Comprehensive Analysis of Energy Management Systems in Smart Homes

Análisis Exhaustivo de los Sistemas de Gestión de la Energía en Hogares Inteligentes

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Resumen

Introduction— In recent years, the way individuals inhabit their homes has undergone a significant transformation, thanks to the rapid advancement of technologies applied to the household. This development has revolutionized people's interaction with their residential environment, providing greater comfort, security, and efficiency. Currently, homes have evolved from simple static constructions to systems equipped with monitoring and control technologies. These technologies enable users to monitor and regulate the operation of electrical and electronic devices, such as lighting, climate control, entertainment, and access, giving rise to what we know as a Smart Home.

Objective— The fundamental purpose of this article is to present a conceptual review and related works on Energy Management Systems (EMS) in Smart Homes.

Method— To carry out this review, the FRA on-line method (Frequency Response Analysis with the energized transformer) was implemented. Specialized databases such as SCOPUS, Science Direct, and IEEE were consulted using search strings that included keywords related to Smart Homes and Home Energy Management Systems (HEMS).

Results— There is a clear trend towards the use of classical and stochastic optimization methods, such as linear programming (LP), particle swarm optimization (PSO), and multi-agent systems, to address the minimization (or maximization) challenges inherent in intelligent energy management in Smart Homes. Additionally, the application of methods based on Machine Learning (ML) was reported to add predictability and efficiency to HEMS programming.

Conclusions— Finally, it was evident that the implementation of technologies such as the Internet of Things (IoT), sensor networks, automation, and artificial intelligence in a home can generate economic benefits and enhance comfort through the optimization of electrical consumption. In this regard, Home Energy Management Systems (HEMS) emerge as a suitable platform to integrate these technologies and perform optimization tasks for available energy resources.

Keywords— Smart Homes, Energy efficiency, Energy management, Optimization, Renewable energy sources.

Abstract

Introducción— En los últimos años, la forma en que el ser humano habita se ha visto transformada gracias al rápido avance de tecnologías aplicadas al hogar, revolucionando la manera en que las personas interactúan con su entorno doméstico para brindar una mayor comodidad, seguridad y eficiencia, permitiendo que hoy en día los hogares hayan pasado de ser construcciones estáticas para convertirse en sistemas dotados de tecnologías de monitoreo y control, facilitando al usuario la supervisión y regulación del funcionamiento de dispositivos eléctricos y electrónicos tales como iluminación, climatización, entretenimiento y acceso, configurando lo que se conoce como Hogar Inteligente *(Smart Home)*.

Objetivo— El objetivo de este artículo es presentar una revisión conceptual y de trabajos relacionados a los Sistemas de Gestión de Energía (EMS) en Hogares Inteligentes (*Smart Homes*).

Método— Para su desarrollo se implementó el método FRA on-line (Análisis de la respuesta en frecuencia con el transformador energizado) donde consultaron las bases de datos especializadas: SCOPUS, *Science Direct* e IEEE, usando cadenas de búsqueda que relacionan las palabras clave principales relacionadas con *Smart Home* y Sistemas de Gestión de energía para el hogar (*Home Energy Management Systems*, HEMS).

Resultados— Hay una tendencia marcada al uso de métodos clásicos y estocásticos de optimización, tales como programación lineal (LP), cúmulo de partículas (PSO), sistemas multiagente entre otros, para abordar los problemas de minimización (o maximización) que surgen en la gestión inteligente de energía. También se reportó la aplicación de métodos basados en *Machine Learning* (ML) para agregar predictibilidad y programación eficiente en los HEMS.

Conclusiones— Finalmente, se evidenció que el uso de tecnologías como *IoT*, las redes de sensores, la automatización y la inteligencia artificial en una casa puede generar beneficios económicos y de confort a través de la optimización del consumo eléctrico. En ese sentido, los sistemas de gestión de energía para el hogar (HEMS) presentan una plataforma apropiada para integrar estas tecnologías para llevar a cabo tareas de optimización de los recursos energéticos disponibles.

Palabras claves— Hogares Inteligentes, eficiencia energética, gestión de energía, optimización, fuentes de energía renovable.

I. INTRODUCTION

In today's era, characterized by rapid technological advancements and disruptive innovations, the amalgamation of energy efficiency and artificial intelligence has paved the way for the advent of Smart Homes. These homes, integrated with advanced information and communication technologies, aim to simplify daily life while addressing key energy and environmental challenges. Within this innovative landscape, Energy Management Systems (EMS) have become pivotal in optimizing electricity consumption in Smart Homes [1].

