Cloud-based Home Energy Management (HEM) and Modeling of Consumer Decisions

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Abstract

With the increasing number of smart home devices and the widespread availability of broadband communications, intelligent products built on the computational power and scalability of cloud, have the potential to reach beyond traditional markets. Cloud-based Home Energy Management (HEM) paradigm can provide intuitive and automated services that can not only save money and energy but also improve the quality of lives of consumers. This paper provides a detailed summary of the literature review of HEM and proposes (1) a conceptual smart home model with a special integration of solar powered devices with the cloud, (2) a limited consumer survey, and (3) a Multi-Attribute Modeling (MAM) with an example application for consumer adoption of Home Energy Management System (HEMS) and allied devices. The results of literature research and an online survey point out that the surveyed consumers acknowledge the importance of energy efficiency in their daily lives and lean towards adopting cloud-based smart home devices for their needs. The bottom line for adopting HEMS is the availability of secure, robust and cost-effective solutions coupled with considerable money-saving potential.[2]

Keywords: Home Energy Management, Cloud-based Smart home, Residential Solar, Cost Savings, Energy Efficiency, Smart devices, Home automation

1. Introduction

Smart devices have functionalities that can help with the management and conservation of household energy, thereby, enabling residential consumers to take control of their energy use and bills. Primary factors spurring end-user interest in Home Energy Management (HEM) can be attributed to cost, technical specifications of the device (size, features, and automation), technology, ease of installation and troubleshooting along with long term energy and cost savings potential. These seemingly fuzzy features of HEM products have made home automation, a niche market. However, literature shows that consumers are increasingly attracted to the notion of managing home devices via a fast and efficient mechanism that can save both time and money. There is an influx of devices and technologies in the market that consolidate home energy information and facilitate device control with the touch of a button. Just in the last decade, a variety of smart devices with different levels of configurations, ranging from simple energy meters and renewable energy devices to sophisticated and highly customized multi-storey building energy management systems have hit the market. Yet, (i) Do we, as consumers, have enough knowledge to assess the utility of these devices? (ii) Does an HEMS have the ability to catalyze energy conservation in a home? An approach to HEM that answers both these questions would be to adopt, use and connect smart devices of a home via the

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[1] This study was conducted by graduate student, Poornima Padmanabhan under the guidance of faculty advisor, Gary. R. Waissi
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internet to a single collaborative service in the cloud platform (sharing resources and storage instead of local storage). The objective of this paper is to (1) highlight the concept of HEMS, (2) present a model for integration of smart home devices - solar panels and electric vehicles to a centralized cloud and (3) propose a simple multi-attribute model (MAM) for evaluating the "utility" of choices for adoption of HEMS driven by key consumer preferences.

2. Home Energy Management System (HEMS)

HEMS can be defined as a system comprising of intelligent devices with hardware and software layers that can monitor, control and provide feedback on a home's energy usage [1]. It encompasses components and principles of residential demand response programs (DR), home automation services, personal energy management, data analytics, energy auditing, visualization of energy usage and related security services [2]. HEMS fundamentally requires a Home Area Network (HAN) - "a network that facilitates interoperability among digital devices within a home by acting as a communication network connecting all the components of HEMS" [1]. This network equips consumers with accurate energy data and prompts them to modify their power usage in their smart home. A "smart home" functions as a switchboard for digital information exchange among appliances for enhancing the quality of life of residents through enhanced comfort, convenience and connectivity [3]. It is an energy management system bolstered by the technologies of the smart grid and the power of consumer electronics [4.].
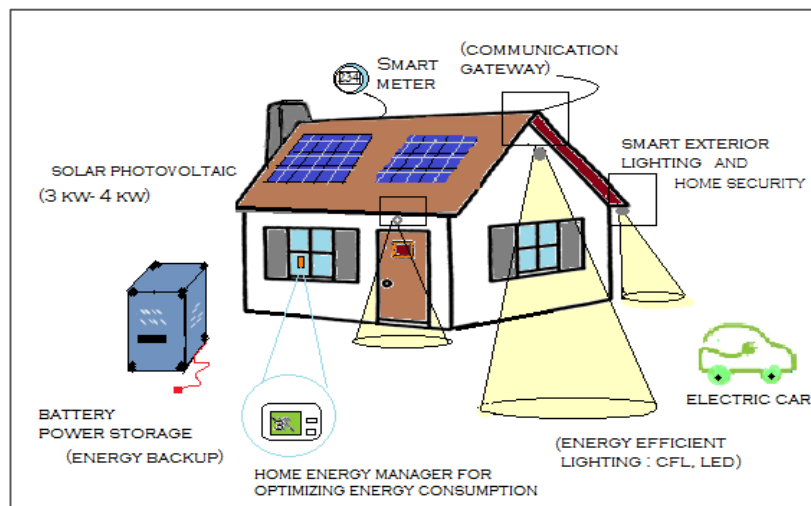

Figure 1. A Smart Home

In a smart home (Figure 1) all components such as appliances, solar panels, electric vehicle *etc*. can be managed to operate in an efficient power-use environment. By intelligently controlling them in a responsive and coordinated manner, these devices can provide leverage for greater energy and cost savings [5]. This capability can benefit all the stakeholders – customers, utilities, and third party energy/technology firms. For instance, a home-owner may not care about peak demand issues faced by a utility company but will be concerned only about his/her electricity bills and supply reliability. Whereas, a utility may be primarily concerned only with meeting the requirements of public utility commission. This disconnect in objectives could disrupt power sector businesses and consumer satisfaction levels. A smart home connects the players and creates an intelligent technology-based platform to meet common goals of energy conservation [4].

2.1. HEM Adoption Levels and Consumer Outlook

The U.S Energy Information Administration (EIA) has estimated that households accounted for approximately 21.4% of total energy consumption in the United States in 2011 [6]. With newer and bigger homes, on an average, a home-owner spends an estimated $2,020 on HVAC, appliances, lighting *etc.* annually [7]. This entails an opportunity for households to make changes that can lead to savings on their energy bills (up to 30%) [7]. A common method for making simple home energy upgrades is though energy audits. With the growing number of initiatives on the Smart Grid front in the U.S, an array of opportunities for smart home adoption can be spawned. End-users can assume an active role empowered with real time information and make favorable energy decisions for their homes and properties [8]. But there are challenges that need to be addressed before smart homes can become deployable to the masses, e.g. service adaptation to different households, dynamic home components, lifestyle, family size, interaction of devices, awareness of benefits and security issues, to name a few [9]. Literature also shows that, in the last couple of years about 21% of Americans have remained unsure if they would consider purchasing HEM products. This is indicative of the existing ambiguity in this new market segment and the need for better marketing of smart home technologies [4]. Ongoing research and marketing efforts are essential to transform consumer motivations as better choices for optimization [10].

