Energy management enhancement of a smart home supplied by renewable energy system

Hasan Hammoodi Shakir[1], Fatma Ben Salem[1,2]
[1]Laboratory of Control Energy Management, Department of Electrical Engineering, National Engineering School of Sfax (ENIS), University of Sfax, Sfax, Tunisia
[2]Department of Electrical Engineering, College of Engineering, Prince Sattam Bin Abdulaziz University, Al Kharj, Saudi Arabia

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ABSTRACT

Solar energy is a reliable and eco-friendly solution for power outages in Karbala, Iraq. This study presents a smart grid technology model for energy management in electrical systems, optimizing power schemes and economic benefits through a unique spatial distribution approach in Iraq, with the primary objective of ensuring consistent base loads for smart homes while achieving other economic goals. The algorithm's effectiveness was tested in three different scenarios. The energy was supplied by the national grid and battery bank-powered base loads. Meteorological data, including temperature and solar radiation, was gathered from a station in Karbala city for testing and evaluation. The study found that energy consumption decreased by 85% in April, with solar energy accounting for 37% of the total consumption. Smart homes saved 48% of energy, reducing reliance on the grid to 15%, as well as the reduction of energy consumption reached up to 47% and 60% in January and July, respectively, with solar energy estimated at 14% and 26% in those months.

Corresponding Author:

Hasan Hammoodi Shakir
Laboratory of Control Energy Management, Department of Electrical Engineering
National Engineering School of Sfax (ENIS), University of Sfax
Sukra, Sfax, Tunisia
Email: hasan-hammoodi.shakir@enis.tn

1. INTRODUCTION

In recent years, there has been a growing interest in the use of renewable energy sources (RES) as an alternative to fossil fuels due to environmental concerns. Among RES, photovoltaic (PV) systems have seen rapid growth and are being used in various applications such as solar battery-charging stations, telecommunications, hybrid power systems, electric vehicles, and smart grid applications [1], [2]. Microgrids, which contain several energy sources, have proven to be efficient and cost-effective for various household loads based on energy requirements. These microgrids have been evaluated for their quality, reliability, efficiency, and economic aspects, following standard grid requirements [3], [4]. Previous studies have addressed energy conservation and peak load energy pricing, where a set of sensors and actuators operate based on programmed appliance run times. Energy management is crucial, as it can lead to significant savings by reducing electrical energy consumption and replacing expensive energy with cheaper alternatives [5]–[7]. Several strategies for energy management have been proposed to reduce environmental pollution when integrating PV sources into the distribution system. However, the output of solar energy depends on optimal conditions. Factors such as the sun angle, the output power capacity of the PV module, and weather conditions can affect the amount of electricity generated [8]–[10]. The amount of electricity generated by PV panels is influenced by factors such as location, time of year, and duration of sunlight. The efficiency of a PV system can be reduced by environmental factors such as shading from trees and buildings, dust, snow, clouds, dirt, and pollution [11], [12].

This model considers a residential load and a smart home design. The loads, which are one of the most critical components in structuring a microgrid system, are categorized into groups based on operational priority. The model aims to balance battery charging and load meeting in emergencies. The state of charge (SoC) of batteries and the amount of energy generated from PV affect operational periods [13], [14]. To establish a good relationship between requested and consumed power, smart houses have been implemented as a solution to overcome the drawbacks of load peaks and interruptions in energy supply. Home automation provides a sophisticated system consisting of elements like sensors that are easy for customers to use [15].

This work addresses the issue of frequent power outages in the national grid due to insufficient energy production compared to demand loads. The base loads can be met by alternative resources, such as PV, at any time in a smart house. The proposed energy management system aims to effectively handle this issue. The contributions of this work can be summed in the following points: i) harnessing solar radiation to generate more energy using PV panels; ii) addressing power outages and supplying the energy needed for base load demand; iii) prioritizing renewable energy sources, starting with household loads, then charging battery banks, and finally feeding the grid with excess these sources's energy; and iv) minimizing electricity consumption from the national grid as much as possible by using renewable energy sources, thereby reducing the electricity bill.

The structure of the work is as follows. Section 2 details the selected system components that meet the appliance requirements in the smart home. Section 3 describes the proposed optimal energy management system. In section 4, The effectiveness and economic purpose of the model are demonstrated through a simulation of a smart home equipped with PV panels and a battery storage system. The simulation results are obtained using the MATLAB program. In section 5 presents the conclusions drawn from the study.

2. METHOD OF THE STUDY

The proposed power system in this study consists of several elements, including PV panels, a battery bank, a hybrid inverter, and electrical appliances. These components are connected to the national grid to ensure uninterrupted energy supply and prevent any outages [16]. This paper uses a 150-square-meter house in the Al Summood region of Karbala City as a case study to represent an example of the selected smart microgrid. Karbala province is geographically located at 32.5°-32.8° latitude north and 44.19°-43.1° longitude east, making it a region rich in sunlight with over 2,800 hours of solar radiance per year [17]. Figure 1 is a small scale the meteoritical data station of Karbala featuring all the measurement' components where the climatic information were obtained from this station as well as the PV array is used to generated energy at smart house during the day.