The importance of efficient energy management is increasingly acknowledged, particularly in light of the growing demand for electricity and the environmental concerns of excessive energy resource consumption. Smart Homes, powered by state-of-the-art technologies, stand at the forefront of this movement. They offer not just enhanced comfort and convenience but also contribute to the reduction of the carbon footprint. This is achieved by implementing sophisticated energy monitoring and control systems vital to sustainable living and environmental stewardship [2].

Within the Sustainable Development Goals (SDGs) established by the United Nations (UN) in 2015 as part of the 2030 Agenda, Goal Number 7 plays a crucial role. This goal emphasizes ensuring access to affordable, secure, sustainable, and modern energy for all. The UN has underscored the significant challenge that approximately 13% of the global population still lacks modern electricity services. Moreover, energy is identified as a primary contributor to climate change, accounting for about 60% of all global greenhouse gas emissions [3].

Furthermore, the International Energy Agency (IEA), in its comprehensive report on world electricity consumption by sector from 1974 to 2019, indicates that the residential sector is the second-largest electricity consumer globally, totaling 6072 TWh in 2019. This figure is surpassed only by the industrial sector, which consumed 9566 TWh in the same year [4]. The IEA acknowledges the ongoing global energy crisis, exacerbated by factors such as the Russian invasion of Ukraine. This crisis has sparked widespread concerns about energy security and the inflationary effects of higher energy prices on global economies. In response to these challenges, the IEA highlights the increased global emphasis on advancing energy efficiency to conserve and better manage energy consumption. The IEA advocates for governments to implement comprehensive measures to promote energy efficiency, suggesting an integrated approach that includes regulatory frameworks, informational campaigns, and incentive programs.

In Colombia, there has been a notable increase in per capita electricity consumption, rising from 832.3 KWh in 2000 to 1492.5 KWh in 2021 [5]. This significant growth in demand is particularly evident in the residential sector and among small businesses. According to data from Colombia's electricity market administrator, XM, these sectors accounted for 67.76% of the country's total electricity consumption in 2022 [6]. Additionally, a household's average monthly electricity consumption is approximately 157 KWh. A breakdown of this consumption reveals that refrigeration, including air conditioning systems, accounts for 48%, followed by 15% for television usage and 14% for lighting. The remainder is distributed among water heating, direct heat, and other electronic devices [7]. This escalating consumption pattern and the nearly 10% increase in KWh prices in January 2023 underscores the urgency of finding efficient solutions for electricity use [8]. Adopting information and communication technologies in homes and transforming them into Smart Homes is emerging as a viable response. These technologies enable intelligent management of electricity consumption, either through deactivating unused devices or programming scenarios tailored to users' needs [9].

However, to maximize energy efficiency in these Smart Homes, the integration of an Energy Management System (EMS) is essential. An EMS is designed to optimize electricity usage based on various criteria, such as cost reduction and occupant comfort, or to incorporate distributed generation sources like solar panels or wind turbines. Consequently, focusing on energy efficiency becomes a crucial strategy to address the challenges posed by the increasing electricity demand and costs in the residential sector [10].

En consecuencia, la importancia del ahorro energético en el sector residencial se hace evidente, especialmente en un escenario donde el consumo de electricidad ha experimentado un crecimiento significativo. La transformación de las viviendas en hogares inteligentes mediante la aplicación de tecnologías de la información y la comunicación se presenta como una respuesta viable a este desafío, permitiendo el control inteligente del consumo eléctrico. Sin embargo, para garantizar una gestión eficiente de la energía en estos hogares inteligentes, se requiere la implementación de un Sistema de Gestión de Energía (EMS). Este sistema tiene como objetivo principal optimizar el consumo eléctrico considerando diversos criterios, como el costo de la factura, el confort de los habitantes y la utilización de fuentes de generación distribuida.

En este contexto, el enfoque hacia la eficiencia energética se convierte en una estrategia clave para abordar los retos asociados al aumento de la demanda y los costos en el sector residencial. Este artículo se propone explorar y analizar los Sistemas de Gestión de Energía (EMS) en el contexto de Hogares Inteligentes (Smart Homes), abordando su conceptualización general en la sección II. Además, se revisarán trabajos relacionados con esta temática en la sección III, proporcionando una visión integral de las aplicaciones y avances en este campo. Finalmente, las conclusiones se presentarán en la sección IV, con el objetivo de ofrecer una perspectiva informada sobre la relevancia y el potencial de los EMS en la eficiencia energética de los hogares inteligentes.