2.2. Utility Modeling

The technology adoption model [11] shows that it can take about 10 years before new technologies are accepted and used in everyday life. Adoption of a new technology is governed by certain socio-economic factors determined in five stages viz. familiarity with the technology, positive attitudes, peer discussions/ advertisements, hands on experience and reinforcement of the decision. Early adopters are exposed to a combination of factors in phases before the actual use of the product (Figure 2). It is rather a combination of variables in socio-economic and psychological paradigms. Perceived usefulness of the product can kindle behavioral intentions to adopt the product [11]. Research also shows that consumer attitude is a more accurate predictor of behavioral intent than other subjective norms and is capable of directly impacting the adoption levels of any technology [13]. It is natural for consumers to be motivated to purchase the most "satisfying" products that can provide comfort or potentially improve their overall living standards. The theoretical model of obtaining the highest levels of utility from a product/service is called Utility Maximization. This is largely dependent on the total income of a household. Considering the various aspects involved in making a purchase decision of a new smart device, a multi-attribute model (MAM) is presented to demonstrate its applicability for HEMS in a later section.
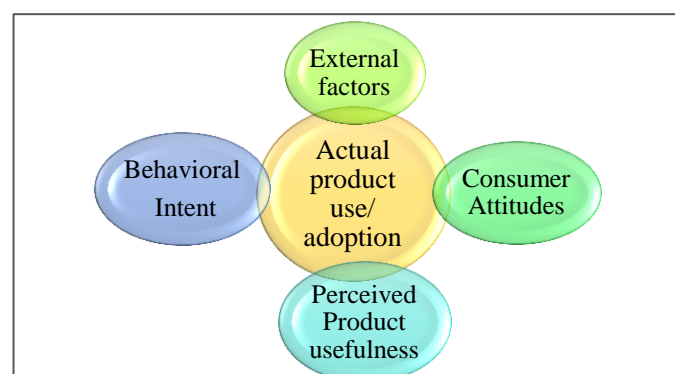

Figure 2. Technology Acceptance Model

Adapted from source: [13]

2.3. Demand Response Programs

DR programs are an important dimension of HEM. The primary goal of DR programs is to reduce peak loads at consumer-end and accelerate energy efficiency. Changes in the levels of energy consumption can be attained with the use of smart devices. Smart devices are electronic in nature generally connected to other devices or networks. Most devices are in the form of deferrable, interruptible, non-deferrable and non-interruptible, operational, PV based, battery-assisted appliances [14]. Furthermore, consumers can benefit from DR programs by allowing system operators to control some of the appliances (Heat Ventilating Air Conditioners load control) during peak hours. In addition to aiding conservation, DR programs can support supply-demand analytics, infrastructure and technological upgrades.

2.4. HEM Technology Frameworks

The IBM vision of a "smarter" home states that there are three characteristics that distinguish the new generation of "smarter" homes from today's smart homes: *Instrumented, Inter-connected and Intelligent* devices [15]. Also, the report states that all isolated devices in a home can be connected to the cloud over the home gateway for intelligence data aggregation. Home gateway is an integrated infrastructure comprising of network access control, middleware and home network technologies. It performs bridging/routing and address translation between HAN and the external network. It permits applications such as Voice/Video over IP and remote access to devices over the internet [16]. Much of the research is underway with special focus on developing interoperability between platforms for cloud integration.

Following the overview of HEMS and its background theory, the internal components of an HEMS unit are discussed in this section. The building blocks of this promising technology can be broadly divided into digital interfaces, hardware, and software. The combination and unique assembly of these peripherals constitute various frameworks and product portfolio. An HEMS unit consists of appliance control units with wired/wireless communication interface (e.g. Internet, ZigBee). Communication protocols can establish connectivity between devices and the utility company for a seamless information exchange over the internet or alternatively via wireless LAN (Local Area Network), Bluetooth/Wi-Fi or cellular network.

According to a Pacific Gas and Electric Company report [1], there are two kinds of capabilities in an HEMS unit - *Information and Control*. Figure 3 shows the different components and sub-components of an HEMS, classified based on their computational capabilities. An information-based system is aimed at offering feedback mechanisms that capture and notify any anomalies in the home envelope.
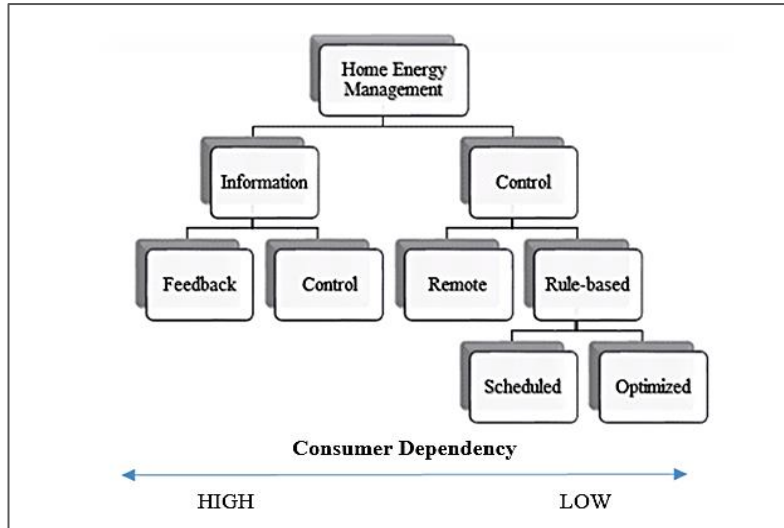
Figure 3. HEM Functionality

Adapted from source: PG&E report [1]

The other category is control-based HEM which determines subsequent actions and controls in a device in response to notifications. All controls are carried out with the application of "rules" inside the system and do not generally rely on the residents' input. A number of optimization and scheduling algorithms form the "rules" that govern the HEMS. For instance, directing energy use, controlling the running time of devices and on/off status during peak hours *etc*. Scheduling algorithms are deployed to dispatch signals appropriately inside the system software. An HEMS acts as a demand-response tool with capabilities of shifting the demand inside a home [17]. Some examples of information-based HEM are load monitors, in-home display dashboard, data analytics platform and website. Examples of control-based HEM are smart lighting, smart thermostats *etc*. [1].

External communication between end-user and the utility company can take place wireless over the Advanced Metering Infrastructure (AMI). This can facilitate the "selection and implementation of strategies according to the energy use" [1]. On the Demand-Side Management front, utilities can upgrade services by taking corrective actions without delays and remain well-equipped for contingency planning. In the absence of smart meters, receiving real-time information (via Wide-Area Measurement) from end-user can be time-consuming and infeasible sometimes. To handle security issues, AMI systems that are resilient to attacks are paramount to this infrastructure. This can be achieved with the deployment of management schemes and substation automation coupled with the use of customer-side appliances [18]. Key elements of HEM as identified by Energy Innovation Project at the *MIT Industrial Performance Center* are summarized in Table 1.

