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Utilization of ICT and AI techniques in harnessing residential energy consumption for an energy-aware smart city: A review

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ABSTRACT

Fusion of Information and Communication Technologies (ICT) in traditional grid infrastructure makes it possible to share certain messages and information within the system that leads to optimized use of energy. Furthermore, using Computational Intelligence (CI) in the said domain opens new horizons to preserve electricity as well as the price of consumed electricity effectively. Hence, Energy Management Systems (EMSs) play a vital role in energy economics, consumption efficiency, resourcefulness, grid stability, reliability, and scalability of power systems. The residential sector has its high impact on global energy consumption. Curtailing and shifting load of the residential sector can result in solving major global problems and challenges. Moreover, the residential sector is more flexible in reshaping power consumption patterns. Using Demand Side Management (DSM), end users can manipulate their power consumption patterns such that electricity bills, as well as Peak to Average Ratio (PAR), are reduced. Therefore, it can be stated that Home Energy Management Systems (HEMSs) is an important part of ground-breaking smart grid technology. This article gives an extensive review of DSM, HEMS methodologies, techniques, and formulation of optimization problems. Concluding the existing work in energy management solutions, challenges and issues, and future research directions are also presented.

1. Introduction

Electrical energy is becoming an integral part of life and is unique in nature due to its ever-growing demand (Yao and Zang, 2021). To meet such ever-increasing demand, the interconnection between power grids has developed extensively (Liu et al., 2020). This results in a complex power system structure, which must perform highly dynamic and near to unpredictable operations (Akrami et al., 2019). However, the usage of non-renewable power generation sources (fossil fuels) raised certain concerns regarding secure and reliable power supply along with many other problems (limited natural resources and carbon emissions, etc.) (Razmjoo et al., 2020). Traditional or conventional grid structure struggles, as the rapid rise in power demand, results in excessive power transportation without giving enough time to modify existing power distribution infrastructure. Such systems are centralized and offer one-way power flow (Mishra et al., 2020). With the passage of time, new power connections are adding rapidly, having a huge diversity of loads and this makes traditional power systems highly vulnerable to frequent failures (Haes Alhelou et al., 2019; Abedi et al., 2019). The connections based on non-linear loads deteriorate the quality of the power supply due to the non-harmonic supply curve (Pires et al., 2019). High PAR of power consumption curve results in huge losses to utilities as well as discomfort to users due to intermittent supply (blackouts) (Afzalan and Jazizadeh, 2019). To meet demands, traditional power grids use more non-renewable sources to produce electricity and result in more carbon emissions (one major cause of global

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warming) (Rehman et al., 2019; Chen et al., 2019; Sama et al., 2019b).

Answer to the said (but not limited to these) problems lies in taking the help from advancements of ICT (Humayun et al., 2020b; Molokomme et al., 2020) and Computational/ Artificial Intelligence (CI/AI) (Tsai et al., 2014; Ali and Choi, 2020). Such layout of a power system gives birth to the smart grid paradigm (Al-Badi et al., 2020; Dileep, 2020). Smart grid is the future of power generation and distribution that opens new gateways for cutting edge technologies (automation and harnessing the potential of ICT that offers two-way communication between supply and demand-side) (Saad et al., 2019; Saponara et al., 2019; Ali and Choi, 2020; Zen and Ur-Rahman, 2017). These features add a remarkable raise in reliability, security, and power efficiency (Farmanbar et al., 2019). Moreover, shifting from non-renewable to renewable sources is a gradual process that ultimately tends to address global threats (Belaid and Youssef, 2017). Further, the advent of Electric Vehicles (EVs), Smart Homes, and Smart Appliances gives a big opportunity to solve energy efficiency problems (Sovacool and Del Rio, 2020; Bhati et al., 2017).

Mainly, smart grid enables efficient use of cutting edge technologies in a conventional grid structure that tends to enhance operational stability, security, and resilience along with self-healing to improve environmental and economic aspects (Kim et al., 2019; Moretti et al., 2017).

Fig. 1 illustrates a vision of the near-future power sector within a smart city. The access of real-time data and information regarding power production and supply plays a huge role in power consumption manipulation. And to achieve normalized demand and supply processes, end-users must actively participate in managing their load in the guidance of information provided by utilities or the grid. This thinking evolved the concept of widely appraised DSM that affects the supply side by normalized PAR and have high impacts on the economy of end-users.

ICT plays a vital role and can be stated as the backbone of the smart grid by sharing real-time critical information amongst utilities and end-users. This helps in automating control and taking measures before time. Using ICT, traditional relays and electromechanical protective instruments are replaced with sensors and Intelligent Electronic Devices that can communicate, and at times, make localized decisions. The centralized power grid is in the process of decentralization by now. Table 1 represents a short comparison between the smart and conventional grids.