Figure 1. Presents the meteoritical data station of Karbala as well the PV panels at smart home

2.1. Solar PV home demonstrator

The solar PV home demonstrator used in this study is installed in the Al summood region (situated in Karbala city at 100 km far from Baghdad). This house has been made with materials ensuring good thermal insulation. It is equipped with all the appliances currently found in homes (refrigerator, air conditioner, oven, microwave, and washing machine), referring to the defined priorities, these appliances have been classified into two types the base appliances (type A) and the shiftable appliances (type B).

The proposed system is managed through a set of conditions that guide the monitoring and utilization of energy in the smart home. This is achieved with an algorithmic capability where the operation of the proposed power system depends on a set of five switches (k1, k2, k3, k4, k5). The state of these switches (ON/OFF) is determined based on the load demand and available energy sources such as the national grid, PV panels, and battery bank in the proposed power module, as shown in Figure 2.

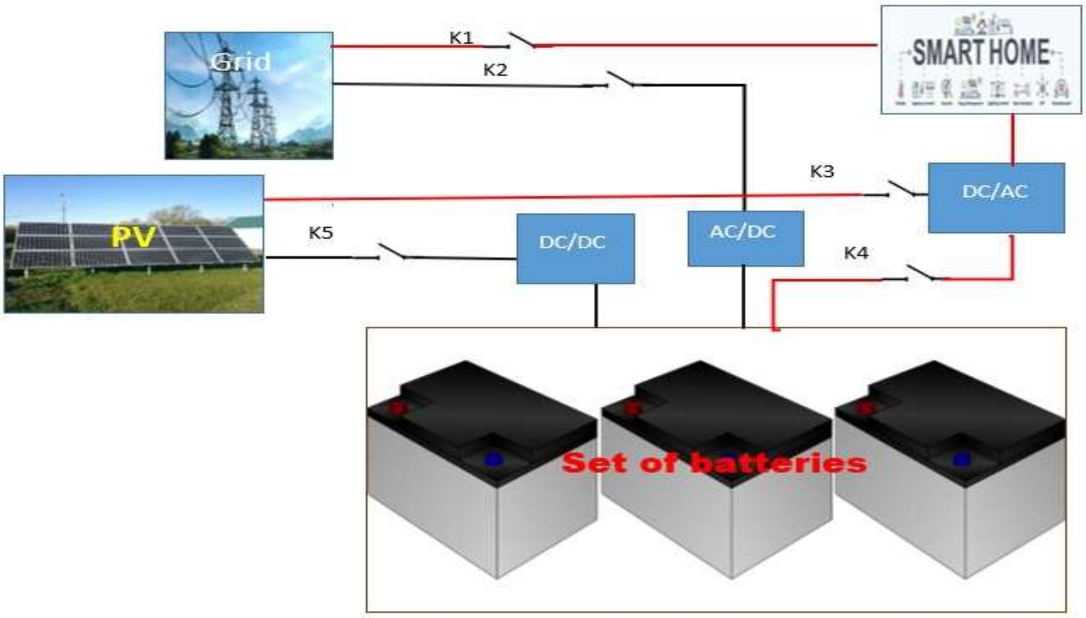

Figure 2. PV system with grid connected at smart home

2.2. Photovoltaic array

The energy produced by PV panels primarily caters to the base loads in smart homes. The PV system is designed to include a 3 kWp PV array, which is based on the specifications of the solar panel. A PV panel can be connected in series, parallel, or a combination of both. These panel connections are implemented through an inverter to a single-phase smart meter.

The efficiency of a PV system is influenced by environmental factors that can reduce it is performance, such as shading from trees and buildings, dust, snow, clouds, dirt, and pollution. The position and duration of sunlight exposure, which varies by day, month, and season, also affect the system's efficiency. Solar power or solar irradiance is measured over time as the energy from the sun that reaches a unit area's surface, expressed in kWh/m^2. This measurement is crucial for estimating the output of the PV array and verifying system performance. Solar energy from the sun is converted into electricity by exposing the PV panels to the sun's radiation. The electricity output value of the PV module at any given time can be estimated using (1) [18]:

$$\mathrm{EPV} = \mathrm{A} \times \mathrm{rpv} \times \mathrm{Np} \times \mathrm{H(t)} \times (1 - 0.005(\mathrm{tc} - 25)) \quad (1)$$

where, rpv is the PV module efficiency, Np is the number of PV panels, tc is the outer air temperature, A is the solar panel area (m^2), and H(t) is the solar radiation updated every 30 minutes (w/m^2). As well as the energy output of the PV panels can be evaluated as [16]:

$$\mathrm{EPV} = \mathrm{P_p} \times \mathrm{rpv} \times (\mathrm{H(t)}/\mathrm{H\,(tstc)}) \times (1 - \alpha\mathrm{t}\,(\mathrm{tc} - \mathrm{tstc})) \quad (2)$$

where P_p is the maximum power of the solar panel in KW, α_t is the temperature coefficient of power (% Cº), t_{stc} is the temperature of panel under STC test is equal to (25º). Table 1 give out the PV display featuring the specifications of all components: battery bank, hybrid inverter and PV array also Table 2. Presents the monocrystalline solar module is rated to generated 42.3 volt and 11.69 amp will generate 495 or 500 watts under the standard conditions: 1,000 W/m^2, cell temperature 25 ºC and air mass 1.5.