Table 1. Benefits of Consumer Controlled and Utility Controlled Energy Management

Adapted from source: [19]

Feature	Utility End	Consumer End
Control	Load control, AMI	Consumer decision/ data control
Pricing schemes	Time-based/ dynamic/Time of Use rates/ demand charge/PPA/DR programs	Incentives/rebates for participating in DR programs and purchasing smart devices
Home Area Network/ Gateway	Provided by utility/third party vendors/telecomm. providers; via proprietary systems	Owned/purchased/rented by consumers with possible incentives from utility; Via internet/ cellular network *etc*.
Data	High data bandwidth. Two way communication line between utility and consumer	Hourly/daily/monthly feedback, low data bandwidth
Cost	More expensive; investments for logistics and system upgrades	Less expensive; financing options; flexibility through DR programs, long term savings offset investments
Benefits/Impact	DR, supply-demand analytics, energy efficiency, contingency planning, Demand shift.	Home scalability, resident comfort, Long term cost savings, Distributed generation, "go-green" approach.

2.5. Barriers in Cloud HEM Deployment

The *Association for Computing Machinery* article lists four significant challenges for HEMS adoption - cost of ownership, inflexible interoperability, poor manageability and security [20]. Some of the prevailing incompatibilities of smart devices may be due to lack of appropriate standards and protocols. This can cause fragmentation in the electronics market. Literature reinforces the need for standardization and a common working platform with collaboration of services, e.g. a centralized service platform or Internet of Technology (IoT), cloud service on-demand software delivery method [SaaS] or infrastructure as service (IaaS) [15]. In addition to the equipment costs and monthly service fees, system upgrade costs and maintenance costs remain unquantifiable at present. Lack of awareness about energy efficiency programs among consumers is also one of the main challenges. Moreover, design challenges in the form of product characteristics, aesthetics, optimization algorithms, UI and emergency public notification systems also continue to exist [21]. These considerations emphasize that the choice of enabling technology is essential for the successful implementation of HEMS [22]. A brief discussion of a couple of HEM prototypes found in the literature can be seen in the next section.

2.6. HEM Models and Adaptations

There are cloud-based implementations in the industry pertaining to a specific purpose or device. For example, streaming media (camera, audio, video), email *etc*. A unique concept of integrating solar powered devices with smart home devices along with the

capabilities of persisting data and exchanging information over cloud is proposed in the following section.

According to the *Universal Implementation Model for the Smart Home* [12], the Central Management Unit (CMU) handles device-control and responds to changing conditions inside a home. The User Interface [UI - viz. touch screens, multimedia interfaces, smart phones *etc.*] is a salient component required for user-interaction through commands and icons. Application programming interfaces (APIs) execute a particular functionality as part of scenario management and allow device-use with built-in functions and communication protocols [12]. Each function operates independently as recognized by the CMU. In order for this model to be generic, a user's access to each one of the supported functions has to comply with at least one of these UI standards - lists, icons, scrolling selection list, 3D widget *etc.* The Database (DB) module is the main storage place for home energy data. Whenever a new device is added to the smart home environment, new records can be created in the DB with related privileges, operations and controls. Intelligence of a smart home can be attributed to the Artificial Intelligence (AI) engine that reacts to dynamic conditions of a home. Another framework called ZUMA (Zero- configuration, Universality, Multi-user optimality, and Adaptability) proposed in the *International Conference on Intelligent Environments* article claims to allow consistent inter-operability between various devices in a user friendly, scalable and extendible fashion [23]. It would be interesting to explore the applicability of these models to upcoming solar powered devices and new technologies.

Literature suggests that any cloud framework with different flavors such as public, private and hybrid must conform to the key specifications to collectively tackle one or more challenges of powerful computing. The challenges are relating to data analysis, processing and event-logging abilities with methods such as context-aware functions, data mining and semantic reasoning [24]. Model matching algorithms incorporated in the system can permit interoperability for new device additions, thereby aiding scalability. The resource management module should be able "talk" with the cloud to provide better experience for the users [25]. Software APIs can be programmed to offer instant notifications to any unusual or life threatening scenarios. This is one of the reasons why they are increasingly becoming a part of geriatric assistive and wellness devices. Response actions such as surveillance or monitoring of the house via a centralized system provide access to shared resources among various stakeholders [21]. Furthermore, the intent of adding more devices to the basic amenities of a smart home can be supported by cloud. Therefore, it is important not to overlook the roles and usefulness of a wide variety of developing devices and actively include solar panels, battery storage, electric vehicle charging stations *etc.* in the context of HEMS discussions and experimentations [26].

3. Model Extension: Cloud-based HEM Implementation

With the goal of designing a smart home that is capable of supporting Solar integration, the model described in the *Universal Implementation Model* [12] has been chosen as the base on which certain adaptations applicable to a future smart home have been conceptualized. The principal assumption for this model improvisation is that all residents implementing a PV system ought to have internet access. The utility can offer cloud service that exposes an interface in the cloud to which residents can send device data, PV device updates, personal information *etc.* Figure 4 shows a "smarter" home with the addition of Electric Vehicle, PV panels, Solar battery/storage, energy-efficient LED lighting system *etc.* (not limited to this list) to today's smart homes. In the future, with the implementation of appropriate technologies, an effective net-zero energy living space can be achieved. With the synchronization of devices, electricity consumption data will be saved to the cloud. This data can be accessed and downloaded at any point in time by residents who are either at home or outside via a mobile app or website. This way the

local storage of a device doesn't get over-used. The computational power of the cloud will enable data aggregation and time-to-time synchronization. The utility company can install smart meters in residences and the same can be maintained by the company to support data aggregation. This can provide insights about consumer energy patterns and prediction of demand during peak hours. Improvements and optimizations can be performed with this emerging technology. The experience of using this technology will be similar to email/social media account/smart phone media. The simple power of cloud computing, service-oriented architecture (SOA) and standards have the potential to provide a platform for building the next generation of smarter HEMS.
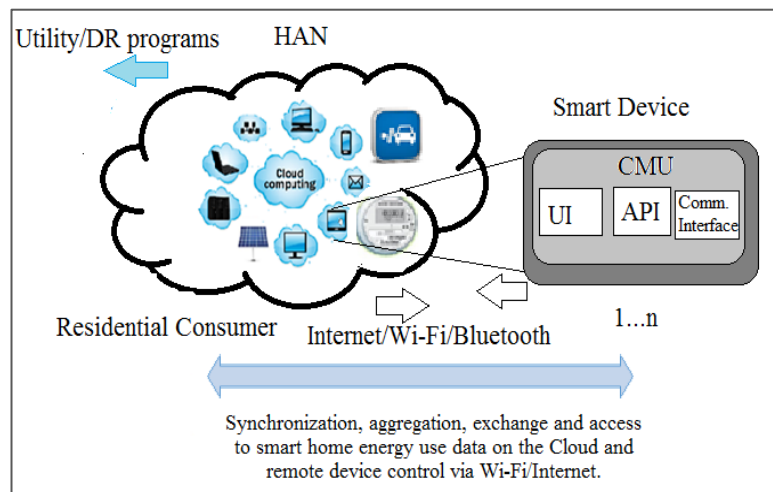

