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Design and Implementation of Wireless Smart Home Energy Management System Using Rule-Based Controller

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DESIGN AND IMPLEMENTATION OF WIRELESS SMART HOME ENERGY MANAGEMENT SYSTEM USING RULE-BASED CONTROLLER

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Declaration of Original Work

I, Eslam Salah Al-Hassan, the undersigned, a graduate student at the United Arab Emirates University (UAEU), and the author of this thesis entitled "*Design and Implementation of Wireless Smart Home Energy Management System Utilizing Rule Based Controller*", hereby, solemnly declare that this thesis is my own original research work that has been done and prepared by me under the supervision of Dr. Hussain Shareef, in the Collage of Engineering at UAEU. This work has not previously been presented or published, or formed the basis for the award of any academic degree, diploma or a similar title at this or any other university. Any materials borrowed from other sources (whether published or unpublished) and relied upon or included in my thesis have been properly cited and acknowledged in accordance with appropriate academic conventions. I further declare that there is no potential conflict of interest with respect to the research, data collection, authorship, presentation and/or publication of this thesis.

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Abstract

Most residential units still rely on conventional energy supplied by utilities despite the continuous growth of renewable energy resources, such as solar and wind energy systems in power distribution networks. Utilities often use time-of-use energy pricing, which increases the interest of energy consumers, such as those in commercial and residential buildings, in reducing their energy usage. Thus, this work demonstrates the design and implementation of a home energy management (HEM) system that can automatically control home appliances to reduce daily energy and electricity bill. The system consists of multiple smart sockets that can read the power consumption of an attached appliance and actuate its on/off commands. It also consists of several other supporting instruments that provide information to the main controller. The smart sockets and supporting instruments in the system wirelessly provide the necessary data to a central controller. Then, the system analyzes the data gathered from these devices to generate control commands that operate the devices attached to the smart sockets. Control actions rely on a developed online rule-based HEM scheme. The rules of the algorithm are designed such that the lifestyle of the user is preserved while the energy consumption and daily energy cost of the controlled appliances are reduced. Experimental results show that the central controller can effectively receive data and control multiple devices from up to 18 m away without loss of data on the basis of a scheduled user program code. Moreover, online adaptation of the HEM scheme confirms significant reductions in the total daily energy consumption and daily electricity bill of 23.5 kWh and $2.898, respectively. Therefore, the proposed HEM system can be remarkably useful for home owners with high daily energy consumption.

Keywords: Home energy management, zigbee, smart socket, power monitoring, appliance smart scheduling.

Title and Abstract (in Arabic)

تصميم وتنفيذ نظام لإدارة الطاقة الكهربائية المنزلية بطريقة لاسلكية ذكية وباستخدام وحدة تحكم قائمة على القواعد المنطقية

الملخص

لا تزال معظم الوحدات السكنية تعتمد على الطاقة التقليدية التي توفرها شركات توزيع الكهرباء، على الرغم من النمو المستمر لموارد الطاقة المتجددة في شبكات توزيع الطاقة، مثل أنظمة الطاقة الشمسية وطاقة الرياح. تستخدم هذه الشركات نظام تسعيرة متغير حسب وقت الاستخدام في كثير من الأحيان، مما يزيد من اهتمام المستهلكين، مثل اصحاب المباني التجارية والسكنية، في ترشيد استخدام الطاقة. من اجل ما سبق، تم تصميم هذا البحث ليقدم تصميم جديد لنظام إدارة الطاقة المنزلية (HEM) الذي يمكنه التحكم تلقائيًا في الأجهزة المنزلية لتقليل فاتورة الطاقة واستهلاك الكهرباء اليوميين. يتكون النظام من العديد من المقابس الذكية التي يمكنها قراءة استهلاك الطاقة لأي جهاز متصل فيها، كما ويمكنها وتفعيل أوامر التشغيل / الإيقاف. كما يتكون النظام أيضاً من العديد من الأدوات الداعمة الأخرى التي توفر المعلومات الأخرى المطلوبة من وحدة التحكم الرئيسية. يتم توفير هذه البيانات بطريقة لاسلكية من المقابس الذكية والأدوات الداعمة إلى جهاز التحكم المركزي. ثم يقوم هذا الجهاز بتحليل البيانات التي يتم جمعها لإصدار أوامر تحكم تعمل بالأجهزة المتصلة بالمقابس الذكية. يعتمد إصدار هذه الأوامر على مجموعة من القواعد المنطقية المعدة مسبقا داخل جهاز التحكم، حيث تم تصميم خوارزمية تعمل على تقليل الطاقة المستخدمة والتكلفة الناتجة عنها دون المساس بنمط حياة المستخدم. تُظهر النتائج التجريبية أن وحدة التحكم المركزية يمكن أن تستقبل البيانات بشكل فعال وتتحكم في أجهزة متعددة من مسافة تصل إلى 18 متر دون فقدان أي من هذه البيانات. علاوة على ذلك، قدمت تجارب نظام HEM المذكور في هذا البحث، تخفيضات كبيرة في إجمالي استهلاك الطاقة اليومي وفاتورة الكهرباء اليومية بما

إجماله 23.5 كيلو واط في الساعة و 2.898 دولار على التوالي. ولذلك، فإن نظام HEM المقترح يمكن أن يكون مفيدًا بشكل ملحوظ لأصحاب المنازل الذين يستهلكون كميات كبيرة من الطاقة يوميًا.

مفاهيم البحث الرئيسية: دارة الطاقة المنزلية، النظام اللاسلكي (زيجبي)، القابس الذكي، مراقبة استهلاك الطاقة، الجدولة الذكية للأجهزة المنزلية.

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I am exceptionally appreciating the extraordinary support that my parents, brothers, and sisters have provided me during the time I was pursuing my studies. In addition, special thanks are extended to the Seelawi family for their assistance and friendship.

Dedication

To my beloved family and friends

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List of Abbreviations and Symbols

AC	Air Conditioner
ADC	Analog-to-Digital Converter
ANN	Artificial Neural Networks
API	Application Programming Interface
AT	Transparent
BSS	Battery Storage System
CAD	Computer-Aided Design
CO_2	Carbon Dioxide
CP	Critical Peak
CPP	Critical Peak Pricing
DGs	Distributed Generators
GUI	Graphical User Interface
HEM	Home Energy Management
I/O	Input/Output
IR	Infrared
L	Lux Value
LED	Light Emitting Diode
ML	Machine-Learning
NN	Neural Networks
PC	Personal Computer
PCB	Printed Circuit Board
PF	Power Factor
PIR	Passive IR Red
PQA	Power Quality Analyzer

PV	Photovoltaic
PWM	Pulse Width Modulation
QI	Quality Index
RMS	Root Mean Square
RTP	Real-Time Pricing
S	Schedules
TOU	Time of Use
T_{REF}	Internal Refrigerator Temperature
T_{Room}	Room Temperature
T_W	Water Temperature
Vs	Vacancy state of the room

Chapter 1: Introduction

1.1 Overview of Home Energy Management (HEM) Systems

The global trend in electrical energy consumption has been exponentially rising in recent years because of economic development and the increasing population. Utility regulators attempt to reduce end-user consumption in many ways, such as introducing high tariff rates, time of use (TOU) tariff, and demand response programs, due to limitations in electrical energy supply systems. Energy regulators also attempt to decrease fossil fuel dependency because of oil reserve depletion; oil price volatility and negative environmental impacts, such as CO_2 emissions [1]. Therefore, end users must reduce their energy consumption by changing their energy use patterns and by using energy-efficient equipment and devices. Governments around the world encourage energy users to decrease energy use by increasing their awareness, introducing incentives for users with low energy consumption, and promoting green energy solutions [2, 3]. Other possible solutions include the reduction of energy use and utility bills by introducing integrated photovoltaic (PV) systems, notifying consumers about their energy usage, using energy-efficient devices (e.g., light emitting diode [LED] lamps), replacing conventional devices with smart devices (e.g., remotely controllable sockets), and adopting intelligent energy management systems that control smart devices to reduce electricity bills and benefit from government incentives [4].

An HEM system is accountable for monitoring and managing the operation of in-home appliances and enables load shifting and peak saving according to a specified set of requirements [5]. Moreover, the main expectation of consumers from HEM systems is an increase in energy efficiency and decrease in electricity consumption. Figure 1 shows the HEM system architecture.

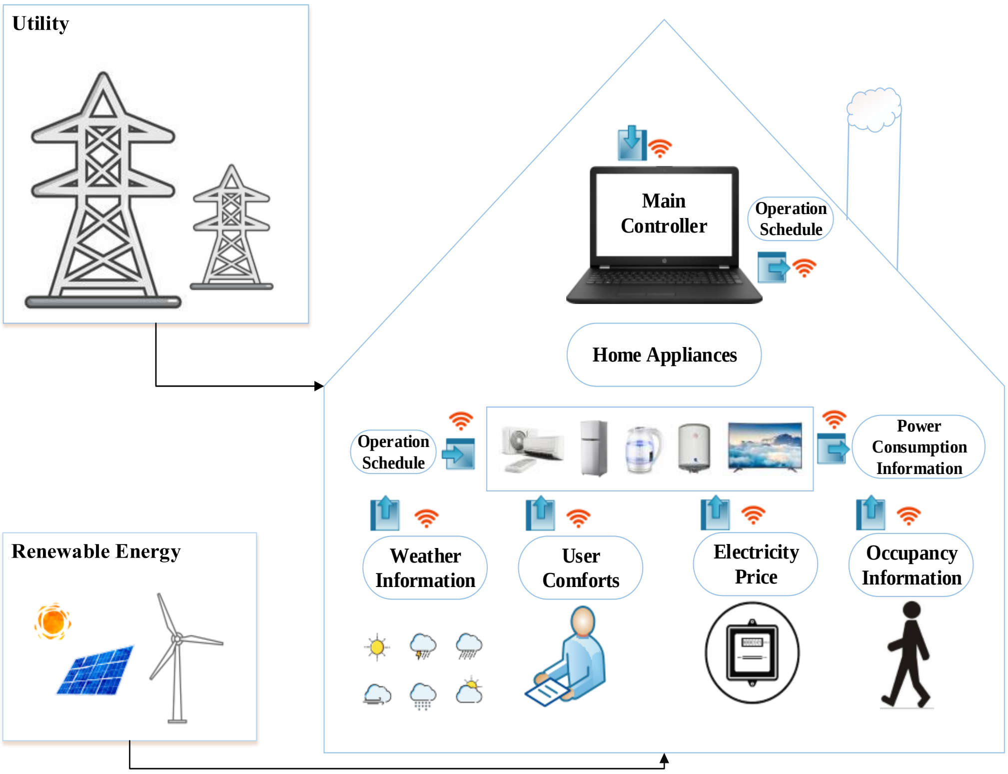


Figure 1: Main components of the HEM system

Figure 1 shows that energy saving and energy cost reduction are performed by an algorithm integrated in a main controller, which receives various inputs from the developed hardware parts in the system. Thus, the HEM system can have two main parts. The software side contains the algorithm that produces the scheduling commands on the basis of various inputs, such as user comfort, power consumption of each appliance, and electricity pricing scheme. The hardware part mainly comprises smart sockets that provide power consumption information to the main controller and actuate incoming commands from the same controller.

1.2 Problem Statement

Statistical reports show that providing information about end-user habits toward energy consumption regularly can effectively solve electrical energy wastage. Desley et al. [6] show that providing energy usage information can help the user to adjust appliances usage and reduce energy consumption by as much as 20%. Many devices and applications have been developed for personal electrical energy usage monitoring and energy management in homes and commercial buildings. Some of these methods only help determine energy consumption levels [7], whereas others offer additional information about the merits of energy saving, such as the financial benefits of turning off unnecessary appliances or shifting usage time. Other techniques include providing detailed load characteristics or representing them with emotional icons, such as an image of a polar bear on a melting iceberg, which informs users about the importance of reducing energy consumption.

The automatic control of individual devices has become feasible in recent years because of technological advancements. This progress began with the introduction of HEM systems that mainly relied on smart power sockets/plugs that can handle individual loads any time of the day. HEM systems help users reduce electricity costs by monitoring and controlling home appliances without affecting the level of user comfort. A research conducted by the National Building Controls Information Program identifies a link between energy consumption and control-related problems in buildings [8]. This study demonstrates that most problems related to inefficiency in building energy utilization systems stem from control problems linked with input devices, software programming, and operator interference. The aforementioned requirements for energy efficacy and management indicate that smart sockets encounter design problems, such as being equipped with a fixed voltage signal to avoid voltage sensor utilization, which may lead to inaccurate information and simplified programming code used in power and energy calculations.

HEM systems themselves have various drawbacks, such as lack of coordination between manual commands by users and the automatic scheduling algorithms and system impracticality, which has only been virtually simulated because of the incomplete consideration of all the comfort constraints required by users, thereby obliging users to trade off comfort for a decrease in their electricity bill. Furthermore, practically implemented systems can also lack important instrumentation for appliance performance monitoring. For example, the online information of room temperature is necessary in evaluating the comfort and energy reduction feasibility of any scheduling command from a main controlling algorithm.

These drawbacks are sufficient reasons for developing practical systems that can reduce energy consumption without affecting user comfort, and this study describes the design and development of such a system. The developed system consists of multiple smart sockets, programmable air condition (AC) remote, and room condition monitoring node that provide comfort inputs to the main controller. All the system's components are wirelessly connected through the Zigbee communication protocol to be easily implemented without any complex wiring. The system's reliability is also verified by the establishment of a rule-based algorithm that aims to reduce energy consumption in a 24-hour window.

1.3 Objectives and Scope of Work

This work primarily aims to develop and implement an HEM system that can reduce energy usage in a residential property. Sub-objectives defined to achieve this goal are as follows:

1) To develop a prototype HEM system that uses communication protocol, smart sockets, and other supporting circuitries

2) To develop an intelligent home energy coordination algorithm that helps users respond to time-of-use (TOU) tariff while being sensitive to consumer context and lifestyle using a deterministic rule-based technique.

The Zigbee communication protocol is selected to achieve the first objective. Various circuitries, such as smart sockets, room condition monitors, and light-dimming instruments, are developed to measure the needed inputs by using the coordination algorithm. Smart sockets are used also to turn attached appliances on/off depending on the remote commands received from the central controller.

The second objective is accomplished by determining the required user comfort, implementing a forecasting technique to expect and precoordinate according to the day-ahead price, and setting the rules of the algorithm such that energy reduction is guaranteed while user comfort is maintained.

1.4 Literature Review

This section includes a review of the state-of-the-art HEM systems described in the literature. Various techniques are generally used to simulate or design a practical HEM system. A summary of the work on developing algorithms is given. In addition, practical development trials are covered in the following subsections. Finally, background information and recent advents of the smart socket are also illustrated.

1.4.1 HEM Algorithms

Figure 2 shows the three main groups of HEM algorithms, namely, rule-based, artificial intelligence (AI)-based, and optimization-based methods.

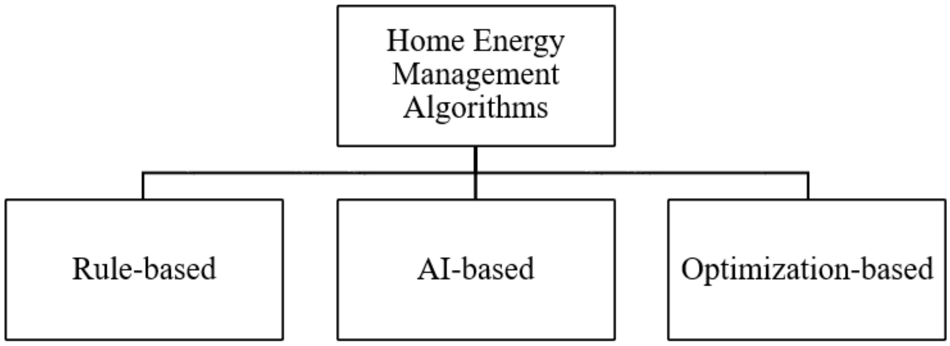


Figure 2: HEM algorithm categories based on the energy reduction technique performed

Rule-based algorithms use if/then rules built by experts who translate user comfort preferences and energy usage targets into organized thresholds. Accordingly, these rules must be followed to achieve the ultimate goal of the system, that is, decreased energy consumption without affecting the lifestyle of users.

AI algorithms are techniques that can be trained to learn the normal daily schedule of each appliance and the normal lifestyle of users by obtaining historical data related to these inputs. Then, such algorithms attempt to reconstruct appliance schedules such that the learned lifestyle is not affected. Artificial neural networks (NNs) (ANNs) are common examples of these algorithms.

Any optimization problem typically consists of an objective function and a group of constraints. The main goal of an optimizer is to find the most suitable solution for the objective function in the form of a minimum value, maximum value, or, as in this specific application, an optimal management schedule.

In addition, a pricing scheme should always be associated regardless of the algorithm to be used along with the hardware, for preventing use of the attached appliances during high-price times. Three common schemes are generally introduced as electricity pricing, namely, TOU, real-time pricing (RTP), and critical peak (CP) pricing (CPP).

The most common method among the three is the TOU scheme, where a day is divided into three main time slots, namely, max, middle, and minimum pricing periods [9]. Electricity producers commonly use this method to motivate end users to reduce and maximize their energy use during the maximum and minimum time slots, respectively.

The actual situation of the supply and demand required from the utility in the RTP or dynamic pricing is reflected in hourly energy price [10]. Electricity producers claim that this pricing scheme is the most efficient, flexible, and acceptable in the electricity market [11].

In CPP, end users are given incentives by suppliers when they shift their energy usage from the peak time to other times during the day. CP occurs when electricity demand increases dramatically, and users are notified upon occurrence of this phenomenon through the sending of electricity price to them [12, 13]. Retailers follow this scheme to take advantage of the large reduction at CPs.

1.4.1.1 Rule-based Methods

Many studies have used rule-based algorithms by setting the limits of comfort and energy usage. In [14], energy is controlled via smart taps in a network structure. Rete algorithm collects data and process rules by using smart taps. Similarly, descending priority is used to create if/then rules for scheduling home appliances to reduce energy consumption [15].

1.4.1.2 AI-based Methods

In [16], convenient thermal environment should be acquired in a domestic building that uses ANN. The ANN-based algorithm enhances thermal comfort by controlling the thermal loads in the building. In a related work, an HEM system is proposed using a machine-learning (ML) method [17] to train the energy consumption trend and optimization of the user and thus provide the best management schedule that will respond to the learned consumption trend. However, the implementation of such algorithm and the use of many regulatable and smooth energy variations are not practically available.

1.4.1.3 Optimization-based Methods

A greedy iterative algorithm is applied in [18] to schedule multiple users' appliances in a smart grid system. The objective is to minimize the aggregated energy use of all the consumers, which mainly depends on day-ahead hourly energy price. However, the authors' conclusions are based only on simulations and lack practical justification. In addition, many constraints, such as user preference and comfort, are not properly incorporated into the optimization problem.

Reference [19] uses an appliance modeling software to consider the realistic operation of various home devices in the simulation of an HEM controller. The controller mainly aims to reduce load peaks and smooth the power consumption trend. The proposed optimization algorithm considers updatable day-ahead price and outdoor temperature information along with user preferences. The authors claim that considering the proposed appliance models for the development of an optimized HEM controller is realistic. Adika and Wang in [20] propose a demand-side management and smart scheduling system for households with PV systems. The developed scheduler computes the expected load profile and PV generation of the user on the basis of the weather forecast for a specific day of a week. After the energy consumption of all the appliances is aggregated, the value of aggregated energy is minimized using an optimized schedule that uses a PV generator whenever possible [20]. Nevertheless, no comfort and user override constraint are considered in this simulation work.

Similar to the work presented in [17], the research presented in [21] considers three types of loads to simulate the optimization problem. The proposed controller receives the outdoor temperature, cost of energy usage, and price signal as inputs to the optimization problem. A convex cost function is used as the main objective function while the user comfort level is being maximized. The use of a convex objective function may not be accurate from a practical perspective because appliance-switching operations create discontinuity in the energy consumption pattern.

Reference [22] uses smart meter data, namely, energy consumption and price signal from utility, to simulate an HEM system. The system performs multi-objective optimization that minimizes daily electricity cost while maximizing user convenience. The main drawback of the proposed method is the use of limited constraints in the optimization, that is, room and water temperatures. In a linked effort, Moghaddam et al. [23] develop a programming model that solves the mixed-objective optimization problem of energy usage and user comfort level. Instead of using smart meter data, the authors assume that the required data can be retrieved from users and local energy resources, such as PV systems. Although the simulations decreased energy and user satisfaction using the algorithm, the research still lacks the consideration of user manual bypass operations in practical situations [23].

A direct load control scheme is proposed in [24] through a cooperative game union between distribution companies and customers. This union aims to find an optimal means of controlling loads to minimize costs. The research uses forecasting algorithms to address problems such as price fluctuations caused by updating the price information only once a day.

In relation to previous literature, an approach that aims to perform peak shaving by real-time scheduling of home appliances is illustrated in [25]. The research models common electrical appliances. The total power consumption of an electrical appliance is computed by multiplying its logic function by the rated power during its on time. The authors assume that no power is consumed when the appliance is inactive, which is not completely realistic. The system controller generates the on/off logic command according to the scheduling algorithm for peak saving and improved user comfort.

The incentive-based optimal scheduling technique is simulated in [26] to maximize earning and minimize daily energy cost by using a mixed-integer optimization approach. Although several constraints are assumed in the research, user comfort is not fully considered.

In [27], a scheduling algorithm that optimizes the starting time of flexible appliances and the power consumption level in non-flexible loads is proposed. A supplier sends the price signal to consumers every 24 h to enable each consumer scheduler to optimize the schedule of household operation. The authors define the source of discomfort caused by managing each appliance and then formulate the discomfort function by using the Taguchi loss function [28]. In spite of the good simulation results, no practical implementation of the proposed algorithm is discussed.

In addition, another optimal scheduling technique is developed in [29]. This research aims to minimize the cost of consumed energy by shifting loads from the peak price time to a period with less price whenever possible. However, such implementation might create undesirable peaks in the period of minimum time, thereby possibly affecting the utility side. In [30], an optimized operational scheme for household appliances is introduced by using a demand-side management-based simulation tool. The tool uses a particle swarm optimization algorithm to minimize customer cost and determine a source management technique. In [31], the authors develop an HEM system that provides optimum scheduling to operate electric appliances and control the amount of power provided back to the grid from the excess local PV generation using mixed-integer linear programming. Similarly, Deconinck and Decroix [32] present a common service architecture developed to allow end users to interact with other consumers and suppliers in an integrated energy management system. For users, the architecture facilitates renewable micro-generation for integration with the electric grid.

1.4.2 Practical HEM System

Reference [33] bridges the gap between the simulations and the practical implementation of HEM systems. This work consists of developing a test bed that can schedule lighting loads attached to a smart plug. The control scheme is based on the received power consumption information at the controller terminal, which in turn actuates the on/off commands of the load. In spite of developing the practical test bed, other important loads, such as thermal loads, which play a major role in the energy consumption and user comfort requirements, are not considered by the authors. These constraints act as key elements in the acceptance of the practical system to maintain user convenience while managing the energy in residential units [33].

Contrary to previous works, [34] develops a comprehensive HEM algorithm that incorporates distributed generation and a battery storage system (BSS). The developed controller aims to optimize the utilization schedule and time to charge of the appliance and discharge the BSS to minimize the daily energy cost of a household. The main contribution of the research is the consideration of a large number of home appliances and the usage of real data to simulate multiple usage scenarios.

A practical implementation of the energy management systems that consist of a home server and Zigbee-connected home appliances is proposed in [35]. The server reads forecasted weather information from the Internet to estimate the required energy generation from the connected distributed generators (DGs). A user interface is established to show the previous load profile and the generation history from the DGs along with the forecasted weather information. Nonetheless, the test bed cannot monitor necessary information that can be used to maintain user comfort. Such details as room temperature, thermal appliance set points, and water temperature in the electrical heater, can contribute to improving the efficiency of any HEM system [35].

Previous studies only consider low-energy-consuming appliances and assume that the management does not evidently impact the daily bill. Certain works do not consider many user comfort constraints, thereby affecting user lifestyle and causing system design inefficiency. Such issues are considered in the proposed design of the physical system in this research by the development of supporting circuitries that provide online information about inputs related to user comfort and lifestyle, such as room temperature.

1.4.2.1 Role of Smart Sockets in HEM System

Smart sockets are the core hardware devices in an HEM system. A smart socket reads the power consumption of any home appliance attached to it. The data are then transmitted in real time to the main controller to act as inputs to the management algorithm. The socket can also control the attached appliance by turning it on or off. Figure 3 shows the conceptual design of the smart socket.

