A Survey of Home Energy Management Systems and their Efficacy in South Africa

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Nkosinathi Madushele
Mechanical Engineering
Durban University of Technology
Durban, South Africa

Pavel Tabakov
Mechanical Engineering
Durban University of Technology
Durban, South Africa

***Abstract*— In 2022, South Africa experienced a total of 3776 hours of power outages, commonly known as load shedding. This had a significant economic impact, with estimates from the South African Reserve Bank suggesting a Gross Domestic Product (GDP) loss ranging from 0.7% to 3.2%. To address this issue, various initiatives are currently being implemented, including the implementation of renewable energy projects, effective maintenance of existing infrastructure, and a proposal to introduce smart meters to address challenges related to demand-side management (DSM). The electricity market in South Africa is transforming, and this is leading to the emergence of potential technologies that can help address the aforementioned challenges. One such technology is the Home Energy Management System (HEMS). This paper surveys this technology and assesses its potential effectiveness in the South African context.**

Keywords*— *Computational Intelligence; Demand Side Management; Home Energy Management System; Smart Sensors

I. Introduction

In 2019, the Energy Information Administration (EIA) published a report revealing that the residential sector in the United States accounted for approximately 25% of total energy consumption [1]. As for South Africa, the Department of Mineral Resources and Energy indicated that residential consumption in South Africa is approximately 18% [2]. Drivers of this residential demand include the rapid urbanization of the country, and inadequate maintenance of energy generation assets [3, 4]. Nations in the industrialized Global North encountered power outage incidents in the recent past, and in 2022, a European power utility had to implement what is effectively "stage 4 load-shedding" as a result of fuel shortages [5]. It is evident that energy challenges are multi-faceted, and require a balancing act between maintaining existing infrastructure, optimizing energy consumption, and expanding the energy infrastructure.

To manage the increasing demand for energy in the residential sector, there have been significant advancements, exemplified by the emergence of Home Energy Management Systems (HEMSs). These systems incorporate Internet of Things (IoT) devices aimed at energy monitoring, and energy consumption scheduling amongst others [6]. The adoption of these technologies in the Global North is increasing, as they are used by households to minimise their energy bills. On the other hand, South Africa does not have a time-of-use (ToU) tariff structure for the residential sector (where HEMSs are predominately used). However, HEMSs may be used to address peak demand challenges [7]. Against this background, a survey of the technological requisites driving HEMSs becomes imperative, and the current paper is based on that premise.

For this investigation, three primary databases, namely Scopus, Science Direct, and World of Science, were utilized to collect pertinent literature. The search was conducted using specific keywords, including "Smart Sensors", "HEMS", "Home Energy Management System", "Global South", "Global North", "Artificial Intelligence", and "Machine Learning". The search scope was limited to the most recent five years, focusing on scholarly peer-reviewed journal articles and conference proceedings.

This research is structured into five main sections, commencing with Section I serving as an introduction that highlights the rationale for this study. In Section II, we delve into the technological requirements of HEMSs. Section III elucidates the computational intelligence models employed within HEMSs. Subsequently, in Section IV, the key factors impeding HEMS adoption in South Africa, as well as opportunities are presented. Finally, in Section V, presents concluding remarks.

II. Technological Requisites of HEMS

One of the cornerstones of energy management lies in Energy Auditing (EA), a practice that furnishes a structured methodology for the establishment of an energy consumption baseline. Moreover, EA plays a pivotal role as the genesis for developing a business proposition for an energy project. EAs may be used to quantify the financial viability of procuring HEMSs by households. As previously outlined in Section I, residential zones accounted for about 18% of the total energy consumption in 2019. In this context, the implementation of HEMSs is crucial to facilitate the efficient operation of energy-consuming devices. Before evaluating the efficacy of HEMSs in South Africa, the technology's architectural framework should be expanded upon. HEMSs are comprised of three integral stages: 1. Data Acquisition, 2. Communication Network, and 3. Data Analytics, which are discussed in the following subsections [8].