Figure 4. Future Smart Home Envelope

The journal of *Open Cloud Networking* by Dell, points out a number of barriers in the deployment of cloud technology. Cloud computing has not yet been realized to its fullest potential due to obstacles such as behavioral barriers, industry fragmentation, ownership issues, capital constraints, rebound effects, lack of energy efficient programs, lack of awareness and information on Greenhouse Gas (GHG) emissions *etc*. According to the report published by *Northeast Energy Efficiency Partnerships*, HEMS barriers can mostly be attributed to "Early Adopter Challenges" [1]. Complexity, security and elasticity of data storage, quality of service, vendor viability, data and application management, change control, transparency, portability, and disaster recovery, legacy and organizational risks require new integration methods for effective cloud deployment [27]. Encryption of data and high levels of masking are required to protect the identity of residents [28].

4. Benefits of Cloud Enhanced HEMS Integration

Table 2. Benefits of Cloud-based HEMS to Stakeholders

Adapted and modified from [1]

Category	Residents	Utility	Third-party Vendors
Energy Savings	Automated systems for effective device control and energy conservation.	Advanced technologies for data analytics, clear insights on demand & supply	HEMS can be used as Measurement & Verification tool

Safety & Convenience	Increased visibility, control, connectivity and instant access to devices and operations, remote access, enhanced safety and care for residents	Real time demand response data (data access can be either allowed or restricted based on resident preferences)	Home monitoring can facilitate surveillance with necessary support for installation and troubleshooting
Renewable Energy	Residential solar generation can help residents for energy storage/backup. Consumer + producer -> 'prosumer'.	Power generation can supplement additional resources for the grid & offer efficient resource management	Platform for savings with collaborative partnerships, innovations and market research
Cost Savings	Energy optimization resulting in money savings for customers	Excess power can be fed back into the grid to address deficit/shortage; independent of repairs or power crisis. Operational and transport cost savings	Revenue streams in terms of monthly fee for service management, PPA, internet subscriptions, rentals and real time monitoring and customer service
Cloud-based HEMS	Advanced ability to sense and monitor dynamic aspects of home. Scalability with reduced complexity of software, addition of newest devices, simplified troubleshooting	Utility can optimize peak usage, customer engagement and satisfaction by integrating business workflows and processes, charge power rates according	Potential revenue stream for maintenance/services *etc*.

Some important benefits that integrated HEMS can provide to homeowners, utility and third party vendors are discussed in Table 2. The table shows advantages such as cost and energy savings, scalability for residents, revenue increase, data modeling *etc*. The table also provides an account of both energy and non-energy benefits (enhanced safety, health, security, environment, efficiency, process control, waste minimization, Peak Load Reduction *etc*.). A noteworthy result of an HEMS project, as discussed in the NEEP report [1], shows that 8-22% Energy (Electricity & Gas) savings have been achieved at the United Illuminating UE3 Pricing, USA in the year 2011.

Consumers do not need to have the expertise to install or work with the aspects of this technology in order to reap the benefits. There is very little consumer-side effort in using cloud technology. Cloud makes smart home adoption convenient and hassle-free. Complexity of managing multiple home device software is broken down to offer enhanced device usability [25]. In the form of "software as a service" (SaaS) or "infrastructure as a service" (IaaS), the service management module improves device life cycle and reduces cost for service management. Residents can enjoy a one-stop service for information access and distribution of resources according to their home needs [29]. User-centric applications such as storage for personal audio, pictures and video, multi-player online gaming, feature interaction between devices, automated monitoring, security, health and wellness, surveillance *etc*. are possible with cloud [30].

5. Challenges and Implications of Cloud-based Smart Home

Despite the numerous benefits that cloud-based HEMS can offer, there is no denying that purchase of devices can be capital-intensive. But, there have been claims and customer testimonials that long term savings can eventually offset initial investments. On the other hand, privacy is another issue that can concern a lot of residents who are thinking of adopting a cloud based smart home. Considering that cloud is operated by

several data-centers, any minor component failure can result in connectivity issues or improper back up or loss of data. There is no universal fault-tolerant system (yet) that is not prone to failure. A temporary disconnection of internet can be surely problematic. Therefore, to accommodate a resilient system, a backup network subscription may be required. But this could lead to increased network line, costs and additional network traffic for the home-owner. Finally, selecting a cloud vendor can be tedious to home-owner who does not have prior knowledge or experience about products and services offered by third party vendors.

6. Smart Device and Solar Technology Trends – Opportunity Assessment

A systematic review of smart homes can create avenues for future research in the *Ubiquitous Home* domain [31]. Devices that can self-learn in a resident's spatial and behavioral context can provide a multitude of benefits. Wearable, in-plant technology, assistive sensors (in walls, floors *etc*.) and interactive robotics have the potential to revolutionize today's smart homes. Wearable sensor garments can measure body temperature using psycho-galvanic sensors to capture patient's heartbeat, Electro Cardio Gram (ECG) and other vital functions. The analog signals can be collected through a grid of conductive fiber sensors knitted into the fabric [32]. The device can be programmed to notify family or physician in case of an emergency.

Furthermore, a solar standalone system with load profile for a Plug-in Hybrid electric vehicle can be one of the vital additions to today's homes. Electric vehicles with advanced cascaded power converters are supported by renewable energy integration. They are particularly aimed at reducing stress on the power grid. Allied product development is still in its nascent stage and is open for much research, development and validation. It is necessary to combine technical advancements with the right marketing tools to appeal to the present-day tech-savvy consumers. Virtualization of wireless sensor network (VSN) containing heterogeneous and sophisticated nodes such as temperature, humidity, sound, and video can be an opportunity for capturing customer base, (e.g. millennials) in a cost-effective way. In this regard, virtualization in sensor network can be a propitious future research topic for large-scale commercial sensor network and smart homes. Smart Home in the future will be an intelligent ecosystem - interactive and adaptive to residents' lifestyle patterns e.g. vision-based sensors via a centralized computer system [33]. According to a report by Continental Automated Buildings Association 2013, efforts have been maximized towards innovative services to improve the scalability of cloud to support more energy efficient devices. Studies show that 13% of all U.S households are expected to have HEMS installed by 2020 and nearly 20% are expected to have surveillance or security systems within the next two years. This trend is promising as far as wide-spread adoption is concerned [34]. HEMS can also offer easy energy disaggregation. It is a set of statistical approaches for extracting appliance-level data from a building without any plug-level sensors. This will be a leap in the energy management arena [35]. Last but not least, on the solar energy generation front, California Energy Commission defines 'net metering' as an approach by which utilities can measure the net amount of electricity consumed by residents using solar (Photo-voltaic panels). In order for this arrangement between home-owners and utilities to work, smart meters must be in place. Net metering merits include credits to customer at full retail rates and accurate capturing of energy information. Utilities are engaging in solar power purchase agreements (PPA) to earn the benefits of clean electricity generation [36]. Literature suggests that current research is focused on assessing new materials and fabrication processes for improving the efficacy of organic and inorganic solar cells, feasibility of low cost rooftop applications and battery storage. New technologies of HEMS such as solar powered windows, 3-dimensional solar cell technology and solar powered car paint