Table 1. The specifications of the energy sources and storage system

Source	Type	Rating
Solar PV array	Monocrystalline solar module (Trina solor)	3 kWp
Battery bank	Solar Gel (12 V 200 Ah 4 battery's series with 3 arrays parallel)	28.8 kWh
Hybrid inverter		5.5 kW

Table 2. Specification of monocrystalline solar module (Trina solor)

Parameter	Value
STC power rating Pmp (W)	500
Open circuit voltage Voc (V)	51.5
Short circuit current Isc (A)	12.3
Voltage at maximum power Vmp (V)	42.8
Current at maximum power Imp (A)	11.69
Temperature coefficient of PMAX.	-0.36%/C
Dimensions	2,176×1,098×35 mm

2.2. Battery storage

A battery bank with a capacity of 28. 8 kWh is used to maintain the stability of the system through daily charge and discharge processes. The state of charge for this battery bank is regulated between 20% (as the minimum level) and 96% (as the maximum level). The storage system, such as a battery system, is considered a crucial tool for managing load demand in smart home. It provides energy during peak load periods at night, during off-grid periods, and on autonomy days. Additionally, any excess energy generated by PV panels can be stored in these batteries. This makes the system highly efficient and reliable [19], [20].

$$SoC_{BAT}(t) = E_{BAT}(t-1) + \delta.\eta^{B.Etch} - \frac{\delta E^{d}t}{\eta B} \tag{3}$$

SoC_{BAT} (t) is a term that represents the level of electrical energy at a specific time slot, denoted as (t). This term signifies the battery's charge level per hour and is determined by the battery's rate of charge or discharge, measured in kilowatt-hours (kWh). The symbol of (δ) is used to denote the time limt period, which is measured in hours. The efficiency of the battery's charge and discharge processes is represented by η^B. E_{BAT} (t-1) is a term that signifies the initial level of electrical storage, measured as kWh. Lastly, $E_{t\,ch}$, and E_t^d are terms that represent the rate of electrical power charging and discharging, respectively. These rates are measured in kilowatts (kW).

2.3. Hybrid inverter

The primary benefit of a hybrid inverter, such as the model Solarhome-5.5 kW, is it is ability to integrate with a renewable energy system. This system utilizes various energy sources, including batteries, to maintain a balanced electricity supply in smart home. In addition to batteries, the hybrid inverter can also connect to the national electricity grid and various electrical appliances commonly used in smart home. The inverter boasts impressive efficiency rates: it has a 98.3% efficiency in the DC/DC conversion state and a 96.9% efficiency in DC/AC conversion state [8].

3. STRATEGY FOR OPTIMAL ENERGY MANAGEMENT

Consumers often aim to reduce energy consumption during peak load periods. The operation times of various electrical devices are primarily determined by the consumer' needs. Electrical appliances are classified based on the consumer's priority needs. Some appliances are identified as based loads, meaning the are essential and operate continuously. Additionally, there are controllable loads, which are appliances that can be operated at any time of day [21], [22]. In a smart home, various types of domestic loads are present. The proposed system focuses on sampling these loads based on their electricity consumption and rescheduling them as depicted in Table 3.

Table 3. The specifications of the residence load and the energy demand through 24 hours at the smart home

No.	Appliances	Type of load	Power rated (kw)	Run time (hour/day)	Time of interval (hour)	Total energy (kwh)
1	Light	A	0.3	18	24-6	5.4
2	Fan	A	0.2	24/7 month	24-0	4.8
3	Cooling unit	B	1.5	12/5 month	18-6	1.260
4	Water heater	B	3	2-1/5 month	2-0	6
5	Heating unit	B	1.8	12/winter	12-0	21.6
6	Refrigerating	A	0.15	24	24-0	3.6
7	Water pump	A	0.55	1	10-8	1.1
8	TV	A	0.06	16	24-8	0.96
9	PC	A	0.09	18	24-6	1.62
10	Wash machine	A	0.5	2/day/week	13-14	0.285
11	Hair dry	B	1.5	0.2	12	0.3
12	Electric iron	B	1	0.2/3day in week	12	0.085
13	Oven	B	2	1/2day/week	13	1.142
14	Micro wave	B	1.18	0.2 day	7	0.236
15	Space heater	B	1.8	4/winter	7	7.2