II. GENERAL CONCEPTS

A. SMART CITY, SMART BUILDING, AND SMART OFFICE

Throughout history, humans have consistently endeavored to build cities that offer their inhabitants convenience, comfort, safety, transportation, connectivity, and quality of life. In modern times, integrating technological services into urban areas has revolutionized how people interact with their city environment. The concept of a "Smart City" encompasses incorporating diverse technologies into urban infrastructures. These technologies are designed to gather data and interact with citizens, providing intelligent services in various domains such as mobility, economy, environment, livability, health, security, and governance [11].

A Smart City is envisioned as a community where the management and optimized control of essential infrastructures, including electricity, water, transportation, logistics, health, and information, are seamlessly integrated [12]. Implementing a Smart City concept directly involves both public and private urban infrastructures. Consequently, integrating Information and Communication Technologies (ICT) in commercial, administrative, and residential buildings has given rise to new paradigms such as Smart Buildings, Smart Offices, and Smart Homes.

A Smart Building employs various technologies, including sensors, actuators, data acquisition, analysis, and visualization systems, to provide high-quality, cost-effective, and safe services to its users or residents [13]. *The Smart Office concept applies these technologies to public and private spaces, enhancing productivity, work efficiency, employee safety, and health* [14].

In the following section, the concept of the Smart Home will be discussed in more detail, exploring how these advanced technologies are transforming residential living spaces into more efficient, comfortable, and intelligent environments.

B. SMART HOME

A Smart Home can be described as an application of "pervasive computing," where intelligent systems monitor the domestic environment to provide context-adapted services and facilitate remote control of household systems [15]. From a formal perspective, a Smart Home represents the "integration of various services within a house through a unified communication system" [16]. The objective is to ensure the house operates economically, safely, and comfortably, incorporating elements of intelligence, functionality, and flexibility. Today, technologies used in smart homes have broadened their scope beyond mere comfort and security, extending into health-related applications that are particularly beneficial for elderly individuals living alone [17].

The typical architecture of a Smart Home consists of three primary layers: the application layer, the network layer, and the sensor layer. This multi-layered architecture enables the Smart Home to make autonomous decisions and provide personalized assistance services without user intervention [18]. Fig. 1 illustrates this architecture, highlighting how the sensor layer, serving as the foundational layer, gathers data from the home's various electrical and electronic devices. This data is subsequently transmitted through the network layer to the application layer, which is utilized for various intelligent functions.

Incorporating innovative technology for home control can result in significant economic benefits, mainly when used to optimize the electricity consumption of appliances. To fully realize these benefits, it is essential to pair these technologies with Home Energy Management Systems (HEMS). HEMS is designed to monitor, measure, and control energy consumption and generation (including self-generation). These systems are crucial in managing energy use within Smart Homes, contributing to economic savings and environmental sustainability.

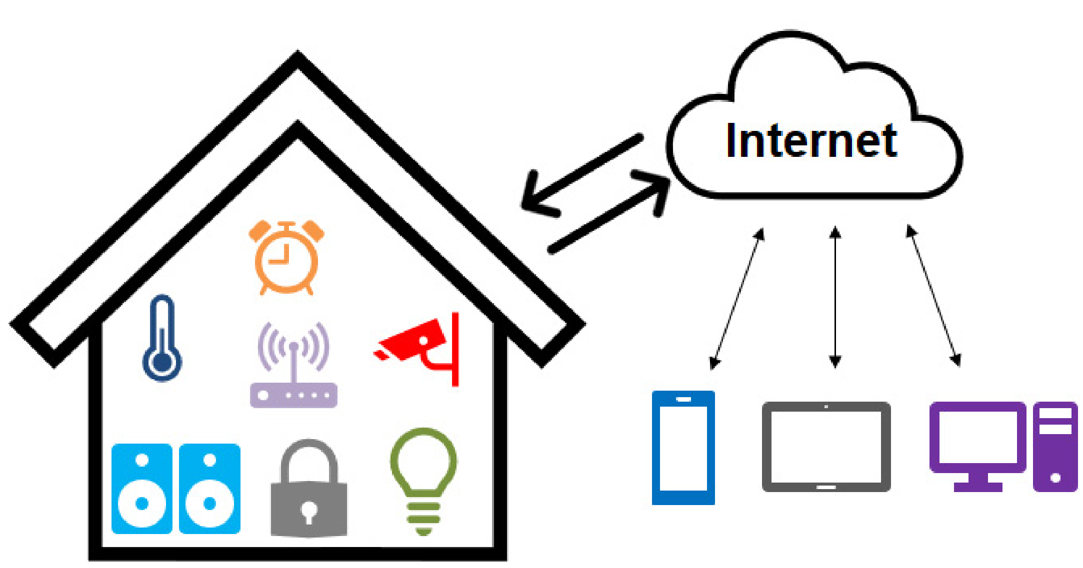

Fig. 1. Smart Home arquitecture.
Source: The author.

