to both the power utilities and customers [23]. Therefore, with the consent of the customers, the HEMS can play an important role for optimal coordination and scheduling of various smart appliances and building renewable facilities.

The objective of this paper is to provide a comprehensive review of the development status and research progress on smart HEMSs with renewable and stored energy sources. First, a brief overview on the architecture and fundamental functions of HEMS is surveyed. Then, the advanced HEMS configurations and home appliances in smart houses are analyzed and presented. Third, the utilization techniques for various building renewable energy resources in smart houses, including solar, wind, biomass and geothermal energy, are reviewed. Moreover, various home scheduling strategies for optimal operations of smart HEMSs are further investigated. Lastly, the concluding remarks are drawn.

2. HEMS overview

2.1. Concept of HEMS

Under the smart grid paradigm, the AMI devices enable a reliable two-way communication between power utilities and home consumers [24]. It provides an opportunity for economic incentives of smart home to manage the demand-side resources by shifting their electricity usage during peak-load periods in response to the changes in electricity prices. The economic incentives include the saving in electricity bill, the improvement in utilization efficiency of household appliances and residential energy conservation [25]. Hence, smart HEMS is defined as the optimal system providing energy management services in order to efficiently monitor and manage electricity generation, storage, and consumption in smart houses [26,27]. With the communication and sensing techniques in HANs, the information collection for energy consumption from all household appliances can be provided, and the remote real-time monitoring and control for different operational modes of smart home devices can even be achieved by a personal computer or smart phone [28]. Besides, HEMS can provide not only the optimum utilization status of home appliances, but also energy storage and management services for distributed energy resources (DERs) and HESS [29].

2.2. Architecture of HEMS

The overall architecture of a representative smart HEMS is shown in Fig. 1. The HEMS center includes a centralized smart

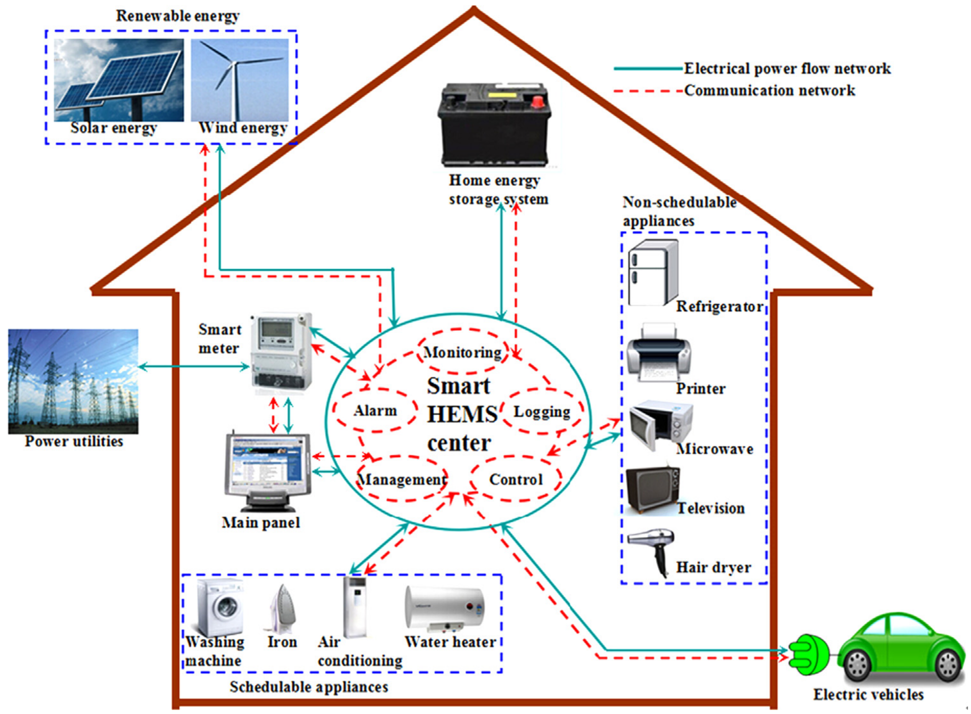

Fig. 1. Overall architecture of a representative HEMS.

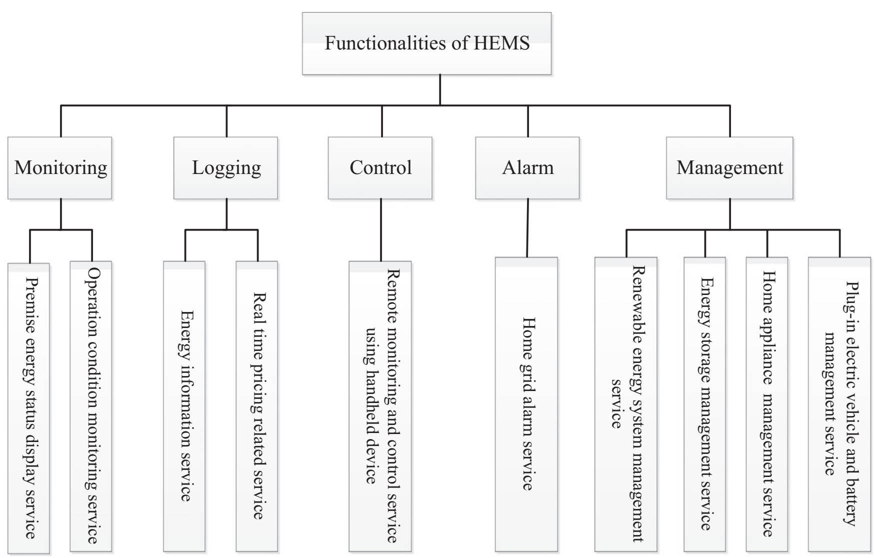

Fig. 2. Functionalities of a representative smart HEMS.