Reducing household energy consumption can be accomplished by analyzing the consumption profile of various appliances. The analysis of consumption energy data gives the characteristic of natural loads such as cooling units in the summer season and water heating and heating space units in the winter season [23]. A daily load profile is defined by the power rating and operating times of the appliances in a home. This study uses actual load profiles of energy consumption over three days in the winter, summer, and spring seasons as examples. The power flow, which is a function of time or a specific moment, is represented by (4) [18].

$$P_i = P_L - P_{Bat} - P_{PV} - P_G \tag{4}$$

In this context, Pi is defined as the power flow at the interconnection point in a smart home. P_L represents the power consumed by the electrical appliances. PBat refers to the rate of power charging and discharging of the battery, measured in kilowatts (kW). PPV is the power generated by the PV system, and PG is the power supplied from the grid. Between time slots (t-1) and (t), the battery controller regulates the power flow during the charge and discharge processes. This regulation occurs between the battery bank and the PV panels or the public grid. The available energy is stored in the batteries, which can be calculated using the following formula [24], [25]:

$$E_{BAT} = \int_{t-1}^{t} (Ppv - Pl)dt \ \ldots \ if \ Ppv > Pl \tag{5}$$

The efficiency of battery banks has been enhanced through the implementation of a newly proposed management algorithm in smart homes. This algorithm operates based on various modes that can be switched on or off (represented as 1 or 0) depending on the status of switches (k1, k2, k3, k4, and k5). These modes govern processes such as charging and discharging, or other operations that supply energy consumption from the public grid to the smart house. The workings of this algorithm are illustrated in Table 4.

Table 4. Mode operation of switches

Mode	Switch in state ON	State
1	K3 and K5	Supply the load and charge the battery by PV
2	K3 and K1	Feed the load and excess to the grid from PV
3	K3	Supply the load only BY PV
4	K3 and K2	Supply th load by PV and battery by grid
5	K1 and K2	Feed the load and the battery by grid (k3 is on state /an interval of sunrise)
6	K3 and K4	Supply the load by both PV and battery
7	K1	Part of load connected to grid directly

The development of energy management and efficiency in distribution power systems is supported by an energy flow management algorithm, illustrated in Figure 3, which ensures optimized utilization of energy resources and improved overall system performance. This algorithm includes eight modes (mode 1, mode 2, …). Each mode represents one of the following states feeding domestic loads by either the grid, PV panels, bank battery's or both of them. In addition to, the processes of charging, discharging of batteries and supply the surplus energy to the grid.

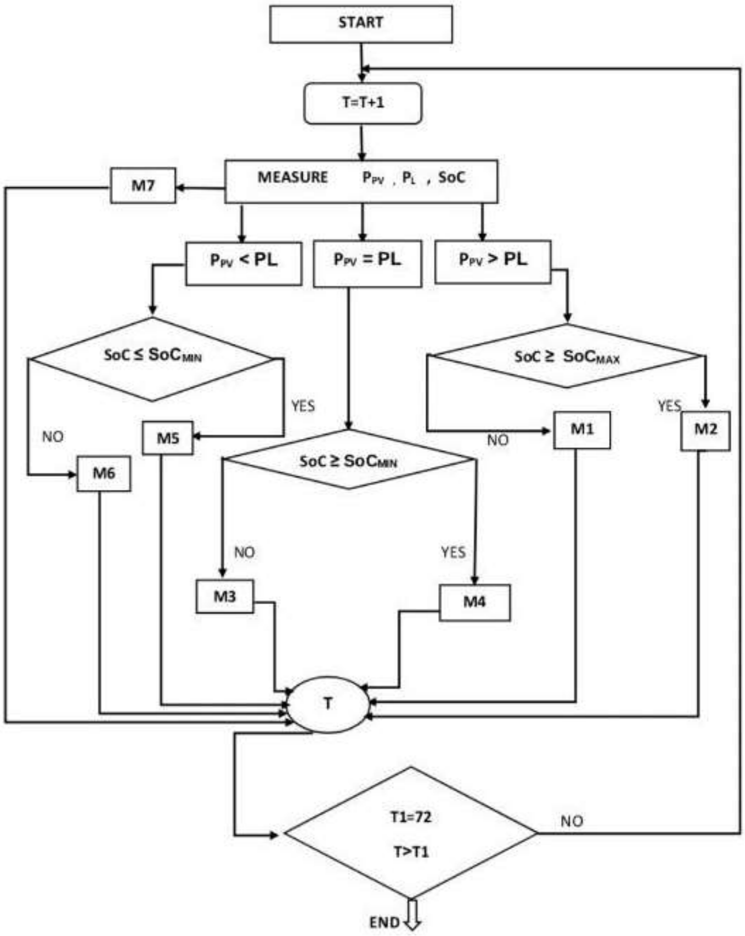

Figure 3. Flow chart of energy management

4. RESULTS AND DISCUSSION

This study focused on estimating the economically optimal state of energy management in a smart home. Data collected from the Karbala meteorological station in April 2022 were analyzed, including variables such as average daily ambient temperature, daily solar radiation intensity, and the length of the daytime. Cities in Iraq typically experience long daylight periods, with solar radiation exceeding 3,000 hours, varying from 833 W/m^2 in June to 416 W/m^2 in January in Karbala city. Additional energy sources, such as PV panels, were integrated with the grid to optimize the smart system, aiming to achieve savings in electrical power and reduce the electrical bill. The proposed smart system utilized sensors to minimize household energy waste and ensure an uninterrupted power supply for domestic loads. This example specifically focuses on a smart home in Karbala City.