are capturing the attention of entrepreneurs. One of the recent ground breaking technological innovations is PV spray-painting on surfaces and paintable batteries [37]. This disruptive technology can transform any painted surface to a rechargeable solar battery. It is encouraging to note that solar industry is migrating towards neighborhood-scale programs such as Aggregated Net Metering as well as Community Solar. With the use of smart meter technology, community net metering can allow aggregation of power load from multiple meters to a centralized solar panel system with a shared subscription mechanism.

7. Online Survey Results of Consumer Knowledge and Preferences

Consumers tend to gravitate towards smart devices for a number of reasons. To understand the perceptions, an online survey (Tool: Qualtrics Research Suite) was conducted among 80 people between the age group of 20-60 years. The results of the survey have helped us gain a leap of understanding of consumer preferences, savings-expectation and the adoption potential of solar and cloud based HEMS. Roughly 35% are moderately familiar with the HEMS concept. About 50% of the respondents spend money on new devices once in every 2 years. Importantly, none of them responded that they will never invest in smart home devices. There is a possibility that even respondents who do not have any familiarity with smart devices, could consider exploring HEMS options. A whopping majority of respondents, i.e. 91% agree that they would like to save money on their electricity bills and 80% are willing to invest in smart devices (Figure 5). This universal motivation among consumers can pave ways for innovative measures to save energy and money. With regard to cloud technology, 78% rated 'Security' as a crucial factor for cloud-based HEM and 66% rated 'Performance' (Figure 6). About 68% prefer DIY without any third party assistance and about 45% prefer a simple mobile app for device control and monitoring. The survey also created an opportunity to understand what will be a critical factor for smart home adoption. Clearly, a less expensive cloud-based smart home technology solution is the ultimate factor driving adoption. About 35% of respondents also prefer technologies that can yield savings of USD500 annually on electricity bills for a large household. About 19% support the energy conservation objective (Figure 7).
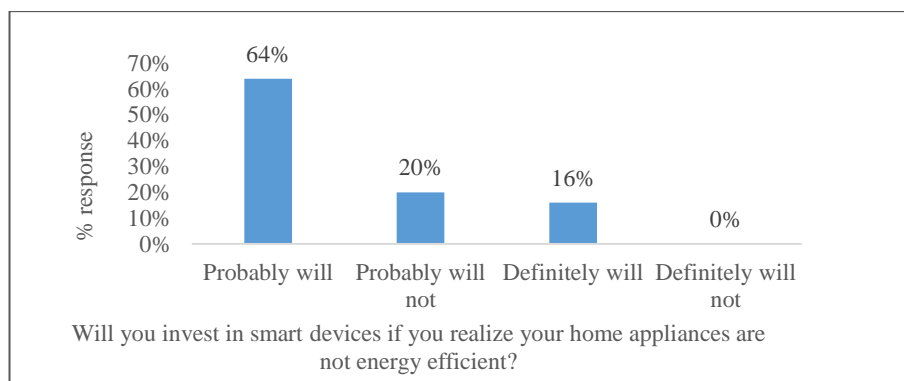

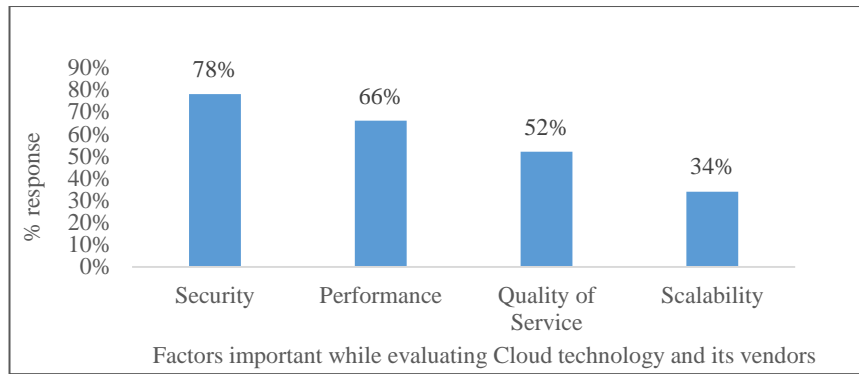**Figure 5. Likelihood of Investing in Smart Devices**

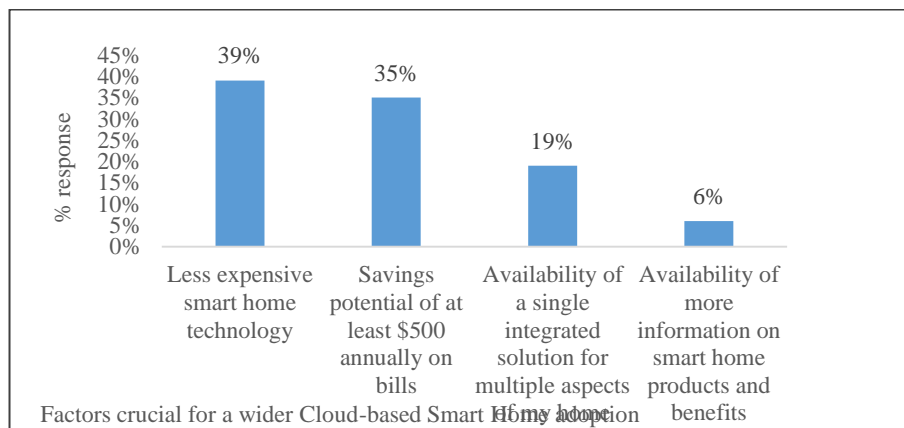**Figure 6. Key Characteristics of Cloud Technology**