controller to provide the homeowner with monitoring modules and control functionalities based on the home communication network [30]. The real-time electricity consumption data from in-home appliances, including schedulable and non-schedulable appliances, can also be collected by the main panel of smart HEMS to implement optimal demand dispatch. In addition, the house gateway, such as smart meter, can be utilized as an interactive communication interface between power utilities and the smart house in real-life deployment. Typically, the smart meter receives a demand response signal from power utilities as an input to the smart HEMS, and the optimization of home appliance scheduling can be implemented for the residential demand response [31]. Electric vehicle (EV) is a special type of schedulable load. It not only consumes energy from power grids to meet the residents' transportation requirements, but also provides emergency power for other household loads within the smart community environment [32]. Currently, the distributed renewable generations in residential areas most commonly involve solar photovoltaic (PV). The residential on-site energy sources can be fully integrated in the interactive generation management and operations of HEMS, and allow the smart houses not only rely on the bulk power from the transmission systems. Due to the inherent intermittence and randomness of solar energy, the energy storage devices play an important role to improve the power quality and energy efficiency as well as maintain the energy system reliability [33,34].

2.3. Functionalities of HEMS

For the purpose of participating in electricity saving and demand response, HEMS should be more flexible to manage and control smart home appliances, renewable energy resources and

Table 1
Functional modules of HEMS.

HEMS modules	Service description
Monitoring	Monitoring offers easy access to real-time information on energy consumption and allows users to focus on the electricity saving. It can also provide display services for the operational modes and energy status of each home appliance.
Logging	Logging is to collate and save the data information on the amount of electricity usage from appliances, generations from DERs and energy storage state. This service also contains demand response analysis for real-time prices from grid utility.
Control	There are two types of control, namely, direct control and remote control. Direct control is implemented on both the equipment and control system; whereas, remote control means customers can online access to monitor and control the usage patterns of in-home devices via handheld personal computer or smart phone from outside.
Management	Management is the most important function of HEMS to enhance the optimization and efficiency of electrical power usage in smart house. It covers a range of services including renewable energy system management service, energy storage management service, home appliance management service, and Plug-in EV and battery management service.
Alarm	Alarm will be generated and sent to the smart HEMS center with information on the fault locations, for example, if there is any abnormality detected.

HESS [35]. Moreover, the active control services, including real-time information on the amount of energy consumption and the pricing of energy in smart homes, can be provided to the consumers on the basis of HEMS. The household consumers can choose their preferences via the human-machine interface to schedule the service time of various appliances to enhance their energy utilization efficiency [36]. Fig. 2 shows the typical functionalities of a smart HEMS center with five main functional modules, including monitoring, logging, control, management and alarm. Further detailed description on the five HEMS modules are illustrated in Table 1 [36,37].

3. HEMS infrastructures

The in-home infrastructure of HEMS is composed of smart HEMS center, smart meters, communication and networking system, HESSs and other smart devices [34]. With these smart infrastructures, HEMS can access, monitor, control and optimize the performance of various DERs, EVs, household appliances and equipment. Furthermore, HEMS is capable of supporting full integration of smart appliances and smart home as well as two-way interaction with users and electric power utilities. Many attractive features of smart grid such as cost- effectiveness, flexibility, provision of differentiated services and user friendly advanced smart power technology with open standard assessment can also be implemented via the HEMS [38].

3.1. Communication and networking system

So far, various HEMSs have been designed based on different communication schemes with hardware implementation [39–46], such as power line communication [36], ZigBee [39], BACnet [40], Bluetooth [45] and human–machine interface systems [42,43]. Extensive investigations have been done on communication and networking technologies for HANs. Young-Sung Son believed that the combination of a smart meter and power line communication could provide remote access, facilitate planning, and save the energy consumption of home appliances [36]. Dae-Man Han suggested a new Smart HEMS based on an IEEE802.15.4 and ZigBee which divides and assigns various home network tasks to appropriate components [39]. With the support of active sensor networks which compose of sensor and actuator components, HEMS can integrate diversified physical sensing information and control various household devices [39]. Also, Kastner Wolfgang introduced the necessity of the building automation, systems and communication infrastructures based on BACnet [46]. Considering the potential of the easily embedding Bluetooth technique in communication devices and household appliances, Lilakiatsakun proposed a method to establish a complete home network using Bluetooth technique [45]. In addition, Fangxing Li designed a human–machine interface system which can be used in HEMS. It is supposed that HEMS shall have five main components referred as application processor, communication interface, user interface, sensor interface and load interface to facilitate user's operations on this system [42,43].

Based on the evaluation analysis of various communication technologies, ZigBee is chosen to demonstrate the proposed HEMS [42]. ZigBee, a wireless communication technology that is developing rapidly in recent years, has laid solid foundation on networking, security and software-related technical standards. ZigBee makes use of the world's most common 2.4G–2.4835 GHz frequency band. In terms of the low energy consumption and durability, ZigBee is with the low power consumption, low cost technology and can support a large number of characteristics of the network nodes, and thus can be used in a wide range of industrial applications [30].