4.1. Scenario 1

The performance of the flow energy management algorithm was tested in various scenarios, and its efficiency was evaluated based on the energy demand. The algorithm automatically switches between different modes (k1, k2, k3, k4, and k5) depending on the available energy, as depicted in Figure 4. In scenario 1, which spanned a 72-hour running period, the focus was on the power grid and energy storage system under two operational conditions: power supply interruptions in the public grid and three consecutive cloudy days. These conditions could occur in different seasons, like winter, spring, or autumn. The strategy involved charging the energy storage system during grid availability and then switching to discharging mode during electricity outages, lasting around 20 hours each day. This was necessary due to shutdowns or insufficient energy generation in electrical plants, particularly in Iraq. The energy storage system maintained a charging mode when the grid was available and switched to a discharging mode during outages. The bank batteries' capacity constraint ranged from 20% (minimum state of charge) to 96% (maximum state of charge), ensuring uninterrupted power supply for the base load over extended periods, as illustrated in Figure 5.

Figure 4 depicts the states of k1, k2, k3, and k4 switches based on whether the system is operating on the grid or off the grid. Specifically, the figure shows that k1 and k2 switches are in the "on" state for one hour during each six-hour period when the system is connected to the grid. On the other hand, the k3 switch is in the "on" state during the sunrise period.

Figure 5 illustrates the state of charge of batteries over a 72-hour time interval from April 1-3, 2022, specifically during three cloudy days in a smart home. Due to the cloudy conditions, the generated power from the PV array is negligible and not sufficient. In Figure 5, the state of charge of batteries is accurately estimated and maintained within a reasonable range, represented by mode five. This mode spans from 0 am to 24 pm (24 hours), and the batteries undergo a charging process for 12 hours during the 72-hour time interval.

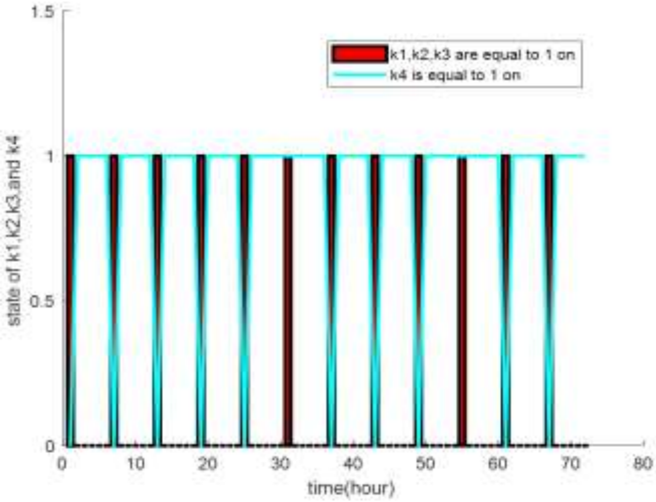

Figure 4. The k1, k2, k3, and k4 states based on the state of on grid or off grid

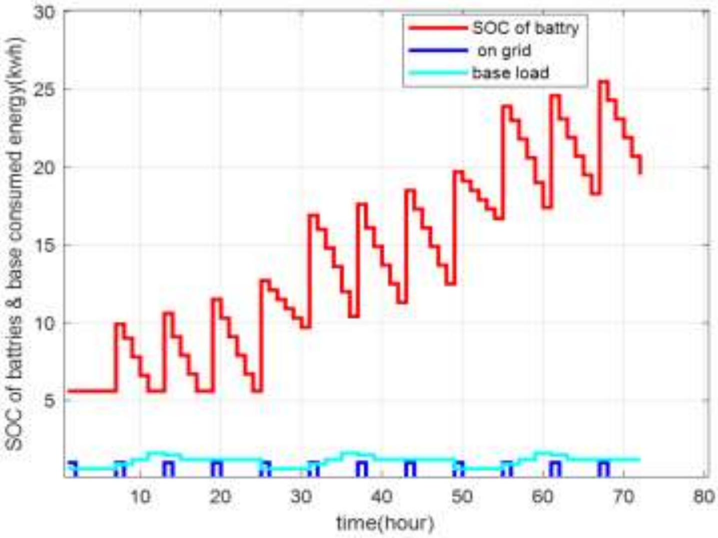

Figure 5. Illustrate the state of charge of batteries for three cloudy days at smart home on April 1-3, 2022

4.2. Scenario 2

The results of scenario 2 are presented in Figures 5 and 6. These figures depict the average generated power from the PV system on April 10-12, 2022, specifically during the period from 8:00 am to 4:00 pm, repeated over 72 hours. In Figure 5, the states of k1, k3, k5, and k4 switches are illustrated. When the batteries are capable of discharging, the k4 switch is in the "on" state.