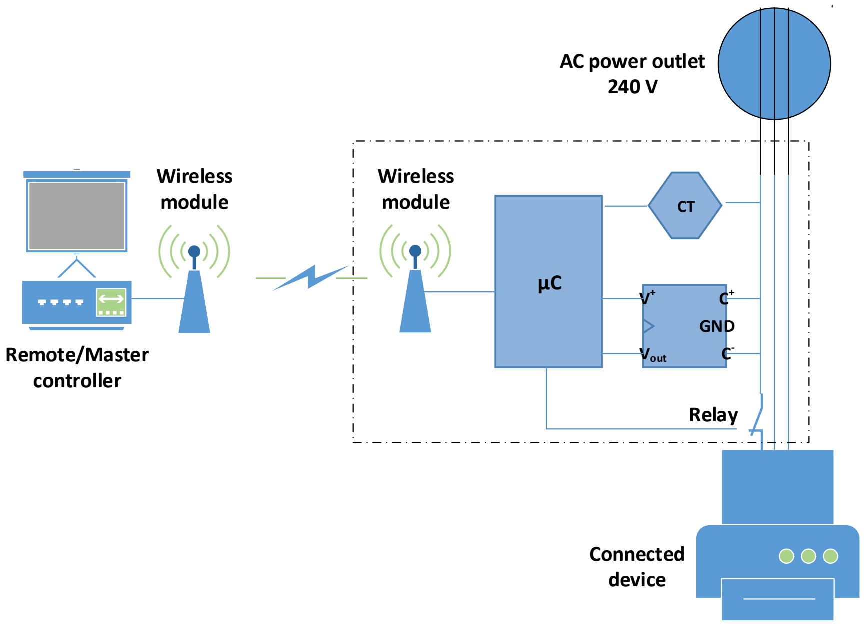


Figure 3: Conceptual design of the smart socket

Various methodologies can be followed in the design of the functionalities of a smart socket. Generally, the differences among these techniques can be found in the sensors used to read the currents and voltages and the communication method applied to send the measured data and receive the remote commands to and from the central controller. Typically, smart sockets perform wireless communication with the main controller. The most common wireless communication protocols are shown in Table 1 [36].

Table 1: Comparison among various wireless communication protocols

	Zigbee	Bluetooth	Wi-Fi
Price	Lowest	High	Highest
Coverage range (m)	10–100	10	100
Network topologies	Point to point, star, mesh, and tree	Piconet	Extended service set
Power required (mW)	63	100	Up to 500

1.4.2.2 Development of State-of-the-art Smart Socket

Many studies have been conducted to propose different prototypes of the smart socket because they act as the core instrumentation in any practical HEM system. Guangming [37] proposes a wireless power outlet that controls the home appliance attached to it without the need to add control wires or power cables during building construction. In the prototype, the Zigbee wireless protocol with 2.4 GHz frequency band is used as transmission medium. In a similar work [38], a smart socket with a Zigbee microcontroller and a user interface is developed [38]. The socket in this study comprises a current sensing part and a set of resistors arranged such that it divides the voltage until it reaches the suitable limit for the power metering chip. The total and individual power consumption of the connected device can be obtained through the device interface using the socket. However, the device is limited by its low sampling rate and limited communication coverage at the short distance of a few tens of meters only.

Subsequently, a power plug is developed in [39] to simultaneously provide real-time data on power consumption using a node and a control actuator. The plug comprises an Arduino Duemilanove microcontroller, which can measure sample current using a current transformer. However, a constant voltage value is used in calculating real power, and no variations are assumed in the root-mean-square (RMS) voltage for the main supply. In addition, an Ethernet module is used as a communication medium with on/off options for the electrical appliance.

In [40], research is conducted on a smart socket that can wirelessly monitor and control attached loads through a main controller. The smart socket comprises the following components: an ATmega328 microcontroller, which acts as the manager of all other plug components; a current sensor, which provides current information to the microcontroller; and a Zigbee transceiver, which communicates with another Zigbee transceivers connected to the user interface; and an actuating relay that turns the load on or off [40].

The design in [40] does not consider any measuring unit for the voltage signal because power consumption is estimated using the current drawn from the socket similar to the designs in previous studies, thereby fixing the voltage level to a reference value. In a related work, Ahmed et al. [41] introduces an alternative smart plug design for residential load monitoring. This design depends on a Zigbee PRO microcontroller and supporting sensing circuits for voltage and current measurements. After the Zigbee module in this design transmits information to a master computer, a predeveloped software with all the necessary formulas is used for power calculation and energy plotting. However, this design may exhibit calculation errors due to false or unreceived data from the power plug node [41].

Similar to [41], Raju et al. [42] construct a wireless sensor network to monitor and control electrical devices in residential units. Similar to [40], this work uses a current sensor and step-down transformer with a full-bridge rectifier to set the condition for the current and voltage signal suited for the Zigbee microcontroller. However, contrary to previous setups, this design adopts a Raspberry Pi microcontroller linked to a Zigbee transceiver for the master controller. Nevertheless, the use of a typical step-down transformer for voltage measurement may lead to incorrect power factor (PF) calculation because of the phase shifts between the primary and secondary voltages of the transformer [41, 42].

In [43], an active smart socket is developed to control the active power of loads connected to the socket by controlling the system's voltage. Four main units, namely, a sensor unit that contains current and voltage sensors for power calculation; a communication unit that sends measured data to the main controller; a control unit attached to the socket that handles the computation; and a main controller that serves as the remote control, are considered in the design. When the main controlling unit receives a regulating command, the device uses the voltage modulator unit to regulate the socket voltage.

In [44], an analog-to-digital converter (ADC) is used to measure voltage, and this setup affects the end values that represent active power reduction for a particular device. Han et al. [45] propose a smart home appliance control operated by human speech by linking previous efforts. The design involves the actuation of preset voice commands collected by the command executer, deployment of microphones throughout the area, and execution of command after processing. The set commands vary for each home appliance, but the command executer architecture is similar for all appliance units. The command executer comprises four main parts, namely, environment interface, statement interface, reasoning module, and command generator [45]. Despite the well-received concept of [45], the design lacks the capability of power monitoring systems. The controlling commands are also limited to specific commands, and updates are required each time a command is added.

In [46], a smart socket that can provide information to a connected appliance is developed. The socket comprises a Zigbee communication module, a power metering chip, and a microcontroller. The socket can wirelessly deliver power consumption and TOU readings to a gateway. This design can update the readings on the cloud server for easy consumer access. However, the socket design does not include a control unit and thereby does not provide any option for controlling the attached appliance.

Singaravelan et al. [47] developed a similar smart socket that can drop the standby power to zero when the user turns off the appliance; that is, the socket turns the device off completely when the user is not detected by an integrated motion sensor. By contrast, the smart socket switches the appliance to normal operation when the user is detected. The smart socket turns the power off completely when the task of the utilized appliance is finished by the user. The socket uses a microcontroller and a current sensor to ensure that the device remains in standby mode when user presence is detected near the device [47]. However, the socket does not include a real power monitoring option in its hardware design, and the current sensor, which can determine whether the appliance is turned on/off or in standby mode, is used instead to approximate the real power.

The aforementioned limitations and problems reveal the need to develop a smart socket that can accurately and efficiently measure various electrical parameters in addition to controlling connected loads. Thus, as presented in the current work, an enhanced smart socket that can be utilized for HEM is developed.

1.5 Chapter Summary

This chapter provides an overview of existing HEM systems and the background required for an understanding of the main components and terms related to the research of this thesis. Moreover, the main problems that are addressed in this study are clarified along with previous research on the development process of HEM systems. Further details of the developed system are explained in the following chapters. The organization of the thesis is depicted in Figure 4.

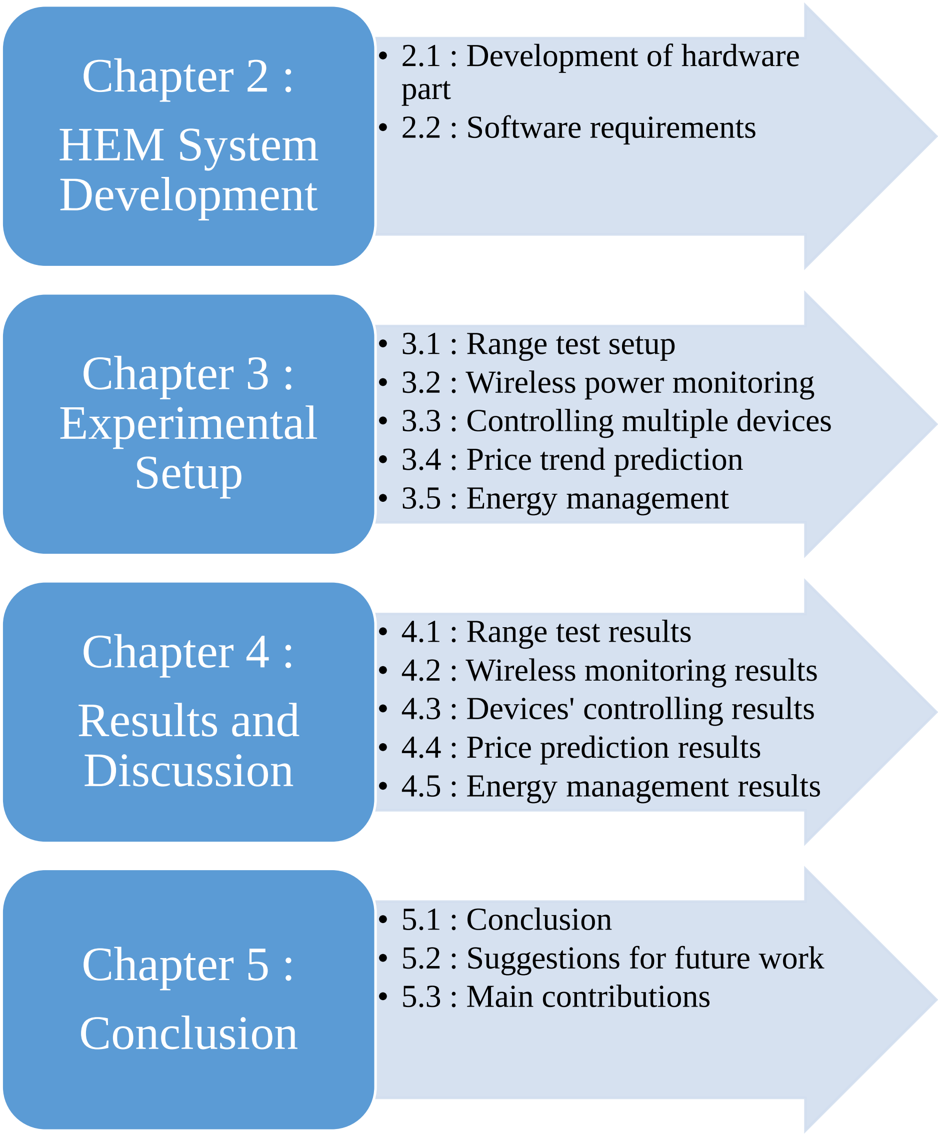


Figure 4: Thesis organization

Chapter 2: HEM System Hardware Development

The hardware development process and the software's involvement in the hardware are illustrated in this chapter. The components used in constructing the different instruments are provided along with their main roles, and details of the hardware construction of different instruments are explained. Moreover, the software part of each instrument is explained in the second subsection of this chapter.

2.1 Hardware Development

2.1.1 Description of Components

Many components are used to construct the various instruments used in building the HEM system. Important components and their corresponding functionalities are detailed in the following.

2.1.1.1 Microcontroller

Signals are initially processed by the microcontroller and stored in its memory. Then, the processed data are transferred to the communication module for transmission. The microcontroller can process the incoming commands from the main controllers before generating the actuating command to its connected components. Thus, the microcontroller is the most important part of the instruments constructed in this research. Arduino Nano V3.0 is a component that is mostly used as a suitable microcontroller due to its small size, sufficient memory, and suitable programming development platform [48].

The Arduino Nano microcontroller has 13 digital input/output (I/O) pins that can be configured as inputs to the microcontroller or outputs from the microcontroller that are used to send or receive commands at certain voltage levels. The microcontroller also contains eight analog pins, with the onboard analog integrated to the digital converter channels via the ATmega328 controller. Each channel has a resolution of 10 bits, indicating the capability of returning integers that range from 0 to 1023. Although such analog pins are usually used as inputs from analog sensors, they can also function as I/O pins. The Arduino Nano can operate at different voltage levels, namely, 5 V for the supply and 3.3 V for the onboard voltage regulators. These sources can also be used to supply power to other units in the constructed instrument. The use of a single supply source can unify the voltage references of all modules integrated into the developed instrument. The recommended voltage of the Arduino Nano ranges from 6 V to 12 V, but the specific power depends on the attached sensors or the Arduino Nano's shield. Figure 5 shows the full layout of the Arduino Nano microcontroller.

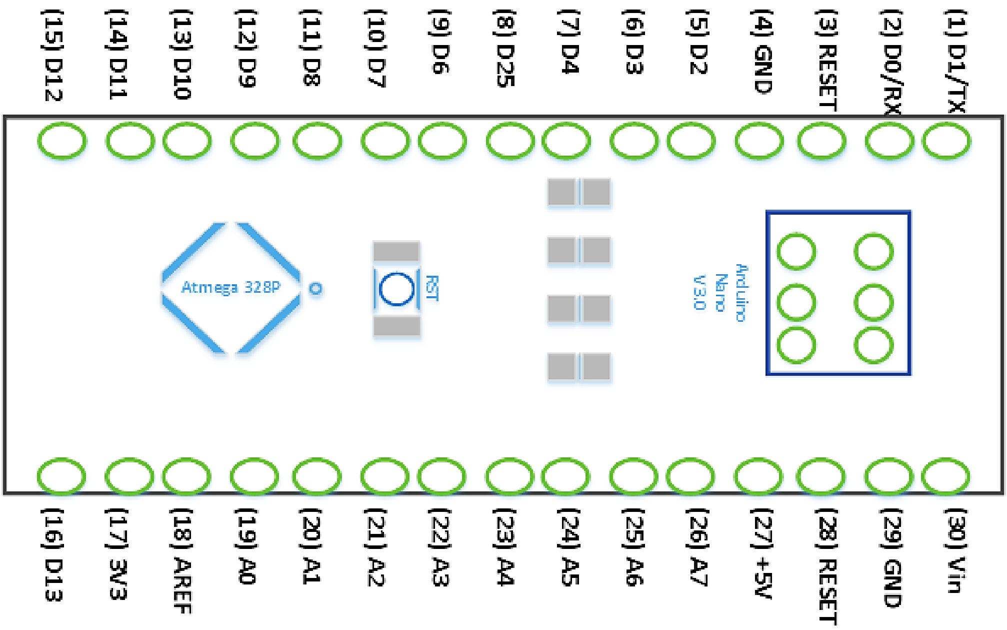


Figure 5: Arduino Nano with pin specifications

2.1.1.2 Power Supply and Actuating Relay

Switch-mode power supplies are used to supply the Arduino boards. The utilized power supplies provide 12 V with 0.85–1 A and are therefore sufficient for this application.

A 10 A relay with a coil voltage of 12 V is used to control the device connected to the smart socket instrument. This relay can activate its contacts on the basis of the input command generated by the Arduino Nano, thereby acting as a switch. The connection of the relay is shown in Figure 6.

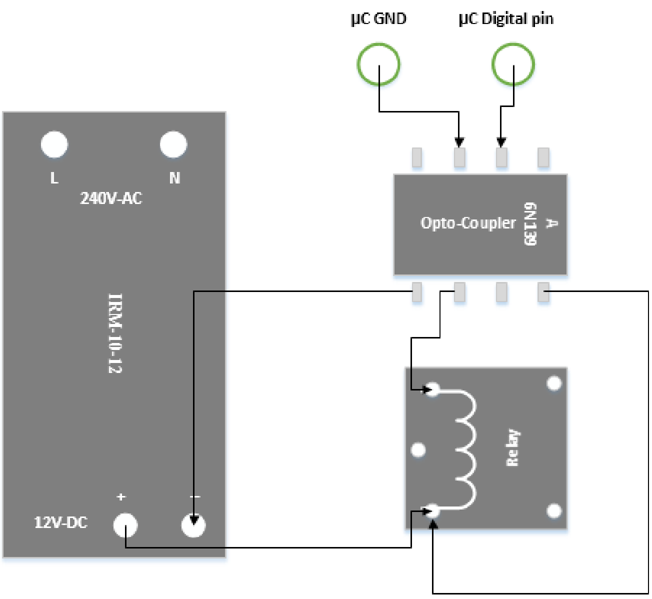


Figure 6: Power supply and relay

2.1.1.3 Communication Module

A communication module is needed to transfer the calculated voltage, current, power, and PF to the user interface. Numerous communication protocols, such as Zigbee, Bluetooth, and Wi-Fi, are available. The Zigbee protocol is selected due to its various advantages, such as the low cost modules, wide-ranging applications, various options for network configuration, and low power requirements (Table 1).

The Zigbee protocol can be used with the XBee communication module (Digi International), which produces more than 30 combinations of such modules [49]. XBee can be categorized into two main series. Series 1 is excellent for point-to-point communications, whereas Series 2 offers various network topologies, such as star, tree, and mesh organizations. Only modules with the same series can communicate [49]. Series 2 modules are used in this design because they can offer the required network organization and provide various kinds of modules that differ in terms of coverage range, transmission power, and antenna type. XBee-Pro S2C is particularly selected for application because of its 100 m indoor coverage range (line of sight) with only 63 mW of transmit power.

XBee S2C is an embedded system that can provide the required communication solution by using the Digimesh Zigbee protocol. A single XBee module comprises 20 pins with 2.4 mm spacing between each pin [49]. A total of 12 pins can be generally used as I/O digital pins, among which four can be used to read analog data from sensors. Such pins require 3.3 V supply to function properly. These pins can interact with the Arduino Nano in addition to transferring data wirelessly. Figure 7 shows that the interaction between Arduino Nano and XBee modules can be performed by connecting the Rx and Tx pins of the XBee module to those of the Arduino Nano.

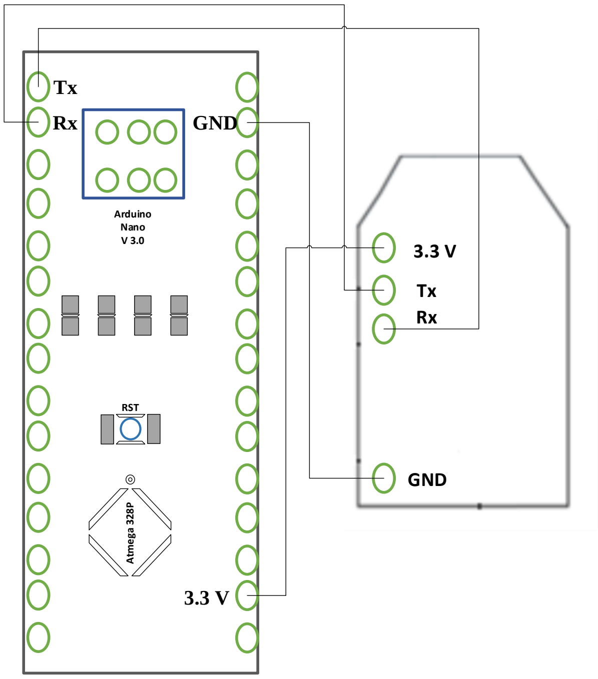


Figure 7: XBee and Arduino interface

2.1.1.4 Current Sensing Module

The line current can be measured by a sequential connection of a resistor between the lines. This connection ensures that the voltage drop across the inserted resistor is proportional to the current. However, this technique is cumbersome and difficult to implement because frequent calibration and a high-wattage resistor are required. Thus, the ACS712 Hall effect current sensor is used to overcome this problem.

Among the many alternatives, the ACS712 current sensing module is selected to measure the current signal because the sensor is compatible with the nano microcontroller and can be supplied by the 5 V supply integrated into the microcontroller. Furthermore, the output of the sensor is suitable for the ADC channel in the main microcontroller chip.

The ACS712 is a Hall effect-based current sensor that should be placed in series with the load. This sensor can provide accurate current measurements with a total output error of ±1.5%. The sensor also provides current measurements in the form of voltage signals that range from 0 V to 5 V, depending on the measured input current. Moreover, ACS712 comes in three different modules that comply with the amount of the measured current. The modules are as follows: 5 A module with 185 mV per Amp output sensitivity for small loads, 20 A module for average loads with 100 mV per Amp output sensitivity, and 30 A module for large applications with 185 mV per Amp output sensitivity. The 20 A module is used in the power socket design because the loads can vary up to 13 A. The sensor output is filtered by a low-pass filter to smooth the current signal before it reaches the analog pin A2 on the Arduino Nano board, where the ADC conversion occurs.

2.1.1.5 Voltage Sensing Module

A resistive dividing circuit is constructed and used as voltage sensor because the power line voltage is higher than the maximum input voltage required by the microcontroller ADC. Therefore, the voltage signal must be attenuated to approximately two-thirds the maximum ADC input to ensure the elimination of clipping in the signal. In addition, the ADC channels on the microcontroller can only vary from 0 to 1023, and thus, a DC offset is required to shift the voltage signal up and ensure compatibility with the analog pin on the microcontroller board. In this circuit, two resistors with the same value (R and R') are used to force the voltage signal to oscillate at a reference point, which is half the applied voltage (VCC = 5 V). Therefore, the center of the voltage signal shifts to 2.5 V instead of the original 0 V. Figure 8 shows the DC offset circuits required for the power line voltage-conditioning circuit.

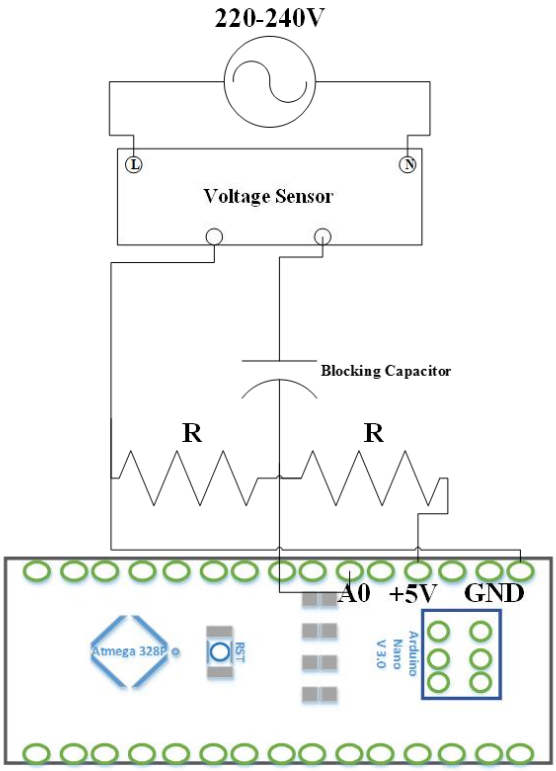


Figure 8: DC offset circuit and voltage sensor connection to the microcontroller

2.1.1.6 Room Temperature Sensing Module

DHT22 sensor is used to read the room temperature and update the microcontroller with new data every two consecutive seconds. Basically, the DHT 22 consists of a thermistor, which measure the temperature and ADC to produce a digital signal to the microcontroller, which then carries the temperature information. Moreover, the sensor needs a power supply of 3–5 V, thereby allowing for easy integration with the Arduino Nano microcontroller.

2.1.1.7 Waterproof Temperature Sensing Module

The DHT22 temperature sensing module is not suitable for applications where the water or inside temperature of a refrigerator need to be measured. For this purpose, the internal temperature of the refrigerator and the heater water are measured using a

DS18B20, a waterproof temperature sensor. The sensor comes in the shape of a probe, making it easier to be placed inside the refrigerator or the inlet/outlet pipe of the water heater. This module is also combinable with the Arduino Nano microcontroller because it can be powered from the 5 V source integrated in it.

2.1.1.8 Light Illuminance Intensity Sensing Module

A TEMT 6000 light sensing module is used to continuously read the light intensity inside a room through the analog pins of the microcontroller. However, a calibration process is needed to make the reading lux values instead of voltage levels. For this purpose, the commercial lux meter shown in Figure 9 is used.

Figure 9: ST-1309 commercial lux meter

The TEMT 6000 sensing module and the commercial meter reading probe are placed in the same location during the calibration process. Next, the lighting intensity is varied, and the voltage level read by the sensing module is captured along with the corresponding lux read from the commercial meter. Then, a polynomial equation is formulated using a curve fitting tool on the basis of the voltage and the lux value. The obtained relationship given in Equation 1 is implemented in the microcontroller to read the lux value directly through the sensing module.

$$lux = 455.02 \times \text{voltage read on analog pin} + 25.368 \qquad \text{Eq. (1)}$$

2.1.1.9 Infrared (IR) Command Decoder

A TSOP38238 IR receiver diode is used to learn the preprogrammed IR commands from the original AC remote controller. This module decodes IR commands into readable arrays by using the Arduino Nano microcontroller so it can store the commands in its internal memory and use them when needed.

2.1.1.10 Human Detection Sensors

A passive IR red (PIR) motion detection sensor is used to detect movement inside a room, and an SEN 1059 carbon dioxide (CO_2) sensing module is utilized to read the increment in the CO_2 concentration that resulted from human presence inside the room. Subsequently, this information is used to detect the occupancy status of the room.

2.1.2 Developed Instruments

All the aforementioned components are used in different combinations for creating instruments with different functionalities to provide the main controller with the needed inputs and to actuate its commands. The constructed instruments are as follows.