3.2. Smart meters

Smart meters are the advanced energy meters that measure the energy consumption of a consumer and provide additional information to power utilities using a two-way communication scheme [47,48]. As a result, customers are able to make optimal decisions to schedule the electricity usage of in-home appliances as well as actions of DERs and HESS [49]. As the foundation of data acquisition, data processing and advanced metering equipment management, smart meters are the latest techniques blended with computer science, modern communications and measurement techniques. Considering that smart meters are the basis of smart electricity, the functional design of smart meters should take into account the current facts and future development, such as the access of DER and the actual capacity of communication channel [47].

Main functions of smart meters include the following [50]: 1) Measuring the multi-period and multi-mode power rates of active and reactive energy metering usage; 2) Supporting two-way communication, sending data information and accepting instruction information, such as real-time information query, real-time electricity standard rates, meter upgrade program settings, etc.; 3) Enabling the response in terms of the requirements to achieve smart load shedding and cooperating with smart meter and smart interactive terminals during the islanding transition when a failure happens on the main power grid; 4) Collecting data with smart gas meters, water meters and other versatile value-added services.

3.3. Smart HEMS center

Smart HEMS center, analogue to the brain of entire smart electricity home, is the core of HEMS and implements the smart energy management. Smart HEMS center is located in user's houses as a home appliance. Main functions of smart HEMS center are as follows [51]: 1) Receiving a large amount of data sent by smart meters, main control panel, and real-time display. The control commands issued by the consumer are sent to all household equipment. Consequently, the automated demand response can be achieved; 2) Providing a friendly human-machine interface and supporting user's real-time browsing, online monitoring, task setting and other functions to arrange the usage of electricity; 3) With high scalability, the smart HEMS center can set water, electricity, gas, and other indoor controls; 4) Integrating DERs, energy storage devices and electricity regulator of EVs as well as analyzing and forecasting distributed generations to achieve the optimal control of DERs.

3.4. Home appliances

Various household appliances and energy storage devices can be thoroughly analyzed and modelled based on the device characteristics and preference usages. In order to implement the optimal coordinated appliance scheduling strategies, the smart home appliances can be divided into two categories: 1) Non-schedulable home appliances, e.g. refrigerator, printer, microwave, television, hair dryer; 2) Schedulable home appliances, which can be scheduled for optimal operation or switched on/off at any time, e.g. washing machine, air conditioner, iron, water heater, EVs. The appliances which can complete a task without any manual control, such as air conditioner and water heater, are schedulable [51]. While non-schedulable appliances, such as lights, computers and televisions, rely on manual control to complete a task and are needed only when the users are home. Since the comfort level of users is quite sensitive to the timely services of non-schedulable appliances, their usage would usually not be delayed.

Schedulable appliances can be further classified into 'interruptible' and 'non-interruptible' in terms of the continuity of operation time [52]. Generally, the interruptible appliances are usually more schedulable than non- interruptible ones. The non-interruptible appliances are constrained by fixed operation period called 'hold-time' [52]. As a unique load, the EV becomes more important and extensive as the part of HEMS. Experts expect that the amount of EVs will be increased in the following years, which helps to reduce air pollutants and greenhouse gas emissions [53]. Since EVs can be charged or discharged when connected to the grid, a growing number of practical services can now be realized in power grid [54]. Vehicle-to-grid, as a new concept, indicates that the electric energy stored in the EV battery can also be transmitted to the power grid [55–57]. In the smart HEMS, EVs are capable of balancing the peak power, which means that EVs can supply power during peak periods while users consume power during off-peak periods.

4. Renewable energy resources in smart houses

4.1. Current status of renewable energy sources in smart houses

Since 1990s, the utilization of renewable energy sources has increased with an average annual rate of 2.0% [58]. Additionally, renewable energy has been consumed in various fields, including the industrial, residential, commercial, and public sectors. As shown in Fig. 3, only 31.1% of renewable energy is used for electricity and heat production worldwide, while 50.4% is used for residential, commercial and public purposes in 2012 [58]. It also indicates that the research on the use of renewable energy in HEMS is of great significance and developing prospects. With the rapid development of sustainable energy technologies and increasing demand for low-emission generations, the utilization of renewable energy shows promising prospects for smart houses.

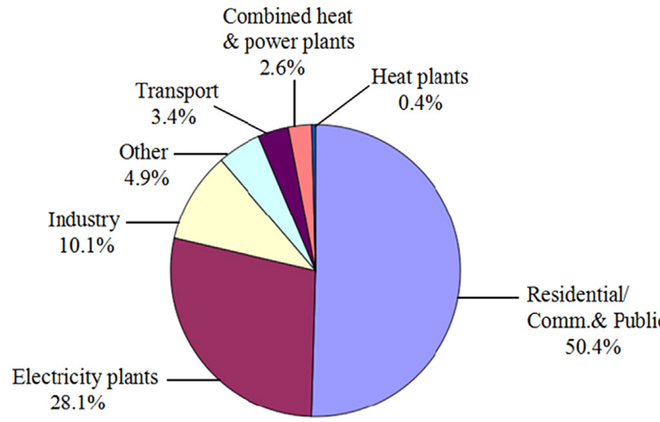

Fig. 3. World sectoral consumption of renewables in 2012.