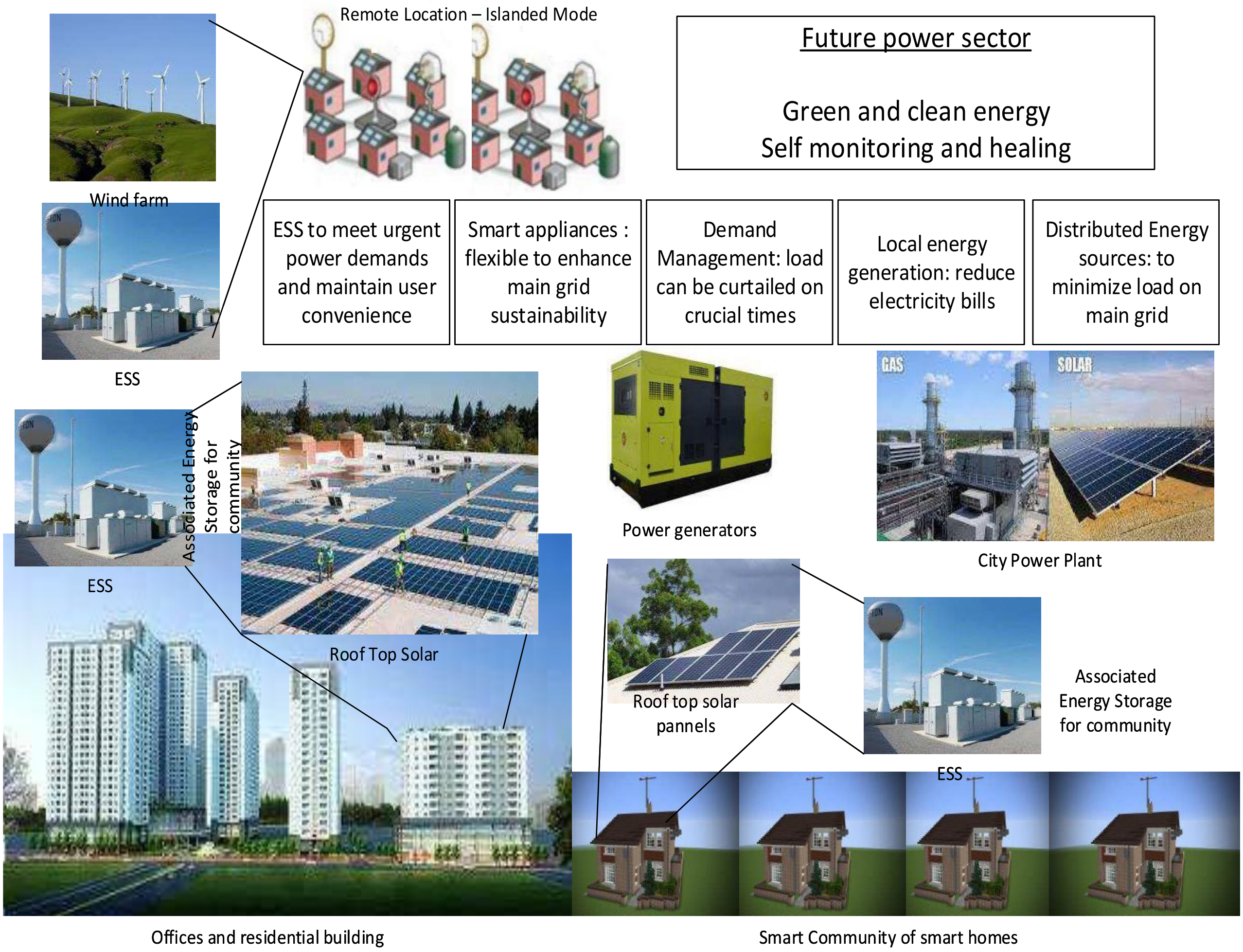

Fig. 1: Future power sector

2. Demand response programs

As stated earlier, a conventional grid is choking and needs to increase its lace length to meet ever-increasing power demand. Merging ICT and CI gives a fresh breath, while the concept of DSM is based upon these features. Besides advocating users to take an active part in the power sector, DSM also appraises distributed power generation sources (Arteconi et al., 2017; Sarker et al., 2021). To prevent line losses due to distant transportation of power, localized small-scale power generation plant/s (capable of handling local load based on forecasted demand) is a vital solution. DSM deals with everything on the demand side of the power sector and is dependent on the response of the customer. To get positive responses from end-users, the concept of Demand Response (DR) programs emerged. Numerous DR programs are developed to attract end-users. Utilities urge end users to take an active part in provided DR strategies by offering financial incentives. The required permanent results are global in nature, i.e., attaining energy efficiency. Considering weeks and days, Time of Use (ToU) and basic DR programs are focused to optimize demand-side electricity consumption patterns. ToU is related to the pricing mechanism that tends to give incentives regarding the use of power at low-priced hours. Low-priced hours are times, where electricity is in abundance and can be provided easily, however, during peak demand hours, the price is kept high normally. This is a major aspect due to which, end users reschedule their loads. DR programs, often do not contribute to minimizing electricity usage, but advocate altering power usage patterns in order to minimize the rebound effect. The rebound effect is due to ambiguity in desired or forecasted demand which in reality is more than evaluated. It is also a major cause of differences between actual and laboratory results considering any specific EMS. There are mainly two kinds of DR programs as explained in Palensky and Dietrich (2011) i.e., DR based on incentives to users and DR based on ToU and can be seen in Fig. 2 as well and Fig. 3 shows generic HEMS architecture. Mentioned DR programs are a few out of many, however, these are more appraised in literature.

- DR programs based on incentives:
- Direct Load Control, in which utility company enjoys decision power of user power consumption processes, a user has to pay fewer bills.
- Curtail-able rates, where Users involve themselves with scheduled sheds regarding electric load.
- Emergency DR program, where volunteer users give response to emergency situations.
- Demand bidding programs, in which users bid for an attractive tariff of load curtailing.
- DR programs based on time:
- ToU rates: Fixed and predefined rates are applied. Critical Peak Pricing: Reward users for reducing load.
- Real-Time Pricing: Real-time changes in price are forwarded to users.
- To support these DR programs, there is a cushion of "power reserves" to deal with abrupt changes in power demand. These power reserves can be storage devices or small-scale Renewable Energy Sources (RES) or a combination of both (Distributed Energy Resources (DER)). An extensive review of DSM tools is presented in Hussain et al. (2020), Sarker et al. (2021), Tang et al. (2019), and Khan (2019).

Table 1: Traditional Vs smart grid

Feature	Smart Grid	Traditional Grid
Generation	Distributed	Centralized
Restoration	Self-healing	Manual
real-time monitoring and surveillance	Extensive	Inadequate
Reaction time	Quick	Slow
Blackouts	tends to reach islanded mode, Adaptive	can choke due to excessive demand
Technology	Digital	Electromechanical
Communication	Two way (power and data)	One way (power only)
Backup plans	Energy Storage	No energy Storage
Control Coordination	Increased customer participation	Control by Utility
Faults and errors	Focus on prevention	Give response after occurring
Security	Resilient to attacks	Vulnerable to attacks
Power quality	issues identified and solved prior to manifestation	Slow response
DER	Towards Plug and Play	Problems in connecting

3. Residential energy management systems

Global power consumption can be categorized into two major aspects i.e., industrial and residential. Industrial includes production units, transports, and other business-oriented buildings that must follow strict schedules and timelines. Whereas, in comparison, the residential sector has more flexibility in energy consumption patterns. Considering only the US, residential buildings consume more than 37% of the energy consumed, out of which 30% is due to household electrical appliances (Derakhshan et al., 2016).