2.1.2.1 Smart Socket

The proposed socket can monitor the power consumptions of an attached appliance with a rating of up to 13 A and turn it on or off by using the relay integrated in it. The instrument determines and processes the single-phase power line voltage and current of the connected device. The socket sends the captured data to the master node when connected to a master node or controller. The socket utilizes the aforementioned communication module to use wireless connectivity and its memory for storing the raw data provided by the microcontroller. Figure 10 shows the components (left) used to develop the plug prototype on the right.

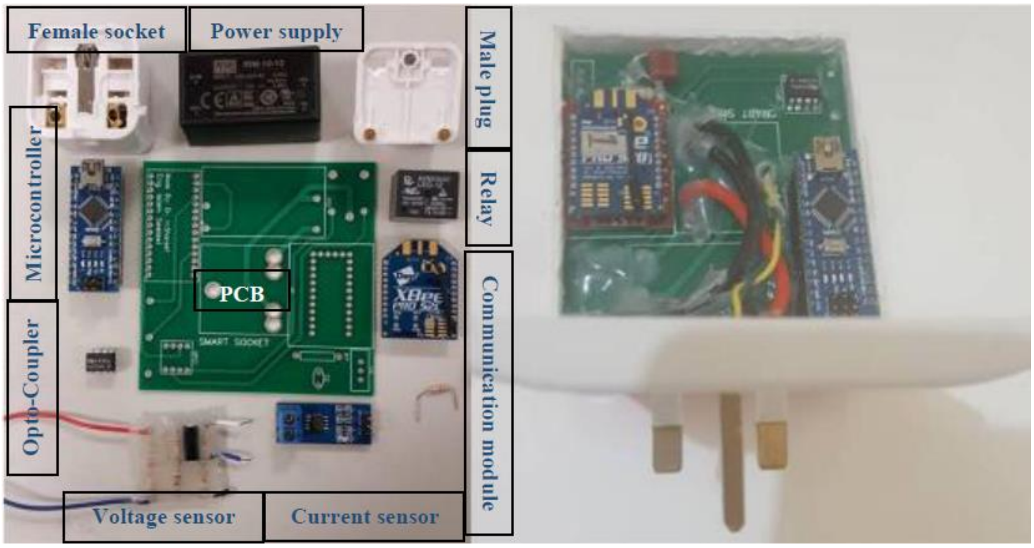


Figure 10: Smart socket instrument

A printed circuit board (PCB) is manufactured to replace most of the wired connections using copper traces for size compactness and for the separation of high- and low-voltage connections. A two-sided PCB is designed to realize the high-voltage connection at the bottom and low-voltage connection on the top of the setup. The components are also soldered to the PCB to complete the hardware set placed inside an isolated box; the female socket side is used for appliance connection, and the other side is composed of three male pins for the wall power plug.

2.1.2.2 Room Condition Monitoring Circuitry

An ambient condition monitoring circuit that can transmit room temperature, room humidity, illuminance, and CO_2 concentration is constructed. It can also detect motion in the room due to the added motion sensor, thereby providing the main controller with the necessary inputs for the decision-making algorithm. The circuit with the employed sensors are shown in Figure 11.

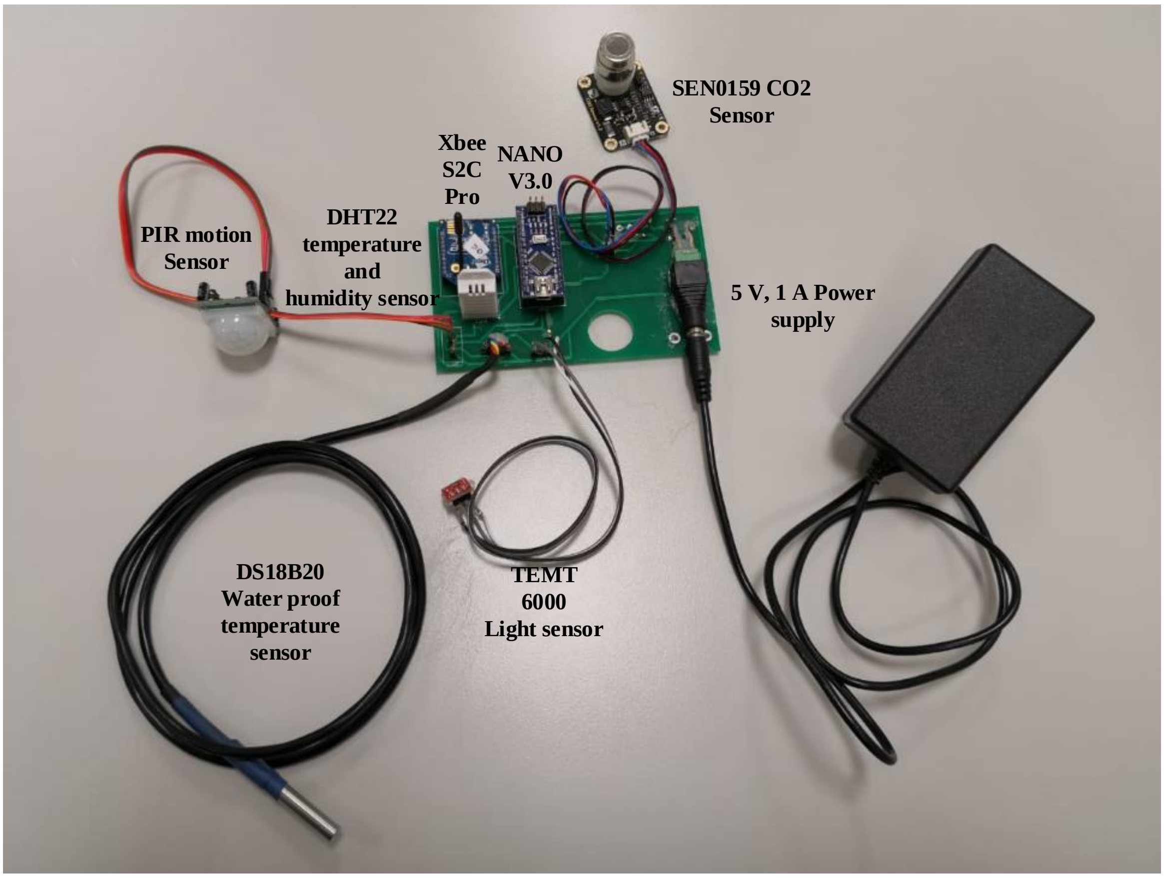


Figure 11: Room condition monitoring circuit

2.1.2.3 Zigbee-connected Light Dimmer for LED Light

Lights are major appliances used in residential units. Many home owners neglect to turn off or dim their lights when natural light is adequate or the room has no occupant. Therefore, a Zigbee-connected dimmer is designed for providing options that could reduce energy consumed by LED lights by decreasing the light intensity when conditions are favorable. Figure 12 shows the developed dimming circuit.

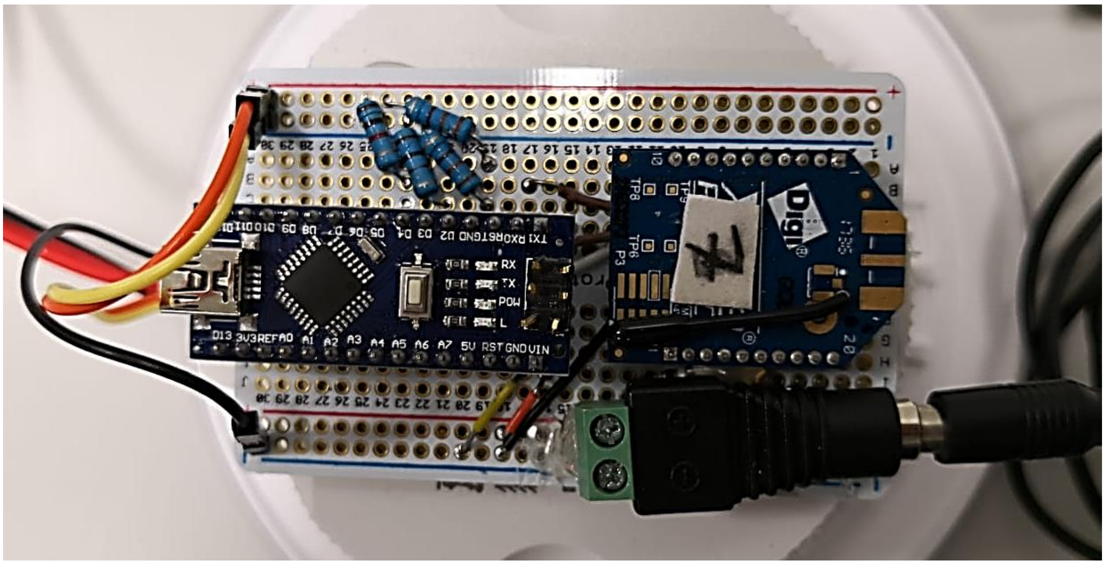


Figure 12: LED light dimming circuit

As depicted in the figure, when the communication module embedded in the dimmer circuit receives a dimming command, it passes the command to the microcontroller for processing. Subsequently, the microcontroller generates a sequence of pulses that dims the light to a certain level based on the remote command.

2.1.2.4 Zigbee-connected IR Remote for AC

For flexibility in controlling AC units, a learner IR remote with Zigbee connectivity is designed. The remote uses an IR receiver diode to learn the preprogrammed IR commands from the original AC remote controller. An ordinary IR transmitter is used to actuate the received commands from the scheduling controller terminal. Figure 13 presents the remote circuitry.

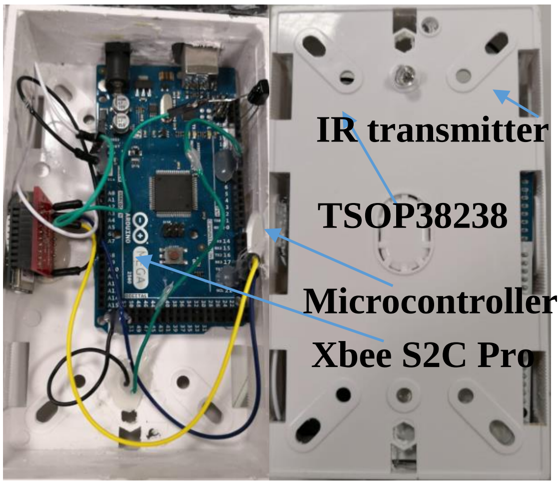


Figure 13: Zigbee-connected IR learner remote controller

Figure 13 shows that the remote can learn the IR digital code patterns from the original AC remote controller by using the TSOP decoding diode and the Arduino Mega microcontroller. This microcontroller saves these patterns as on and off commands and various temperature settings in the internal memory. When a remote command is received from the scheduling controller terminal via the integrated Zigbee communication module, the microcontroller reveals one of the IR codes learned earlier using the IR transmitter. Hence, the Zigbee connectivity of the remote allows the user to control the AC units using remote commands from the scheduler algorithm or by manually utilizing the commands in the user interface. Figure 14 illustrates the remote functionality.

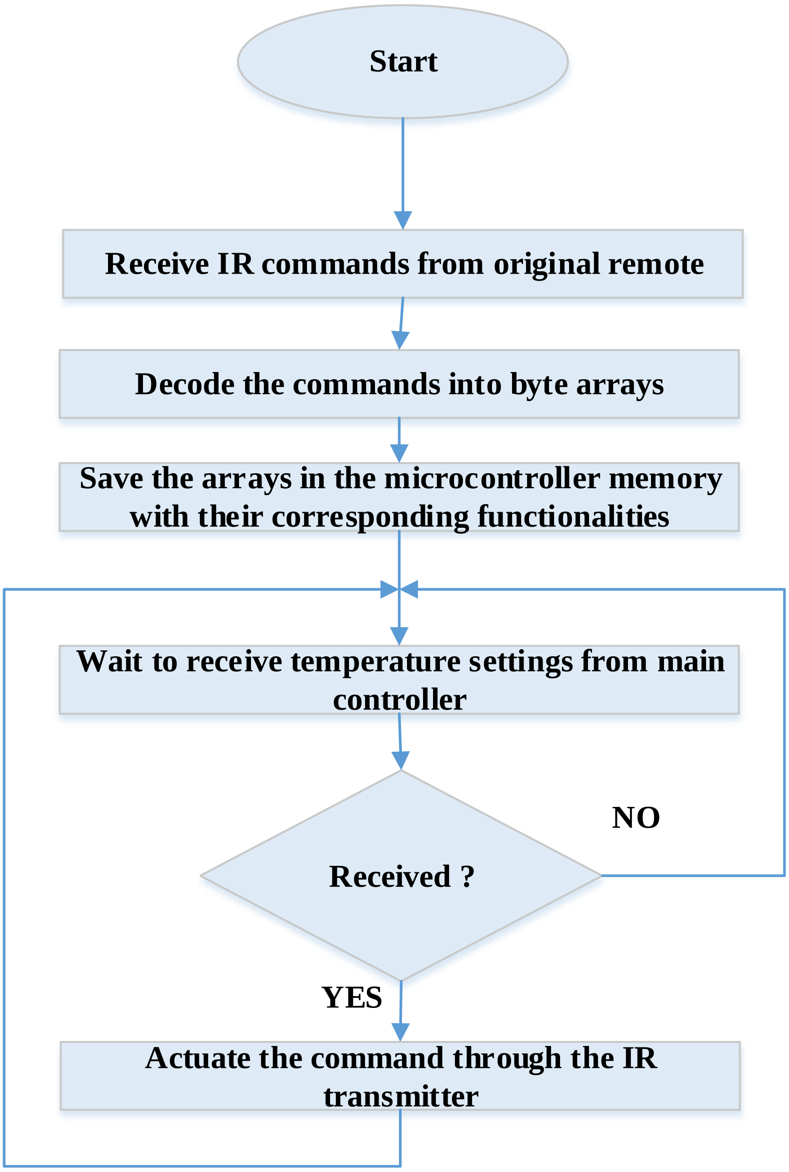


Figure 14: Working principle of the Zigbee-connected remote

2.1.2.5 Scheduling Controller Terminal

All aforementioned instruments are governed and controlled wirelessly by a personal computer (PC) supported by the software MATLAB and connected to a communication module through a USB dongle.

2.2 Software Requirements

Four software packages, namely, DipTrace computer-aided design (CAD) for the PCB, XCTU for the XBee module configuration, Arduino (IDE) for the microcontroller program, and MATLAB for the main controlling algorithm and graphical user interface (GUI), are mainly used to design the aforementioned instruments.

2.2.1 DipTrace for PCB Design

DipTrace is a CAD software used to design single or multiple PCB layer/s. The software package comprises different user interfaces with varying capabilities. The first interface allows users to design the component symbols for the second interface. The second interface allows users to design a full schematic of a certain circuit. The third interface allows the design of the actual footprint of the component before it can be used to plan the layout of the final PCB. The software is used to print the circuit boards of the smart socket and the room condition monitoring circuitry.

2.2.2 XCTU

XBee modules can operate in transparent (AT) and application programming interface (API) modes. The AT option allows a user to use the digital pins on the XBee board to collect and send data to a remote XBee without formatting any data package. The AT mode is usually used for point-to-point communication. Whereas, the API mode provides a user additional options to build the network as point-to-point, star, or mesh networks.

Mode selection is determined by using the XCTU configuration software (Digi International), which allows users to specify the attached module as a coordinator or router in the specified network. In the proposed HEM system, all the modules are configured to operate in API mode with one of the modules acting as the network coordinator connected to the user interface. All the other modules act as routers that transmit data values from the microcontroller.

2.2.3 Arduino IDE

All the microcontrollers of the aforementioned instruments are programmed to read the attached sensor inputs and transmit these readings to the main controller through their interface with the attached communication module in their instrument using IDE. The IDE allows the programming procedure to be conducted using C/C++ programming or Arduino language. After completion and compilation, the code is uploaded to the board by a USB cable. However, the functionality of the microcontroller in the smart socket is complicated because it is where PF function and real power calculations are handled. In this specific case, microcontroller board programming is performed by taking 100 samples (n) of voltage and current sensor readings and storing them in the two arrays used for RMS calculation. The RMS values of the current (I_{rms}) and the voltage (V_{rms}) are calculated by Eq. (2) using a program code [50].

$$X_{rms} = \sqrt{\frac{1}{n}(X_1^2 + X_2^2 + \cdots + X_n^2)} \qquad \text{Eq. (2)}$$

The Vrms and Irms values are used to calculate the apparent power using the following expression [50]:

$$S = I_{rms} \times V_{rms}. \qquad \text{Eq. (3)}$$

Instantaneous real power (P(n)) is initially calculated by Eq. (4) using the 100 samples obtained from the voltage and current sensors [50].

$$P(n) = i(n) \times v(n) \qquad \text{Eq. (4)}$$

Then, the average power is obtained as follows [50]:

$$P_{AVG} = \frac{1}{n} \times \sum_{i=1}^{n} P(n). \qquad \text{Eq. (5)}$$

Finally, PF is derived from the calculated average power and apparent power as follows [50]:

$$PF = \frac{P_{AVG}}{S}. \qquad \text{Eq. (6)}$$

Moreover, the values to be transmitted in all instruments are converted into data bytes and combined with the sending node address to assume the form of data packets for subsequent transmission. This transformation can be conducted by using the union function provided by the C programming language. This function can convert a float or integer value into a 4-byte array. Then, the procedure is reversed in the receiver node to retrieve the data and identify the sender.

The flowchart in Figure 15 summarizes all the steps of smart socket functions, including reading, calculating, and transmitting various socket powers. The figure also describes the generation of commands of the remote controller to different sockets.

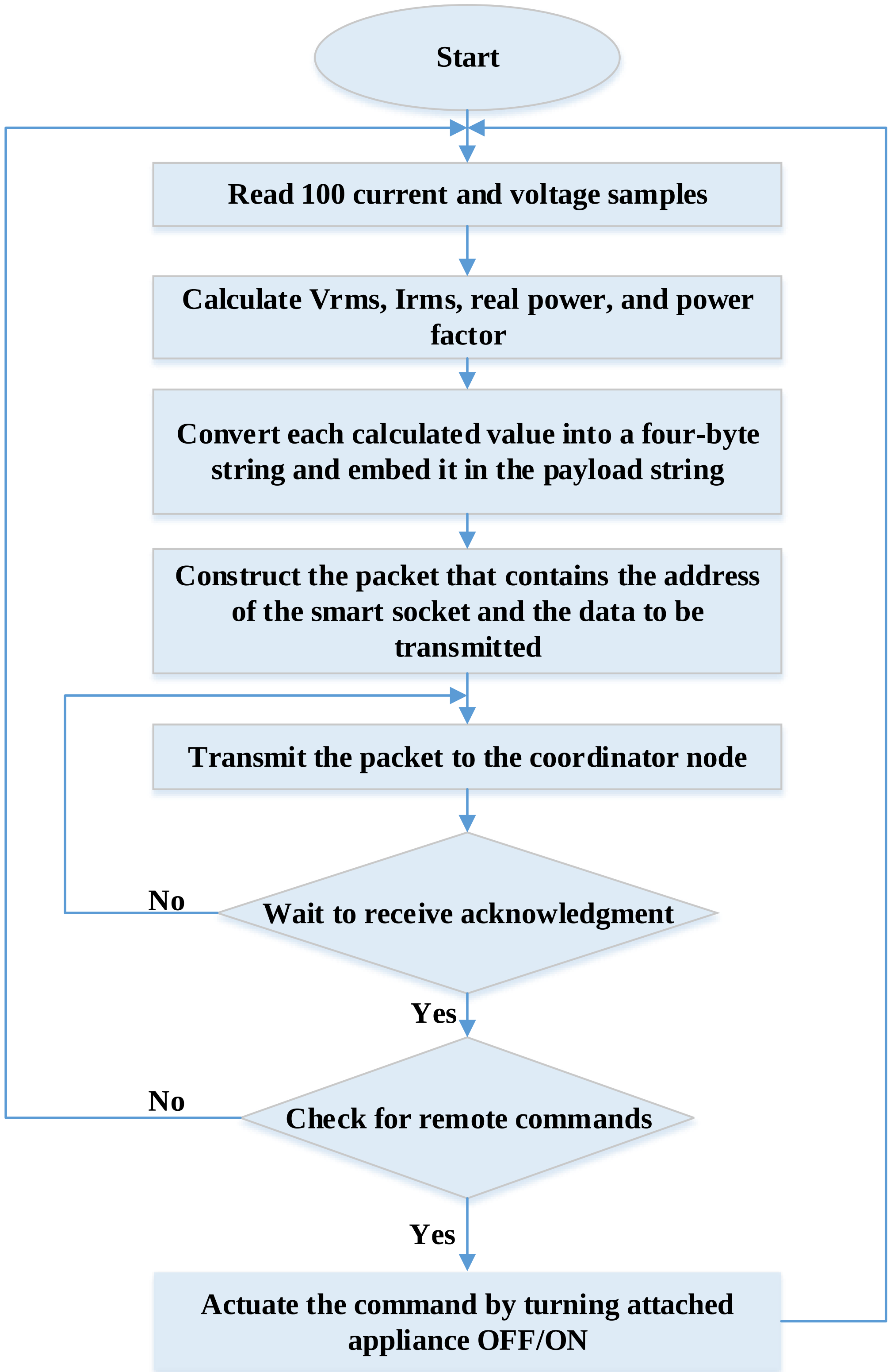


Figure 15: Smart socket data processing steps

2.2.4 MATLAB Software and User Interface

A MATLAB program supported by a GUI on the main PC is developed to contain the automatic scheduling algorithm and aims to give the user freedom to overcome automatic scheduling by controlling the inputs and outputs shown on the GUI screen. Figure 16 shows a screenshot of the developed main GUI window.

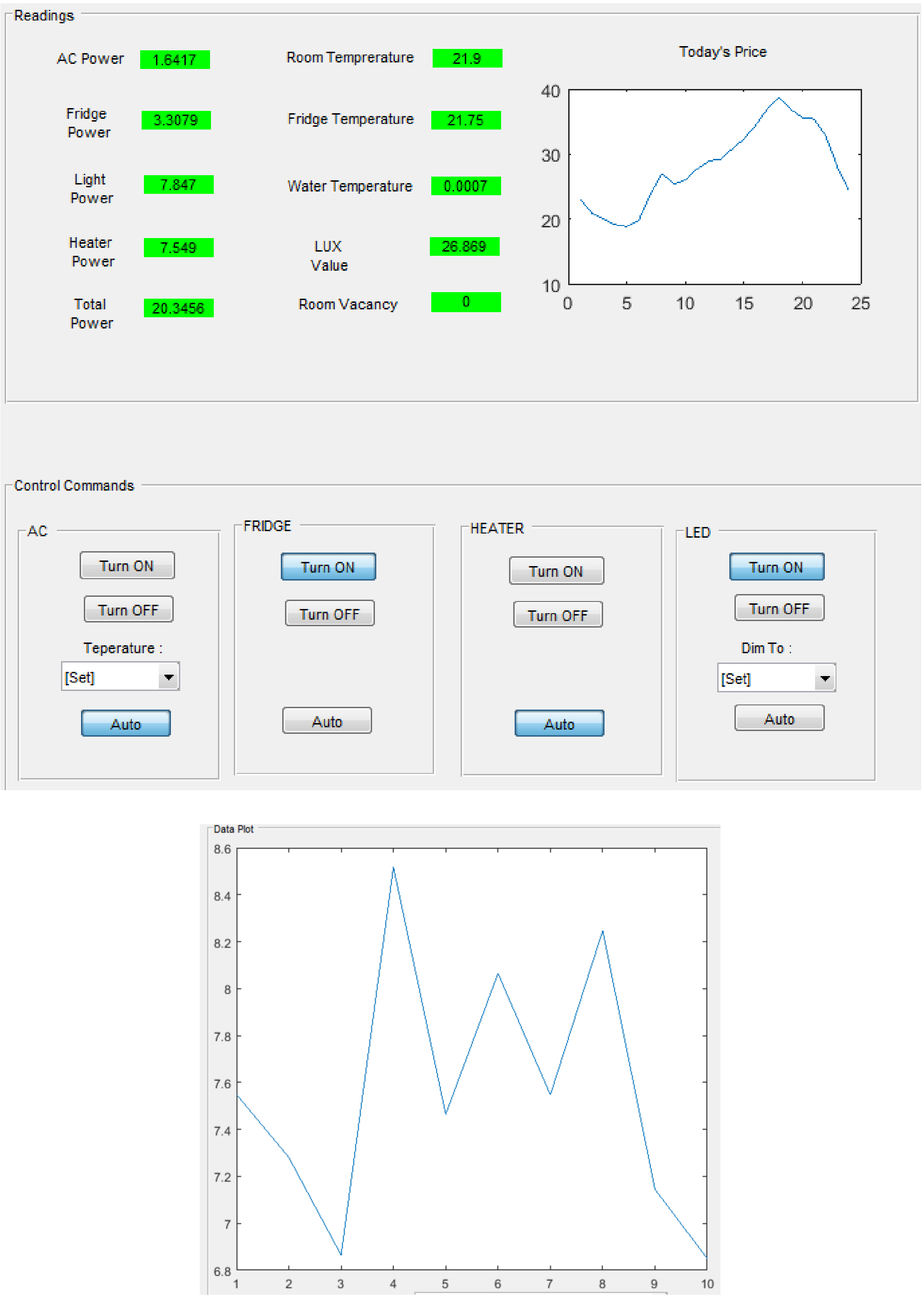


Figure 16: Graphical user interface of the proposed energy management system

2.3 Chapter Summary

This chapter describes the development of the system components that are utilized for obtaining real-time inputs and actuating the commands that come from the main scheduling terminal. The use of these instruments and their interaction with the main controller are further explained in the next chapter.