From the technical and economic aspects, it is quite feasible to substitute fossil fuels with renewable energy for home electricity supply [59]. Meanwhile, with further development of smart grid technologies including communication and monitoring, control, and self-healing, the smart home energy utilization has been improved to accommodate multiplying renewable resources [60].

Due to its rapid development of renewable energy resources in the past 15 years, Germany is a forerunner in renewable electricity [61]. In 1998, Germany began to implement "100,000 Roofs Plan", aiming at obtaining 300 MW solar power from the roofs of citizens. Presently, there are about 0.9% of German families using solar power system. Residents sell rooftop solar electricity at a high price to power grid during the day, however, at night, they buy electricity for use at a fair price. Therefore, residents become energy producers and consumers [62]. Thanks to its easy installation and low cost, the solar PV is widely used in smart houses. Cyprus, known as a leader in solar water heater in the world, is a country where 92% families and 53% hotels are using solar water heater systems, equipping with about 937,363 m^2 of solar collectors, nearly 1 m^2 per person [63]. Moreover, the solar PV cell productivity in China in 2008 was about 4 GW, 3 GW PV of which was module capacities. The cumulative capacity of installed PV power was 150 MW. At the same time, the solar water heaters have covered over 125 million m^2 in buildings, reaching about 60% of the worldwide total [64].

Wind power is characterized by many merits such as clean, renewable, widely distributed and land-saving [65]. Therefore, wind power is more widely used than other resources to solve severe environmental problems. For example, in 2013, one third of Denmark's electricity is produced by wind and over 83 countries in the world are using wind power to produce electricity [66–68]. Estimates show that the annual electricity generated by wind power system will amount to 1.7–5.0 TW h by 2020 if new buildings and existing buildings are all equipped with wind power systems [69–71]. Obviously, the utilization of wind power in smart houses is of great potential.

As an important means of access to energy, the application of biomass combustion power generation technology in smart houses is foreseeable. Since the 1990s, Denmark, Austria and other European countries have started the development and research of biomass power generation technologies. After years of efforts, boilers have been developed for power generation with wood chips, straw, chaff, etc. At present, biomass power generation has been used in households throughout Denmark [64]. Straw power generation and other renewable energy sources have accounted for more than 24% of the national energy consumption. The installed biomass power generation capacity in HEMS of United States has reached 10.5 million kW, while the biomass power generation techniques get faster development and higher utilization rate in Japanese cities. Likewise, China's utilization of biomass has been developed substantially. Achievements have been made in biogas, biomass power generation and liquid bio-fuel, while the majority usage belongs to electricity and heat generation. The installed capacity of biomass power generation increased to 4 GW in 2010, which was about 25% of the total. 1600 large-scale digesters and over 30 million home biogas digesters were built for smart home, and the annual biogas output was about 14 bcm and 1.65 Mt for bio-fuel [64]. Furthermore, great importance has been attached to the combination of biomass power and smart home energy dispatch. The immature technologies, the absence of comprehensive product standards, and inadequate supply chain are major barriers to the further development of biomass energy in smart houses.

Geothermal energy, defined as the heat from the underground, is an ideal renewable energy resource that is not intermitted and distributed usually around volcanic areas. There are two forms of geothermal energy utilization: geothermal heating and geothermal generations, and the latter has experienced a rapid development over recent years in the world [72]. So far, the chief geothermal energy suppliers for households are the United States, Iceland and Philippines. All around the world, Icelandic geothermal power is widely used to generate electricity due to its reliable base load and low cost. Thus, 87% of the smart houses in Iceland are heated by geothermal energy [73].

4.2. Utilization of renewable energy resources in HEMS

The world environmental condition, increasing need for energy demand nowadays, and the development of alternative energy technologies have brought forth a large amount of opportunities to develop various sustainable resources. Various building renewable energy resources, including solar, wind, biomass, geothermal energy and HESSs, have been utilized in smart houses.

As of today, solar energy is the richest inexhaustible and clean energy among all kinds of renewable energy resources [74]. Solar energy can be utilized in various aspects including solar water heater (SWH), solar PV, solar drying and solar cooling, etc. Due to easy installation and low cost, the SWH is widely used in households. Hot water heated by the solar energy can be used for showering, cooking and washing. In order to improve the conversion efficiency of SWH and reduce electricity consumption, legislations have been enacted to install SWH on each new building. Besides, more electricity bills are charged for the household who uses electricity to heat water [75]. Solar energy utilization can be classified into two types: solar thermal and solar PV. PV technique, known as the best means to convert solar energy, can directly convert the sunlight into electricity without any help from heat engines [76]. The solar PV is prevailing among residences where the annual sunshine is abundant [77]. Owing to its easy installation and maintenance, solar PV is quite suitable to incorporate into smart home to provide locals with energy and be utilized in various ways with less conversion failures. In addition, HEMS is usually equipped with an HESS which could store the energy for future or emergency use. The HESS also works as a buffer to make the HEMS reliable and improve network control [78,79]. The solar PV module is the most important part of a solar home system (SHS) and its supporting components should be properly adjusted according to direction and tilt of the module. Apart from the low price, the roof mounting for solar PV module is more suitable than ground or pole mounting and requires less wiring. The supporting components should be firmly attached to the roof beams instead of roof tiles [80]. In a stand-alone PV system, it is the irreplaceable charge controller to protect the battery from overcharge and over discharge. The charge controller is necessary for systems with unpredictable loads, user intervention, optimized or undersized battery storage and other characteristics that would allow excessive battery overcharging or over discharging, as the low voltage load will shorten the battery lifetime and diminish the load availability [81]. DC/AC inverters are used in SHS with a power larger than 100 Wp to provide customers with AC electricity. Only a few types of inverters are suitable for SHS, which are of square wave, modified square wave, and pure sine wave [82].