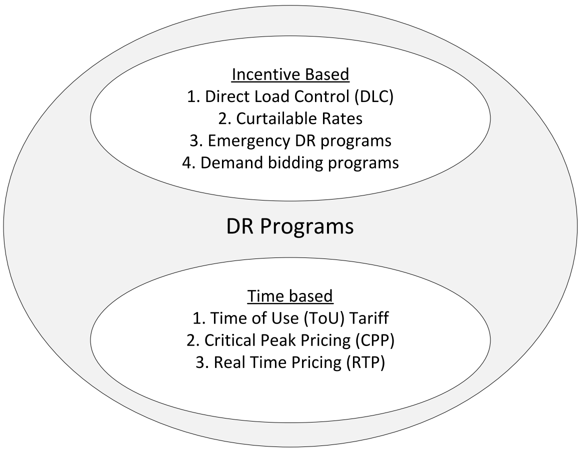

Fig. 2: Major DR programs

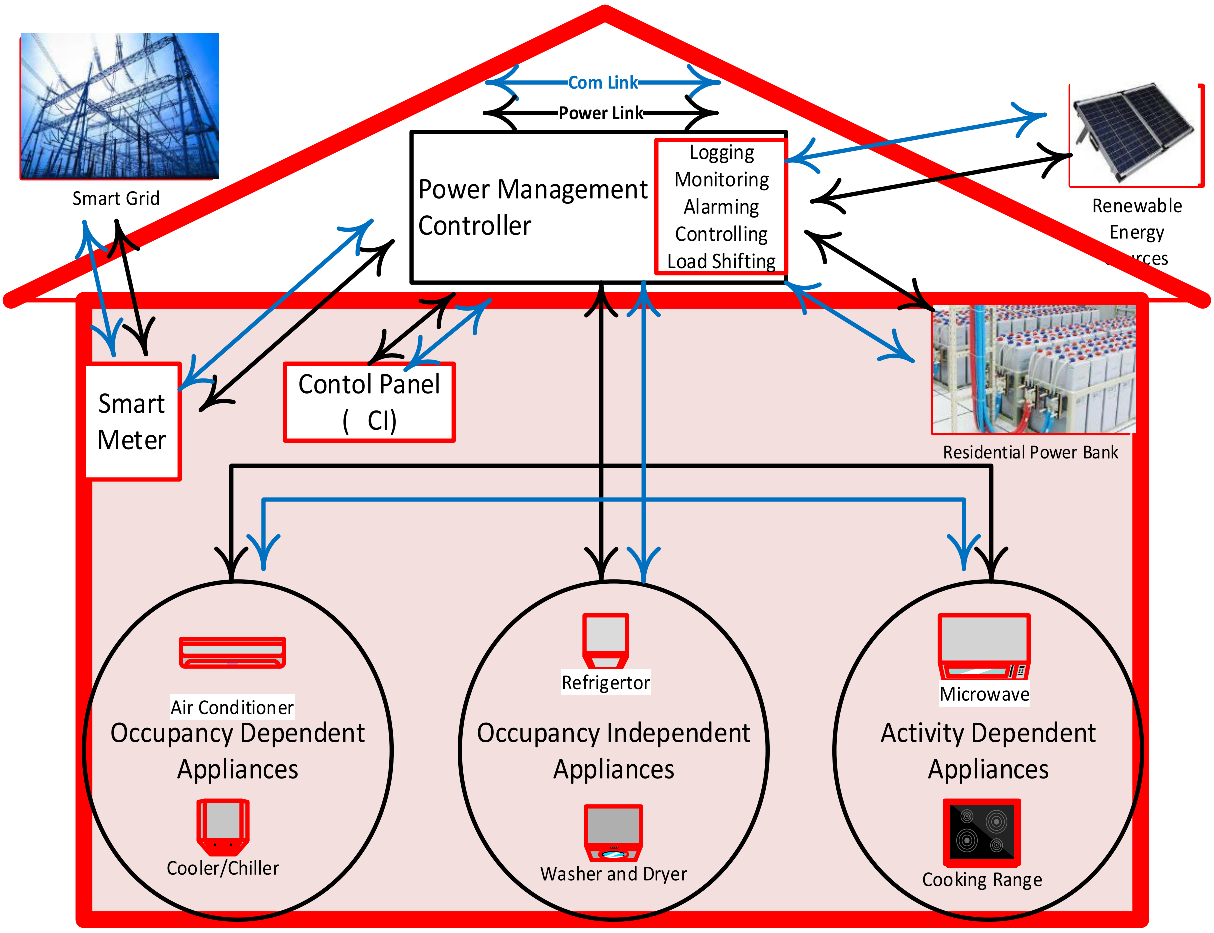

Fig. 3: Generic HEMS architecture

Tolerable power usage patterns of residential units invited scientists and engineering industries to think of solutions that can optimize the use of power in the residential sector. Research, as well as engineering industries, has led to the upgradation of the traditional grids into the smart grids with enhancements of computing and communicating capabilities. Other characteristics involve user-friendliness, resilience to attacks, self-healing and tends to accommodate distributed power generation sources along with multiple power storage options (Almusaylim et al., 2020). Today, AMI, electricity managers (PMC) and HANs are in the process of integration in power grid infrastructure. AMI measures the power consumption with respect to time. This measurement is communicated via HAN to electricity users (for effective power usage purposes), whereas PMC manages and computes the received data to provide optimum electricity usage patterns. Meeting power demand resourcefully is the basic concept in energy management.

Controlling and influencing power demand tends to clip peak load and reshape demand profiles, thus increase smart grid sustainability. There are numerous management strategies, however, some of the most outstanding tact's are scheduling load with respect to the demand curve, consumption peak clipping, power conservation, and flexibility in load usage patterns. Advertising "day ahead per hour price" of electricity is a major pricing mechanism and shifting electric load to low-priced hours is a promising solution to lower electricity bills and lower PAR. In this article, the residential sector is in focus, and manipulating electricity usage within a smart home for optimality in energy consumption is a major concern.

3.1. Architecture and tasks

The generic system architecture is illustrated in Fig. 3. A major component of basic HEMS architecture is Power Management Controller (PMC) which is also called the Smart Scheduler or Energy Management Controller in literature. PMC is responsible for monitoring and controlling smart appliances. A Computational unit creates load usage schedules with respect to load, ToU, and price signal or information from the utility. Smart meters also have computational capability to some extent. Hence, smart schedules can be made within the smart meters. Smart meter receives price signal from the utility company (Haider et al., 2016), and in response to this price signal, the load is shifted to low-priced hours. A recent development is the use of EVs for balancing the load. EVs act as a smart appliance for transportation, and during crucial hours they can also be used as an alternative power source (Zhao et al., 2016b). Besides Energy Storage Systems (ESSs), RES is highly appreciated in the power industry. ESSs play vital role in provision of system reliability and efficiency (Mesarić and Krajcar, 2015; Missaoui et al., 2014). To retain maximum benefits, HEMSs have to be more flexible in the management and control of smart appliances, ESSs, and associated RES (Sehar et al., 2016; Olatomiwa et al., 2016; Gholinejad et al., 2020). These control and management services include real-time information regarding the amount of power consumed along with the price at ToU (maintaining a log) and providing human-machine interaction to optimize load in terms of user preferences and requirements (Samadi et al., 2020).

3.2. HEMS: Generic components

HEMS is the composition of multiple components that work in a joint manner to yield required results. As discussed earlier, PMC is the heart of HEMS. Besides PMC, there is a smart meter that receives information from the utility company and sends this information to PMC. In the same fashion, smart appliances within residential unit transmit and receives control signals from PMC. Networking and communication amongst these components must be robust (Missaoui et al., 2014). Fig. 4 illustrates key players involved in generic HEMS. Major factors involved are:

- Local generators: Small scale power generation plants whose produced power can be utilized locally or injected into the main course of power by SG.
- Smart appliances: Which are capable of communicating besides. Hence, can be controlled remotely.
- Sensors and communication network: To sense attributes within the residential unit. Used to control and monitor power consumption and smart appliances.
- Storage devices: Take an active part in enhancing the flexibility of HEMS and user convenience.
- Energy managers: Often in literature termed as power/energy management controller, computations and time allocations to load are conducted here.

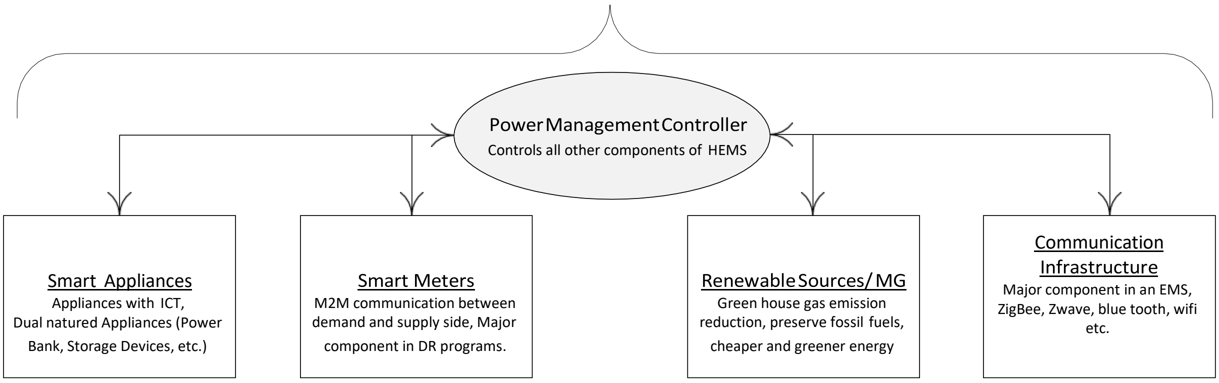

Fig. 4: Major components of HEMS

3.2.1. Smart meters

The basic purpose of meters is to measure consumed electricity and based on the readings, electricity bills are calculated. In addition to this, smart meters have the capability of two-way communication (between utility and users) along with computational power (Manic et al., 2016; Zhao et al., 2016a). Due to additional information, end users are able to devise optimal decisions regarding load shifting for economic and other benefits (Albu et al., 2016; Bahmanyar et al., 2016; Sama et al., 2019a). A smart meter is the blended version of the latest techniques of computer science and instrumental and measurement units (Borges et al., 2015; Shateri et al., 2020; Alquthami et al., 2020; Alkawsi et al., 2021). Hence, smart meters are the foundation of EMSs. Additional attributes of the smart meter comprise increased computational capabilities and communication channel capacity.