C. HOME ENERGY MANAGEMENT SYSTEMS

Recently, there has been an increasing focus on household electricity consumption due to factors such as the high service cost, environmental concerns related to energy generation, and the global energy crisis. These issues have led to various initiatives to regulate consumption, promote responsible usage, and encourage efficient energy use. A notable initiative in Colombia is the implementation of electricity consumption subsidies, which are determined based on kilowatt hours (KWh) consumed. For regions located at altitudes above 1,000 meters above sea level (MSNM), the subsidy applies to 130 KWh, while for areas below 1,000 MSNM, the subsidy extends to 173 KWh. The subsidies vary depending on the socioeconomic stratum: 60% for stratum 1, 50% for stratum 2, and 15% for stratum 3 [19]. These measures underscore the urgency of finding alternative solutions to reduce energy consumption.

In this context, Residential Energy Management Systems (HEMS) emerge as a technological innovation to optimize home electricity consumption. HEMS is designed to monitor and manage electricity generation, storage, and consumption in smart homes efficiently [20]. By employing appropriate measurement and monitoring devices, the collected data can be utilized for automation, control, event scheduling, and even predictive analysis, optimizing energy usage in smart homes.

The general architecture of a HEMS includes measurement devices and sensors, smart appliances and actuators, a user interface, and a central platform, as shown in Fig. 2 [21]. HEMS creates an intelligent environment leveraging technologies like the Internet Of Things (IoT), providing a flexible framework for interconnecting sensors and actuators and facilitating data sharing between platforms. This enables the development of advanced analytics in consumption data, generation, and prediction. An IoT architecture within HEMS can be physical, virtual, or hybrid, encompassing a variety of physical devices such as sensors, actuators, control units, and cloud services [22].

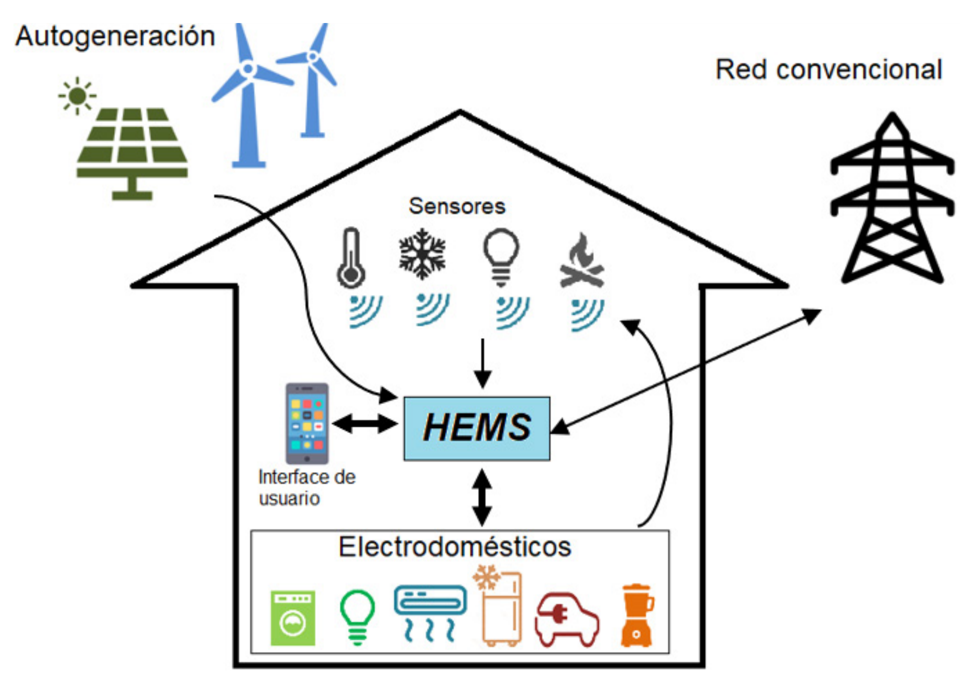

Figura 2. HEMS arquitecture..
Source: The author.

D. INTERNET OF THINGS (IOT)

The Internet of Things (IoT) is a concept that refers to a network of interconnected physical objects equipped with sensors, actuators, and communication technologies. These objects can collect and exchange data over the Internet. Spanning a diverse range of items, from simple electronic devices to complex machinery, vehicles, environmental sensors, and home appliances, IoT facilitates the interaction and integration of these objects with applications and computer systems. This integration unlocks opportunities for automation, real-time data collection, and intelligent data analysis.