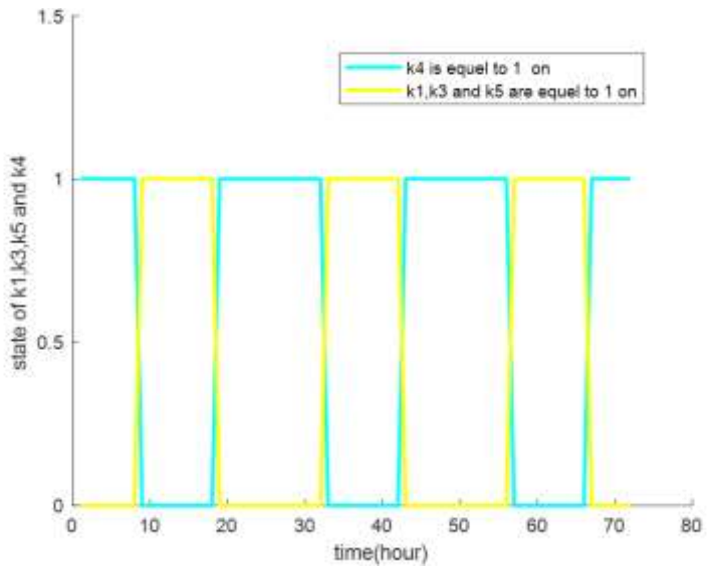

Figure 6. The k3, k5 and k1 state according to scenario 2

Figure 7 displays the states of k3, k5, and k1 switches following scenario 2. It provides a clear depiction of when these switches are in the "on" state during the specified conditions and time. Figure 7 illustrates the output of the PV system in a smart home, which is used to power the base loads and handle any excess energy. The storage system is actively controlled to maximize productivity and minimize waste. In an ideal scenario where the PV array generates power from sunrise to sunset, the produced energy would be distributed among three components: supplying the base loads within the smart home, charging the batteries for energy storage, and any surplus power that can be fed back into the national grid. The distribution and utilization of the PV system's energy are represented in Figure 7.

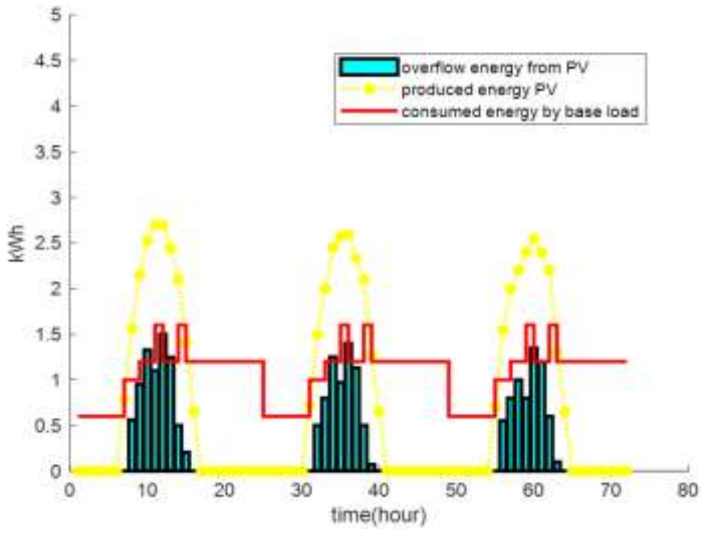

Figure 7. Shows the pv output that is fed the base loads (type A) at smart home on April 10-12, 2022

4.3. Scenario 3

The scenario 3 presents a comparison between the power consumption at home and the power consumption at smart home as well the saving power in a smart home on April 10, 2022. Figure 8 presents two curves depicting the power consumption in a smart home on April 10, 2022. The first curve represents the power consumption when the home is solely reliant on the grid, without any smart devices or additional energy resources. The second curve shows the power consumption profile when the smart home is connected to a microgrid, which includes PV panels and smart devices. In this configuration, the smart home benefits from the generated power from the PV panels and utilizes smart devices to optimize energy usage. The Figure 8 indicates the estimated amount of saved power achieved through the proposed smart home model. This representation corresponds to mode 1, mode 6, and mode 7 of operation.