Figure 7. Crucial Factor Governing the Adoption of Cloud-based HEM

Regarding the likelihood of HEM expansion, about 72% agreed that they will include more devices such as solar panels or electric vehicle in the future to their present home environment (Figure 8). Consumer perceptions towards devices revealed that 75% would like to own general appliances that are energy efficient, whereas 66% prefer smart LED lighting and 20% want to have senior/disability or wellness devices (Figure 9). More than half, i.e. 60% are interested in residential solar and about 25% are very likely to install solar panels in their homes in the next 5 years (Figure 10). On the contrary, about 16% responded that they are very unlikely to adopt solar panels for a number of reasons which may include: apartment living, lack of roof space, inflexibility in payment options, lack of awareness and non-cooperation from Home Owners Association *etc*. However, about 70% are willing to participate in Solar net metering schemes by which excess power can be fed back to the power grid. This shows that there is opportunity for launching community solar garden initiatives.
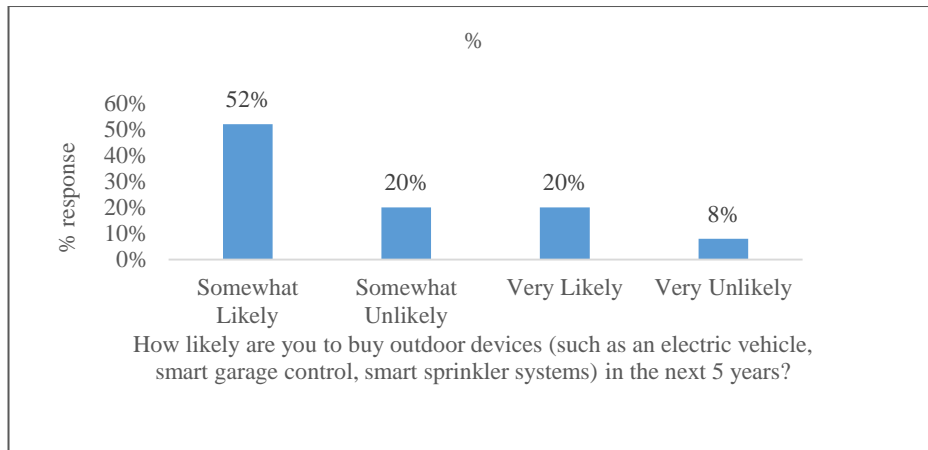
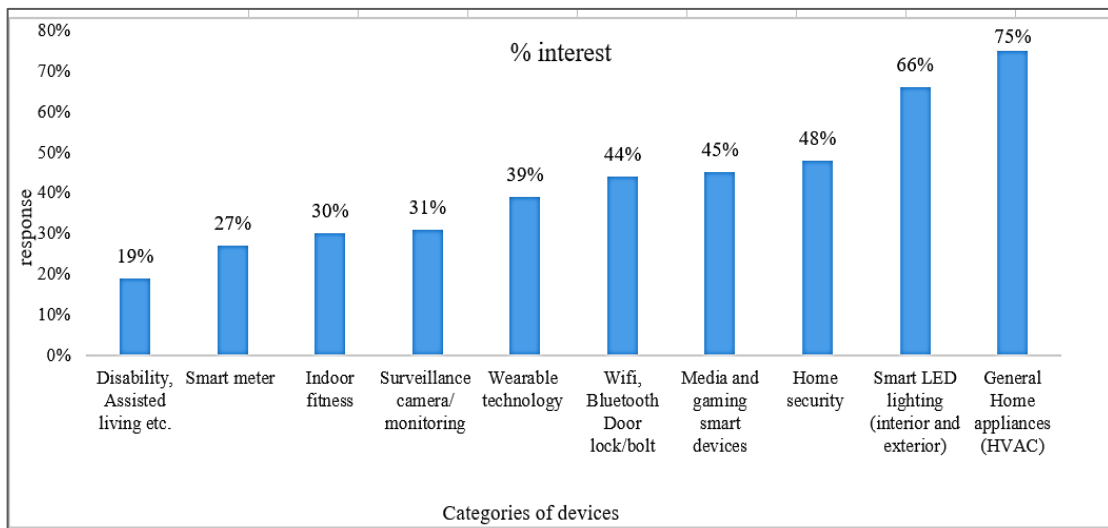**Figure 8. Likelihood for Adding More Devices to a Smart Home**

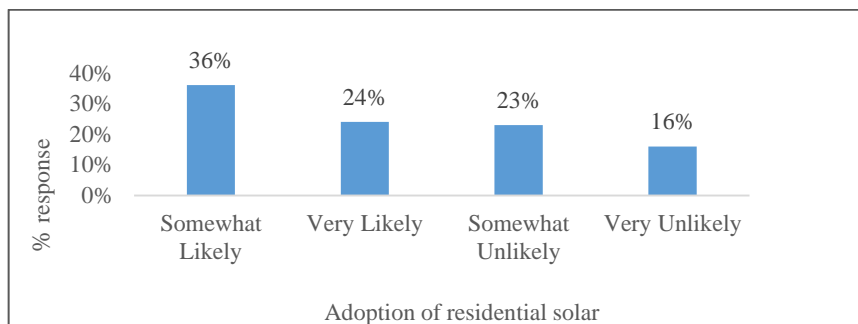**Figure 9. Various Categories of Smart Devices**

Figure 10. Adoption Likelihood for Residential Solar Panels

Overall, the survey results suggest that consumers show interest towards adopting energy efficient appliances and will purchase PV panels and electric vehicles within the next 5 years. This notion is further strengthened by the findings that more than 50% of the respondents have experienced savings on bills in the past with the use of one or more smart devices (Smart thermostat, energy efficient washer/dryer *etc*.). With an abundance of opportunities in this domain, utilities and consumer electronics companies can devise measures such as financial incentives or rebates to help consumers take complete

advantage of energy programs. Telecommunications companies should invest in solutions that ensure security in the Cloud services to prevent data loss/breach, traffic hijacking, insecure interfaces or APIs, threats/malicious attacks/hacking, denial of service, and other technology vulnerabilities as identified by the *Cloud Security Alliance*. Ubiquitous connectivity, limitless resources, user-friendly mobile apps and context awareness should be some of the main considerations while interfacing with cloud-based smart devices. The results denote that integrating devices inside and outside a home can be a welcome factor for tech-savvy residents with progressive home/energy needs.

8. An Example Application of Multi-Attribute Modeling for Consumer Adoption of HEMS

The overall problem is to choose an integrated HEMS, including devices and features that can maximize the consumer's utility within the multi-criteria decision environment. An HEM "package", in this example case, is defined as a professionally selected integrated set of energy saving appliances and devices, in different price and efficiency (energy use) ranges, different acquisition and maintenance cost categories, offered to home-owners for their particular situation or need. The modeling approach also allows consumers to create their own customized package.

An HEM package consists of, for example, major appliances (refrigerator, freezer, stove, washer and dryer, *etc*.), solar energy generating devices and systems (appliances, panels, surfaces), lighting systems (both interior and exterior), home heating and cooling (HVAC) systems, electrical tools, computers, laptops, entertainment systems, small appliances, vehicle charging station, *etc*. Any energy consuming devices and appliances that can be integrated into the home can be considered for an HEM package. The development and use of multi-attribute modeling (MAM) for home-energy management can be described using the following steps:

1. Develop a suitable set of attributes by decomposing the HEM problem into sub-problems. The sub-problems have to be meaningful, well-defined, measurable, non-overlapping, and orthogonal.
2. Develop a tree (or hierarchy) of attributes (aggregate and basic attributes).
3. Develop the utility functions (qualitative and/or quantitative).
4. Assign weights (based on preferences of individual consumers) to attributes.
5. Develop HEM packages.
6. Evaluate HEM packages via the attributes and the utility functions to determine the aggregate utility of a package.
7. Compare cumulative utilities, and choose the HEM package with highest utility.