A. Data Acquisition

The emergence of Internet of Things (IoT) technologies has significantly enhanced the feasibility of data acquisition, especially in instances that necessitate the processing of large amounts of data. In the realm of HEMSs, the acquisition of data is made viable through the utilization of smart sensors, which can be integrated at different levels, including the grid-level, area-level (smart meters), smart plugs, or appliance-level [8]. It's noteworthy that while the cost of smart sensors has progressively decreased over time, their adoption, especially in regions like the Global South, remains in the nascent stage, and this can be attributed to a shortage of technical competencies as well as the perceived trustworthiness of the technology amongst others [9].

The current unbundling of the state-owned utility company ESKOM SOC coupled with the uptake of renewable energy sources via Independent Power Producers (IPPs) will inevitably lead to distributed energy resources (DERs). However, IPPs produce intermittent renewable energy, and it is not impossible to conceive the migration towards a ToU electricity billing model in South Africa. In 2023, at the National Demand-Side Management Indaba, ESKOM SOC suggested the implementation of smart meters in every household in South Africa. The smart meters are anticipated to reduce energy consumption during peak times. Preliminary projections of the project are a roll-out duration of four years, and the project is expected to cost at least sixteen billion South African Rands [10]. The initiative would serve a dual purpose. At the first level, the utility aims to address the issue of load shedding by deploying smart meters capable of notifying customers about their energy consumption patterns and controlling the amount of energy that can be used at any given moment. On the second level, the utility could introduce ToU electricity rates that would fluctuate throughout the day. These ToU rates are anticipated to alleviate stress on the national grid, primarily through Demand Side Management (DSM) during peak hours.

Additionally, the project offers the potential for non-intrusive load monitoring (NILM) capabilities, representing an added value. Historically, HEMSs have relied on intrusive load monitoring (ILM) sensors for data acquisition, which necessitates the installation of various hardware components to monitor diverse parameters in household appliances. This configuration increases the complexity of the system and consequently makes it challenging to develop a streamlined data acquisition pipeline required for intelligent energy management. The ILM configuration is not only intricate to set up but also more costly compared to its NILM counterpart. NILM dissects the total power consumption of a household by scrutinizing the unique electrical signatures of individual appliances. Consequently, NILM is not only easier to install but also more cost-effective when compared to its ILM counterpart [11].

B. Communication Networks

Ferreira *et al.* highlighted a prevailing trend in the literature, wherein cloud computing methodologies dominate the communication network layer within the architecture of HEMSs [12]. While conventional HEMSs widely employ this approach, a significant limitation lies in their dependence on relatively inexpensive external connections, which may expose them to cyber threats, albeit with ample computing resources as a compensating factor [13]. The vulnerability of these external connections to cyber-attacks is a matter of significant concern, especially in the context of legislation such as South Africa's Protection of Personal Information Act 04 of 2013 [14]. The compromise of external connections not only risks the exposure of personal information but could have far-reaching consequences, particularly if the computational intelligence models discussed in Section III are exploited to transmit malicious actuation signals to household devices.

In scenarios where the communication network is compromised, and malicious data is transmitted to the data analytics layer, the safety of connected appliances is potentially jeopardized. It's worth noting that HEMSs are a relatively recent addition to the field of energy management, and as a result, cybersecurity protocols that should be integrated into the system architecture have yet to be formalized and standardized. Additionally, South Africa lacks a cybersecurity framework for distributed energy networks, and protocols remain within the purview of suppliers.

To address the challenges associated with cloud-based computing approaches, Ferreira *et al.* have proposed an open-source edge computing alternative. Beyond the advantages of local data residency associated with edge computing, this architecture offers secondary benefits in HEMS, including low latency and high bandwidth [12]. The approach introduced by Ferreira *et al.* for the communication network layer in the HEMS architecture is a promising option that can be applied by regions in the Global South. This approach aligns with resource efficiency by employing cost-effective hardware.

Condon *et al.* have also explored two scenarios, one utilizing IoT sensors in the development of a HEMS that integrates an edge computing device and the other leveraging AWS IoT core functionality [15]. Both the cloud and edge-based computing options share common HEMS features. However, one of the primary distinctions, aside from the cybersecurity concerns addressed earlier, is the scalability challenge faced by the edge computing option in contrast to its cloud computing counterpart.