IoT represents a paradigm that merges elements and technologies from various fields [23], including ubiquitous computing, pervasive computing, the Internet, sensor technologies, communication technologies, and embedded systems. The amalgamation of these technologies aims to create a system where the real and digital worlds converge in a symbiotic interaction.

The applications of IoT are vast and varied, but they can generally be categorized into four main domains [24].

1. Personal and Home, focusing on smart home applications and personal devices.
2. Enterprise, which includes industrial and business applications.
3. Services encompassing a range of service-oriented applications.

The significance of IoT lies in its ability to enable devices and objects to interact and collaborate towards achieving shared objectives. This interaction facilitates the creation of efficient, reliable, and secure services tailored to specific applications [25], enhancing functionality and user experience across various sectors.

E. INDUSTRY 4.0

Industry 4.0 represents a transformative model marking the onset of the fourth industrial revolution. This paradigm shift is characterized by integrating intelligent, virtual, and digital systems within industrial settings, building upon the foundational changes the three preceding industrial revolutions brought about. Industry 4.0 is synonymous with advanced manufacturing, incorporating a broad array of integrated technologies that enhance the safety and efficiency of human labor in industrial processes.

At its core, Industry 4.0 is the amalgamation of three primary elements: intelligent factories, innovative production methodologies, and advanced logistics [26]. The successful transition to an Industry 4.0 model necessitates adopting and integrating various emerging technologies. These include Big Data analytics, autonomous robotics, cyber-physical systems, simulation technologies, horizontal and vertical system integration, cloud computing, adaptive manufacturing techniques, and augmented reality applications [27].

This integration is pivotal in driving industrial innovation, enhancing operational efficiencies, and fostering a more interconnected and responsive manufacturing ecosystem. As such, Industry 4.0 stands as a cornerstone of modern industrial strategy, setting the stage for a new era of digitalized and interconnected manufacturing.

F. SENSOR FUSION

In Smart Homes and HEMS, various sensors are essential for perceiving the environment and measuring energy consumption variables. These increasingly wireless and Internet-connected sensors form part of IoT sensor networks and Wireless Sensor Networks (WSN). The data generated in real-time by these sensors present several challenges, including the vast quantity of unrefined data and the high resource consumption required for processing [28]. The primary objectives of IoT sensor networks are to measure environmental and physical variables, convert this physical information into digital format, and extract relevant data from these measurements to aid in decision-making.

The number and placement of these sensors vary based on specific applications and user requirements. Consequently, the raw data from IoT sensors often include extraneous and non-useful information. This necessitates preliminary data processing to 'clean' the data, enabling subsequent analysis to extract pertinent information. Sensor data fusion is a critical strategy to address the challenges of using multiple heterogeneous sensors. Its goal is to amalgamate data from two or more sensor sources to produce a more coherent, accurate, and reliable estimation of the measured system. This approach often yields better results than using individual sensors, minimizing costs, reducing the number of required components, and enhancing accuracy and reliability [24].

Data fusion in multisensor systems is particularly relevant in Smart Home applications, especially for home health care (HSH). In HSH applications, data fusion is used to monitor the health status of patients at Home, aiming to reduce hospital stays, prevent avoidable hospitalizations, and manage diseases more effectively within the Home setting [25].

G. WEARABLES IN SMART HOME

In addition to the wired or wireless sensors installed in a Smart Home, which are crucial for acquiring environmental data, another key method for gathering information, particularly about the inhabitants, is through wearable devices. Wearables are defined as devices that can be worn as accessories or incorporated into clothing. These devices are equipped with one or more sensors that measure the physiological variables of the user and, in some cases, provide user identification capabilities. Wearables are designed to capture detailed insights into a person's behavior and physical conditions, making them valuable tools for human activity recognition (HAR) tasks [26] human activity identification utilizing MotionNode sensors is becoming more and more prominent. A difficult issue in ubiquitous computing and HCI is providing reliable data on human actions and behaviors. In this study, we put forward a practical methodology for incorporating statistical data into Sequential Minimization Optimization-based random forests. In order to extract useful features, we first prepared a 1-Dimensional Hadamard transform wavelet and a 1-Dimensional Local Binary Pattern-dependent extraction technique. Over two benchmark datasets, the University of Southern California-Human Activities Dataset, and the IM-Sporting Behaviors datasets, we employed sequential minimum optimization together with Random Forest to classify activities. Experimental findings demonstrate that our suggested model may successfully be utilized to identify strong human actions for matters related to efficiency and accuracy, and may challenge with existing cutting-edge approaches.","container-title":"International Journal of Communication Networks and Information Security (IJCNIS).