Major functionalities of smart meters can be stated as:

- Two-way real time information communication, Measuring and calculating the amount of energy used,
- Demand and Response information-sharing regarding load consumption, and
- Data collection regarding other value-added services.

3.2.2. Communication infrastructure

Considering sensing infrastructure different standards and protocols have been adopted for HEMS (Avancini et al., 2019; Sharma and Saini, 2017; Hu and Li, 2013; Humayun et al., 2020c). Major of which are Power Line Communication (PLC) (Saha et al., 2016), ZigBee (IEEE 802.15.4) (Avancini et al., 2019), Bluetooth (Hu and Li, 2013), WiFi (IEEE 802.11)(Humayun et al. 2020c), along with human-machine interface Systems (Sharma and Saini, 2017). Authors in Saha et al. (2016) suggested using PLC in conjunction with smart meters as it is more appealing to preserve electricity on the demand side. IEEE 802.15.4 based ZigBee Alliance is utilized in HEMS in reference (Avancini et al., 2019). This research used tiny sensors and actuators to accomplish different tasks resulting in efficient HEMS. In Hu and Li (2013), authors proposed a Home Area Network (HAN) based on Bluetooth technology that is used in electrical appliances and communication modules to minimize electricity usage. HEMS by using Human-Machine Interface Systems is proposed in Sharma and Saini (2017). The author proposed five major interfaces in his designed system as "Application Processor, Communication Interfaces, User Interfaces, Sensor Interfaces, and Load Interfaces". Considering the ease of availability, complexity, and initial investment, ZigBee seems a better option. Properties like low power, low range, wireless connectivity, and ease of access across the globe have given ZigBee a prominent place in the field of sensor networks for many applications.

Major Communication protocols used for HEMS are:

- PLC (Saha et al., 2016)
- ZigBee (Avancini et al., 2019)
- Human-Machine Interface Systems (Sharma and Saini, 2017)
- Bluetooth (Hu and Li, 2013)
- WiFi (Humayun et al. 2020c)
- BACnet, Z-wave, etc.

3.2.3. Electric appliances at the demand side

Categorizing electrical appliances in HEMS is a vital aspect to limit electricity bills. Normally, in literature, household electrical appliances are categorized into two major classes i.e., schedulable or non-schedulable. Schedulable appliances refer to those appliances that do not need the ultimate attention of the user and can be automated to switch on or off. While non-schedulable appliances are those which need proper user attention in their usage. Given the major categories, appliances are further subdivided into interruptible, non-interruptible, and thermostat-controlled in literature. Interruptible and thermostat-controlled groups of appliances fall in the schedulable class of appliances. The appliances that fall in the non-schedulable class, can be programmed to minimize electric load usage and electricity bills (Fletcher and Malalasekera, 2016) up to user comfort level. Table 2 shows process cycle: Energy management system.

3.2.4. Special electrical appliances

There are some appliances that have dual nature. These appliances can behave like a simple power-consuming appliance at a time, and at other times, these may behave as an Alternate Energy Source (AER). Power Bank or ESS may store energy at low demand hours when the electricity price is low or from renewable sources and act as AER at high priced hours. The stored energy tends to avoid load peaks on the grid side and minimize electricity bills on the demand side. Integrating such dual-natured appliances in EMSs is a complex task and numerous approaches are investigated in the literature. Considering the current era, another appliance that has taken the role of the power bank is EV. EVs are a step ahead in the global objective of minimizing carbon emissions. Besides minimizing carbon emissions, these EVs can also perform as power bank or energy transportation systems and have a diversified role in the future power systems as expressed in Rasheed et al. (2015), Nunna et al. (2016), and Kempton and Letendre (1997).

Table 2: Process cycle: Energy management system

Step	Component/Actor	Task/Description
1	EMS	Idle state waiting for notification from the utility
2	Utility company	Notifications regarding price and response are issued
3	AMI	Receives signal from utility and forward to PMC
4	PMC	PMC receives the signals from AMI and response is devised, control consumption according to signal. The response is devised by using optimization techniques or other methods.
5	PMC	After a devised response, it implements it using HAN and sends a signal back to the AMI system i.e., the load dropped to required (x%) as informed.
6	AMI	Receives signal from PMC and forwards it to utility.
7	EMS	The EMS is restored to the pre-event state.

3.2.5. PMC

The brain of any EMS is its controller. PMC is responsible for energy management. Data from sensors, smart meters and appliances are gathered at this core module to get the desired output in form of efficient load scheduling to reduce power consumption and ultimately electricity bills. Major functions of PMC can be represented as Humayun et al. (2020a):

- Receiving Bulk of data from appliances, sensors, and smart meter, transmitting control signals to fully automate DR program
- Real-time Human-Machine interface (monitoring, force starting/ stopping an appliance, etc.)
- Tackle scalability issues regarding the number of appliances with different parameter settings
- Ensure cooperative and optimized power consumption from smart grid and AERs (if installed) etc.

To meet the ever-growing electricity demand, research, as well as engineering industries, has led to the upgradation of the traditional grid into a smart grid with enhancements of computing and communicating capabilities. Other characteristics involve user-friendliness, resilience to attacks, self-healing and tends to accommodate distributed power generation sources along with multiple power storage options (Almusaylim et al., 2020; Zhao et al., 2013). Today, AMI, electricity managers (PMC), and HANs are in process of integration in power grid infrastructure. AMI measures the power consumption with respect to time. This measurement is communicated via HAN to electricity users (for effective power usage purposes), whereas PMC manages and computes the received data to provide optimum electricity usage patterns. Meeting power demand resourcefully is the basic concept in energy management.

Controlling and influencing power demand tends to clip peak load and reshape demand profiles, thus increase smart grid sustainability. There are numerous management strategies, however, some of the most outstanding tact's are scheduling load with respect to the demand curve, consumption peak clipping, power conservation, and flexibility in load usage patterns. Power consumption peak trimming focuses on lowering PAR and result in Direct Load Control (DLC) strategy. DLC advocates that control of power for a residential unit rests with utility and it is turned off or on, considering the load curve.

3.2.6. Generic HEMS process cycle

One of the most widely accepted and effective answers is shifting of load from high-priced hours to low-priced hours, in other words from high-demand hours to low-demand hours. There are loads that are flexible in their operations. To shift these loads on to low demand hours is one vital solution. Mainly, sensors, optimization techniques, and a combination of sensors and optimization techniques are the foundations of devising any HEMSs in literature. HEMSs need HANs and utility AMI to respond to the commands or information concerning grid stability and other socio-economic factors. Major steps involved in HEMS are depicted in Table 2.

HEMS after installation waits for the notifications from the utility. These notifications may be regarding the electricity tariff of the instance or asking to curtail load at some specific time. Once, utility company issues its notifications, the smart meter receives and forwards to PMC for devising a response. This response is devised by using any one of numerous techniques and tools, mostly optimization algorithms. After the response is planned, it is activated by using HAN that informs certain appliances to stop or shift their operations. If there is an AER then, the load is shifted on that source (in case of curtailing in demand notification). The response is transmitted to AMI, informing the current status which is further forwarded to the utility. Once, that process completes EMS again rests in an idle state waiting for the next notification from the utility company.