C. Data Analytics

The primary objectives of HEMSs revolve around empowering end-users to minimize their energy expenditure, optimize their energy consumption, and reduce the environmental impacts associated with energy usage. To achieve these goals, data-driven techniques play a pivotal role, and these techniques can be categorized into four key approaches [8]:

Load Monitoring: Comprehensive data collection is paramount in HEMSs, as end-users require a clear understanding of how and when electricity is being utilized. Besides, load monitoring aids in the identification of energy-intensive appliances. As previously mentioned, NILM and ILM technologies are employed for load monitoring. However, each option has its advantages and drawbacks. NILM sensors are generally cost-effective and have relatively simpler deployment processes compared to their ILM counterparts. Nevertheless, they often rely on a smart sensor configuration, which disaggregates data based on the electrical signatures of various appliances. Load monitoring presents an entry point for HEMSs in South Africa, as the utility may switch off energy-hungry devices during peak periods of energy consumption through the use of smart meters.

Load Forecasting: In regions like the Global North, where the electricity market operates under a markets-driven framework (unlike many areas in the Global South), electricity prices are closely tied to the concept of ToU [16]. HEMSs have intelligent data-driven algorithms that are trained to predict future consumption requirements based on historical data. The effectiveness of these algorithms heavily depends on the quality of data obtained from load-monitoring devices. Section III of this study delves into several learning algorithms utilized for load forecasting.

Comfort Level Optimization: HEMSs employ clustering and reinforcement learning techniques to optimize comfort levels within households while concurrently optimizing energy consumption. These techniques observe user-specific behaviours related to devices such as air conditioning and lighting requirements. Since individual preferences for home comfort levels vary among households, clustering and reinforcement learning techniques are instrumental in this aspect of HEMS operation.

Scheduling and Control Methods: HEMSs are equipped with a Graphical User Interface (GUI) that guides end-users in determining the most optimal times for operating their devices. This feature empowers end-users to automate and manage appliance operations, potentially resulting in cost savings when appliances operate during off-peak hours.

III. Computational Intelligence in HEMS

In Section II, the necessity of data analytics within HEMSs was introduced. Computational intelligence plays a crucial role in analyzing data related to load monitoring, load forecasting, optimizing comfort levels, and implementing scheduling and control methods. In this section, some cases where computational intelligence is used in the data analytics of HEMSs are presented.

Load forecasting stands out as a critical analysis within HEMS, particularly in regions employing ToU pricing. Shifting electrical loads to time slots with lower electricity costs not only yields financial benefits but also assists in mitigating supply constraints during peak hours. Gheouany *et al.* introduced a multi-objective non-linear programming approach to address this challenge. Their model encompassed two target functions: minimizing electricity expenses and minimizing peak load. The model was constrained by various factors, including appliance categories (certain appliances permit load shifting from peak hours, while others do not), and the peak-to-average ratio (PAR) which signifies the ratio between peak power and average power (a condition necessary for grid stability). The authors leveraged the Multi-Objective Particle Swarm Optimization (MOPSO) algorithm for the optimal scheduling of devices, and their findings indicated that their model resulted in a 28% reduction in electricity costs while concurrently reducing the PAR by 49.32% [17].

While the research conducted by Gheouany *et al.* provides compelling evidence of electricity cost savings and a substantial reduction of nearly 50% in the PAR. It's important to acknowledge that smart sensors come with inherent limitations. These limitations can result in noisy disaggregated electrical signals from appliances, influenced by various factors including harmonics [18]. Consequently, the accurate classification of devices by smart meters remains an ongoing area of investigation. Considering these challenges, developing a multi-label classification system for electricity consumers within a household can be quite complex. Franco *et al.* have proposed an IoT-based appliance recognition framework to address this issue. Their framework is divided into training and inference components. They employed three algorithms for appliance classification tasks: Feedforward Neural Network (FFNN), Long Short-Term Memory (LSTM), and Support Vector Machine (SVM). This framework represents a positive step towards addressing the challenges of multi-label classification. However, it's worth noting that they reported relatively low accuracy in the classification models when applied to new data. This implies that the model will require retraining when implemented in new households [19].