The integration of wearable technology into Smart Homes enhances the personalization of the user experience. These devices are particularly beneficial in applications designed for individuals with motor limitations or chronic conditions, as wearables enable them to interact more seamlessly with the house and its appliances [27] assistive wearables technologies based on Internet of Things (IoT). By syncing with the broader Smart Home system, wearables can provide real-time health monitoring, adjust home settings to suit individual needs, and even assist in emergencies, enhancing both comfort and safety for residents.

III. RELATED WORKS

Residential Energy Management Systems (HEMS) has a significant focus on optimizing energy consumption, employing a diverse range of techniques from linear programming to advanced Machine Learning algorithms. The core functionalities of HEMS include monitoring, collecting, and storing consumption data alongside control, management, and generation of alerts. Among these, energy management emerges as a pivotal function, facilitating the optimal and efficient utilization of electrical energy [33] network communication, information infrastructures, bidirectional communication medium's, energy conservation methodologies and diverse techniques, Home area networks (HANs).

A comprehensive literature review reveals that various optimization techniques have been applied to enhance the efficiency of HEMS. Notably, these techniques predominantly utilize metaheuristic methods. Among the most prominent metaheuristic methods employed in HEMS optimization, the following have been identified:

1. Genetic Algorithms (GAs): These algorithms simulate the process of natural evolution, leveraging mechanisms such as selection, crossover, and mutation to find optimal solutions to complex problems.
2. Particle Swarm Optimization (PSO): Inspired by the social behavior of birds and fish, PSO is used to find the optimal solution through the collective movement and intelligence of particles in a swarm.
3. Ant Colony Optimization (ACO): This method mimics the behavior of ants in finding the shortest paths from their colony to food sources, effectively solving optimization problems.
4. Simulated Annealing (SA): SA is inspired by the process of annealing in metallurgy. It utilizes a probabilistic technique to approximate the global optimum of a given function.
5. Artificial Neural Networks (ANNs): These are computational models inspired by the human brain, capable of machine learning and pattern recognition, which are used in HEMS for predictive analysis and decision-making.

Each technique offers unique advantages in solving the complex optimization challenges of managing home energy consumption. They contribute significantly to making HEMS more intelligent, adaptive, and efficient in reducing energy costs and consumption while maintaining or enhancing user comfort and convenience.

In [22], researchers proposed a multi-objective optimization method focusing on two primary objectives: minimizing energy consumption costs and maximizing user satisfaction. They introduced a novel version of the Butterfly Optimization Algorithm (BOA) and compared it with the Particle Swarm Optimization (PSO) technique to assess its effectiveness. The study found that the proposed method improved convergence speed, demonstrating its potential for efficient energy management in Smart Homes. Another significant contribution is outlined inn [34], where a multi-objective optimization strategy based on genetic programming was employed. This approach utilized decision trees to predict energy buying or selling to the grid and storage in batteries, considering various factors such as energy prices, production, consumption, and battery charge states. The model's predictive capabilities were instrumental in optimizing energy management decisions.

In [35] demand response has become a hot issue which has been widely concerned. Smart home energy management system, as a necessary means to realize the demand response, has become the focus of research. A smart home energy management system with multilayer structure is designed in this paper, which includes the interface layer, the control layer and the load layer. The interface layer is the human machine interface (HMI, an optimal planning model for HEMS was proposed, which combined the Search Harmony (SA) and PSO optimization algorithms. This innovative blend of algorithms enhanced the charging curve of the system, effectively reducing the cost of energy consumed. Complementary, a study presented in [36] proposed a HEMS that optimizes load demand and distributed energy sources. The system was designed considering various factors, including energy price, consumer satisfaction, and distribution transformer conditions. It encompassed electric vehicles, battery storage systems, and all controllable household appliances. Simulation results from this study indicated that the proposed HEMS could reduce billing costs by up to 31% while meeting user comfort needs.

In [37] a fuel cell (FC, a multi-agent system-based approach for an intelligent residential energy management system was discussed. This system integrated various components like a photovoltaic (PV) generator, a fuel cell, a supercapacitor, and an electric vehicle, all connected to the conventional grid. Using a multi-agent system enabled real-time intelligent coordination among these components in the Residential Energy Management System (RT_HEMS), showcasing the feasibility of a comprehensive and interactive energy management solution.