4. Role of HANs in HEMSs

In this era of the Internet of Things (IoT) and Big Data, sensor networks are considered as a backbone. The role of sensors/sensor networks is obvious in almost every domain of life and science. Considering the Smart Grid domain, sensors are helpful in:

- Power generation system: Voltage and current sensing, temperature and moisture sensing, continuity and phase sensing, distributed generation sensors.
- Power distribution system:

  - AMI systems
  - Smart capacitor sensors that can control capacitor storage remotely
  - HT voltage line temperature
  - sensors
  - Smart homes

Fig. 5 shows power management using sensor networks.

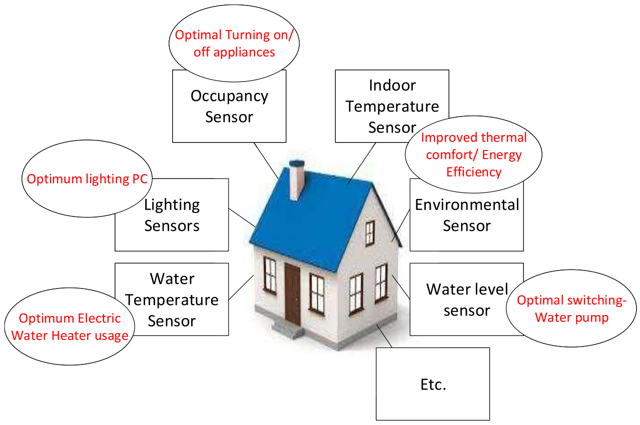

Fig. 5: Power management using sensor networks

Two major roles of sensor networks in HEMSs can be stated as:

- Providing communication infrastructure
- Provide assistance in energy optimization

Fig. 5 depicts optimized power consumption using sensor networks. Considering HEMSs, communication is the vital source that enables monitoring and controlling remotely. Home automation or appliance automation is not possible without underlying communication systems. Advancing towards smartness in energy management, two features are needed regarding communication networks, i.e., device control and energy management (Zhao et al., 2013). Ubiquitous networks open new horizons of research in almost every field of life. HEMS is also a major user of such networks. Authors in Zhao et al. (2013) presented a novel control architecture for intelligent and automated home networks. User convenience and energy savings are the major points of concern in the proposed architecture.

Machine to Machine (M2M) communication is cutting-edge technology. Authors in Yao et al. (2015) explained the integration of M2M technology in HEMSs. The authors proposed a network design, that collects power demands from home appliances, and then clusters are formulated for efficient HEMS traffic. To reach the optimum result of energy and cost savings, a dynamic programming algorithm is applied that ensures minimal power consumption and electricity cost of a residential unit.

An intelligent HEMS is proposed in Avancini et al. (2019) that enhances user comfort along with cutting excessive power consumption and bills. The proposed system is distributed in nature and a Multi-agent system is utilized, assigning different tasks to different agents. Using sensor and actuator networks, the authors proposed a new routing algorithm (Disjoint Multi Path-based Routing), which is tested on a real-time testbed. Han and Lim (2010) presented an investigation regarding remote monitoring and control of smart microgrids using IEEE802.15.1. The proposed system uses a Photovoltaic (PV) system as RES, which further can be extended to other renewable sources as well. The authors suggested Bluetooth technology for home applications considering its high penetration and ease of access in the market globally. Moreover, the authors developed an "experimental demonstrating tool" to analyses micro grid behaviors. The prototype uses the ATMEGA28P micro-controller, whereas, three power sources are considered i.e., grid, the PV system, and ESS. The power source selection is based on sensed data and optimal switching between power sources is conducted accordingly to the problem of inconsistent DR due to end-user needs and comforts regarding the use of appliances. The authors tackled this situation by devising a mixed-integer quadratic problem for thermostatically controlled appliances, which presents different choices regarding appropriate strategy (cost and energy savings) for the user. However, it can be more efficient if, the predicted results of each strategy are also communicated to the end-user.

Within the vicinity of smart homes, there are many devices that are not smart and are considerable contributors to energy usage. Lee et al. (2016) gave a study for such legacy appliances and proposed a "nonintrusive load monitoring (NILM)" component that is capable of integrating legacy appliances by mining data from power measurements. A novel HEMS architecture based on ZigBee communication protocol is presented in Kaczmarczyk et al. (2016). Proposed model results in the reduction of greenhouse gas emissions with minimal electricity bills. Load scheduling is conducted by prioritizing the household load in three groups. Furthermore, the proposed model is capable of extending up to a large-scale micro-grid that will be more effective in carbon Use of HANs in HEMS raise questions on personal information security. To solve the issue, authors in Niyato et al. (2011) presented "secure HAN-centric Smartgrid logical architecture". Load shifting is a promising solution that lowers PAR and electricity bills. To maintain user convenience, home appliances are categorized and scheduled in many ways as can be seen in Cetin et al., (2014) and Chavali et al. (2014). Authors in Jhanjhi et al. (2018) pointed out emission reduction and preserving energy generated by fossil fuels.

5. Role of optimization techniques in HEMSs

Power generation, though is not more than a century old entity, however, each element of the power system requires cutting edge solutions as electricity is becoming an integral part of life. Power system, from generation to distribution and then consumption is a complex task that needs to be optimized at each level.

The domain of optimization in applied mathematics is one of the most diversified subjects. Mainly two types of optimization techniques are discussed as traditional techniques and Artificial Intelligence based solutions. There is also an integration of these two techniques that tends to solve more complex problems and tends to give more optimum solutions. Fig. 6 illustrates major optimization techniques which can be divided into three classes i.e., traditional optimization techniques, Artificial intelligence-based, and distributed-natured optimization algorithms. Distributed optimization techniques ensure decentralized control which is more feasible for distributed or networked grid infrastructure considering power domain. Whereas, Fig. 7 illustrates different optimization techniques.

Focusing on any problem, if we tend to solve it using multiple techniques simultaneously, the answer will be more or less the same. However, achieved results have certain attributes as convergence time or time spent to reach that solution along with robustness and reliability. Every problem has its own merits and requirements and based on requirements, the optimization technique is utilized.

Considering most of the optimization problems, there are predefined limits, and the solution lies within these boundaries. Typically, a single objective of achieving maxima or minima is to be calculated. This simple case is termed as Single Objective Optimization, while, if the problem has multiple objective functions then such optimization is known as Multiple Objective Optimization.

Concerning energy management solutions, operation monitoring, power stabilizing and load schedules are the major optimization tasks. Fig. 6 illustrates a few major optimization tasks in the domain of HEMS.

Jacob et al. (2020) presented a "fuzzy TOPSIS decision-making" mechanism following a real-time pricing scheme to shift appliances efficiently. The proposed system, "fuzzy TOPSIS decision-making", gives an assessment of power consumption of multiple power users and directs for optimum energy distribution. HEMS is proposed in Bae et al. (2014), which is based on binary particle swarm optimization and the major concern is to curtail partially interruptible loads within a smart home. The proposed scheduling mechanism takes care of voltage profile as well as user power demands. Subbiah et al. (2013) defined "Energy Demand Models" to generate individual demand profiles of users, based on their power consumption patterns. The proposed model is associated with appliance usage and computes power consumption with respect to the duration of the operation.

Networks are utilized in the proposed load prediction model (Subbiah et al., 2013). Proposed heuristic-based "NSGA-II" scheduling solution leads to limit electricity bills as well as consumed energy for end-user and utility respectively.