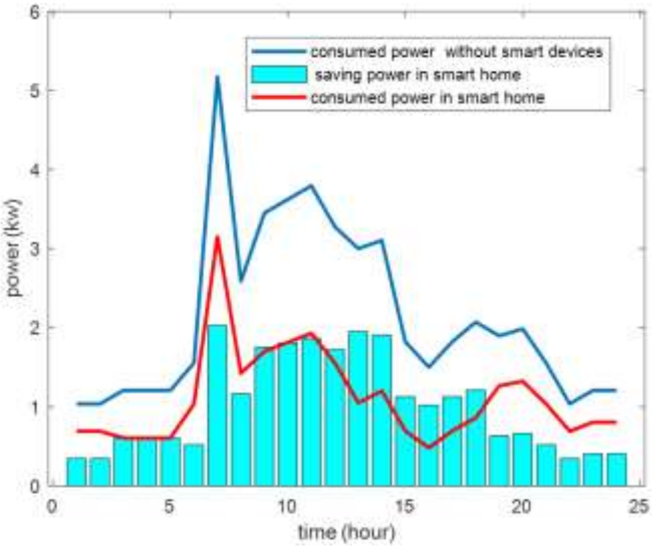

Figure 8. Curves of consumption and saving power for the study case on April 10, 2022

Figure 9 illustrates the amount of saved energy in a smart home on April 10, 2022. The saved energy accounts for 48% of the total energy consumption, thanks to the suitable supply conditions from the grid and optimal temperature for PV energy production. Additionally, the solar panels contribute to reducing the overall energy consumption, with the saved energy from the grid amounting to 37% of the total loads on that day. The remaining 15% of electricity is supplied by the grid. The economic benefits are significant, with the estimated cost savings in the electrical bill reaching up to 85% of the energy purchases for the home.

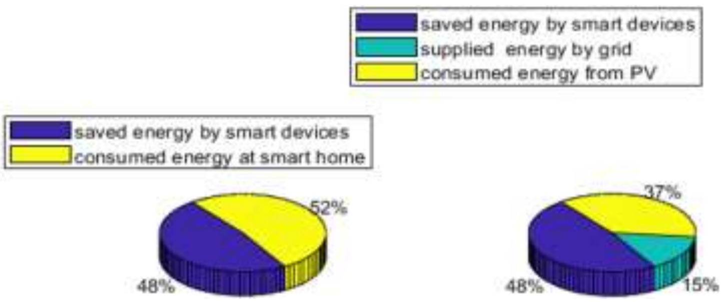

Figure 9. Shows the saved energy at smart home on April, 10 2022

4.4. Scenario 4

The scenario 4 presents a comparison between the power consumption at home and the power consumption at smart home as well the saving power in a smart home on July 4, 2022. Figure 10 illustrates the amount of saved energy in a smart home on August 1, 2022. The saved energy accounts for 33% of the total energy consumption. Additionally, the solar panels contribute to reducing the overall energy consumption, with the saved energy from the grid amounting to 17% of the total loads on that day. The remaining 50% of electricity is supplied by the grid. The economic benefits are significant, with the estimated cost savings in the electrical bill reaching up to 50% of the energy purchases for the home.

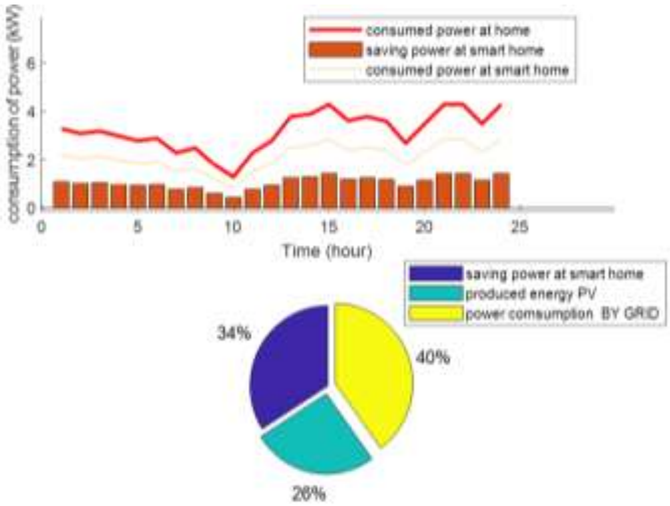

Figure 10. Shows curves of consumption and saving power for the study case on July 4, 2022

4.5. Scenario 5

Figure 11 illustrates the amount of saved energy in a smart home on January 2, 2022. The saved energy accounts for 33% of the total energy consumption. Additionally, the solar panels contribute to reducing the overall energy consumption, with the saved energy from the grid amounting to 14% of the total loads on that day. The remaining 53% of electricity is supplied by the grid. The economic benefits are significant, with the estimated cost savings in the electrical bill reaching up to 47% of the energy purchases for the home.