Chapter 3: HEM System Implementation and Testing

This chapter contains detailed explanations about the five experiments conducted to validate the performance of the designed HEM system. The first experiment validates the reliability of the Zigbee protocol used in this application. The second experiment validates the accuracy and reliability of the smart socket prototype in measuring the real powers of different appliances (i.e., smart socket as a wireless power meter). The third experiment determines the capability of multiple smart sockets and the central controller in simultaneously transmitting and receiving data and controlling various end-node smart sockets. The fourth produces a price trend-predicting technique for day-ahead appliance scheduling. Finally, the fifth experiment investigates the effect of using the HEM system on energy usage and daily bill.

3.1 Experiment 1: Effective Range of Zigbee-connected System Components

In this experiment, the smart socket is placed in a fixed position and used to read and transmit the power data of an attached home appliance. In addition, the central controller is positioned at 2.25 m increments toward the farthest direction of the house until the end of the intended coverage area (with room walls as barriers) is reached. The received signal strength is subsequently recorded every 2.25 m step using XCTU to check signal quality according to the location of the central controller (Figure 17).

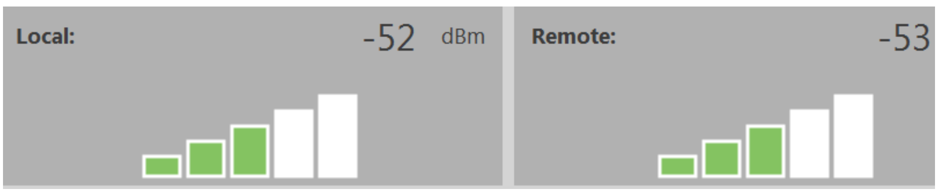


Figure 17: Sample screenshot of range test indices

3.2 Experiment 2: Smart Socket as Wireless Power Meter

Various home appliances (Table 2) are used to test the accuracy and reliability of the prototype smart socket as a power meter. Among these appliances, the refrigerator is monitored the longest to observe the reliability of the designed smart socket.

Table 2: Appliances used with smart socket for power consumption monitoring

Home appliance	Monitoring period (s)	Power rating (W)
Refrigerator (LG-Gr-B522GLHL)	132068	190
Air conditioner	360	2800
TV	678	92
Blender	156	100–500
Microwave oven	406	1050
Kettle	360	1850–2200

Figure 18 shows the experimental setup used to collect the voltage, current, various power values, and PF from the refrigerator using the prototype smart socket. A power quality analyzer (PQA) is simultaneously used with the smart socket for data verification. The smart socket data are wirelessly transmitted to the central coordinator PC, and the data file is updated every 2 s. Although the PQA only allows the saving of real power data in its internal memory for subsequent retrieval using an RS-232 serial interface, the analyzer can show the values of other parameters, such as voltage, current, apparent, and real and reactive powers, in real time. A similar setup is used with the other devices.

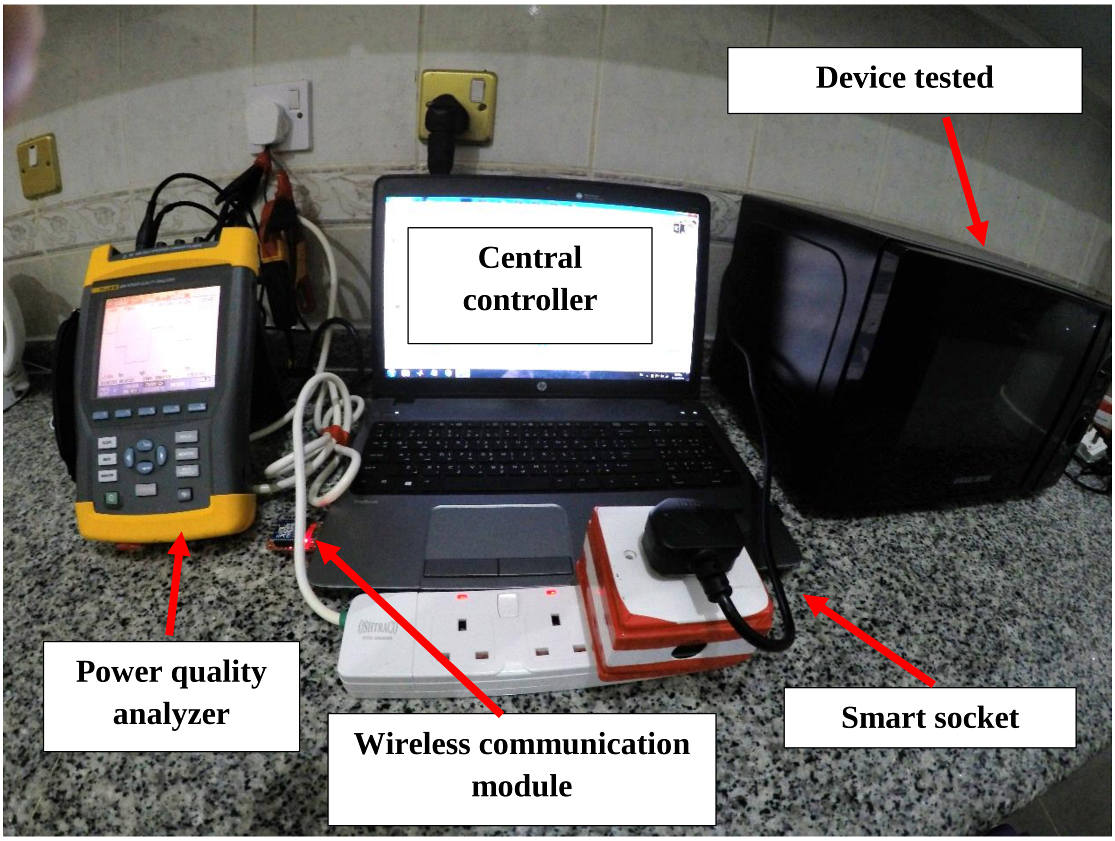


Figure 18: Setup for Experiment 2

3.3 Experiment 3: Controlling Multiple Smart Sockets

Three home appliances from Table 2 are selected to demonstrate the controllability of the smart socket by using the on/off combinations for the selected devices (Table 3). Each device is connected to a smart socket, and the three sockets are connected to the same circuit using a power extender. This setup allows the PQA to measure the aggregated power consumption of the on/off combinations of the connected devices (Figure 19). The third experiment aims to reveal the two-way communication between the central controller and each individual socket while retrieving data and ensuring coordination among the sockets.

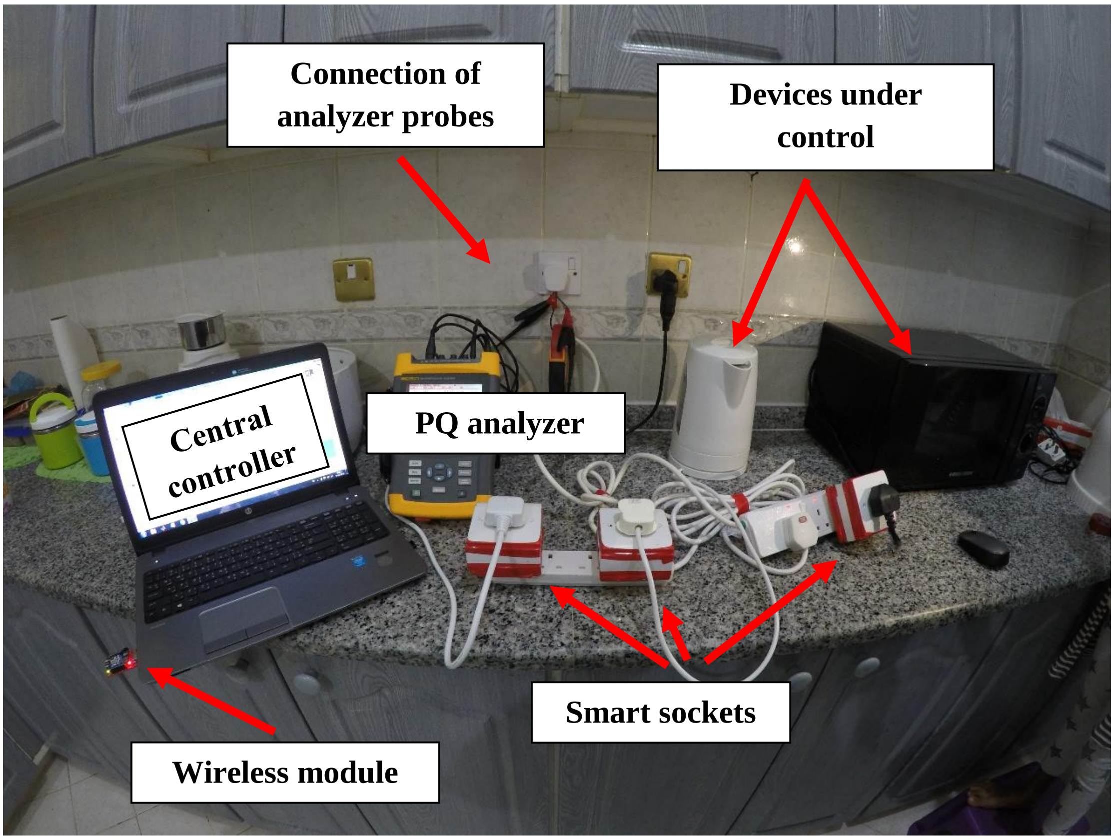


Figure 19: Setup for Experiment 3

Table 3: On/off combinations of selected devices produced by control of their respective smart sockets

Refrigerator	Kettle	Microwave
ON	ON	ON
ON	ON	OFF
ON	OFF	ON
ON	OFF	OFF
OFF	ON	OFF
OFF	OFF	ON
OFF	OFF	OFF

For each combination in the test, the total power trend of the devices is recorded in real time using the PQA connected at a common point for all devices. Each socket individually sends the power consumption of the connected load using the proposed wireless communication medium. The on/off controlling commands of the sockets are generated by the central controller.

3.4 Experiment 4: Price Trend Prediction

The ANN model is utilized and trained in this experiment as a method of predicting the day-ahead electricity price trend, which is to be used as input to the management algorithm. ANN is an ML method that is influenced by the biological NN in the brain of the human body. The term “neural” comes from the processing units in the ANN called neurons, which are connected by synapses to mimic an actual NN. Each ANN model consists of at least three main layers, namely, the input layer, where the inputs of the model come from; the hidden layer, where the training and the processing of the model are performed; and the output layer, where the output is expressed to the user. Moreover, ANN models come in various kinds, depending on the algorithm used by the model to be trained and to perform the required task, such as Bayesian regularization, scaled conjugate gradient, and Levenberg–Marquardt. The Levenberg–Marquardt is used in the present work to predict the price trend because it utilizes the feedforward technique for training and testing. Therefore, after the network is trained, the information moves in only one direction through the neurons and does not perform the learning process. Figure 20 shows the structure of a single neuron.

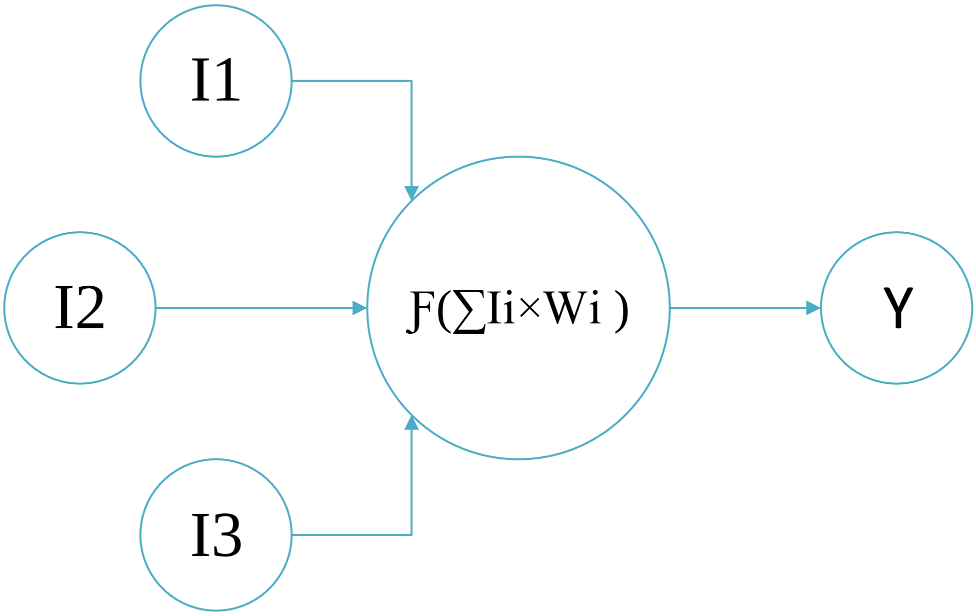


Figure 20: Structure of a single neuron

Consequently, multiple neurons are connected to form the three layers of the price prediction model. The inputs are transferred to the hidden layer in vector form (I = [I1, I2, I3… In]) along with the weights (W= [W1, W2, W3… Wn]) to be processed in the hidden layer. Next, a threshold (B) is added to each neuron to bias the outputs before being processed. Data are transferred into the input layer as vectors in the form A = (A1, A2, A3… An), and their corresponding weights and biases, also known as threshold, are added to the neuron. Then, the inputs are multiplied on the basis of their corresponding weights. The output function of the proposed method is described in Equation 7.

$$Y = K(\sum_{i=1}^{n}(WiIj + Bj)) , \qquad \text{Eq. (7)}$$

where Y is the output; K is the activation function of the jth neuron; I and B are the input and the bias of the same neuron, respectively; and W is the weight given to the inputs. In the proposed design, 8 input layers and 20 hidden and output layers with a single output are used for price prediction (Figure 21).

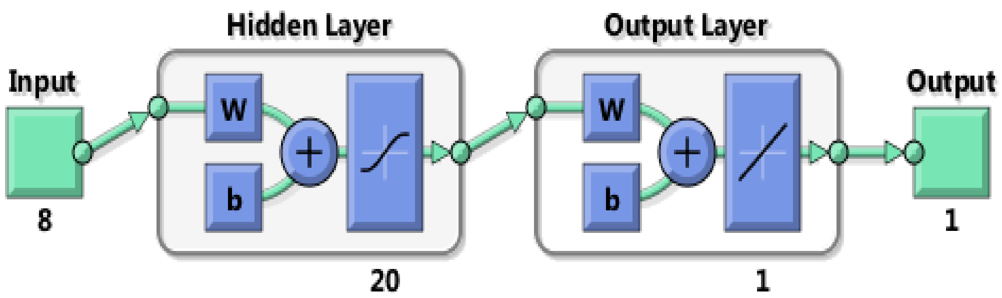


Figure 21: ANN model for price prediction

The learning process is iterated during the training period of the proposed method. The input data from the testing part are transferred to the model, and the error between the actual and predicted values is calculated and propagated back to the input to adjust the weights, biases, and number of hidden layers after each iteration. The data of the previous price, outside temperature, and the total load are fetched from [51] and then used to train the model. The hourly data of these parameters during the period of 1614 days are shown in Figures 22 to 24.

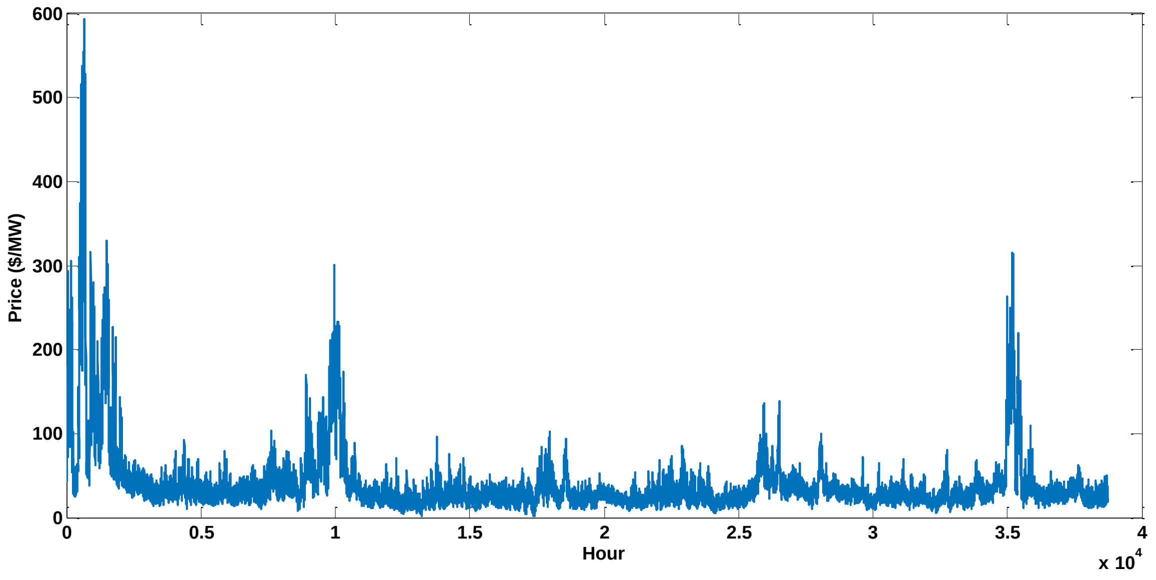


Figure 22: Previous electricity price used to train the ML models

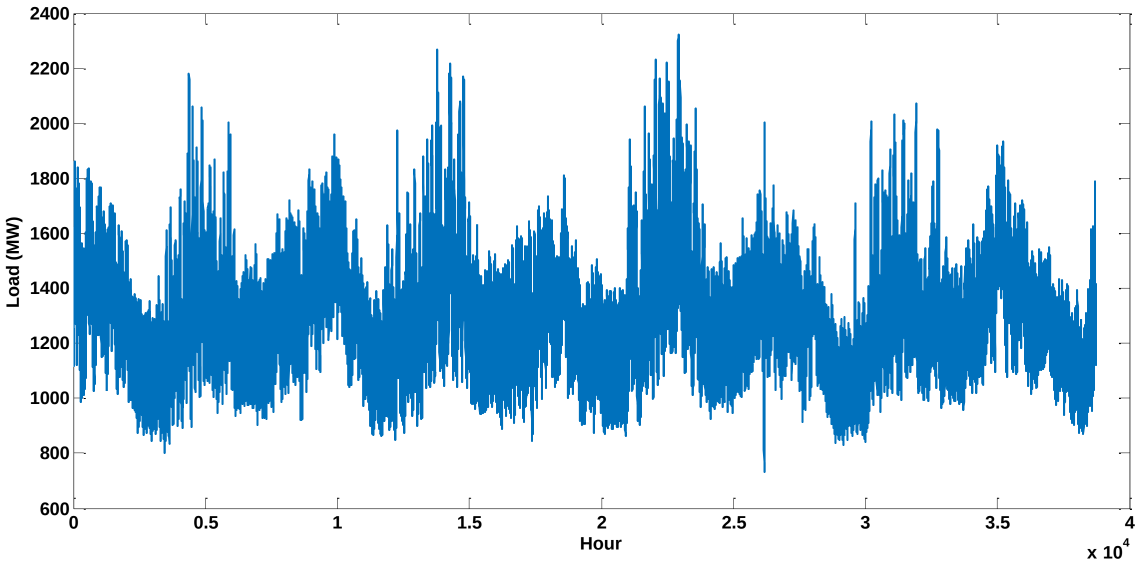


Figure 23: Previous hourly load used to train the ML models

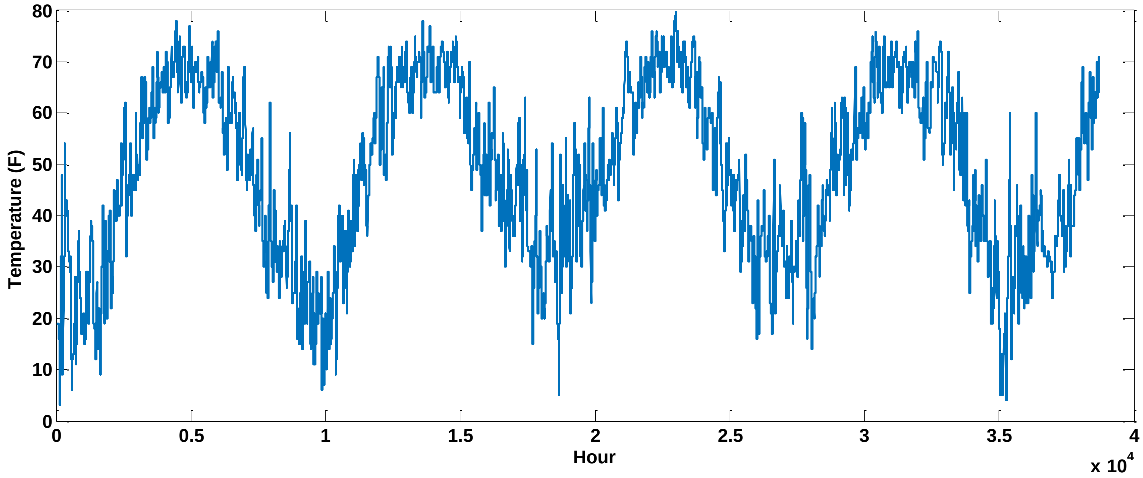


Figure 24: Previous outside temperature used to train the ML models

3.5 Experiment 5: Energy Management Algorithm and Appliance Scheduling

3.5.1 Hardware Organization

Four home appliances are selected for the application of the energy management algorithm. Table 4 shows the details about the chosen appliances.

Table 4: Appliance specifications and power ratings

Appliance	Model	Power rating (W)
Refrigerator	Super General 035H	90
Air conditioner	NIKAI NPAC12512A4	1200
Water heater	Florence FWH-50-15A	1500
LED	V-tac-22w	22

In this part of the experiment, each appliance is attached to one smart socket to monitor their consumed energy and continuously transmit the read information to the main controller in the scheduling terminal. Moreover, the temperatures of the first three appliances are monitored using the appropriate sensing modules integrated in the condition monitoring circuit mentioned in the previous chapter.

3.5.1.1 Heater Setup

Figure 25 shows the organization of the heater power and temperature monitoring experiment. In this case, the heater is attached to a smart socket, and two waterproof temperature sensors are plugged into the inlet and outlet water pipes of the heater.

Figure 25: Experimental setup of the water heater

The inlet and outlet water are thermally monitored by the waterproof sensors, and the temperature readings are gathered by the microcontroller to be transmitted in 2 s time intervals. Moreover, the power consumption is read by the smart socket, where the power cord of the heater is attached. The heater can be turned on or off on the basis of the remote commands received by the smart socket.

3.5.1.2 Refrigerator Setup

Similarly, the refrigerator is attached to another smart socket, and an added waterproof temperature sensor is placed in it to read its inside temperature (Figure 26).

Figure 26: Experimental setup of the refrigerator

The temperature information inside the refrigerator and its power consumption data are transmitted to the main controller wirelessly by using the Zigbee communication modules built in the condition monitoring circuitry and the smart plug. Similar to the smart socket of the heater, that of the refrigerator can also be turned on or off when a remote command is actuated using the relay inside the smart socket.

3.5.1.3 AC Setup

Contrary to the two previous appliance setups, the purpose of the smart socket where the AC is connected is only to monitor and transmit the power consumption to the main controller (Figure 27). The cooling performance is identified by the room temperature, which is measured by the DHT22 temperature sensing module.

Figure 27: Experimental setup of the AC power monitoring

The controlling process of the AC unit is conducted by using the functionalities of the Zigbee-connected IR remote in Section 2.1.2.4. All the IR patterns that the remote learns from the ordinary AC remote are stored in the memory of the mega microcontroller inside the remote. Once a remote command arrives at the remote through its Zigbee connectivity, the microcontroller actuates the command by releasing the corresponding IR pattern through the IR-transmitting LED attached to microcontroller output pin. Normally, the remote can turn the AC unit on or off and set the AC thermostat to a specific temperature.

3.5.1.4 LED Light Setup

In the same way as that of the AC experimental setup, monitoring is the only functionality of the smart socket because the controlling task is assigned to the light dimming circuit in Section 2.1.2.3. Figure 28 shows the connections required by the LED energy management process.