Machine Learning (ML) techniques have been increasingly applied in developing Home Energy Management Systems (HEMS). In [38] minimize energy cost, and maximize user comfort. In this study, instead of interfering with appliances and changing residents' behavior, the proposed hour-ahead DR strategy first learns the appliance usage behavior of residents; subsequently, based on this knowledge, it silently controls the energy storage system (ESS, the authors utilized supervised learning alongside Mixed Integer Linear Programming (MILP) for HEMS. This combination enabled the system to "learn" residents' appliance usage behavior and subsequently control energy storage systems (ESS) and renewable energy systems (RES) to minimize daily energy costs. MILP was particularly useful in managing the uncertainties associated with renewable energy sources and real-time pricing. Another notable work is presented in [39] where the HEMS-IoT system, based on Big Data and ML, aims to enhance comfort, security, and energy savings. The system employed the J48 ML algorithm to learn and classify user behaviors and energy consumption patterns. Additionally, it featured an energy-saving recommendation system tailored to user preferences. However, this system had limitations, including compatibility issues with only Android devices and specific IoT sensors and its inability to generate personalized energy-saving recommendations.

In [40], a HEMS employing various ML-based regression techniques was proposed. This system focused on collecting, enhancing, and preparing environmental data to predict and schedule the operation of programmable household appliances, achieving up to 36% reduction in consumption in a case study. Moreover, the study in [41] explored Predictive Trend Neural Networks (RTPNN) for efficient residential demand control. RTPNNs simultaneously handled the generation prediction from renewable energies and the scheduling of household appliance operations, eliminating the need for separate algorithms. In the same way, a combination of Artificial Neural Networks (ANN) and Multi-Agent Reinforcement Learning (MARL) was used to address uncertainties in future price predictions and decision-making for various household appliances, leading to reductions in consumer billing costs was developed in [42].

In [43] presented a methodology that synergizes HEMS with supervised and unsupervised ML algorithms, focusing on the prosumer model. This approach involved renewable energy sources like Photovoltaic Systems, wind turbines, electric vehicles, energy storage systems, and flexible loads. General Regression Neural Networks (GRNN) and Elman Neural Networks (ENN) were employed for energy price and generation predictions from renewable sources. At the same time, mixed integer linear programming (IMLP) was used to optimize the HEMS. In addition, in [44] researchers extensively studied the design, implementation, and performance evaluation of an innovative Rectenna system, which is pivotal for energy harvesting and data communication in IoT devices. The study encompassed designing and fabricating a gain-enhanced triple-band antenna integrated with a rectifying circuit. The antenna's four-layer stacked structure exhibited high gain and a wide impedance bandwidth, making it adept for multiple frequency bands and thus suitable for energy harvesting and data communication. Incorporating the rectifier circuit was a key innovation, enabling the efficient conversion of RF power to DC power, which is essential for powering IoT devices. The comprehensive measurements and analyses confirmed the Rectenna system's high-performance metrics.

Conversely, [45] details the methodology for implementing a facial recognition system in a smart office setting, leveraging faster R-CNN and IoT technology. This system involved collecting and processing RGB-format images of employees for feature extraction. Utilizing the Faster R-CNN classification algorithm, the system could accurately detect and track multiple employee faces, verifying their affiliation with the organization. The system's effectiveness was assessed using accuracy, specificity, and sensitivity metrics, achieving a remarkable 99.3% accuracy rate in face identification. Furthermore, a comparative analysis with other deep learning and machine learning models demonstrated the proposed system's accuracy, showcasing its superiority in facial recognition technology.

In the national context, significant research has centered on Energy Management Systems (EMS) for Microgrids. For instance, [46] with the main objective of reducing the cost of the energy purchased to the utility grid. This approach considers the state-of-charge (SOC presents an EMS for the daily dispatch of energy from Battery Storage Systems (BBS) in direct current (DC) grids. This system aims to reduce energy purchase costs from suppliers by accounting for the state of charge of BBS, output variations from wind and photovoltaic generators, and fluctuating energy consumption and costs. The study employs Particle Swarm Optimization (PSO) and successive approximations to optimize BSS operation. Complementary, another study [47] through mathematical estimations, the electrical load profile and consumption patterns of buildings, which can be applied in Energy Management Systems (EMSs developed a method for estimating buildings' load profile and consumption patterns, which is crucial for EMS applications. This study categorized building demand and load profiles based on the relationship between consumption patterns and hourly occupancy.