A consumer selects a customized HEM package, or customizes his/her own package. Using the MAM model, the utility of each selected HEM package is evaluated by comparing aggregate (cumulative) utilities of alternative packages. Additionally, a consumer will have the ability to adjust the weights (importance) of attributes to test and evaluate personal preferences of different customized, or self-created option packages. The consumer can also conduct "what-if" analysis with different preferences and weights, different package contents to compare costs (acquisition and maintenance) and energy savings.

The multi-attribute utility function, assuming a linear additive form, can be presented as follows:

$$U[x_1, x_2 \dots x_n] = w_1 U[x_1] + w_2 U[x_2] + w_3 U[x_3] + \dots + w_n U[x_n] = \sum_{i=1}^{n} w(i) U[x(i)]$$

Where,

- $U[x_1, x_2, \dots, x_n]$ is the aggregate [cumulative] utility, the sum of weighted utilities of attributes

- $U[x_i]$ is the utility of attribute x_i for *n* attributes *i = 1 to n*
- w_i is the weight *i* applied to utility *U* of attribute x_i such that $\sum_{i=1}^{n} w(i) = 1$
- attributes x_i are independent for all *i = 1 to n*
- The utility function is linear and additive.
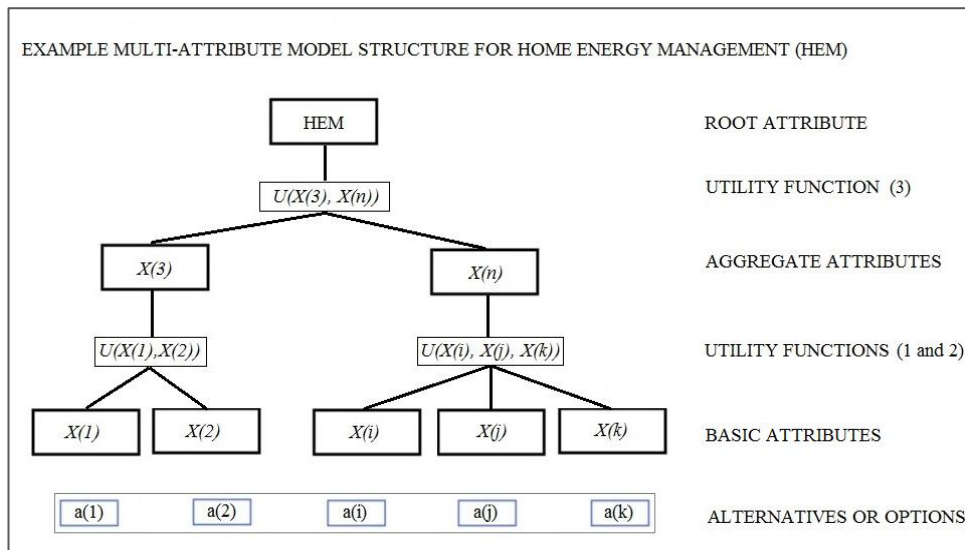

Figure 11. Multi-Attribute Model Structure for Home Energy Management (HEM)

Figure 11 shows a typical structure of the multi-attribute model for an HEM package selection. In figure 11, a (1), a (2), a (i), a (j), a (k) represent alternative packages, x(1), x(2), x(i), x(j), x(k) represent basic "leaf" attributes, U(x(1), x(2)) and U(x(i), x(j), x(k)) represents utility functions, x(3) and x(n) represent aggregate attributes, U(x(3),x(n)) represents a utility function, and HEM represents the root attribute aggregate utility of the evaluated package. To provide more specific context, we will next develop a simple, qualitative, multi-attribute model for the HEM package selection. Consider the following attributes for HEM:

1. Total cost of an HEM package
a. Purchase price
b. Installation cost
c. Annual maintenance cost
d. Annual operating cost

2. Basic (necessary) features and characteristics
a. Major appliances
b. Heating and cooling (HVAC)
c. Small appliances (including computers, TVs, entertainment systems, phones, small kitchen appliances)
d. Lighting systems (interior, exterior)

3. Options – electricity generating and -consuming devices and appliances
a. Energy generating devices and installations (solar-, wind-, geothermal-, …)
b. Energy storage systems (batteries, backup systems, …)
c. Electric vehicle charging
d. Electric power tools, equipment and devices
e. Pools, hot-tubs, and other exterior appliances and devices.

Each one of the attributes represents decision sub-problems. As can be seen from the above list, the three main categories (1. Total cost; 2. Basic features; 3. Options) represent aggregate attributes. Each of these aggregate attributes is further sub-divided into (basic or aggregate) attributes identified above.

The aggregate attribute "Total cost" is divided into four basic attributes: a) Purchase price (PRICE); b) Installation cost (INST); c)Annual maintenance cost (MAIN); and d) Annual operating cost [OPER]. In this example, and in order to simplify, each basic attribute PRICE, INST, MAIN, OPER can assume three values only, respectively: "high", "medium", "low". The values for the basic attributes are provided by experts, and included in the HEM package.

The aggregate attribute "Basic features" consists of four attributes: a) Major appliances (M APPL); b) HVAC; c) Small appliances (SM APPL); and d) Lighting (LIGHT) systems both interior and exterior. These attributes can be aggregate attributes or basic attributes depending on the desired level of model detail. In this example, and in order to simplify, the attributes are considered basic attributes. Each of the four basic attributes governs the "package" created by an expert, and can assume three values only, respectively: "high" (high end appliances and systems; a high-end "package" created by an expert), "medium" (medium level appliances and systems, partial systems; a medium-level "package" created by an expert), "low" (low end appliances and systems; a low-level, basic, "package" created by an expert). The values for the basic attributes are provided by experts.

The aggregate attribute "Options" consists of five attributes: a) Energy generating devices and installations (including solar-, wind-, geothermal-) (E GEN); b) Energy storage systems (E STO); c) Electric vehicle charging (E CHA); d) Electric power tools (E TOOL); e) Pools, hot-tubs, *etc*. [POOL]. As described, these attributes can be aggregate attributes or basic attributes depending on the desired level of model detail. In this example, and in order to simplify, the attributes are considered basic attributes. Each of the five basic attributes governs the "package" created by an expert, and can assume four values only, respectively: "high" (high end systems with high-end characteristics and features; a "package" created by an expert), "medium" (medium level systems with some but not all characteristics and features; a "package" created by an expert), "low" (low end systems, basic systems; a "package" created by an expert), and the "no" options chosen alternative. The values for the basic attributes are provided by experts.