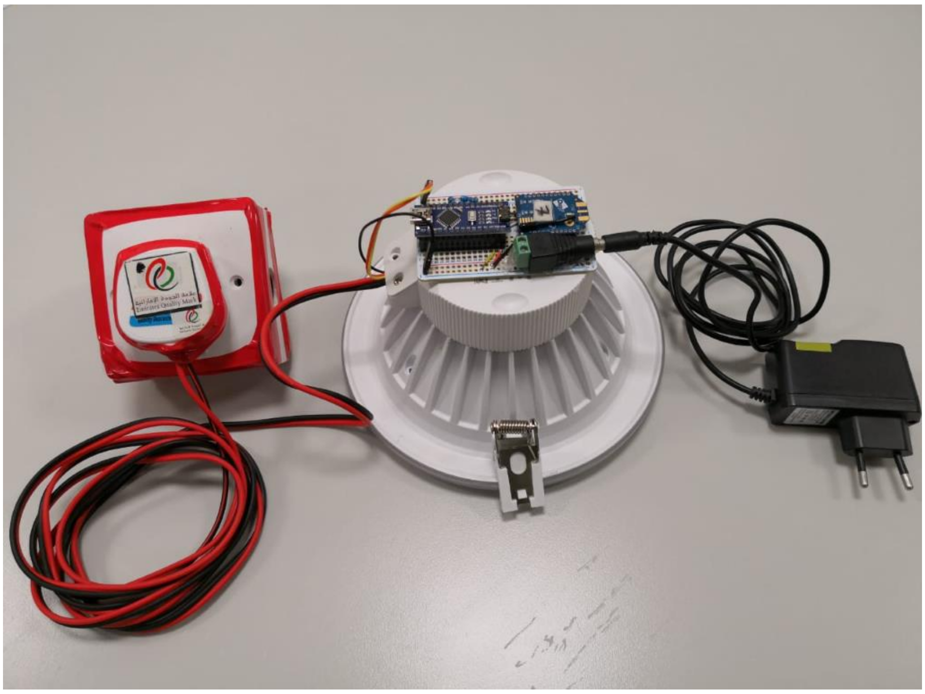


Figure 28: LED energy management experimental setup

The controlling functionality provided by the dimming circuit depends on the principle of pulse width modulation (PWM). Therefore, once the remote command is received by the dimming circuit from the central controller through the Zigbee connectivity between them, the microcontroller in the dimmer side analyzes the command before actuating it by giving a PWM pattern to the pin where the LED driver is connected. The LED lightning levels varies between 0% (i.e., turned off) to 100% (i.e., fully on) in steps of 25%.

3.5.1.5 Room Occupancy Information

Plenty of energy is wasted when appliances are turned on but not used. AC units and lights in a specific room should be turned on only when that room is occupied. Therefore, the idea of utilizing CO_2 and motion sensors to identify room vacancy status is applied in this work.

A two-way identification process is used to serve as room vacancy detector. The first method depends on the information that comes from the PIR motion sensor, which gives a value of 1 when motion is detected inside a room. The appliances should stay on for five more minutes from the time the last 1 is received from the motion sensor. This time margin is allowed to overcome the problem that may result from having a presence in the room without detectable motion due to an outrage of the PIR sensor trigger.

During the 5 min time tolerance, the CO_2 sensor reads the concentration of the CO_2 gas in the room. With a continuous increase in CO_2 levels, the central controller maintains the vacancy status of 1 to indicate user presence inside a room regardless of the readings of the motion sensor. By contrast, with a decline in CO_2 gas levels, the central controller continuously searches for a value of 1 given by the motion sensor to keep the room vacancy status as 1; otherwise, the vacancy status is changed to 0 as an indication of a vacant room. The flowchart in Figure 29 describes the vacancy identification process.

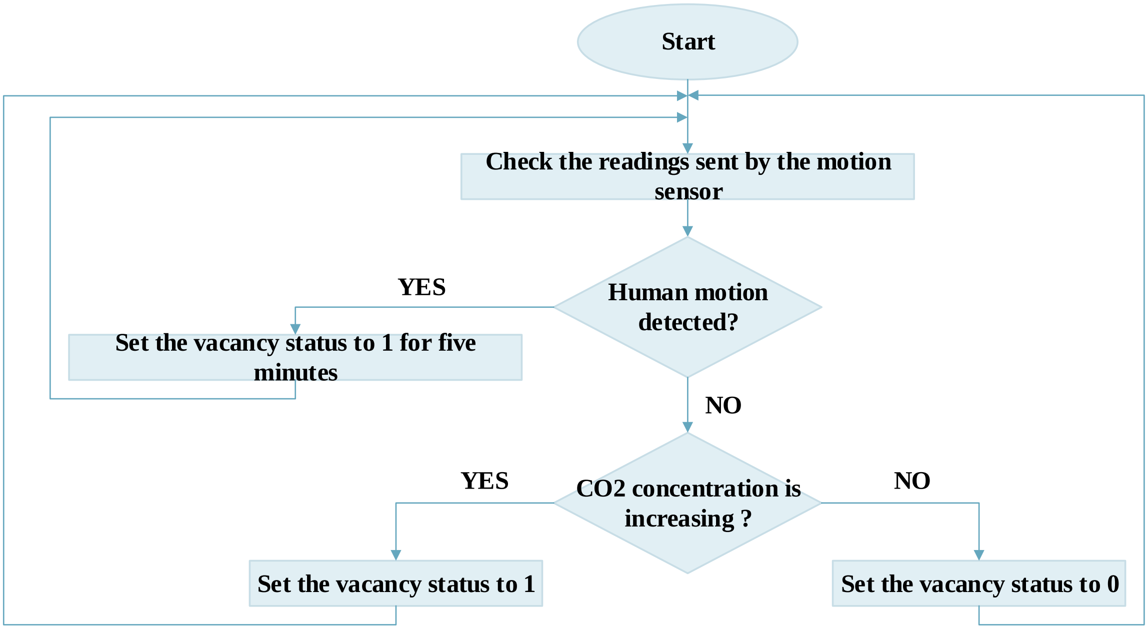


Figure 29: Room vacancy identification process

Nevertheless, the utilized CO_2 indicates the increase in the gas levels inside the room due to the decrease in its read voltage. Thus, the sensor is placed in the experiment room, and the sensor readings are monitored during the periods when the room is vacant and occupied. Therefore, a voltage threshold is set to recognize the occupancy status; a reading above the threshold indicates a vacant room, and a reading below the threshold indicates an occupied room. Figure 30 shows the relation between the CO_2 sensor readings and the vacancy status of the room.

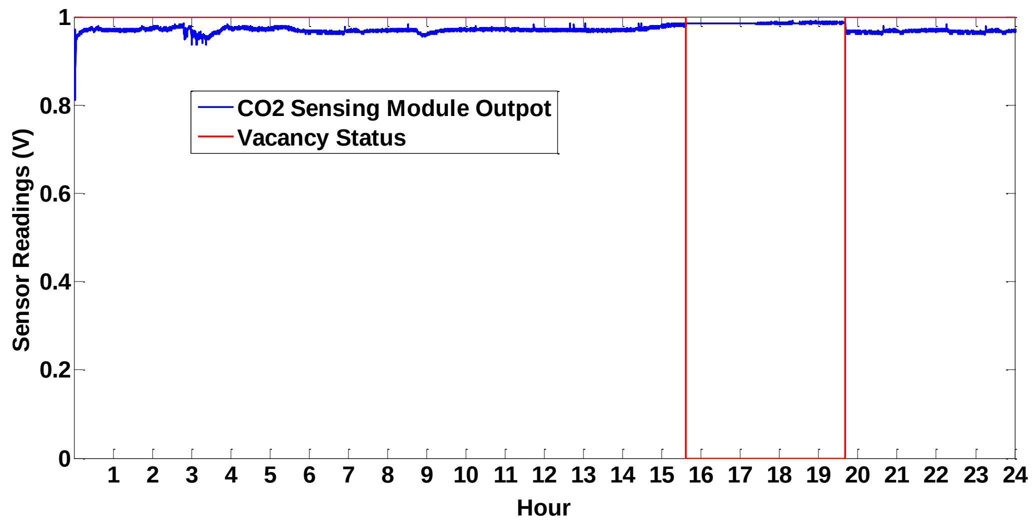


Figure 30: Relationship between CO_2 sensor readings and the occupancy status of the room (24 h monitoring period)

The voltage readings of the sensor increase above a certain threshold when the room is vacant and decrease when a user enters the room. When the CO_2 concentration in the room settles to a certain level, the value of the read voltage is always below this certain threshold while the user is inside and exceeds the threshold after the user leaves the room empty.

3.5.2 Energy Management Algorithm

A rule-based algorithm is developed to manage the performance of the aforementioned appliances. The algorithm uses predetermined user preferences and day-ahead electricity pricing signal, in addition to the inputs from the previous circuitries, to generate the most convenient and energy-efficient usage pattern for households.

A survey with 50 participants is conducted to identify the most common preferences of users in using managed appliances to set the thresholds used by the algorithm rules. Table 5 shows the questions of the survey and the corresponding answers of the participants.

Table 5: User preference survey

Question	Choice #1	Choice #2	Choice #3
How do you describe your preferred room temperature?	Warm (25 °C–30 °C) 7 users	Cool (20 °C–25 °C) 28 users	Very Cold (17 °C–20 °C) 15 users
How do you prefer your refrigerated meals?	Fresh (5 °C–7 °C) 38 users	Cool (3 °C–5 °C) 9 users	Very Cold (1 °C–3 °C) 3 users
How do you describe your favorite water temperature?	Cool (25 °C–35 °C) 6 users	Warm (35 °C–40 °C) 36 users	Hot (>40 °C) 8 users
What light brightness would you consider using your living room at?	Dark (<200 lux) 3 users	Bright (200–350 lux) 29 users	Very Bright (>350 lux) 18 users

An answer is chosen by the majority of the participants for each proposed question. Thus, this result is the starting point in formulating the appliance scheduling and light-dimming rules. Moreover, the algorithm requires online information of illuminance, room temperature, water temperature, and refrigerator temperature variations from the room condition monitoring circuitry, along with the TOU pricing variation fetched from the predicting algorithm embedded in the main controller.

Thus, the room condition parameters are sent wirelessly to the main controller using the aforementioned circuitry. The circuitry can measure the lux value (L), internal refrigerator temperature (T_{REF}), room temperature (T_{Room}), water temperature (T_W), and the vacancy state of the room (Vs.).

The algorithm is supposed to use the user preferences to set the comfort ranges for each utilized appliance to immediately use the previous measurements, as shown in Eq. (8).

$$\begin{aligned} & T_{REF\_\min} \le T_{REF\_t} \le T_{REF\_\max} \\ & T_{ROOM\_\min} \le T_{ROOM\_t} \le T_{ROOM\_\max} \\ & LUX_{\min} \le LUX_{ROOM\_t} \le LUX_{\max} \\ & T_{W\_\min} \le T_{W\_t} \le T_{W\_\max} \end{aligned} \quad , \qquad \text{Eq. (8)}$$

Where T_{REF_t} indicates the online value of the refrigerator's inside temperature; T_{ROOM_t}, Lux_{ROOM_t}, and T_{W_t} represent the present room temperature, current luminance level, and current water temperature, respectively. Labels min and max specify the limits of comfort level chosen by the user. Table 6 shows the minimum and maximum limits of each parameter specified on the basis of the conducted survey (Table 5).

Table 6: User comfort constraints

Parameter	Minimum limit	Maximum limit
Refrigerator temperature (°C)	5	7
Room temperature (°C)	20	25
Luminance (lux)	200	400
Water temperature (°C)	38	42

Thus, the algorithm is now authorized to control the appliances in a fashion that only permits these parameters to stay in the ranges described in Table 6. Each appliance schedule is determined by a set of factors, such as the TOU, power consumption, room vacancy, and the desired performance of the appliance measured by different circuitries. Equations 9, 10, 11, and 12 describe the schedules (S) of light, air conditioner, refrigerator, and water heater, respectively.

$$S_{LIGHT} = \begin{bmatrix} 0\%, & LUX_{ROOM\_t} = 0 \Rightarrow \text{ if } v = 0 \\ 90\%, & LUX_{min} \leq LUX_{ROOM\_t} \leq LUX_{max} \Rightarrow \text{ if } v = 1 \ \& \ t = t_{nonpeak} \\ 100\%, & 0 \leq LUX_{ROOM\_t} \leq LUX_{min} \Rightarrow \text{if } v = 1 \ \& \ t = t_{nonpeak} \\ 50\%, & (LUX_{max} + LUX_{min})/2 \leq LUX_{ROOM\_t} \Rightarrow \text{ if } v = 1 \ \& \ t = t_{peak} \end{bmatrix}$$

Eq. (9)

$$S_{AC} = \begin{bmatrix} 0, & T_{ROOM\_min} \leq T_{ROOM\_t} \leq T_{ROOM\_max} \Rightarrow \text{if } V = 0 \\ 21, & T_{ROOM\_min} \leq T_{ROOM\_t} \Rightarrow \text{if } V = 1 \ \& \ t = t_{min} \\ 23, & T_{ROOM\_min} \leq T_{ROOM\_t} \leq T_{ROOM\_max} \Rightarrow \text{if } V = 1 \ \& \ t = t_{nonpeak} \\ 25, & T_{ROOM\_t} \leq T_{ROOM\_max} \Rightarrow \text{if } V = 1 \ \& \ t = t_{peak} \\ S_{AC\_t-1}, & T_{ROOM\_min} \leq T_{ROOM\_t} \leq T_{ROOM\_max} \Rightarrow \text{if } V = 1 \ \& \ t = t_{nonpeak} \end{bmatrix}$$

Eq. (10)

$$S_{REF} = \begin{bmatrix} 1, & T_{REF\_max} \leq T_{REF\_t} \\ 0, & T_{REF\_t} < T_{REF\_min} \\ 0, & T_{REF\_min} \leq T_{REF\_t} \leq T_{REF\_max} \ \& \ T_{ROOM\_min} \leq T_{ROOM\_t} \Rightarrow \text{if } t = t_{peak} \\ S_{REF\_t-1}, & T_{REF\_min} \leq T_{REF\_t} \leq T_{REF\_max} \Rightarrow \text{if } t = t_{nonpeak} \end{bmatrix}$$

Eq. (11)

$$S_{Heater} = \begin{bmatrix} 1, & T_{Heater\_t} \leq T_{Heater\_min} \\ 0, & T_{Heater\_max} \leq T_{Heater\_t} \\ 0, & T_{Heater\_min} \leq T_{Heater\_t} \leq T_{Heater\_max} \Rightarrow \text{if } t = t_{peak} \\ S_{REF\_t-1}, & T_{Heater\_min} \leq T_{Heater\_t} \leq T_{Heater\_max} \Rightarrow \text{if } t = t_{nonpeak} \end{bmatrix}$$

Eq. (12)

By taking specific examples of the rules from these equations, the algorithm dims the light to 50% when the room is vacant, and the illuminance is still within the comfort range during the peak time to assure energy reduction without affecting user comfort. Moreover, the AC is allowed to perform cooling at the lowest possible set point during the minimum pricing time to increase the compressor off period when the minimum time is over. Another example from the refrigerator equation is that the refrigerator is turned off when the minimum temperature set point is reached regardless of the pricing signal. Finally, the heater is to be turned on when the current water temperature is less than the minimum allowed temperature. Other light-dimming levels for various conditions are indicated in Equation (9), whereas other scheduling rules for the rest of the appliances are found in Equations (10)–(12). A comprehensive look is depicted in the flowchart shown in Figure 31.

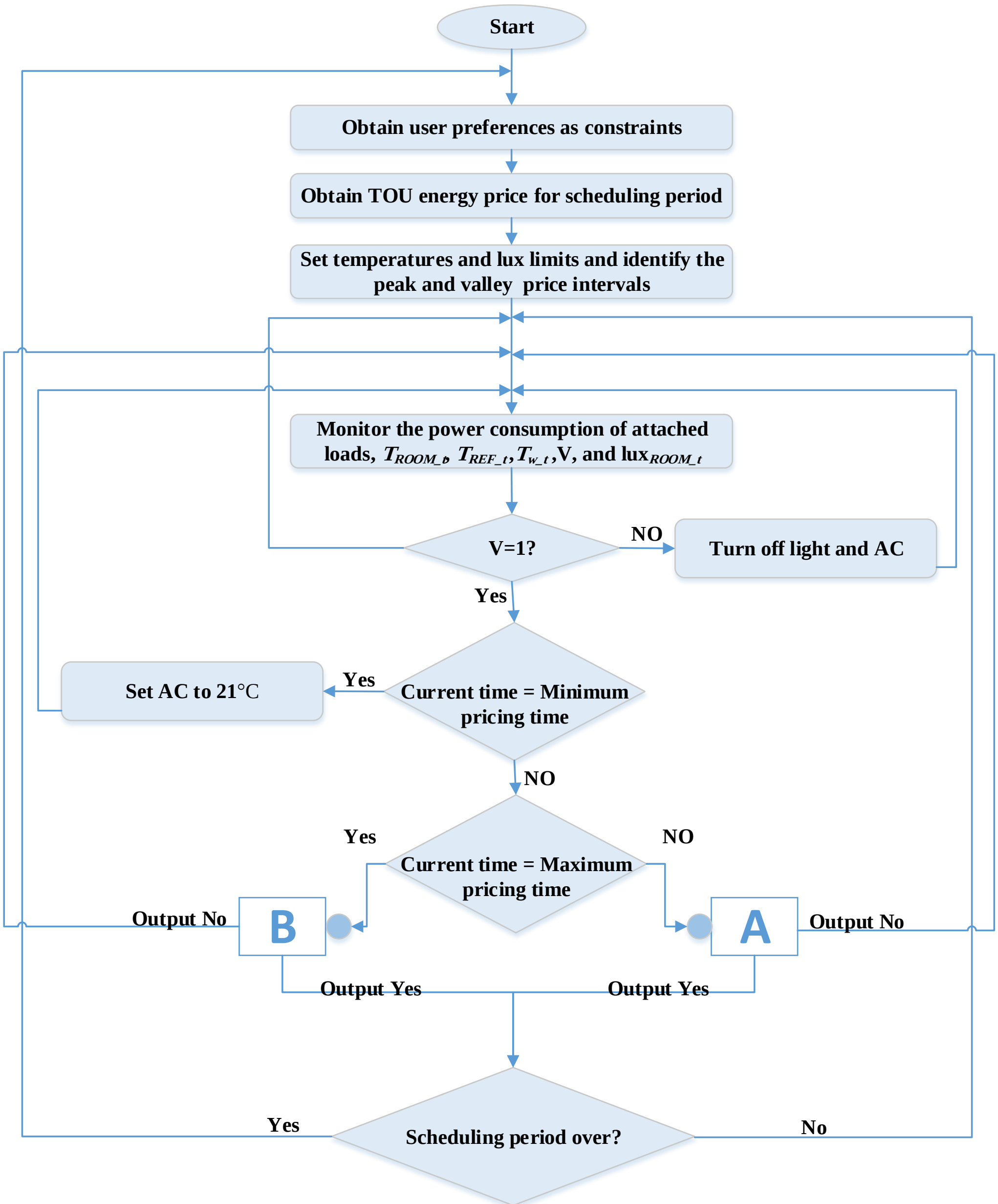


Figure 31: Details of the energy management algorithm

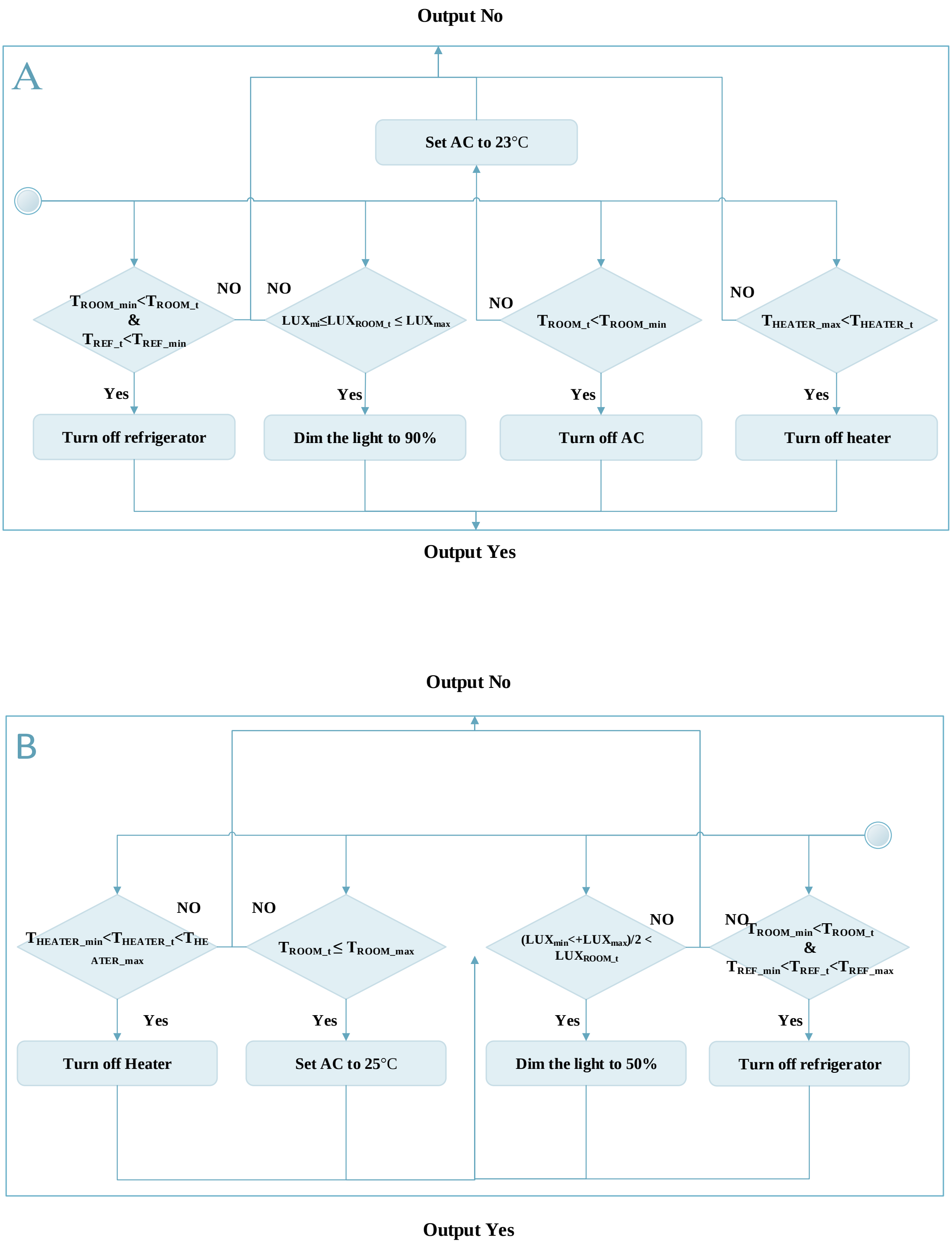


Figure 32: Details of the energy management algorithm (Continued)

3.6 Chapter Summary

Two 24-hour experiments are conducted after locating the hardware setup and specifying the inputs and outputs of the energy management algorithm to show the capability of the designed circuitries of monitoring and controlling the aforementioned electrical appliances and to illustrate how economical the application of the energy algorithm described in Subsection 3.5.2 is in the process of energy reduction.

Initially, the power consumption of the appliances is monitored and recorded for a whole day while being used normally by the user. The temperature and lux parameters are also recorded for future development in the energy management algorithm. The next step is to apply the energy management algorithm for another 24-hour period under the exact utilization circumstances for the appliances while recording the temperatures and lux parameters along with the power consumption of each load.

The results of the monitoring and scheduling of the aforementioned appliances during both periods are illustrated in the next chapter.

Chapter 4: Results and Discussion

This chapter collates the results of the aforementioned experiments. Then, the performance of the smart socket prototype is compared with that of the PQA to validate the findings. Then, the results of monitoring and scheduling the appliances with and without HEM are illustrated.

4.1 Experiment 1: Effective Range of Zigbee-connected System Components

The range test experiment described in the previous chapter demonstrates the suitability of the proposed communication protocol for HEM. The results are plotted in Figure 32. Quality index (QI), which is the variation in the received signal strength (Range: 0–255), is used to demonstrate the capability of the proposed system to effectively cover a sufficient distance with obstacles, such as walls and doors.