In [48] including the maintenance costs of the PV sources. The second objective function is the reduction of the expected daily energy losses regarding all resistive effects of the distribution lines. The third objective function concerns the minimization of the total emissions of CO2 into the atmosphere by the substation bus or its equivalent (diesel generator an EMS for disconnected and grid-connected microgrids in DC distribution networks was proposed. Based on photovoltaic (PV) generation, this system utilizes nonlinear programming to minimize operational costs, energy losses, and CO2 emissions. A Salp Swarm Algorithm (SSA) was implemented for function minimization and compared with other optimizers, demonstrating its effectiveness. The authors in [49] introduced an EMS focusing on the optimal operation of PV generators in rural and urban areas of Colombia. Utilizing the Antlion optimizer, this system addresses a nonlinear programming problem to improve the network's economic, technical, and environmental aspects. The method employed a "master-slave" approach, with the master stage handling energy dispatch via the Antlion optimizer and the slave stage using successive approximations for objective function evaluation.

An experimental microgrid testbed is described in [50], aimed at emulating real-time consumption and generation prediction tasks in a microgrid cluster. This setup utilizes a cloud-based HEM with Machine Learning algorithms to solve dispatch problems.

Lastly, [51] explores energy bill savings by altering consumption patterns through gamification, predictive models, and low-cost HEMs using affordable hardware and open-source software. The study involved a comparative consumption data analysis before and after HEM implementation on a test bench with common household appliances. It also proposes a gamification approach using HEM and predictive models to enhance user consumption habits.

IV. TECHNOLOGY PLATFORMS FOR ENERGY MANAGEMENT IN SMART HOMES

The market offers various commercial devices and technology platforms designed to add "intelligence" to homes and optimize electrical energy consumption. Additionally, for those with hardware and software knowledge, numerous DIY (Do It Yourself) tools are available for creating Smart Home systems. Some of the most popular solutions include:

Amazon Echo: This smart speaker integrates with Amazon's Alexa virtual assistant, enabling control of connected devices, music playback, information retrieval, and home scene management via voice commands [52].

Google Home: Like Amazon Echo, Google Home works with Google Assistant. It offers functionalities like device control, searches, music streaming, and scene creation through voice commands or a mobile app. It is compatible with various smart device brands [53].

Samsung Smart Things: A platform that connects and controls various smart devices at Home, offering extensive compatibility with products from different manufacturers [54].

Enphase Energy: Specializing in solar energy management for Smart Homes, this system monitors and controls solar production, home energy consumption, and backup battery charging [55].

Sense: his platform provides a real-time energy monitoring system installed in the Home's electrical panel. It tracks the energy usage of individual devices, identifies usage patterns, and offers energy-saving recommendations [56].

Schneider Electric Wiser Energy: This residential energy monitoring system delivers real-time consumption data through a mobile application, thereby aiding in identifying specific areas for energy usage reduction [57].

Home Assistant: An open-source platform that allows control and automation of various brands and technologies. It is highly customizable and supported by a community developing numerous device integrations. Home Assistant is compatible with popular DIY platforms like Arduino, Node MCU, and Raspberry [57].

OpenHAB: An open-source project offering a flexible home automation platform. OpenHAB supports a wide range of technologies and protocols, allowing the integration of different devices and custom automation rules. It also provides compatibility with Arduino and Raspberry platforms [58].

V. CONCLUSIONS

Integrating technologies such as the Internet of Things (IoT), sensor networks, automation, and artificial intelligence in residential settings can yield significant economic and comfort benefits by optimizing electricity consumption. Home Energy Management Systems (HEMS) is an ideal platform for incorporating these technologies to optimize available energy resources.

Research in this area indicates a strong inclination towards employing classical and stochastic optimization methods to tackle the challenges in smart energy management. These methods include linear programming (LP), Particle Swarm Optimization (PSO), and multi-agent systems, which are utilized to address various minimization (or maximization) problems inherent in intelligent energy management systems. Additionally, implementing Machine Learning (ML) based approaches in HEMS has been noted for their ability to enhance predictability and efficient scheduling.

In the context of Colombia, however, there is a lack of significant studies on the application of HEMS in Smart Homes. This observation suggests that the country's research focuses more on energy management systems for Smart Grids and decentralized distributed generation than residential energy optimization through HEMS. This gap indicates potential future research and development opportunities in Smart Home energy management within the Colombian context.

VI. FUTURE WORKS

Home Energy Management Systems (HEMS) can significantly benefit from integrating technologies like Human Activity Recognition (HAR). This integration can enhance the efficiency of electricity consumption in Smart Homes. By applying Machine Learning techniques to both HAR tasks and smart home energy management, HEMS can be optimized to respond more intelligently to residents' behaviors and preferences. Such an approach would enable HEMS to not only automate and control home energy usage based on detected activities but also to learn and adapt to changing patterns over time. This could lead to more personalized energy management, further reducing unnecessary consumption and optimizing energy use for better cost-effectiveness and sustainability in Smart Homes.

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