Wind energy is an important alternative energy, and its utilization in smart houses is always a hot topic over the years. Typically, the fan can generate electricity at the wind speed of 2.7 m/s, achieve rated power at 25 m/s, and ensure continuous electricity generation at 40 m/s. The device required by wind power generation is called wind turbine generator, which generally includes fan, generator, steering gear, tower, restricting and safety mechanism, and energy storage device [65]. In smart houses, the building hinders the linear motion of the air so that the air deflects to the top and sides of the building and produces pressure difference around the fan, which makes the generator rotate and generate electricity. Usually, the electrical energy generated is generally used for home lighting equipment, communication equipment and electrical tools [83]. Due to the volatility and intermittency of wind generations, the specific plans on the adjustable reserve capacity are of intense importance. Also, an accurate forecast on wind speed is indispensable to reduce the reserve capacity with the improved reliability [84]. HEMS can provide a well-designed storage platform to schedule the electricity generated by wind turbines through the charging/discharging strategies of HESS.

Primarily used for home cooking, heating and lighting, the biomass energy is widely used in smart houses. Numerous investigations have been studied on the biomass energy utilization, including the biomass energy in high-rise buildings [85], the biomass exploited for building heating [86], the influence of biomass boilers on energy rating [87,88], and the biomass fueled tri-generation system for selected buildings [89]. At present, the biomass power generation used in smart houses includes biomass combustion generation, biomass gasification generation, and biogas power generation. Biomass combustion generation is to combust biomass with excess air in the boiler, then the hot smoke generated exchanges heat with the heat exchanger of the boiler, and the high temperature and high pressure steam generated expands in gas turbine and hence generates electric power [86]. Biomass gasification generation technique means the thermochemical conversion of biomass into gas fuel, which is put into the combustion chamber of boiler, diesel generator, internal combustion engine generator and gas engine after purification to generate electricity. Lastly, biogas combustion generation is a biogas utilization technique that appears with the development of biogas technique. Biogas is utilized in the engine and equipped with integrated power generating units to product electricity and heat, constituting an important way for efficient utilization of biogas [89].

Geothermal energy is characterized by low cost and cleanness, and the most traditional and popular usage of the energy is to generate heat directly [90]. Over the last decades, plenty of geothermal devices have been installed in smart houses. Compared to the deep geothermal energy utilization, the shallow systems do not need the extraordinary geological settings and high geothermal gradients with clean and eco-friendly traits [91–93]. So far, the main utilization of shallow geothermal energy is air conditioning used in residential households, and the heat pump techniques are applied to pump up and utilize the shallow underground low-temperature heat sources. Ground source heat pump is an efficient energy-saving air conditioning technology to utilize shallow geothermal resources for heat supply and cooling [72]. The exploration and development for geothermal resources is an emerging industry with high investment and high risk due to the geographical distribution limitations of geothermal energy [92].

4.3. Techniques to renewable energy in smart HEMS

The alternative energy techniques in smart houses generally refer to the renewable resources developed and utilized using smart grid technologies. In this section, home energy storage system, hybrid renewable energy systems, power electronics as well as control and communication technologies are surveyed.

HESS techniques have an important impact on the utilization of renewable energy in smart houses. Recent commercial advancements in large energy storage and power electronic technologies offer new opportunities in intermittent generation stabilization, optimum management, power quality improvement, and peak load shaving. Currently, lead acid batteries, flow batteries, ultracapacitors and chemical energy storages have been widely used in HESSs [94,95]. The electricity generated by solar and wind energy is always fluctuant and volatile, and the balance between energy supply and demand at any time is required in household energy systems. Consequently, the coordinated charging/discharging schemes of HESS can effectively balance the variability and volatility of renewable energy generations and maintain a stable and reliable power supply. Moreover, in smart houses, the roof mounting solar PV, wind energy and other DERs are main power sources during the peak-load periods, and the energy storage devices and EVs in HESS are of the essence for interactions between households and power utilities [59]. On the other hand, during the electricity outage periods, the HESS can be employed with various renewable generations to form an independent generating installation to provide electricity supply for the critical load consumers so as to enhance power grid resilience [29].

Due to its inherent seasonality, variability and periodicity, a single renewable energy source, such as solar, wind, and geothermal, is inadequate to provide a continuous and economic power supply for HEMS [96]. Thus, the hybrid energy system with multiplying renewable generations can be formed and utilized to alleviate the intermittent and unstable effects of electricity supply [59]. For most of HEMSs, the sunlight is sufficient with abundant power generations of PV panels in summer, and thus more energy from PV can be used and stored for electricity supply. On the other hand, sunlight will be weakened in winter and wind power is the main contributor to support more electricity supply. In addition, there are various configurations for different hybrid renewable energy systems in smart houses, such as wind/PV, PV/biomass, wind/hydropower, wind/PV/biomass, and so on [97].