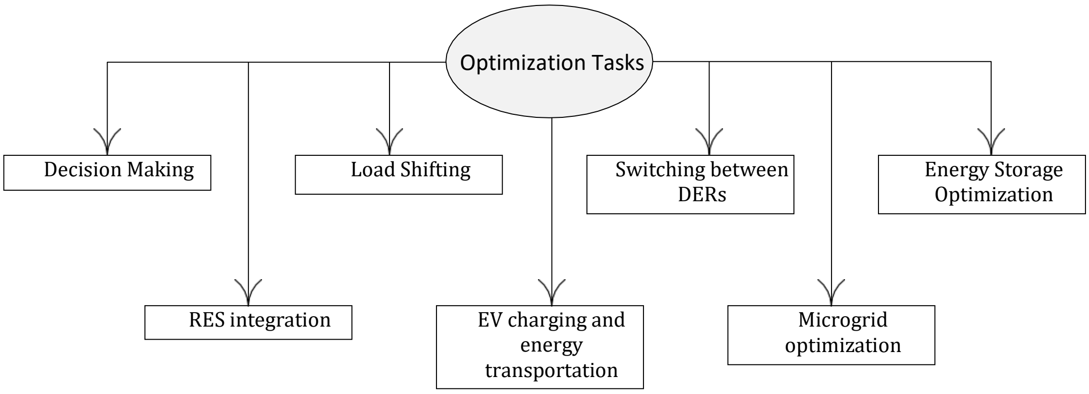

Fig. 6: Optimization domains in HEMS

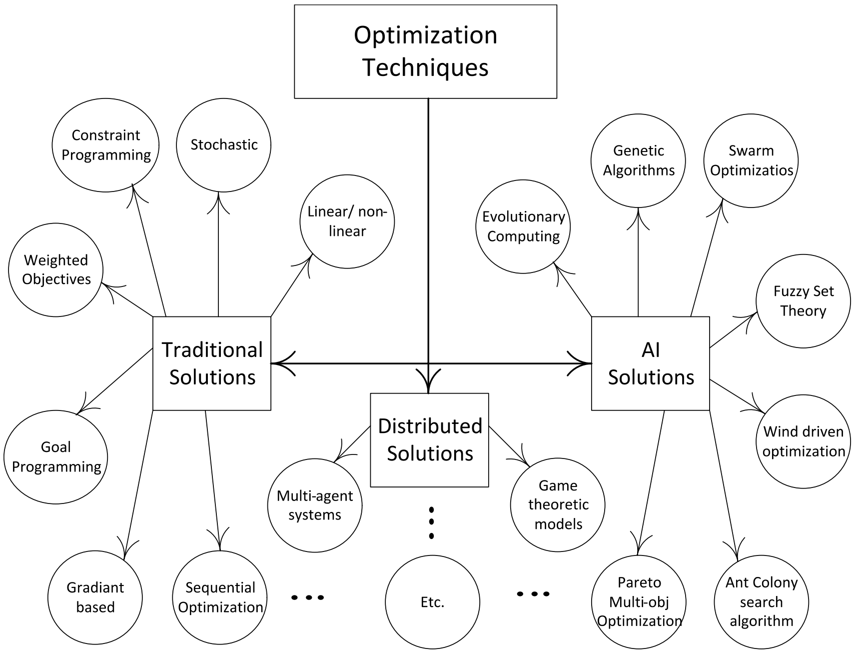

Fig. 7: Classification of optimization techniques

A real-time scheduling mechanism for smart appliances is discussed in Whiffen et al. (2016). The authors suggested a trade-off between expected bills and uncertainty in electricity costs using "conditional value-at-risk". To compute the output of the electricity storage device, a Fuzzy logic controller is used and two rules are formulated regarding charging and discharging of the storage device. Electricity tariff, environmental and water temperature, PV generation, and load demand are taken into account stochastically. THE proposed DR program is able to decrease the cost of electricity consumed. Authors also claim to minimize the gap between forecasted and actual electricity costs.

In Fletcher and Malalasekera (2016), a distributed framework is proposed that minimizes the electricity cost. To attain optimum load pattern, a greedy iterative algorithm is applied on smart home appliances. Moreover, to avoid force start problems in a real-time environment, a plenty term is used that charges predefined plenty on those users who make large changes in prescribed schedules. The proposed model results in lower bills, lower power consumption, and lower power fluctuations.

An automated DR framework is presented in Rasheed et al. (2016) that devises an optimum schedule for smart appliances using a genetic algorithm. The authors used a combination of RTP and IBR pricing mechanisms. The combination of these two pricing mechanisms automatically leads to lower PAR and power consumption. Bae et al. (2014) presented a user-friendly DSM naming it UDSM by exploiting ICT advancements. The foundation of UDSM is timely information regarding price variations. Based on this information, UDSM considered three features i.e., bills, load pattern, and algorithm regarding rebound peak load. Initially, the objective function is set to minimize electricity bills based on load patterns. Once an initial objective is achieved then another objective is formulated, creating a balance amongst power consumption across a time frame to avoid blackouts. UDSM shifts load to low price hours, thus give significant cost savings. However, user comfort considering appliance usage timings is not considered explicitly.

Essayeh et al. (2016) proposed a load shifting mechanism based upon heuristic optimization (genetic algorithm), facilitating flexibility in power demand by integrating renewable sources seamlessly. The authors used artificial neural networks to forecast load demand considering the next 24 hours. A comprehensive technical performance analysis is conducted in Khomami and Javidi (2013), considering energy management solutions.

Table 3 gives the recent state-of-the-art literature regarding optimization techniques in residential energy management solutions.

Table 3: Recent trends: Optimization in EMSs

Focus	Features and findings	Technique used	Objective	Cost reduction	Use of DER/ ESS
(Cetin et al., 2014) HEMS: balancing cost minimization and appliance delay in ToU	Optimum household appliance set formation, optimized scheduling horizon considering user comfort	BPSO	Minimize cost and appliance delay in ToU	yes	yes
(Agneessens et al., 2011) Minimizing Electricity bills for HEMS	Minimized electricity bills for end-users using the RTP mechanism	Partially observable Markov Decision Process	Minimize electricity bills	yes	No
(Kunwar et al., 2013) HEMS for distributed power generation environment	Equipment aging costs reduced however, net benefits also lowered	Heuristic Algorithms	Minimize aging cost relation between net benefits and equipment aging costs is formulated	yes	no
(Hansen et al., 2016) Effective PMC for HEMS	Provides an interface between load and PMC, however, user comfort is not discussed.	Binary backtracking search algorithm compared with BPSO	Minimize cost	yes	yes
(Olsen et al., 2016) HEMS tackling uncertainties	Dealing with uncertainties in the optimum load shifting mechanism	Improved PSO and two-point estimate method	Reduce computational cost and increase the accuracy level	yes	no
(Ahmed et al., 2017) uncertainties in HEMS	Effective classification of household load to solve load shifting problem keeping uncertainties in view. An inverse relation between cost minimization and delay in ToU is discussed	Interval number optimization (integration of PSO and integer linear programming)	Flexibility in demand	yes	no
(Huang et al., 2016) Forecasting load in smart homes	Forecasting load in smart homes and scheduling it in such a manner that reduces cost and preserve energy as well	GA	Forecasting load and minimizing cost	yes	no
(Ahmed et al., 2017) Pricing models for DR Programs	An effective profit-enhancing pricing mechanism based upon user behavior learning.	Genetic algorithm-based distributed pricing optimization algorithm for DR management	Maximize profits of utilities	yes	no
(Behera et al., 2016) Optimum load shifting in smart homes	An online energy management algorithm based on event triggering is proposed for optimal load shifting mechanisms	Lyapunov optimization	Minimize cost and required computational power	yes	no
(Meng and Zeng, 2015) Optimum load shifting in HEMS	Energy management solution depicting user preferences under ToU pricing scheme considering user comfort	multiple knapsack problem formulation	Minimize cost and energy consumption	yes	not discussed explicitly
(Fan et al., 2016) HEMS using nonpredictable Resources	Balanced use of energy in multiple intermittent power sources	Markov Decision Process	Cost minimization	yes	yes

6. Optimization techniques for future networked grid

The future networked power grid is highly distributed in nature that comprises multiple small and large scale power generation sources, including renewable as well as non-renewable. Moreover, integration of microgrids (at personal or community level) with future power systems is also a complex task. A centralized power management system is easier to design, however, it lacks robustness and fault tolerance. Hence, there is a need for local decision making based on required attributes. Moreover, every entity that is given the power of decision-making must have communication capability to communicate with other players or agents of the system. Game-theoretic framework and Multiagent Systems suit well for such distributed environment that offers plug-and-play of resources. Mahmood et al. (2016b) proposed two frameworks regarding smart power consumption i.e., centralized and distributed. For centralized design, authors used the simplex or interior point method to reduce PAR of a power consumption unit with multiple users. While anticipating decentralized design, authors proposed a non-cooperative game to devise optimal power consumption schedules. In this work, distributed power generation sources are not considered.