The MAM model for HEM package selection is shown in Figure 12. The model shown is a qualitative MAM model with four qualitative utility functions.
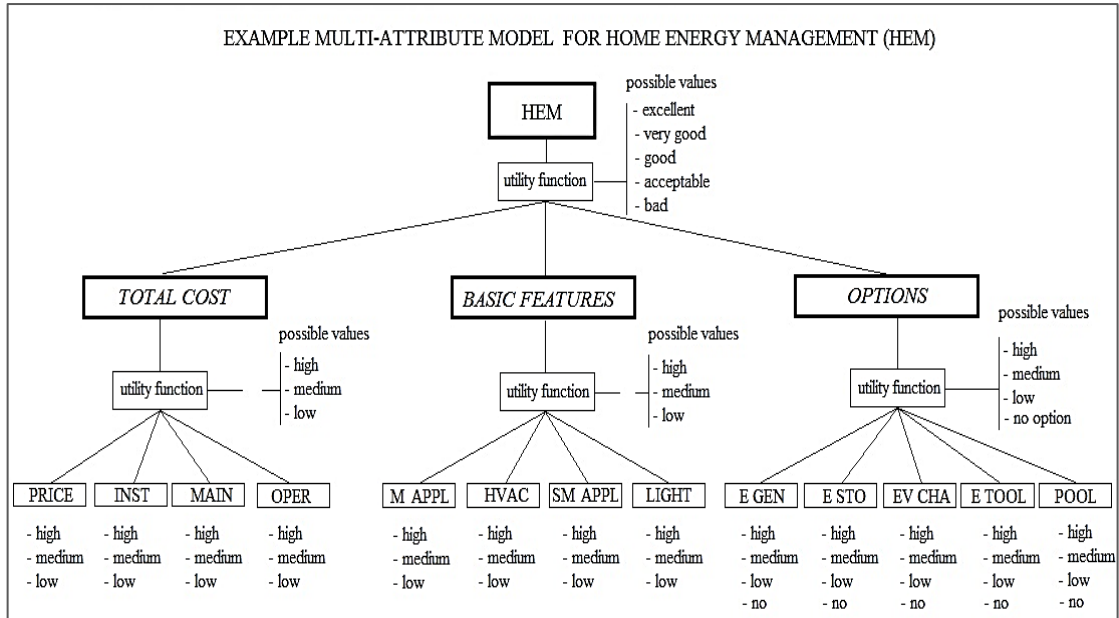
Figure 12. Qualitative Multi-Attribute Model Example for Home Energy Management (HEM)

For example, the qualitative utility function for "TOTAL COST" receives input from PRICE, INST, MAIN and OPER. As stated before, the initial values of the basic attributes are set by experts. Each of the basic attributes can assume three values [high, medium, low]. Therefore, there are 81 (= 3^4) different input combinations as PRICE can assume any of the three values [high, medium, low], and for that INST, MAIN and OPER can independently assume any of their respective basic attribute values. Now to develop the complete utility function for the aggregate attribute TOTAL COST, one has to consider each of the 81 combinations, and assign each combination separately a value that the utility function can assume, in this case "high", "medium", or "low". If now, as an example, the basic attributes PRICE, INST, MAIN, and OPER are all classified as "high", then the expert could consider this combination to translate to "high" TOTAL COST using the utility function. On the other hand, a combination of PRICE "high", INST "medium", MAIN "medium" and OPER "low", might lead the expert to consider the utility of that combination to TOTAL COST as "medium", and so on. The expert would then consider each of the 81 combinations, and assign a value for the combination for the aggregate utility TOTAL COST using the utility function. The same process is used for all basic attributes of all branches of the tree, and all combinations for "BASIC FEATURES", and "OPTIONS".

At the next level, the aggregate attributes TOTAL COST (can assume three possible values], BASIC FEATURES (three possible values) and OPTIONS (four possible values) are considered in a similar way as above. There are 36 combinations, coming from these aggregate attributes, to be considered for the HEM utility function. Consider two of those combinations: TOTAL COST at "high", BASIC FEATURES at "high" and OPTIONS at "high" might be considered "good" by the HEM utility function, whereas TOTAL COST "low", BASIC FEATURES and OPTIONS both at "high" might be considered "excellent" by the expert for HEM level utility.

9. Conclusions

This paper has proposed an extension to existing HEM prototypes by taking some of the important solar device options into account and a multi-attribute modeling (MAM)

approach to smart home adoption. Firstly, in order to increase and expand the number of smart devices in a home, the proposed model add-on has been discussed by drawing conclusions from consumer perceptions captured in an online survey. The goal of this study is to offer a comprehensive account of synthesis–generated insights about HEMS along with the implications of a cloud-based smart home. An integrated HEMS offers a data-driven approach to energy efficiency with the help of programmable devices that can measure the amount of electricity an appliance uses (including phantom loads). The methodologies discussed in the report can help consumers make well-informed decisions regarding HEMS. Secondly, this study calls attention to the principal barriers and challenges in HEMS and cloud technology's reach in today's power landscape. Smart homes with cutting edge technologies make essential activities and tasks in a home environment possible, both manually and remotely. With growing electricity charges and impending power crises, there is a sense of urgency for effective energy efficiency that can save money as well. All of the above can be achieved by using cloud integrated devices because they can provide prudent homeowners with real time information on energy consumption in dynamic scenarios. Thirdly, the most crucial factor of cloud technology determined from the survey results is 'Security'. This information can support Consumer Electronics and Tele-communications companies to tighten security measures in the administration of their cloud computing services. New fault-tolerant platforms to mitigate conformance slips and infrastructure vulnerabilities must be made available to customers. The survey results also signal that there is consumer inclination and enthusiasm towards solar adoption as well as different categories of devices viz. LED lighting, surveillance cameras, and media and gaming devices. Affordability and possible savings potential of such devices can result in a wider adoption of cloud-based HEMS. Thirdly, in the proposed pragmatic concept of HEM system modeling, the critical nature of "functionalities" or "tasks" expected out of a device, as required by a particular consumer in a particular situation (with or without conditions) are selected to form an "HEM package". With this contextual information and other tier-based attribute selections, the aggregate utility function can be formulated. The proposed qualitative methodology to purchasing smart devices has been illustrated with an example. This inventive technique in consumer behavior can be proven to be useful for any HEM package using real-time data. The model can render a purchase option that has the highest utility and lowest cost for the expected feature/functionality in a device. Last but not least, this study emphasizes the benefits of DR programs. Identifying changes in consumer behavior with the introduction of financial incentives and rebates relating to Smart Homes underscores the need for utility companies to offer cash rebates or credit to help end users take advantage of these programs. This will have cumulative effects on both the utilities and consumers. In conclusion, an extensive, robust and a cost-effective cloud-based HEMS with the capabilities of energy data exchange can be a powerful mechanism for handling energy issues across cities.

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