Since most of renewable and stored energy resources are transformed into electrical energy in smart houses, the energy conversion technologies are critical for the utilization efficiency of various renewable energies. The major impact of power electronic conversion technologies on renewable energy development and utilization is to improve power quality, energy efficiency-peak shaving, and control strategies [19]. Power electronic techniques have been increasingly adopted in household energy generation system for grid-integrated solar and wind energy sources [82]. With the extensive utilization of renewable generations and energy storage devices in residential buildings, it is necessary to design the optimal sizing and configurations for power electronic converters [11]. Also, with the highly efficient power electronics in alterative generations, energy management and conversions, user-end interfaces, together with the advanced control solutions, can pave the way for large-scale applications of renewable energies in smart houses [17]. In smart houses, PV systems generate DC power which needs to be converted to single- or three-phase AC, while the wind and microturbine systems generate variable frequency AC output which needs to be converted into the rated frequency AC for appliance utilization. For battery energy storage systems, a bidirectional DC–DC converter followed by a DC–AC inverter is the most general choice [43]. An increasing penetration level of renewable energy systems results in more stringent household demands, and the tasks of power electronics based HEMS are as varied as they are demanding by local end-customers [42]. The specific demands can be summarized as: 1) reliable/secure power supply, 2) high efficiency, low cost, small volume, and effective protection, 3) control of active and reactive power generations, 4) dynamic ride-through operation, and 5) system monitoring and communication in HEMS [11].

Communication and information technologies are required in smart HEMS to implement optimal appliance scheduling and energy management strategies. Within a smart home, the HEMS center with metering devices can collect and deliver information and control signals to optimize the electricity consumption and production schedule [30]. So far, different communication standards have been envisioned within HAN, such as HomePlug (IEEE P1901), Ethernet (IEEE 802.3), X10 (X10 standard), Insteon (X10 standard), ITU G.hn (G.hn), Z-Wave (Zensys, IEEE 802.15.4) WiFi (IEEE 802.11, IEEE 802.15.4), ONE-NET (Open-source) 6LowPAN (IEEE 802.15.4), ZigBee (IEEE 802.15.4), and EnOcean (EnOcean standard) [98]. Therefore, for effective utilization of renewable energies in HEMS, the devices require the ability to broadcast vital information about their state and energy requirements, as well as act based on signals received from the HEMS [39].

5. Energy scheduling strategies in smart houses

5.1. Appliance scheduling strategies for HEMSs

In the deregulated power markets, the implementation of demand response can loosen the control of retail electricity prices and improves the elasticity of demand [99,100]. In recent years, various decision-support tools have been reported to optimize and implement the home appliance scheduling with electrical energy services for residential consumers in smart houses [101–109]. The application of PEVs as dynamic energy storages with their travel patterns to coordinate the optimal home energy scheduling in a residential community has been presented in [102–104]. Automatic energy consumption scheduling strategies with price predictors was proposed in [105,106] to minimize electricity payment in a real-time pricing tariff environment. In [51], an energy management controller was developed on the basis of demand response information from the home gateway, and all appliances in smart houses will operate automatically in the most cost-effective way. Considering various uncertainties on appliance operational time, intermittent renewable generations and variations of electricity prices, the stochastic efficient scheduling schemes for optimized HEMSs have been addressed in [107,108]. Moreover, the distributed control algorithms for household demand response have been presented in [52,109] based on the bidirectional communication network architecture to schedule the in-building appliances and renewable energy sources.

In this context, many countries and regions conducted extensive investigations and practices for the demand response, especially the United States who helped organizations carry out the demand response and achieved satisfactory results. In August 2005, US President George W. Bush signed the Energy Policy Act. The bill clearly defines that the implementation of demand response and enforces it with great support. In addition, a study of demand response was submitted by the US Department of Energy to the Congress in February 2006, elaborating on the benefits of the implementation of demand response and recommendations [110]. Subsequently, the US Federal Energy Regulatory Commission also submitted the annual report of demand response to the Congress in August 2006 and September 2007 which analyzed the background and status of implementation of demand response in

Table 2
A comparison of two demand response schemes.

Schemes	Options	Functional descriptions
Price-based demand response	Time-of-use pricing	A tariff-making model in which the electricity prices vary with time, usually designed over a 24 h day.
	Real-time pricing	A pricing scheme in which the price for electricity typically fluctuates hourly, reflecting changes of wholesale price of electricity.
	Critical peak pricing	A pricing strategy where electricity prices are determined beforehand at peak hours of critical day.
Incentive-based demand response	Direct load control	In order to solve the reliability problem or regional emergency in power systems, the program operator remotely shuts down or cycles a customer's electrical equipment on short notice.
	Interruptible load	Reducing or interrupting the participation of load in emergency situations of the system.
	Demand side bidding	Customers offer bids for curtailment based on wholesale electricity market prices or an equivalent.
	Emergency demand response	Processing the system reliability accident caused by network operating risk, power shortages, black-outs, and so on.
	Capacity/ancillary service program	Dealing with the generator failure, transmission line fault and other system accidents caused by the tight capacity. It can also participate in voltage control, frequency regulation and demand side resources reserve.

residential households, the influence of demand response on power grids as well as the applications of AMI in the demand response and smart houses [111,112].