A novel predictive control framework for real-time data is presented in Singhal et al. (2020), however, the proposed model neglects forecasting errors. Extending the work in Singhal et al. (2020), using a non-cooperative nash game, active players reduce electricity costs by reshaping the respective load profiles (Zhang et al., 2011). Non-active users are also benefited by the proposed scheme due to reduced peak load. Nguyen et al. (2012) proposed a framework based on a game-theoretic model concerning utility companies as well as consumers. Interaction amongst DR aggregator and power generation source is devised using Stackelberg game.

This game has a leader and "n" non-cooperative players. Two basic objectives based on the user's perspective i.e., lowering cost and raising comfort, are formulated in Stephens et al. (2014). In this work, the authors used game theory for modeling load patterns and modified a "regret matching procedure", ensuring cost savings and user convenience. Multiple power sources are not included in this work. Nekouei et al. (2014) considered multiple residential units having different pricing mechanisms. Appliance scheduling for lowering cost is done independently by each user. Moreover, the authors formulated a binary linear programming problem by using a day-ahead pricing mechanism and used game theory to optimize demand response. The proposed model is extendible and energy storage systems and microgrids can be added to it.

A novel pricing model is presented in Yaagoubi and Mouftah (2014) by using a two-step centralized game. This game interacts between utility and community (electricity users). Multiple users are selected in a round-robin fashion. A major objective of this game is to lower the PAR by optimizing users' energy consumption patterns. This ensured overall power consumption reduction within the system. The proposed system is scalable and extendable as with the passage of time, the community may expand.

Saghezchi et al. (2014) presented an energy management solution as non-cooperative and Stackelberg games. Initially, the authors formulated a noncooperative game for smart homes. Afterward, a Stackelberg game is mapped for supply and demand sides. The authors also used net metering facilities for the end-users and excessive energy can be stored or sold back to the utility. Energy cost is reduced and PAR is lowered. A novel non-cooperative game is modeled for load demand management in Fadlullah et al. (2013). Nash equilibrium is achieved by using 0-1 mixed linear programming. While in Soliman and Leon-Garcia (2014), Stackelberg's game with one leader and "n" players is used to develop the power consumption schedule of all electrical appliances within a power consumption unit. An autonomous DR game is proposed in Belhaiza and Baroudi (2014), where each power consumer unit has an energy management controller that can schedule flexible load in low-priced hours to minimize electricity bills and reduce PAR. An energy scheduling game is proposed in Meng and Zeng (2014), where self-motivated players (electricity users) interact with each other to minimize their long-term energy bills. The authors claimed that the proposed model can reduce almost 50% of the baseline cost. Danish Mahmood et al. (2016c) gave a comprehensive overview of multiagent systems in a web-based networked grid environment in Baharlouei et al. (2013).

Besides energy optimization in houses/buildings, the future of power systems lies in DERs. DER comprises small or large-scale micro-grids, RESs, and ESSs that can be used in islanded mode or integrated with the main grid. Table 4 presents the state-of-the-art work, considering.

Optimization techniques used for integration of DERs in main grid infrastructure at personal or community level.

7. Objectives and constraints for HEMSs

Extensive literature review informed that amongst many, a few widely analyzed and worked on objectives regarding energy management solutions for residential units are electricity bill minimization, user frustration avoidance due to unwanted schedules, maximization of distributed generation sources, and maximization of small scale RESs.

Each objective function has certain constraints with respect to its scenario. The most prominent constraints are 1. regarding market models, 2. maintaining an equilibrium between supply and demand, 3. charging or discharging of storage devices at individual or community level, 4. dealing with the element of uncertainty in demand or supply, and most importantly, 5. classification of the household load (smart electrical appliances). Fig. 8 illustrates an outline of generic objectives and constraints in the domain.

8. Smart home energy management challenges

HEMS depicts managing energy for a single smart home, however, it is not that simple task. Numerous players and entities are involved. The advent of the smart grid opens vast opportunities and new horizons of research in utilizing power effectively and efficiently. Concerning HEMS, there is the main power grid that generates power, a utility company that provides power offering any DR program. Based on offered DR program, a smart home tends to reduce its electricity bills and ultimately PAR reduction is achieved for utility and the main grid. Besides the main central grid, the future lies in DERs or AERs.

Power generation using RESs is in the spotlight and clean and green energy is need of the era. However, naturally, power production from these sources is intermittent in nature and one solution is energy storage systems. Either for RESs or to store power from the main grid at low-priced hours, energy storage systems/devices have their vital impact on energy conversation.

In the following subsections, some research directions are pin-pointed.

Eliminate consumption peaks

- Effective power limiter with respect to desired load usage timings.
- Organize load in such a way that peaks are normalized.
- Maintain that; demand < generation.