Despite the notable advancements in the domains of load scheduling, load forecasting, and appliance classification within HEMSs, there persists an underlying assumption: the presumption of having complete knowledge of user behaviour. To address this limitation, Chen *et al.* introduced a graph-based reinforcement learning algorithm. The algorithm not only challenges the assumption but also considers the correlations between usage patterns and various applications. Their approach entailed the creation of a behaviour correlation graph, where a user's energy consumption patterns were linked to a multi-label classification model for the effective monitoring of user-specific load consumption. Subsequently, this behaviour correlation graph served as the foundation for the development of the graph-based reinforcement learning algorithm. This algorithm is designed to enhance the performance of HEMS even under conditions of uncertainty regarding both the environment and user behaviour. To validate their model, the authors conducted experiments using multiple datasets and reported a substantial 18.3% reduction in electricity costs [20].

In the preceding section, instances where computational intelligence found application within HEMSs were examined. Strengths and areas in need of improvement were identified. It's worth noting that the cases discussed here did not encompass the data acquisition and communication network layers of HEMSs.

IV. HEMS Impediments and Opportunities in South Africa

In the year 2022, South Africa encountered a cumulative duration of 3,776 hours of load shedding. According to assessments made by the South African Reserve Bank (SARB), this situation resulted in a slowdown of the economy, causing a reduction in the Gross Domestic Product (GDP) ranging from -0.7% to 3.2% [21]. The energy sector faces numerous challenges, encompassing unplanned maintenance breakdowns and electricity supply limitations. Out of the country's total installed capacity of 48.186 gigawatts (GW), 2022's energy availability factor (EAF) was 59.4% [22, 23]. HEMSs present a promising avenue for addressing some of these challenges. However, the rollout of HEMS infrastructure faces impediments. Encouragingly, Eskom SOC is preparing to deploy smart meters, which may pave the way for HEMS technology integration.

Despite the potential of HEMSs to address energy challenges in South Africa, tailored engineering solutions are essential. The nation is also grappling with an engineering skills shortage. In 2018, the Engineering Council of South Africa (ECSA) reported only 17,226 professionally registered engineers in the country, translating to approximately one engineer for every 2,600 people, significantly deviating from the international standard of one engineer for every 40 people. HEMSs also rely on Fourth Industrial Revolution (4IR) skillsets, including the Internet of Things (IoT), Artificial Intelligence (AI), and blockchain technology. Consequently, the successful deployment of HEMSs in South Africa heavily depends on cultivating a pool of engineers capable of developing these systems.

As previously discussed, Eskom SOC's smart meter rollout holds potential for HEMS adoption. It's worth noting that cloud-based HEMS solutions are more economically viable than edge computing alternatives. However, cloud-based systems are more susceptible to cyberattacks, posing a risk to end-users' personal data. While South Africa has enacted the POPI Act, there is a pressing need to establish a regulatory framework for HEMS cybersecurity to ensure the protection of individuals' information in the context of increasing internet-connected daily lives. Furthermore, there is a notable absence of literature, both in South Africa and globally, addressing a comprehensive strategy for ensuring the security of HEMS firmware and software. South Africa has a unique opportunity to take a proactive stance in this regard.

On a broader scale, no smart grid cybersecurity framework specific to South Africa has been identified. Given the evolving international trajectory of HEMS and their integration with smart grids, parameters such as PAR for HEMS need to be developed through collaborations between utility companies, service providers, and public input. Once again, South Africa is in a favourable position to lead in this area.

V. Conclusion

In South Africa, the persistent issue of power outages, commonly referred to as load shedding, has spanned more than a decade and appears to be worsening. To address this, several strategies have been initiated, including the appointment of an electricity minister, the initiation of renewable energy projects, the maintenance of existing energy infrastructure, and the potential deployment of smart meters. Smart meters can curtail energy consumption during periods of high demand. While these measures are in place, South Africa's energy landscape is evolving, as evidenced by the restructuring of ESKOM SOC and the IPPs in supplying energy through DERs. This transformation underscores the need to consider advanced energy management tools like HEMSs. Energy issues aside, such systems can be used anywhere in the world in any home, since energy savings save both money and valuable resources. South Africa has an opportunity to proactively shape the implementation of HEMSs in the country, with a focus on critical areas such as: establishing a robust cybersecurity framework for HEMS along with complementary legislation, increasing investment in the development of skilled human resources capable of creating HEMS systems, and formulating a comprehensive ToU pricing framework that adheres to principles of fairness and equity.

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