5.2. Price-based and incentive-based demand response strategies

According to the research reports from US Department of Energy, in accordance with the user in different ways to respond, the demand response schemes of power market includes the following two types: price-based demand response and incentive-based demand response [109]. Table 2 shows a comparison of the two demand response schemes [110]. The price-based demand response refers to the retail prices when users are in face of changeable electricity demand, including time-of-use pricing (TOU), real-time pricing (RTP) and critical peak pricing (CPP) and so on. User decision-making process through the internal economy would change the periods of low electricity price and reduce the electricity consumption in high-price periods to conserve electricity costs. On the other hand, the incentive-based demand response stands for the demand response implementation mechanism through the formulation of a deterministic or time-varying policy, including direct load control (DLC), interruptible load (IL), emergency demand response (EDR), demand side bidding (DSB), and capacity/ ancillary service program (CASP) and so on [110]. The function of incentive-based demand response presents its capability in motivating users in the impact of system reliability or timely response by higher electricity prices and demand reduction [99]. These two types of demand response mechanisms are inherently relevant and complementary to each other, and Fig. 4 illustrates their appliances scheduling and commitment strategies with different energy utilization efficiency and time scales in smart HEMS [110]. As can be seen in Fig. 4, with the real-time appliance scheduling strategies, the demand response in smart houses not only can be implemented flexibly on different time scales, but also can participate in the coordination of various appliance management and renewable generation scheduling [113,114].

Modern smart grid infrastructures with two-way communication enable power utilities to provide end-users with a time-dependent electricity price for interactive demand response. Based on communication and sensing techniques in HANs, a smart HEMS center can therefore schedule an optimal real-time and price-responsive electricity usage scheme for home energy storages and residential appliance loads, including schedulable and non-schedulable appliances [100]. The principal objective of optimal demand response scheme of HEMS is to manage the power consumption of home appliances during peak and off-peak periods in order to reduce the electricity cost of consumers and improve the utilization of energy from power generation utilities. Furthermore,

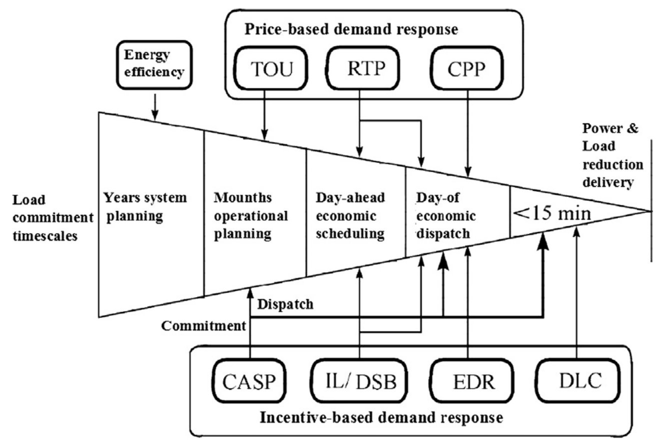

Fig. 4. Demand response scheduling strategies in smart HEMS.

HEMS should also schedule and coordinate the power generated from weather-dependent renewable energies, energy storage devices and user comfort levels to make more reliable and efficient use of electricity in an optimum way. Thus, there arises an urgent requirement for an optimal appliance scheduling scheme of HEMS with renewable and storage energy sources in smart grid environment [101,102]. The progressive development of smart grid infrastructures and advanced energy storage devices has brought new opportunities and challenges in demand response. The smart HEMS should cope with increased uncertainties of renewable energy sources in a large scale, HESS, and consumer comfort preference on home appliances [113]. Besides, a smart HEMS shall be able to respond to renewable generation fluctuations, electricity price, and other human behavior influences in real-time or near real-time to achieve a comfortable lifestyle with financial incentives [114]. The system shall also be flexible enough to accommodate and manage various home appliances, renewable energy resources and HESSs for energy saving and demand response.

5.3. Modelling and control schemes for household appliances

The emergence of smart grids and the increasing concern for electricity saving have presented opportunities for smart HEMS in demand response markets. As an important demand response tool, HEMS shift and curtail household appliance usages to improve the energy efficiency and production profile of a household on behalf of a consumer. HEMS usually formulate optimal consumption and production schedules with the consideration of multiple objectives such as energy costs, environmental concerns, load profiles, and consumer comfort [115]. In general, the main objective of control schemes for household appliances in HEMS is

Table 3
Comparative analysis on electricity cost under different scenarios.

Scenarios	Base case with real-time pricing (B-RT case) ($)	Base case with day-ahead prices (B-DA case) ($)	The robust approach proposed in [119] ($)
Appliance scheduling	14.35	14.17	12.78
Adding energy storage system	13.50	13.02	10.26
Adding electricity selling	13.48	11.52	6.23
Adding solar PV panels	4.39	6.43	0.59
Adding DER set	2.53	6.22	0.42

the minimization of energy consumption [115]. Besides, various artificial intelligence techniques have been applied to the control of both conventional and bioclimatic buildings. Intelligent controllers, optimized by the use of evolutionary algorithms were developed for the control of the subsystems of an intelligent building and in-home appliances [116]. The synergy of the neural networks, with fuzzy logic, and different evolutionary algorithms resulted in the so-called computational intelligence, which now has started to be applied in smart houses [117]. Moreover, the detailed modelling considerations for HEMS, including modelling demand response of devices, modelling of well-being, modelling multi-objectivity, modelling for uncertainty and communications infrastructure requirements inferred based on modelling, are surveyed in [118].