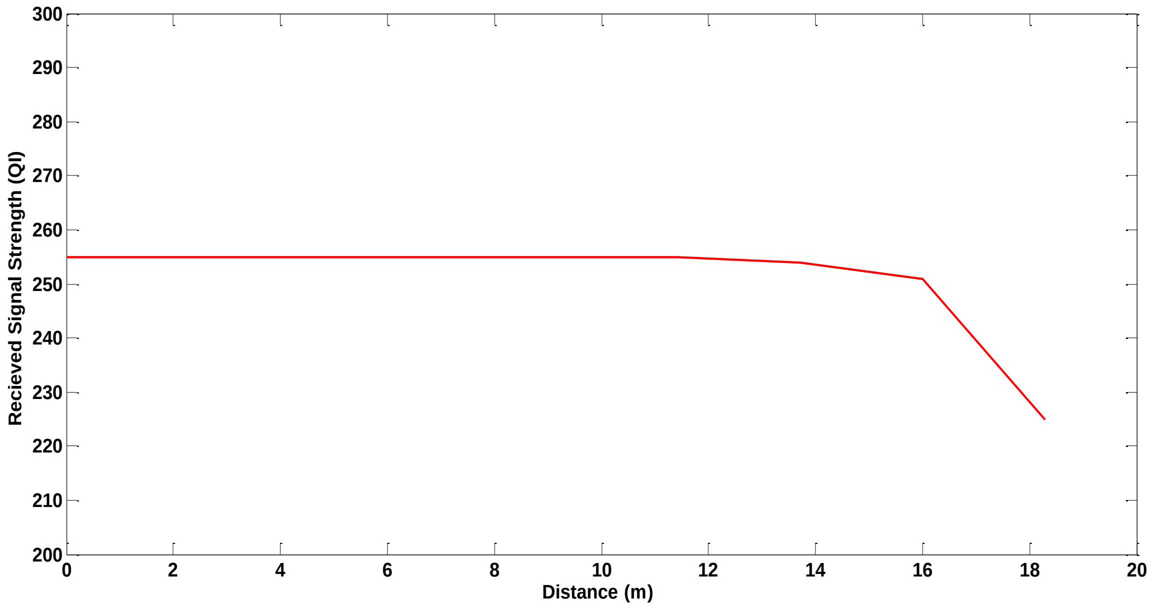


Figure 33: QI variation with distance

The strength of the received signal is at the maximum (QI = 255) at 12 m before dropping to QI 225. Moreover, even at QI 225, the packets are efficiently received and transmitted without data loss. Thus, Zigbee is a reliable protocol for this application.

4.2 Experiment 2: Smart Socket as Wireless Power Meter

Various home appliances are monitored to show the accuracy of the smart socket as a power meter. Figure 33 shows the trend of the power consumption data for the refrigerator retrieved from the smart socket and the PQA.

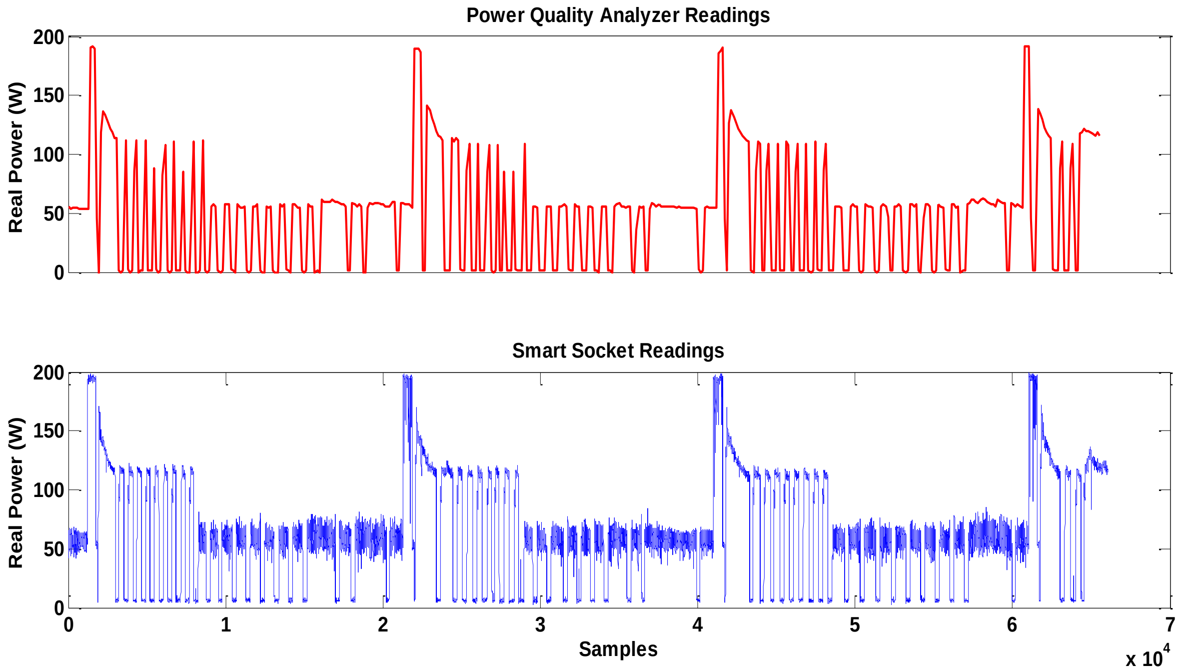


Figure 34: Power consumption trend of refrigerator as monitored by smart socket and PQA

Figure 33 shows that the refrigerator operates in distinct cycles and power consumption changes with different operating modes. At the beginning of the cooling mode, the refrigerator consumes approximately 190 W and gradually decreases toward normal operation. This change in power consumption in cooling mode can be attributed to the inverter-based compressor used by the refrigerator. In defrost mode, the refrigerator consumes approximately 54 W. Between the two modes of operation (i.e., after the designated temperature is reached during cooling or defrosting), the power consumption drops to nearly zero because of the turned-off state of the compressor or the heater. The power consumption recorded by the smart socket and PQA matches closely. Table 4 shows that the average power recorded at the 132068 s duration by the smart socket is 64.12 W, whereas that of the PQA is 62.87 W. Therefore, the measurement error is 1.99 W, which suggests reasonable accuracy.

The next appliance selected for testing is an LED TV. Figure 34 shows the data obtained from the two modes of operation (normal and standby). The smart socket records 54 and 35 W during normal and standby modes, respectively. These values are close to the recorded values of 52 and 30 W by the PQA for the same modes. Table 7 shows that the average power recorded at the 678 s duration by the smart socket is 50.13 W, whereas that of the PQA is 47.86 W. The measurement error is 4.74 W.

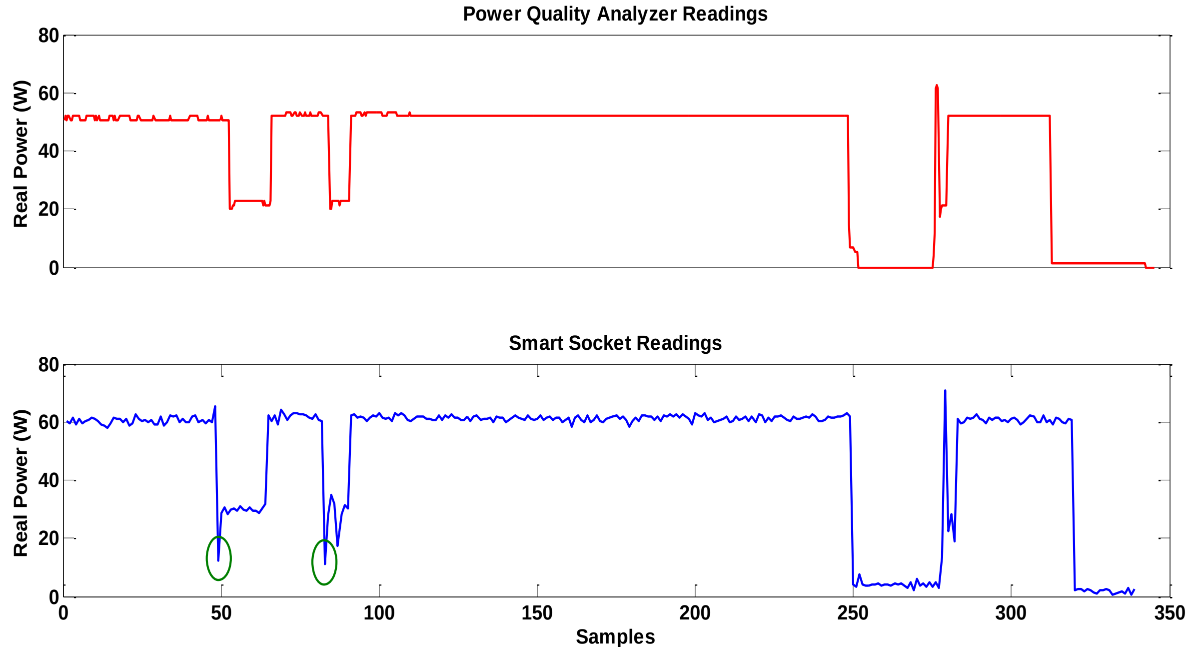


Figure 35: Power consumption trend of LED TV as monitored by smart socket and PQA

Other kitchen appliances, such as an electric blender, a microwave oven, and an electric kettle, are used to further verify the power monitoring capability of the smart socket (Figures 35, 36, and 37, respectively). The figures show that the power consumption trends recorded by the smart socket are in accordance with those recorded by the PQA. The differences in the recorded data are listed in Table 7.

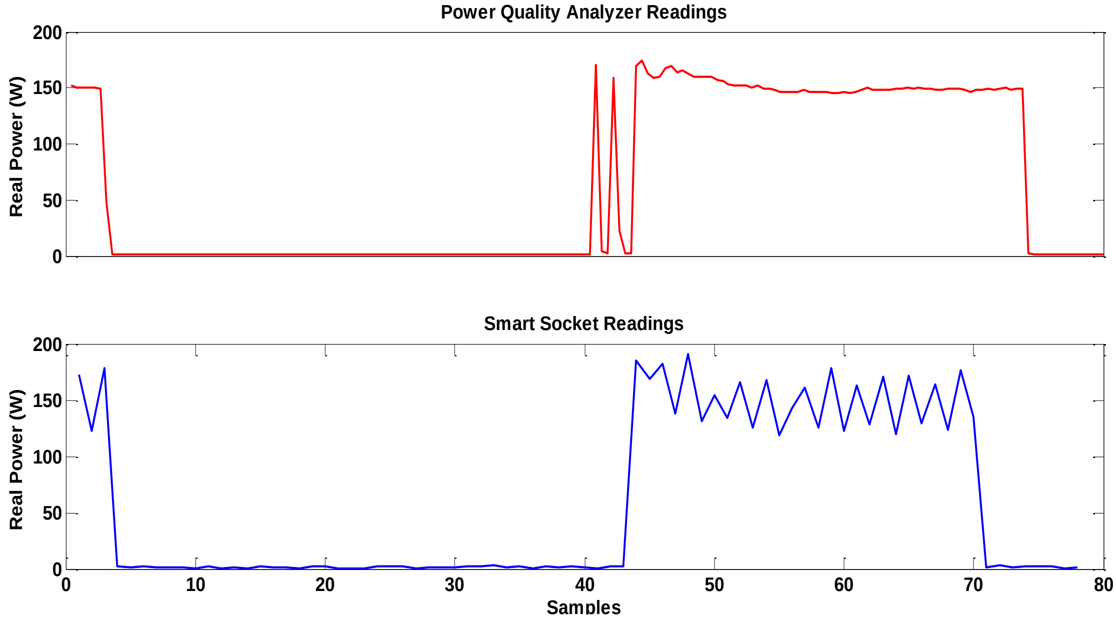


Figure 36: Power consumption trend of electric blender as monitored by smart socket and PQA

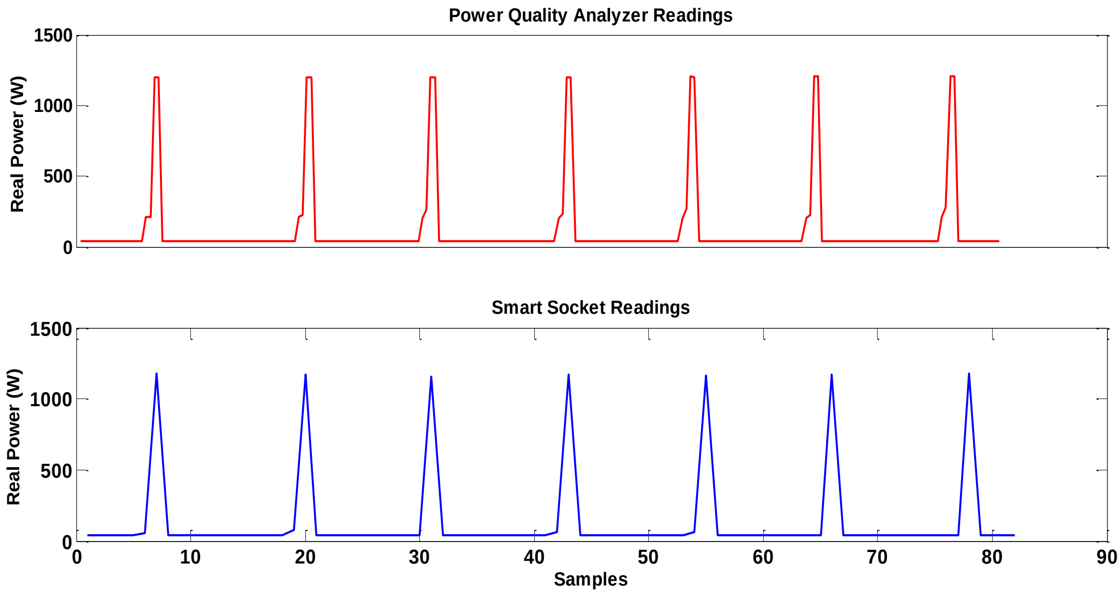


Figure 37 :Power consumption trend of microwave oven as monitored by smart socket and PQA

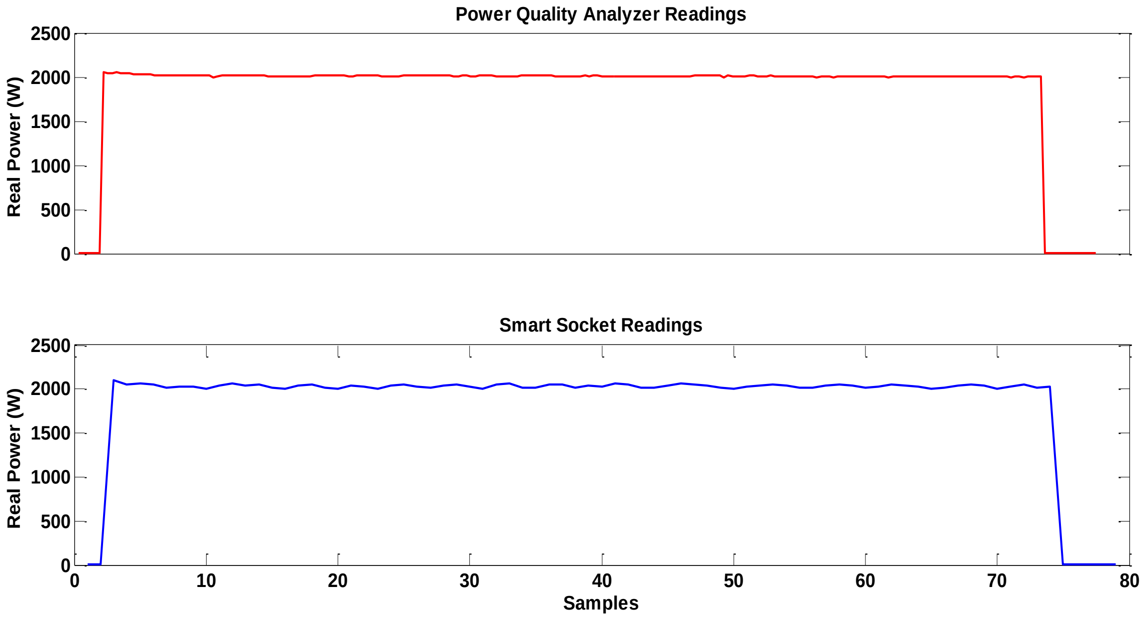


Figure 38: Power consumption trend of electric kettle as monitored by smart socket and PQA

Table 7: Average power recorded by smart socket and PQA

Home appliance	Average power value from PQA (W)	Average power value from smart socket prototype (W)	Experimental error (%)
Refrigerator	62.87	64.12	1.99
Air conditioner	2925.21	2753.95	5.85
TV	47.86	50.13	4.74
Blender	59.05	59.32	0.46
Microwave oven	112.07	105.35	5.99
Kettle	1777.12	1876.95	5.62

The table clearly shows that all average powers obtained by both monitoring devices are close to each other, and the errors are below the acceptable level of 6%. These errors can be attributed to software and hardware differences, such as the sampling rate difference between the PQA and the smart socket prototype. The PQA performs downsampling when the number of samples exceeds a certain limit. The differences can be clearly observed in the comparison of the power consumption trends in Figure 28. In addition, few communication errors in the form of critical sample loss between the smart socket and the central controller PC might have contributed to yielding these monitoring errors. Nonetheless, such loss can be addressed by replacing the average value of the last five samples instead of using the original value. Figure 31 highlights such a case with green circles.

4.3 Experiment 3: Controlling Multiple Smart Sockets

Section 3.3 describes the central controller that has been programmed to turn the devices off and on according to the combinations provided in Table 3. Figure 35 shows the power consumption that corresponds to the performance of the control actions of the connected devices, whose data are received by the central controller.

The individual power consumption trends of the kettle, microwave oven, and refrigerator are depicted by the green, black, and magenta line plots, respectively.

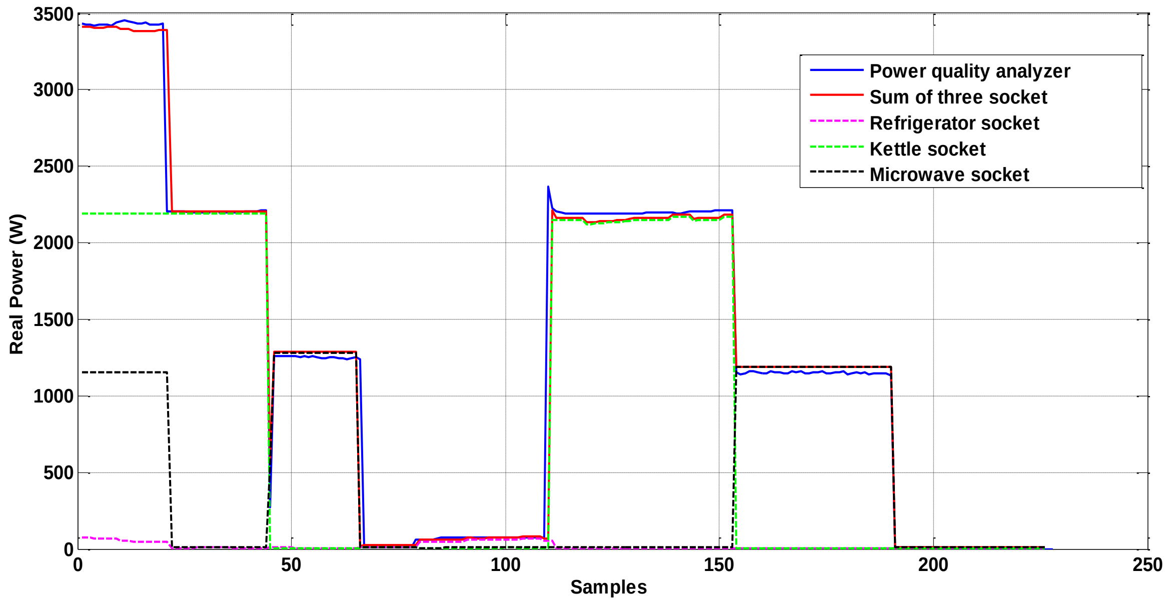


Figure 39: Comparison of power consumption trends of home appliances measured by smart sockets and PQA

The central controller is used to calculate total power consumption by aggregating the individual power trends of the devices (red line plot in Figure 38). The figure shows that the proposed controller can effectively perform the control actions of multiple sockets even while reading the power consumption data sent by the sockets. The accuracy of the received data, which is validated after comparing the aggregated power consumption monitored by the PQA, is represented by the blue line plot.

4.4 Experiment 4: Price Trend Prediction

After completing the training process, the model is tested for a period with known prices, and the predicted price results are compared with the actual ones to verify the capability of the model to predict the daily price trend shape. Figure 39 shows the comparison of both trends.

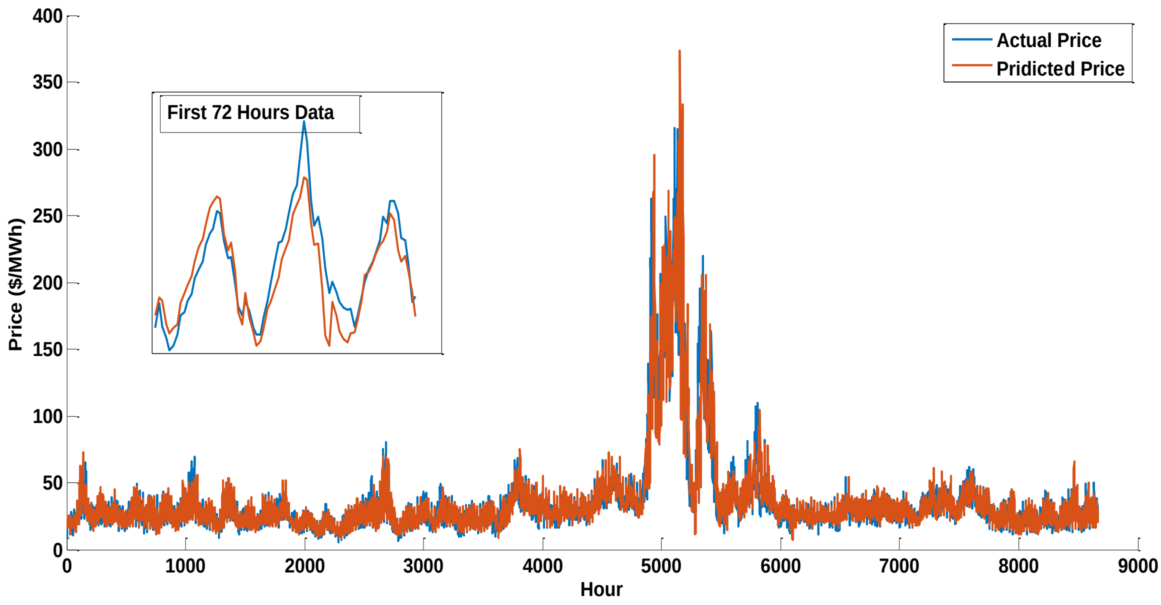


Figure 40: Predicted price trends vs. actual price trend during the testing period

The same trend is followed by the actual and predicted price values because the highest price occurs at the same instance of time, and the lowest price occurs at the same instance in both cases. Thus, the method can be used to predict the daily price of electricity. Figure 40 shows the predicted price trend at the day of applying the energy management algorithm.

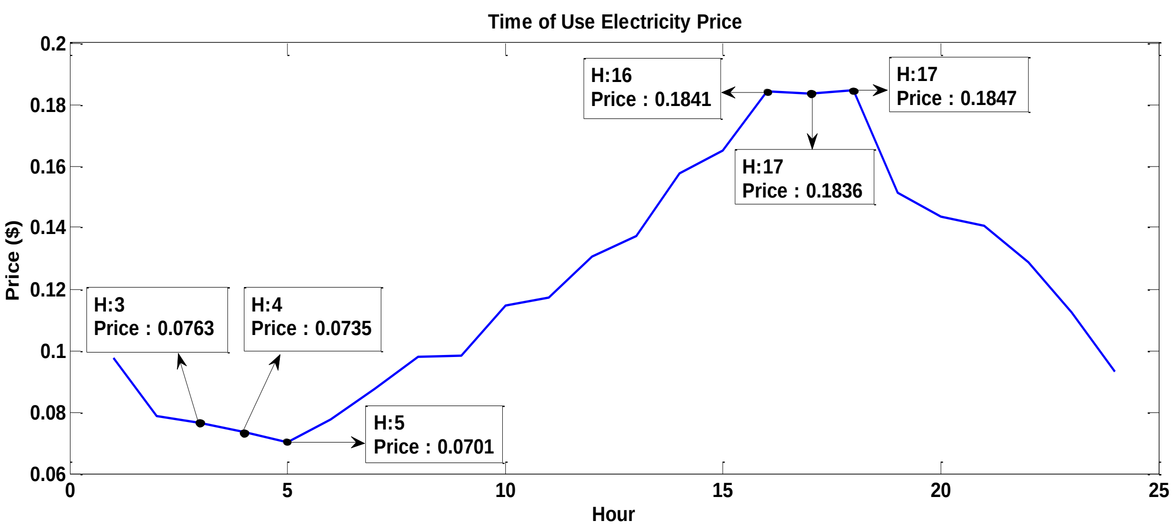


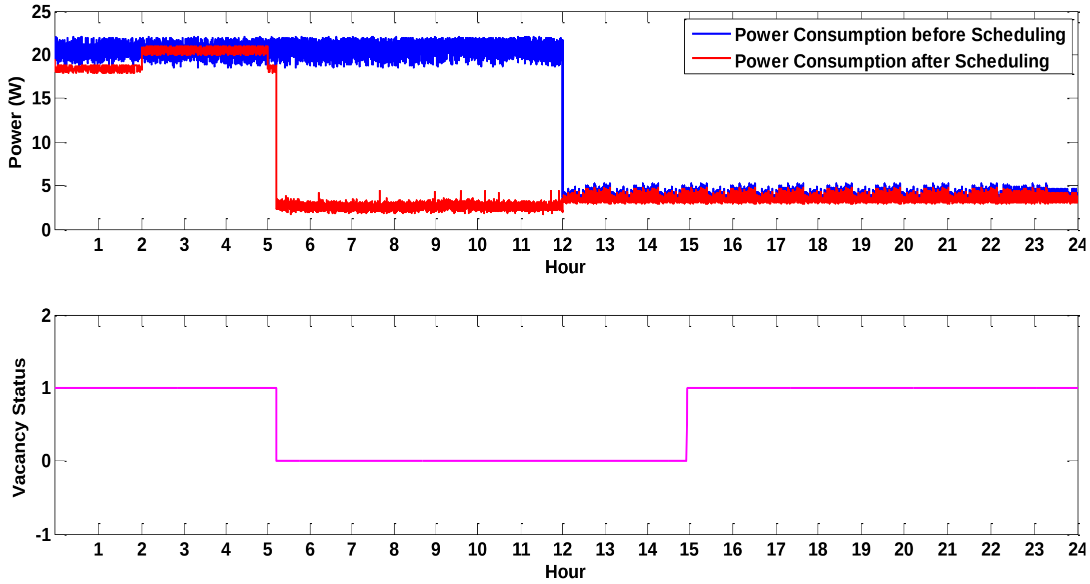
Figure 41: Electricity price trend used in the energy management process

A day can be sectored into three main periods, namely, minimum pricing time that consists of the third, fourth, and fifth hours of the day; maximum pricing time located at the 16th ,17th, and 18th hours of the day; and the normal pricing times that continue the rest of the day. Consequently, the algorithm is expected to manage the appliances in deferent fashion for the three sectors of the day.