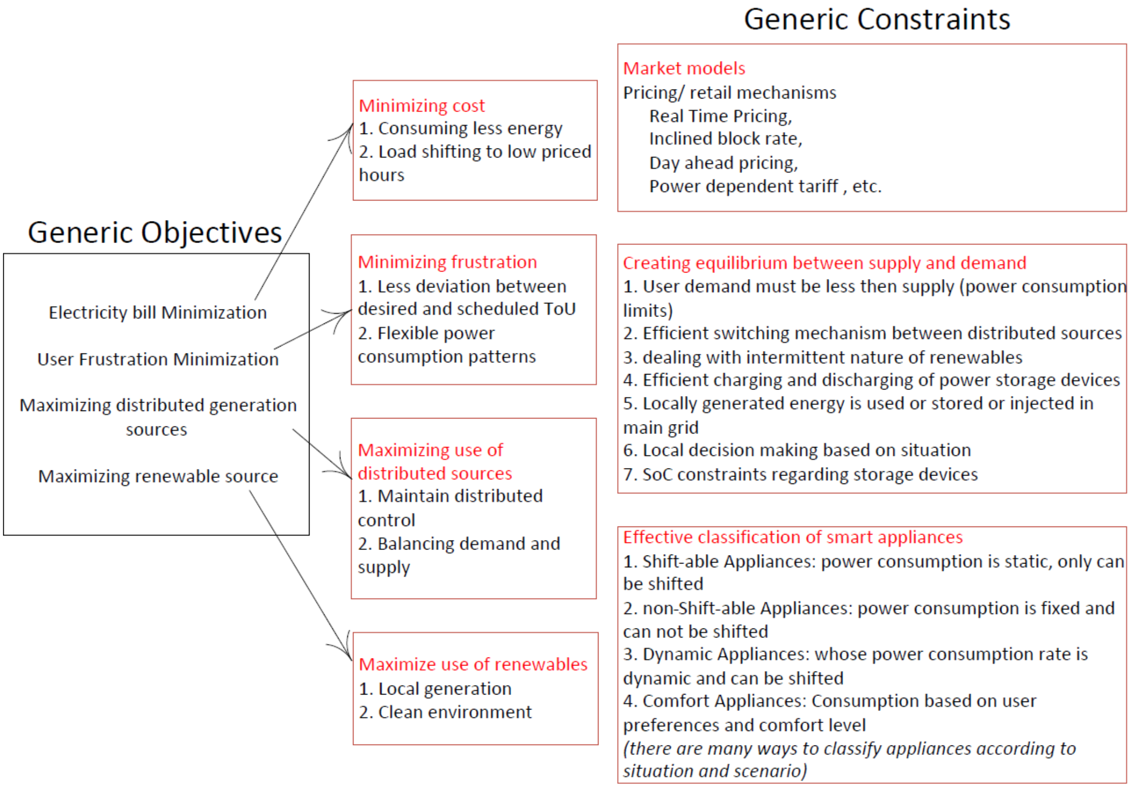

Fig. 8: Generic objectives and constraints in energy management optimization

Table 4: Recent trends: DER integration

Focus	Features and findings	Technique used	Objective	Cost reduction	Use of ESS
(Song et al., 2014) Smart communities- integrate RESs and Evs with the main grid	Solving Voltage Ampere Reactive optimization (VVO) problem anticipating scheduling of load using EVs as energy transportation and storage	Non-cooperative mixed strategy game	Minimize electricity cost	7% bill reduction	yes (Electrical and thermal)
(Mahmood et al., 2016a) HEMS – small scale microgrids	Responsive demand and supply are investigated regarding controllable and uncontrollable generation sources.	Mixed-integer linear programming model	Minimize cost	Reduced bills	yes
(Tushar and Assi, 2017) Microgrid with uncertain RESs and load demands.	Predicted forecasting errors regarding RESs and formulate a smart optimization model for combined RES and the main grid.	Taguchi's orthogonal array (OA) optimization	Minimize generation cost	Generation cost saved	yes
(Marzband et al., 2017) Residential Building EMS	Optimized schedules focusing on energy efficiency and self-sufficiency	Evolutionary algorithm for building operation optimization	minimizing energy consumption and costs	21% w.r.t baseline bills	yes
(Xiang et al., 2015) Residential Building EMS	Optimal energy consumption and control in Residential buildings integrating RES with the main grid.	Rule-based control strategies (Dynamic programming algorithm)	Minimize social welfare cost	yes	yes
(Mauser et al., 2016) Standalone Microgrid	The authors presented a standalone energy management solution of high altitude areas	Direct measurements and Computational Fluid Dynamics (CFD) simulation	Optimize energy flow from all energy carriers.	yes	yes
(Salpakari and Lund, 2016) quantifying the role of RES and ESS integration	Assessing the potential of multiple RES along with storage systems.	Multi-objective stochastic mixed-integer linear programming	Cost minimization	yes	yes
(Proietti et al., 2017) optimal switching from the main grid to variable RESs	The proposed control algorithm is able to maintain the throughput of power while using on-site RESs	Real-time energy flexibility manufacturing system control framework	Energy balancing	60% of total system cost	yes
(Santos et al., 2017) The futuristic approach regarding RES integration with the main grid	A novel economic market model reflecting demand response in RES is presented	Numerical methods	Minimized total cost	yes	yes
(Beier et al., 2017) Integrating maximum RES in the grid without grid upgradations.	The proposed framework is able to accommodate the addition of 45% of RESs without existing grid upgrades	GA and mixed-integer linear programming	Maximize utilization of on-site RES	Not discussed	yes

Increase user comfort and convenience

- Effective constraint formulation.
- Effective classification of load within the smart home.

- Resize the scheduling window for devising schedules.
- User preferences or comfort regarding load shifting.

Sharing power economy amongst multiple smart homes

- Sharing power without involving any market model amongst a smart community.
- No net-metering as reluctance is reported by utility companies on purchasing the bulk of electricity.
- Effective and localized decision-making regarding demand and supply for each smart home in the community.

Distributed power sources

- Economic dispatch.
- Seamless switching between power sources.
- Optimum monitoring and control of distributed sources.
- Uncertainty and fluctuations (intermittency in power distribution).

Energy storage systems

- Renewable generation is prone to fluctuations, dealing with this fluctuation by using storage systems.
- Optimal and seamless switching from one source to the storage device.
- Synergies amongst multiple storage systems.

Self-healing

- Ability of HEMS to prevent, detect and rectify by itself.
- Power re-routing for the dynamic topology of DERs.
- Real-time monitoring and plug and play approach.

***Integrating* power system with ICT**

- Effective response time within the power system.
- Prediction on the impact of system failures/excessive power demand.
- Power consumption in distributed environment such that it yields minimum electricity bills.

Consumer activeness

- Social and normal behaviors of users are hard to predict. There is a need to formulate a study that can give the insight to produce HEMS that tends to reduce the gap between expected and actual energy consumption.
- Highly heterogeneity in user behaviors and reactions. The impact of one HEMS is entirely different as users vary.

Legislation and market models

- Reluctance is reported in net metering. If the bulk of excess energy is sold back to the utility, it is against their business model.
- Effective legislation or market models are needed to incorporate localized/individually generated power and the main grid.
- Concerning islanded mode for a smart home or a bunch of smart homes, economic stability, security, and seamless supply is one major question.

Advancements in power technology

- Integrating advancements in existing infrastructure for more flexibility and capacity.

Distributed Vs central control

- Future networked grids (multiple power plants are joint together, forming a unified power source) still have the following questions to be answered
- What will be the major performance metric of stability in a networked grid environment?
- How to stabilize a self-organized system?
- To what extent which part of the system needs to be self-organized?
- Even in distributed control, is there a need for a centralized control framework?

The multi-agent paradigm is able to answer a couple of above-mentioned questions however, a lot of research is needed to finalize the networked grid standards.

9. Conclusion

Applying HEMSs in the residential sector on a large scale proves its worth for entire grid stability along with using power intelligently and resourcefully. For end-users, this results in low electricity bills and more automation in the general life cycle. Advancements in wireless networks, smart appliances, and computational intelligence algorithms have laid a solid foundation for materializing the concept of HEMS. Considering the near future, EMSs seem to be governing entire energy management in residential as well as industrial regions. In this work, an introduction and brief description are provided regarding energy management solutions specifically HEMSs, their basic architectural designs, and components. Moreover, the role of sensor networks and optimization techniques is also discussed along with recent state-of-the-art work focusing on residential energy management. Though the smart grid is in the spotlight of researchers and engineering industries since the last decade, however, yet there are numerous issues to be tackled for the future power systems. In the last part of this article, major research directions are pointed out for future endeavors.

Electricity user involvement with power systems is an irreplaceable phenomenon. Major goals of the future power systems cannot be achieved without user activeness in energy management solutions.

List of symbols

ICT	*Information and communication technology*
CI	*Computational Intelligence*
EMS	*Energy Management*
DSM	*Systems Demand Side*

PAR	*Management Peak to Average Ratio*
HEMS	*Home Energy Management System*
EV	*Electric Vehicles*
DR	*Demand Response*
ToU	*Time of Use*
DER	*Distributed Energy Resources*
AMI	*Advanced Metering Infrastructure*
PMC	*Power Management Controller*
ESS	*Energy Storage System*
PL	*Power Line*
CH	*Communication Home*
ANA	*Area Network Alternate*
ER	*Energy Resources*
PV	*Photovoltaic*
RES	*Renewable Energy Source*

Compliance with ethical standards

Conflict of interest

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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