Since each appliance has unique characteristics, difficulties may arise for the HEMS to intuitively develop a model that represents each device. Beyond the infrastructure and communication challenges associated with the dynamic inclusion of new devices, such as recognizing one's plug-in hybrid. EVs returning home, the modelling and control of a multitude of appliances can be an evident barrier to the deployment of HEMS optimization [39]. Well-being analysis, relating to the lifestyle of residential consumers, is considered as an important objective to maintain in managing energy consumption [97]. The loss in the quality of service caused by energy delivery can bring inconvenience to the consumer. It is unsuitable to simply infer the inconvenience incurred to the consumer as a result of a shifted load because inconvenience is not time-invariant while consumers are heterogeneous. The work in [69] elaborates the multiobjective optimal models for smart appliance scheduling, and incorporating uncertainty into the scheduling process has the potential to improve the scheduling efficiency. Model predictive control is the most common method for addressing forecast errors, and is an open-loop online control system that approximates the desired solution by reducing the impact of the undesired dynamic properties of the system [101]. The HEMS modelling requirements are dependent on the market and communication infrastructure. In case where information from the grid is minimal or unnecessary, the HEMS only needs to communicate with the devices in the house [112], and the HEMS passively receive the information from the grid, either through the internet or through broad wireless signals [118]. Finally, when active bi-directional communication is required between the HEMS and the utilities, the HEMS should send the information frequently, securely, and with an effective communication protocol.

5.4. Scenarios analysis for HEMS scheduling strategies

A smart HEMS is a residential demand response tool that shifts and curtails demand to improve the energy efficiency and reduce electricity cost based on the real-time electricity price and consumer comfort [117]. In this section, the HEMS scheduling strategies have been analyzed under different operational scenarios. Study on the efficiency of HEMS based on Marc Beaudin and Hamidreza Zareipour indicates that a HEMS could reduce the operational cost of electricity by 23.1%, and decrease the residential peak-load demand by 29.6% [118]. In addition, it can be found from [98] that other advantages with HEMS include the minimization of energy wastage, reduction of household occupant intervention, eco-friendliness, and improvement of resident well-being. In the practical applications, not all users can simultaneously obtain the utilization of power load control, HESS, DER and the opportunity of selling electricity to the power grid. However, the extensive investigations indicate that energy consumption bill can be decreased if users possess HESS, DER, and the chance of selling electricity to the grid. In [119], three appliance scheduling schemes under different HEMS operational scenarios have been implemented and analyzed, and the corresponding electricity usage costs are shown in Table 3. The technical capabilities in the smart house are incrementally increased, including the load scheduling only, and then adding successively the HESS, the capability to sell electricity, and the capability to generate electricity (solar panels, and DER genset). In the basic scenario with the user limited to scheduling controllable loads, the economic gain varies from 9.8% (against B-DA case) to 28.3% (against B-RT case). In presence of the HESS, the proposed algorithm in [119] improves the objective function by 21.2% to 37.7%. If the consumer also has the ability to sell electricity, the robust appliance scheduling method outperforms the base case by 23.3–53.8%. Finally, if the solar panel is also grid-connected to the home energy system, the robust appliance scheduling approach in [119] outperforms the base case by 34.9–86.6%. It can be noted that the B-RT and B-DA scenarios limited to the load scheduling capabilities always lead to higher bills than the corresponding flat price scenario. This illustrates suboptimal energy utilization when residential customers are to cope with dynamic pricing environments not equipped with the proper decision tools. It can also be concluded that the modeling framework proposed in [119] will lead to significant economic savings for both the energy consumer and provider.

6. Conclusions

In the smart grid environment, the smart house with its HEMS plays an important role in the intelligent use of electricity and demand response. The smart HEMS with wireless networks, smart home appliances, digital citizen services, and smart sensor technologies could elevate standards of living and commerce with social and environmental capitals. In recent years, the popularity of HEMS has been increased significantly due to high accessibility, convenience and affordability via smart phone and tablet connectivity. Meanwhile, the development of modernized smart grid infrastructures with a variety of two-way communication, metering and monitoring devices lays a solid foundation for smart HEMS application. In the near future, the extensive use of HEMS will thoroughly change the way of electricity usage and renewable energy utilization in the residential houses. In this paper, the introduction and description for the overview of HEMS architecture have been illustrated, as well as a detailed investigation on the functions of renewable energy, HESSs, home appliances and demand response in HEMS. On the other hand, the utilization of renewable energy in buildings is becoming increasingly widespread. Findings show that solar energy is a main contributor to home energy consumption, while the wind, biomass, and geothermal energy often contribute relatively less and limited due to urban geography and climate factors. The utilization of building renewable energy also demonstrates that remarkable energy savings could be achieved from transmission energy losses and traditional primary energy. Furthermore, the home scheduling strategies for smart appliances, renewable energy and HESS have been investigated and analyzed to reduce the residential electricity cost and improve energy utilization from electric power utilities. Consequently, developing the smart HEMS has become a common global priority to support the trend towards a more sustainable and reliable green energy supply for smart grid.

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