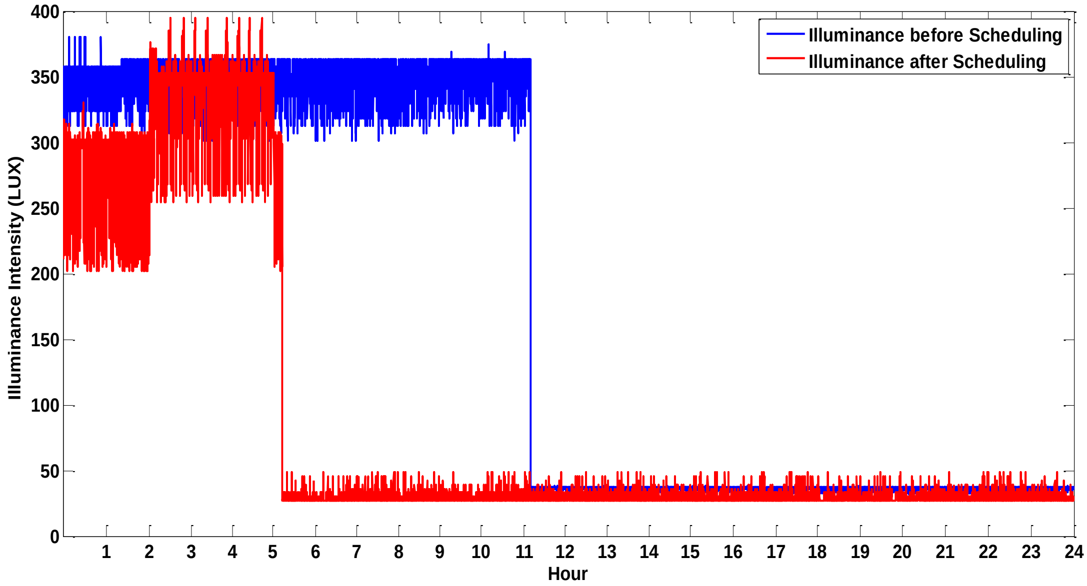
4.5 Experiment 5: Energy Management Algorithm and Appliance Scheduling

4.5.1 LED Light

Although the aforementioned LED light is continuously used for 12 h as the user turns the light off for the next 12 h of the day, the management algorithm can still reduce energy usage during the utilization period. Figure 41a compares the power consumption trends of the LED before and after the application of the management algorithm, and Figure 41b shows the illuminance variations before and after the application of energy algorithm.



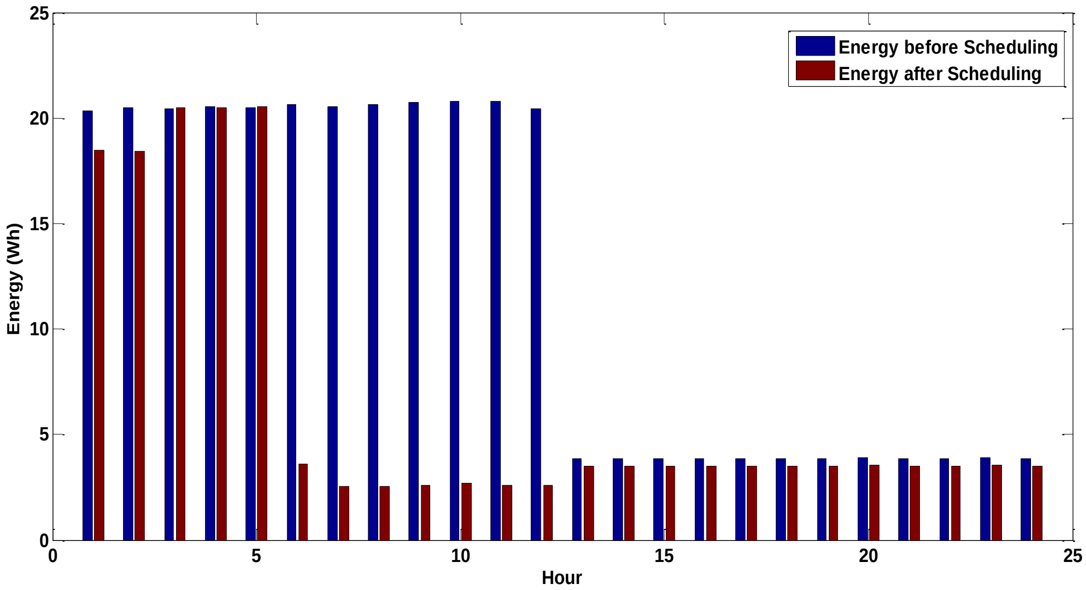
a) Power consumption trend of the LED light before and after the HEM process is utilized along with the vacancy information during the HEM process



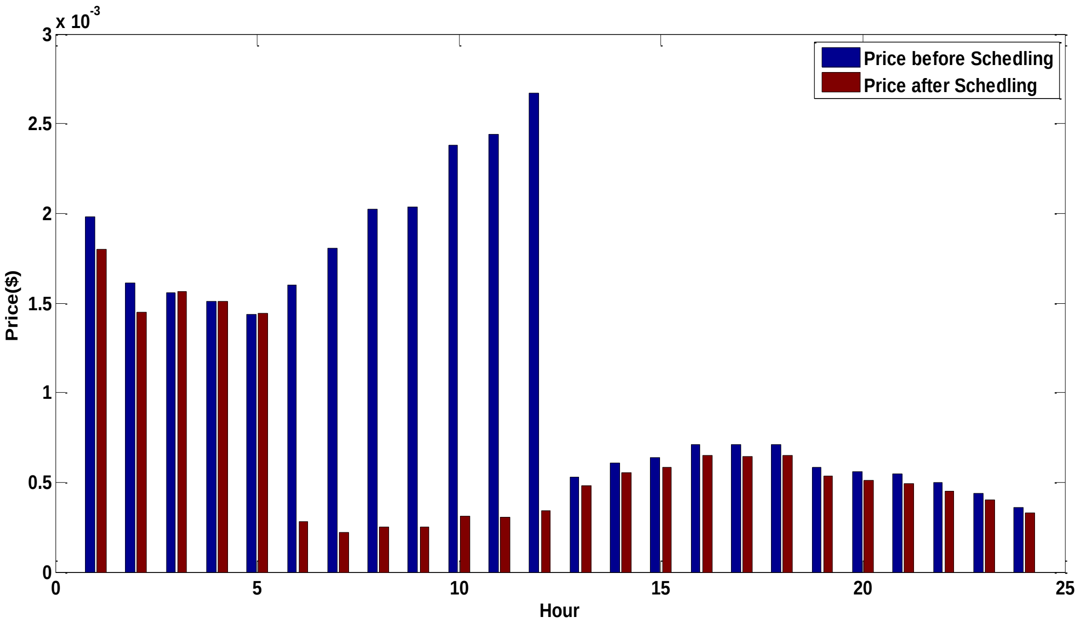
b) Illuminance variations before and after the energy algorithm is applied on the LED light

Figure 42: Power consumption trend and Illuminance variations of the LED light

As shown in part a of the figure, the last 12 h of the day are the off period of the LED light in the normal and scheduled utilizations of the device. However, the light was fully utilized during the normal usage period before the management algorithm is applied. Moreover, the vacancy information depicted in the bottom subplot in part a of the same figure. As noticed, the algorithm turns off the light whenever the room is vacant. The light is dimmed to perform at 90% of its lighting capacity during normal hours, and it is allowed to perform at full lighting capacity in the minimum pricing hours. Dimming commands are performed without affecting the preferred illuminance levels of the user. Thus, Figure 41b shows that illuminance always varies among the constraints set by the user in Table 6 during all scheduling periods and below the maximum constraint by 10% during the non-peak timing, whereas all the constraints are removed during the minimum pricing time. The effect of applying the algorithm on the daily energy and electricity bill is clearly shown in Figures 42a and 42b, respectively.



a) Energy consumption trends of the LED light before and after the application of the management process



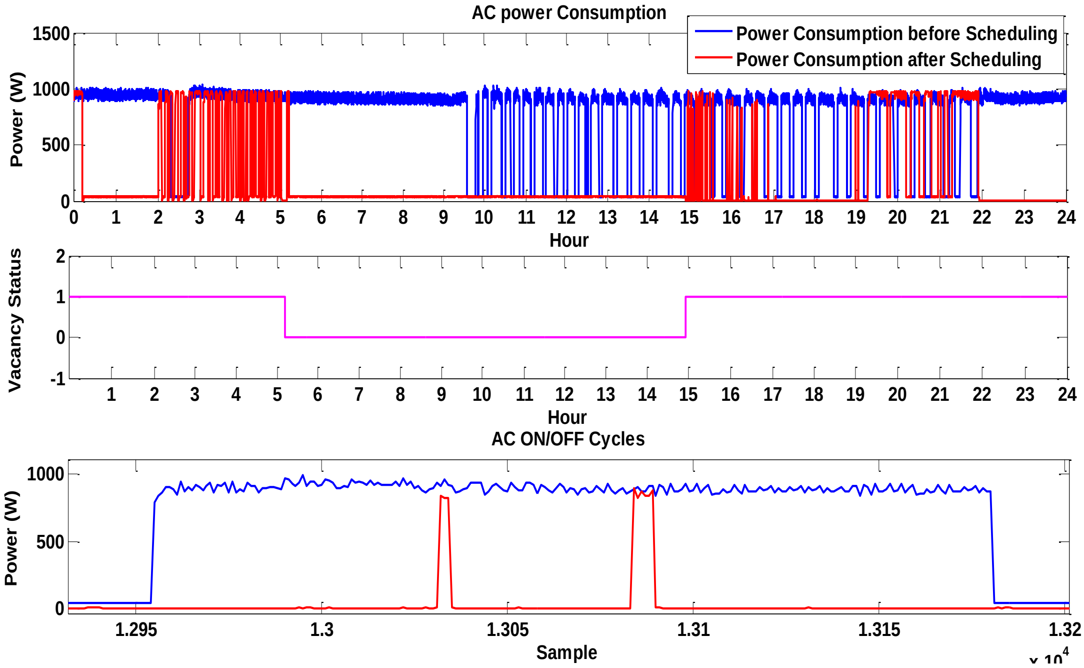
b) Energy price trends of the LED light before and after the application of the management process

Figure 43: Energy consumption trends and price trends of the LED light

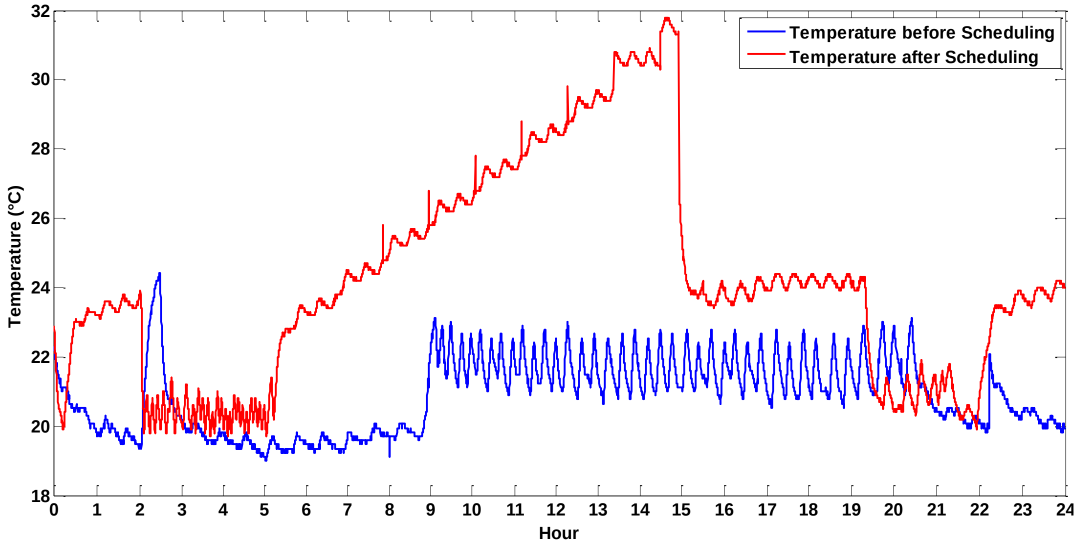
The amounts of energy and price saved due to the implementation of the vacancy principle using the management algorithm are remarkable. However, the energy and price are not reduced in the minimum time period because the energy algorithm enables the device to operate at full capacity at that time. At the end of the day, the algorithm manages to reduce the energy consumed and the daily bill by 0.133 kWh and $0.014, respectively.

4.5.2 Air Conditioner (AC)

In the same way as that of the LED light, the operation of the AC is subject to room vacancy and room temperature variations. Figure 43a shows the power consumption of the AC before and after the scheduling along with the vacancy signal at the monitoring day. Figure 43b shows the temperature variation in the room before and after the scheduling process.



a) Power consumption trends of AC, room vacancy status, and on/off cycles of the AC before and after the application of the algorithm



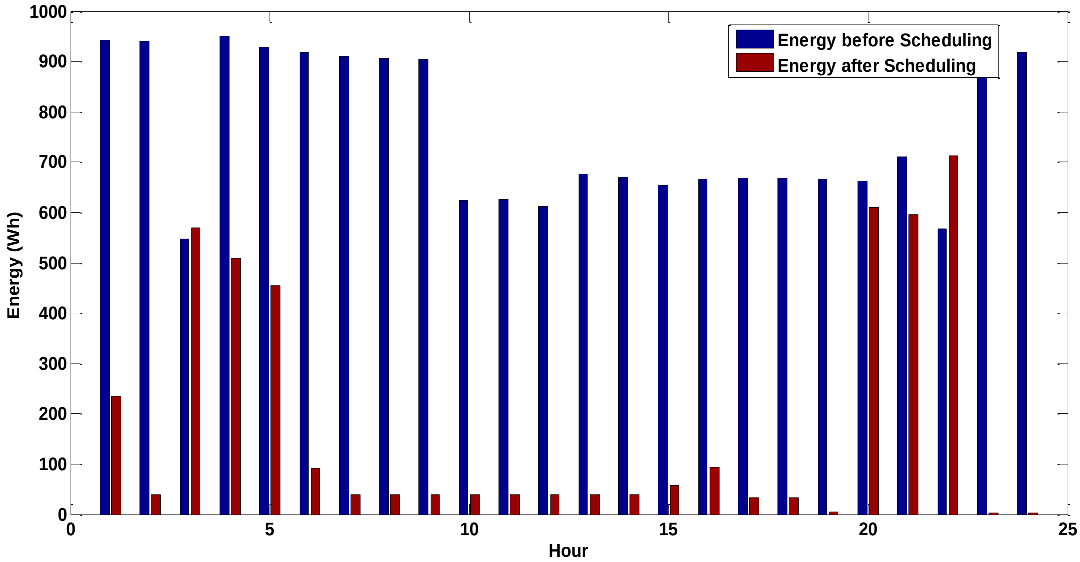
b) Room temperature variation before and after the scheduling of the AC

Figure 44: Power consumption trends of AC and room temperature variation

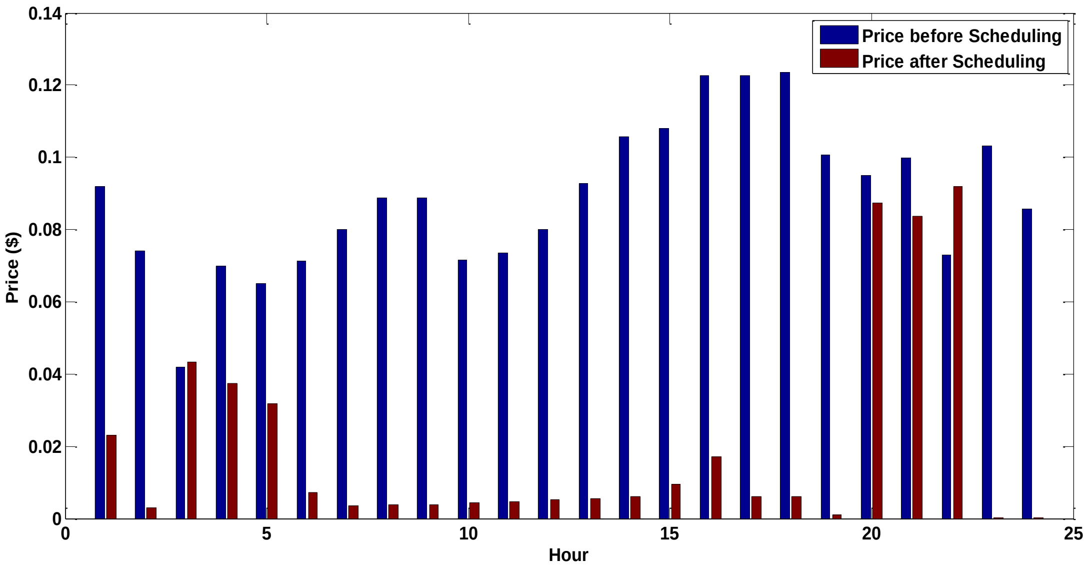
The AC operates continuously until the set temperature is reached before the compressor is turned off automatically. Afterward, the AC alternates the compressor's working status between on and off to save energy when the room temperature reaches the set point on the AC. Moreover, in normal cases, the AC continues operation regardless whether the vacancy status is not turned off by the user himself. However, the management algorithm will allow the AC to operate until the threshold temperature of the room is reached. Although the temperature thresholds vary with the minimum, normal, and maximum pricing hours, the algorithm still can manage to reduce energy during these three cases.

During non-peak pricing times, the AC is allowed to perform cooling as long as the room is vacant and the room temperature is maintained in the middle of the constraints set by the user. In addition, the algorithm allows the AC to operate at the minimum constraint border to cool the room as much as possible by using low pricing at that period, which gives the AC a chance to be turned off during high pricing periods without affecting the user's comfort. Finally, in the third subplot of the aforementioned figure, determining the behavior of the AC during the peak hours, where it is allowed to operate to maintain the room's temperature at the upper border of the temperature constraints set by the user, is clear. However, the AC is turned off more frequently than normal when the room temperature goes further below the maximum temperature set during the peak time. This phenomenon can be observed by the noticeable difference of the on cycles of the AC compressor during the maximum time. Despite all these constraints, the algorithm application manages to keep the room temperature in the permissible temperature range set by the user.

The room temperature in the normal case is only subject to the manual temperature of the AC set by the user. However, this element is vacancy-dependent during the management process, where it is allowed to go more than the maximum comfort temperature when the room is vacant because no user comfort is considered at that time. Moreover, the set temperatures in the minimum and maximum time are the same as those in the normal case. The energy and price trends of the AC can be seen in Figures 44a and 44b, respectively.



a) Energy consumption trends of the AC before and after the application of the management process



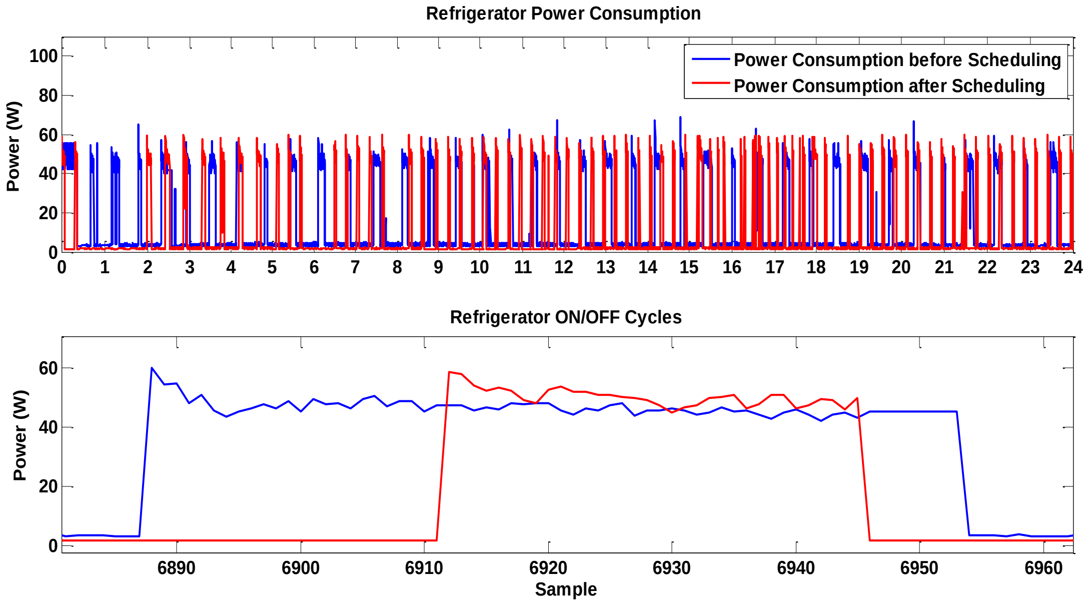
b) Energy Price trends of the AC before and after the application of the management process

Figure 45: Energy consumption trends and price trends of the AC

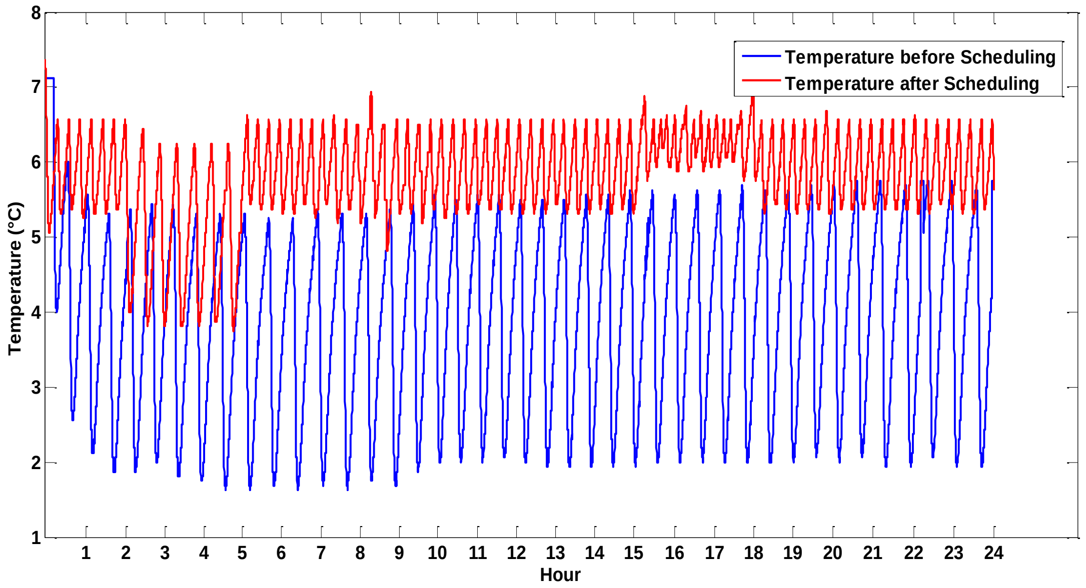
The most used energy and its corresponding price can be found at the minimum pricing hours because the management algorithm maximizes usage at these times while reducing utilization when possible at the maximum times, as shown from the reduction amounts in energy and its corresponding price during peak hours. In total, large amounts of energy consumption and cost are reduced by applying the algorithm due to the application of the vacancy concept and because 13.9 kWh is cut off and $1.64 is reduced from the normal energy use.