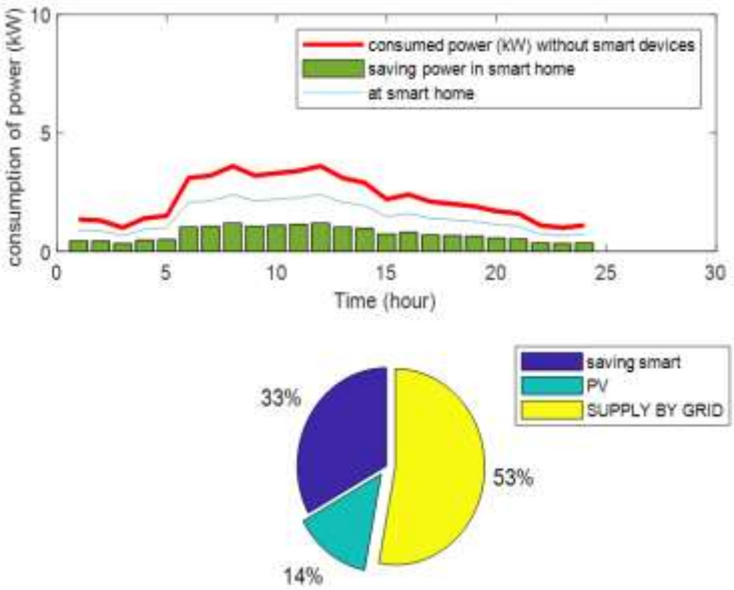

Figure 11. Shows curves of consumption and saving power, on January 10, 2022

Table 5 provides a breakdown of the estimated consumed energy at home, the consumed PV energy, and the energy savings in kilowatt-hours (kWh) specifically for April 10, 2022, on January 2, and on July 4, 2022. Table 5 the estimation of consumed energy at home, produced PV energy consumed and saving energy at smart home in kWh on April 10, on January 2 and on July 4,2022. Table 5 provides an evaluation of energy consumption in a home without the addition of a solar system and smart elements to the electrical appliances. The consumed energy on April 10, January 2, and July 4, 2022, were measured at 51.3, 53.05, and 76.93 kWh. A smart home' elements are connected with each other and can be arrived by one central point a tablet, lap top, smartphone. The elements of automation system at smart home are sensors, actuators, and controllers. However, after converting the home into a smart home by incorporating a PV system and other smart elements within the microgrid, significant energy savings were achieved. The smart home setup resulted in a saving of 44.6, 25.45, and 45.93 kWh of energy on April 10, January 2, and July 4, 2022 the generation of 20, 7.8, and 20.03 kWh respectively of PV energy. Both the energy savings and the generated PV energy contributed to a reduction in the amount of energy supplied by the national grid.

Table 5. Estimation of energy consumption in a home with the addition of a solar system and smart elements to the electrical appliances as well the energy savings in kilowatt-hours (kWh)

Month	Consumed energy	Produce energy PV	Consumed energy at smart home	Saving energy
April	51.3	20	26.7	44.6
January	53.05	7.8	35.4	25.45
July	76.93	20.03	51.2	45.93

5. CONCLUSION

To conclude, harnessing solar energy in Iraq is a feasible option due to the high solar radiation ranging from 2,000 kWh/m^2-year to 2,600 kWh/m^2-year. However, variations in climate can affect the energy production of PV systems. It is crucial to consider future load estimates for effective planning. This study proposes an algorithm for managing the charge and discharge of storage systems, which not only extends battery life but also ensures the storage capacity aligns with the demand. The results demonstrate the positive impact of the proposed system in a smart home. Before the implementation, the daily energy consumption from the national grid on April 10, 2022, was 51.3 kWh. However, after enhancing the smart home strategy, the consumption was reduced significantly to 6.7 kWh. Additionally, the daily consumed energy by the grid on January 4, 2022, was 53.05 kWh. After then the enhancement of smart home' strategy, the consumption energy was reduced to 27.6 kWh. As well the daily consumption energy from the grid on July 4, 2022, was 76.93 kWh, the consumption was reduced to 31 kWh. This reduction in energy usage leads to savings and lowers running costs. This work has economic returns, supporting the grid in both aspects management and production, as well useful environmental effect. This work would prompt the componies and citizens to take advantage of this project in the future.

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BIOGRAPHIES OF AUTHORS

Hasan Hammoodi Shakir he received the BS and the Master's degrees in 1997 and 2018, respectively, all in electrical engineering from the Collage of Engineering, University of Ferdowsi Mashhad. He is a Ph.D. student in the National Engineering School of Sfax, University of Sfax. He is a member of the Control and Energy Management Laboratory (CEMLab) of the University of Sfax. His main research interests cover several aspects related to the advanced control and the medium voltage networks, distribution grids and involved in automotive, renewable energy systems, and smart grid technologies. He can be contacted at email: hasan-hammoodi.shakir@enis.tn.

Fatma Ben Salem was born in Sfax, Tunisia, in 1978. She received the BS, the Master's, the PhD, and the HCR degrees in 2002, 2003, 2010, and 2015, respectively, all in electrical engineering from the National Engineering School of Sfax (ENIS), University of Sfax, Tunisia. She is a full professor of electrical engineering at Prince Sattam Bin Abdulaziz University, College of Engineering, Departement of Electrical Engineering, Al Kharj, Saudi Arabia. She is a member of the Control and Energy Management Laboratory (CEMLab) of the ENIS, University of Sfax. She is an IEEE member. Her main research interests cover several aspects related to the advanced control and the diagnostic of electric machine drives and generators involved in automotive, renewable energy systems, and Smart Grid technologies. She can be contacted at: f.bensalem@psau.edu.sa; fatma.bensalem@isgis.usf.tn.