4.5.3 Refrigerator

Unlike the two previous home appliances, the refrigerator does not depend on the vacancy status of a room. Thus, the scheduling of the refrigerator is conducted on the basis of internal and surrounding temperatures. Figure 45a illustrates the effect of scheduling on the power consumption trend, and Figure 45b shows the temperature variation inside the refrigerator.



a) Power consumption trend of the refrigerator before and after the application of the energy management process

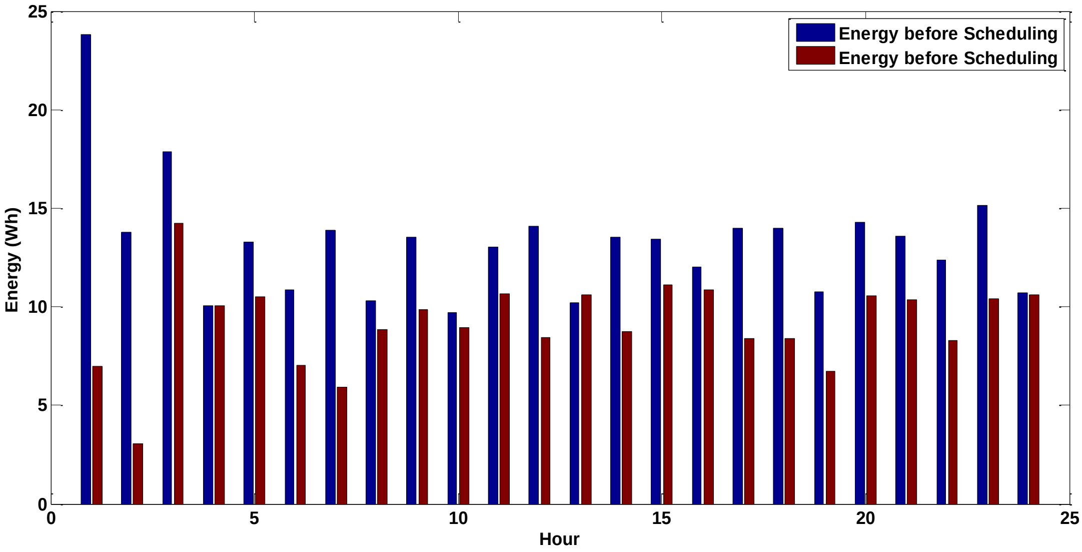


b) Refrigerator inside temperature variation before and after the application of the energy management process

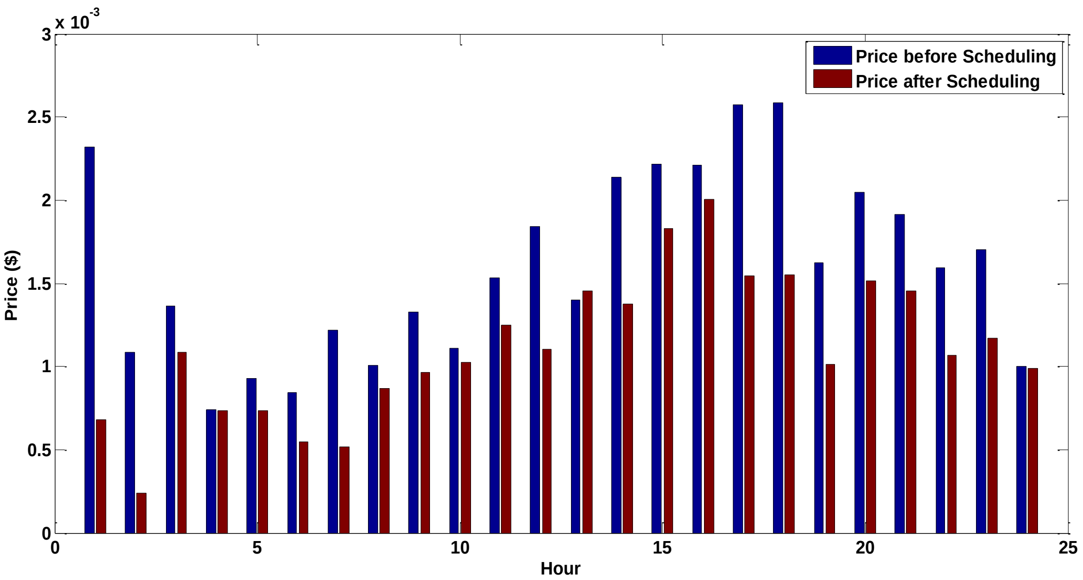
Figure 46: Power consumption trend of the refrigerator and the inside temperature variation

Power consumption is reduced by decreasing the time counts the refrigerator is switched on. Thus, the refrigerator is turned off during the normal time when the lower limit of the constraints set by user is reached, and it is turned off more often during the maximum time in a manner that keeps the internal temperature within the allowed limits. This phenomenon can be clearly observed from the second subplot in the same figure, where the on cycle of the scheduled power consumption trend is narrower than that in the normal power consumption trend during the maximum pricing period. However, regardless of the reduced power consumption and the on time of the refrigerator, the algorithm can quietly manage to keep the inside temperature within the desired range.

The effect on the scheduling algorithm way can be determined according to the hourly energy consumption and the daily price trends before and after the application of the management process (Figures 46a and 46b, respectively).



a) Energy consumption trends of the refrigerator before and after the application of the management process



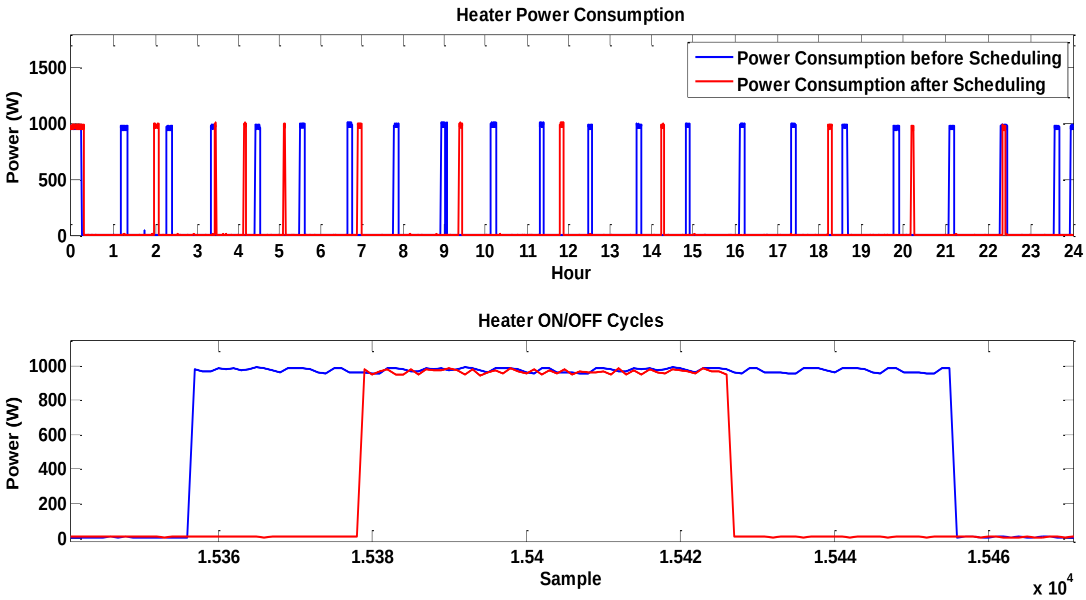
b) Energy price trends of the refrigerator before and after the application of the management process

Figure 47: Energy consumption trends and price trends of the refrigerator

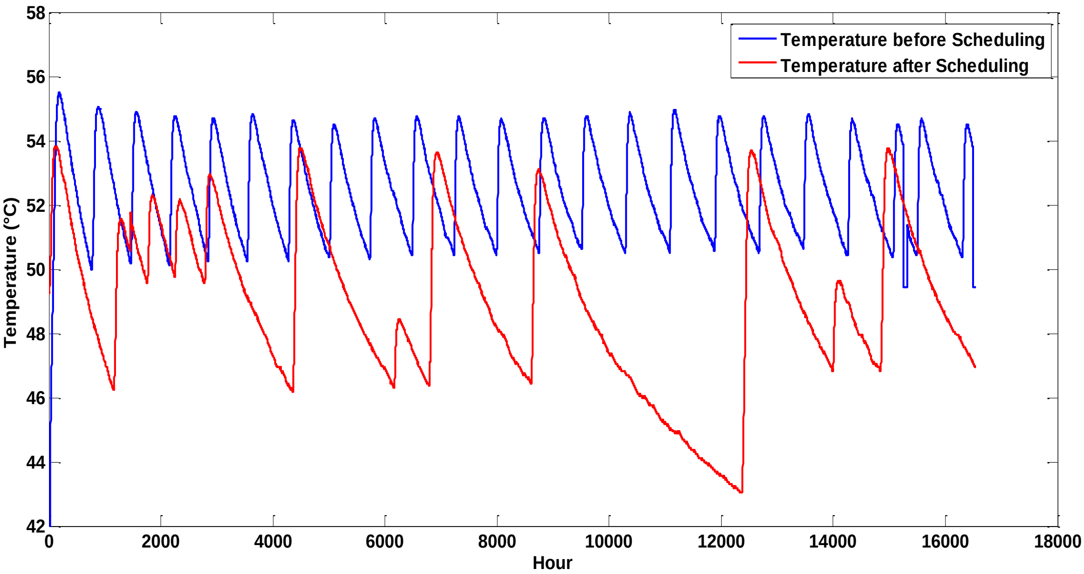
Although the energy and the price of the minimum pricing times are similar, reduction can still be seen during non-peak times. Moreover, reduction is remarkably large during maximum pricing hours. An amount of 0.098 kWh is subtracted from the daily energy used, and the daily bill is reduced by approximately $0.0116.

4.5.4 Water Heater

Similar to the refrigerator, the water heater does not depend on the vacancy status on the room. However, scheduling permeability can be acquired by such appliance type because it conserves the internal temperature more efficiently than the refrigerator because its water tank is not frequently opened as that in a refrigerator. Figure 47a and 47b show the power consumption and temperature variation trends of the heater before and after the application of the scheduling procedure, respectively.



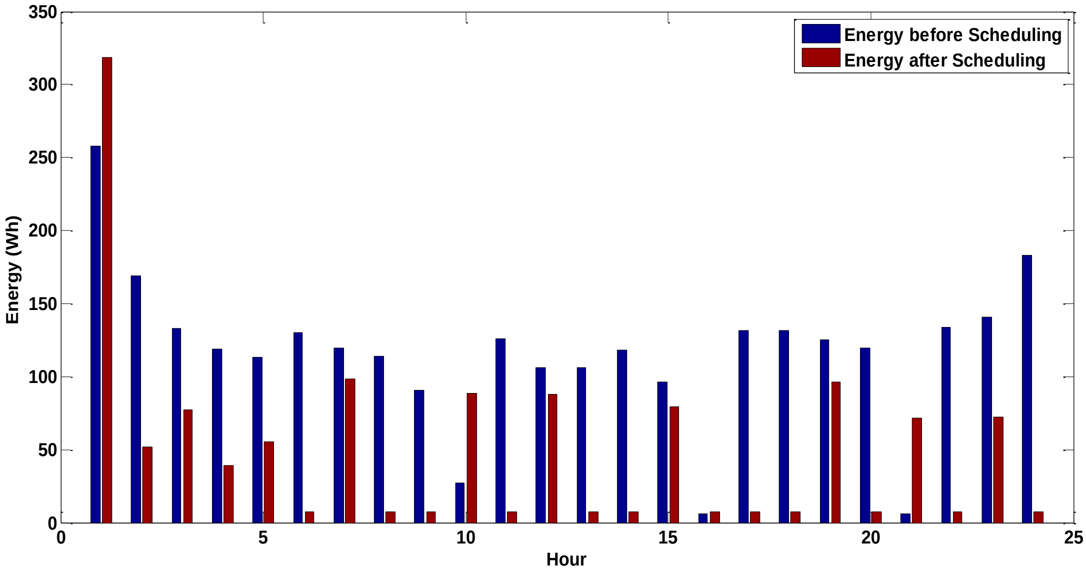
a) Power consumption trend of the heater before and after the application of the energy management process



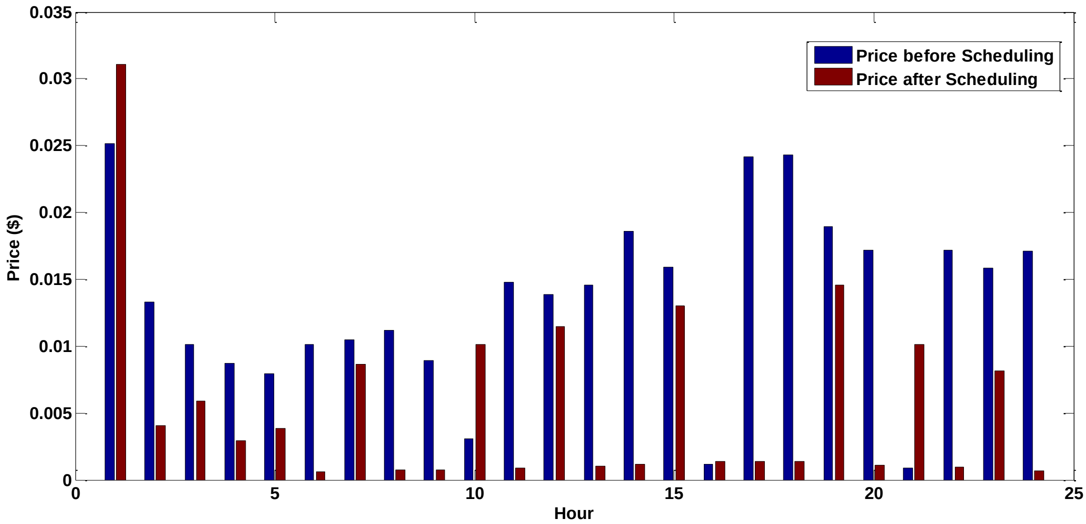
b) Water temperature variation of the heater before and after the application of the scheduling

Figure 48: Power consumption trend and temperature variation of the heater

Considerable decrease in the on cycles of the heater is observed because it can be turned off when the set temperature reaches the middle value between the maximum and the minimum constraints. Moreover, the on cycle time is also narrowed down when possible to reduce energy consumption while keeping the water temperature inside within the limits. Figures 48a and 48b depict the energy and price reduction of the use of heater, where the outcome of the algorithm application is visible.



a) Energy consumption trends of the heater before and after the application of the management process



b) Energy price trends of the heater before and after the application of the management process

Figure 49: Energy consumption trends and price trends of the heater

A substantial amount of energy and price is reduced during the utilization day, especially during maximum pricing hours, where the peak in the normal consumption trend significantly decreases due to the application of the energy algorithm. In total, 1.577 kWh and $0.187 are cut from the daily energy and electricity bill, respectively.

4.5.5 Total Energy Reduction

Figure 49 shows the total power consumption trends of all the appliances before and after the application of the scheduling process.

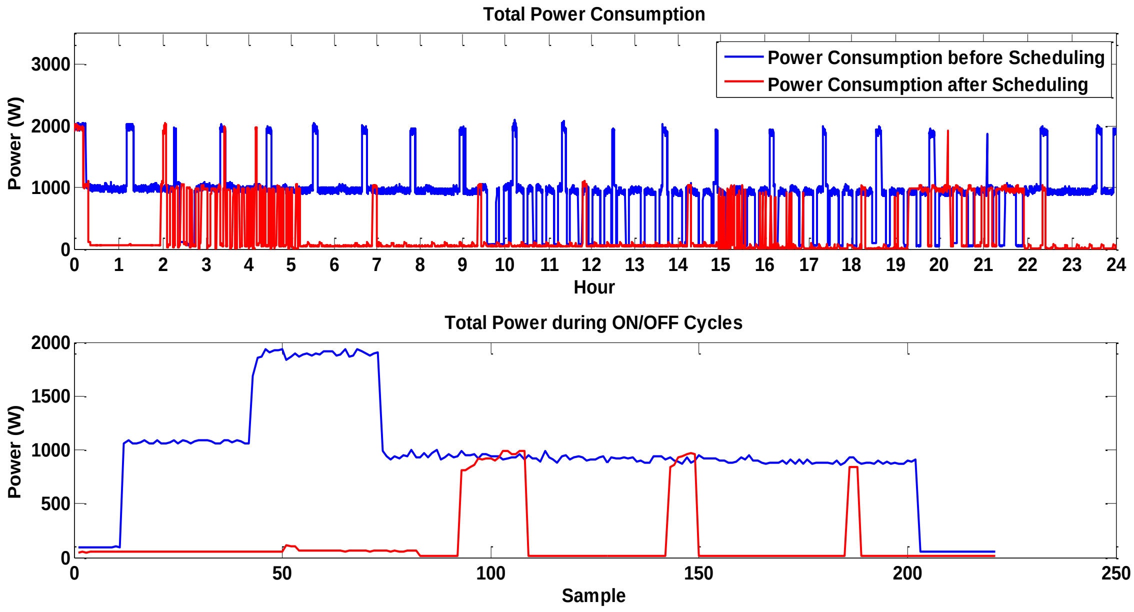
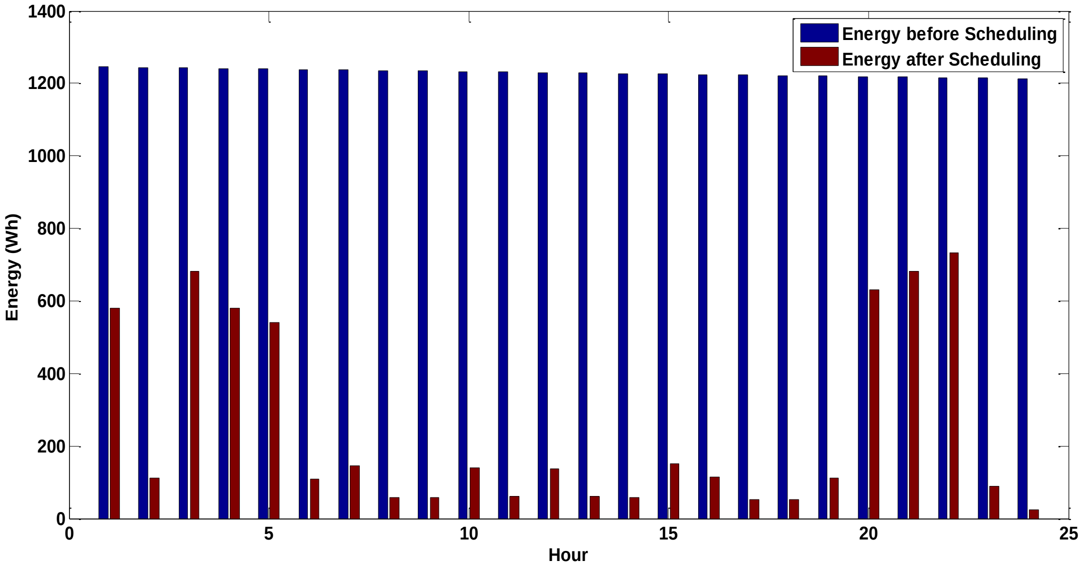


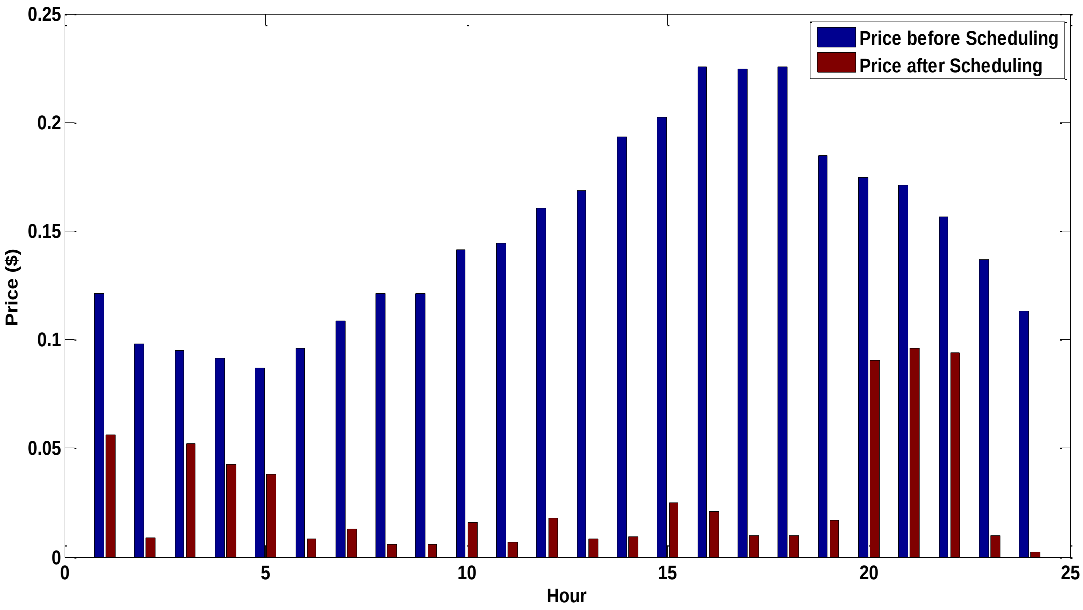
Figure 50: Power consumption trend of all appliances before and after the application of the energy management process

Many peaks result from the concurrent use of all the appliances throughout the normal utilization day. However, most of these peaks are wiped out by scheduling the operation of the appliances. Moreover, the total time of the on cycles of the appliances is reduced.

Ultimately, a large reduction can be noticed after gathering the total energy consumption and corresponding price of all the appliances before and after the application of scheduling. This observation can be seen in Figures 50a and 50a.



a) Total energy consumption trends before and after the application of the management process



b) Total energy price trends before and after the management application of the process

Figure 51: Total energy consumption trends and price trends

The energy consumption in Figure 50a changes from constant consumption during all the timings of the day in the normal consumption way. However, the trend is changed due to the effect of the application of the energy management process. Notably, the maximum allowed consumption is reached at the minimum pricing hours and in the hours following the maximum timing hours due to the low electricity price. Therefore, the algorithm can recover user comfort as soon as possible after the reduction at peak times. A total of 23.5 kWh are reduced from the total energy usage of the household.

In the price trend figure, the peak of the normal trend is dramatically reduced and shifted to the non-peak hours due to the aforementioned comfort recovery. Moreover, the trend resulting from the scheduling is flattened and reduced to provide a total savings of $2.898 in the daily bill.

Chapter 5: Conclusions and Suggestions for Future Work

5.1 Conclusion

This thesis illustrates a methodology of developing a test bed for a smart HEM system controlled by a management algorithm that aims to produce the best utilization scheme for home appliances. This objective is achieved by hardware and software development. Various instruments are developed to provide online information of power, temperature, and illuminance intensity, which help the main controller in generating the remote commands sent to the actuating circuitries and thus achieve the best possible hardware design. The actuating command can be in the form of turning on/off, controlling the temperature settings, and modifying the light intensity of the appliance. In the second part, if–then rules are developed for a management algorithm that receives the inputs from the aforementioned circuitries in real time and automatically controls the appliances in a way that reduces their power consumption without affecting the lifestyle of the user. In addition, five experiments are conducted to verify the credibility of the designed hardware instruments, specifically the smart socket, to show the effect of applying the rule-based algorithm on the daily bill and energy consumption. Results indicate the reliability of the designed smart socket as a wireless power meter and an actuator, to turn the attached appliance on or off. Moreover, the application of the management algorithm resulted with a reduction of 23.5 kW and $2.898 energy and electricity bill per day. Thus, the developed HEM system is an efficient asset for residential unit owners with high energy consumption.

5.2 Suggestions for Future Work

The work presented in this thesis can be further developed in the future. The hardware design can be improved by adding new supporting circuitries or other functionalities. For example, a current-limiting capability can be added to the smart socket instrument to be used in light dimming instead of having two different circuitries for the same appliance. Another improvement can be integrated into the occupancy status property integrated in the room monitoring instrument. The enhancement will allow the instrument to detect the number of persons in the room instead of only the room occupancy status. This approach will allow the management algorithm to consider multiple comfort constraints instead of a single set for a specific user. Furthermore, the management process itself can be further boosted by using complex yet efficient and user-friendly algorithms, such as optimization-based and ML algorithms that can learn the attitude of the users in using their home appliances and use the gathered information in future scheduling processes.

5.3 Main Contributions

The significant contribution of this work can be summarized as follows.

i. An intelligent HEM algorithm is developed to efficiently manage home appliances. The system consists of multiple smart sockets, a programmable AC remote, and room condition monitoring nodes, which provide comfort inputs to the main controller. All previous components are wirelessly connected through the Zigbee communication protocol, thereby allowing for easy implementation without any complex wiring.

ii. User comfort is prioritized during the energy management process to make the integration of the system in the consumer’s daily routine easy without affecting his/her lifestyle.

iii. A rule-based algorithm that aims to reduce energy consumption in a 24 hour window is developed and examined.

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List of Publications

1-E. Al-Hassan, H. Shareef, M. M. Islam, A. Wahyude and A. A. Abdrabou, "Improved Smart Power Socket for Monitoring and Controlling Electrical Home Appliances," in IEEE Access, vol. 6, pp. 49292-49305, 2018.

Doi:10.1109/ACCESS.2018.2868788.

2- H. Shareef, M. S. Ahmed, A. Mohamed and E. Al Hassan, "Review on Home Energy Management System Considering Demand Responses, Smart Technologies, and Intelligent Controllers," in IEEE Access, vol. 6, pp. 24498-24509, 2018.

Doi: 10.1109/ACCESS.2018.2831917