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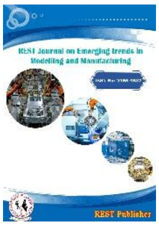

Smart Energy Management of Photovoltaic-Storage Systems Integrating Wireless Communication for Enhanced Efficiency

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Abstract: *Efficient Energy Management (EM) has become critical in today's world to meet increasing energy demands and achieve sustainability. Traditional energy systems, especially in Photo Voltaic (PV) setups, face challenges such as dynamic load variations, energy losses, and limited real-time optimization capabilities. These limitations hinder their ability to efficiently manage energy generation, storage, and consumption. This research proposes a novel framework integrating wireless communication with smart EM techniques for PV-storage systems. The approach leverages advanced control algorithms and wireless data exchange to enable real-time monitoring, adaptive decision-making, and seamless energy flow coordination between PV panels, storage units, and the grid. By addressing inefficiencies in traditional systems, the proposed framework reduces energy losses, optimizes resource utilization, and enhances overall operational efficiency. The integration of wireless communication not only facilitates faster data transmission but also enables predictive control, ensuring the system adapts to fluctuating energy demands and environmental conditions. Results demonstrate a significant improvement in energy efficiency and reliability, underscoring the viability of this approach in advancing renewable energy systems. This study highlights the transformative potential of smart EM and wireless integration in creating more sustainable and efficient energy solutions.*

Keywords: *Energy Management, Photovoltaic, efficiency, wireless communication.*

1. Introduction

Addressing climate change, minimising carbon emissions, and eventually achieving sustainable development globally all depend on the building industry using less energy [1]. One of the Sustainable Development Goals (SDGs) of the United Nations, Goal 7: "Make certain availability of reliable, modern, and affordable energy for all," is really connected to the energy consumption of the built environment. The goals are as follows: "Keep urban regions and communities equitable, safe, resilient, and sustainable," in addition to Goal 13: "Take quick action to deal with climate change and its impacts." Over 17% of these objectives have a direct connection to the construction sector, and 27% have an indirect connection to its activities [2], most of which involve high energy use. Society has been compelled to accelerate the quest for alternative energy technology due to the correlation between ecological problems including the Keeling curve, fire frequency, and the impact of climate change. Energy storage devices and solar panels are becoming more popular as a result of the situation [3]. Though it is not ideal for an excessive amount of newly invented electrical appliances that will result in the network's short-term financial gain, the usage of new energy will considerably reduce the emission pollutants released through the efficient operation of the power grid from the aspect of pollution control. Additionally, weather-induced changes in the amount of light make PV power generation unstable, making power supply to consumers uncertain [4]. Household EM systems have been the focus of specialists to promote the prudent allocation and efficient utilisation of electricity among PV storage, battery-powered devices, and the grid [5]. On the basis of consumer consumption patterns, an energy-efficient water temperature control system is integrated into electric water heaters to maximise their cost and effectiveness [6]. The benefit studies of how various appliances operate and develops a hybrid integer algorithm model of how cost-effectively household appliances operate while accounting for the government's PV installation subsidy [7]. The economic optimal strategy that uses a multifunctional flower pollination technique to address the unpredictability of newly generated energy output in real-time. The scheduling method for energy optimisation is not visually represented by the simulation approach; nonetheless, prior research has successfully reduced home electricity bills for consumers to varying degrees. However, the effect on the system of the absence of data flow from domestic equipment is not considered [8]. Demand response strategies and load management are made possible by IoT in smart buildings. Buildings can adjust their consumption of energy in response to price fluctuations and consumer demand signals by using bidirectional connectivity and real-time energy monitoring systems. Incorporating renewable energy sources, transferring loads, and controlling peak loads are all made possible by this [9]. Centrally managed monitoring and control of smart buildings' power systems is made possible by combination with IoT-based energy management. These programs allow executives in buildings to analyse energy use, set power-saving goals, and remotely manage systems by merging data from multiple sensors and technologies. Demand-side tracking and larger-scale energy optimisation are made possible by integration with distribution networks [10,11]. In addition to technical factors, social factors that are relevant to building energy efficiency—especially those related to tenant behavior—have been given more attention in recent decades. For instance, empowering end users to alter their inactive action and maximise the adaptability of their home energy use is one of the main components of the Renewable Energy for everyone in Europe package. Estimates indicate that this could contribute to a 4% to 30% decrease in household energy consumption. One of the biggest behavioural shifts that may reduce energy and carbon in buildings is lowering cooling or heating levels or putting smart as well as user-centred systems in place to regulate the implementation of networks and devices. However, there is still much to be done because their implementation and performance are highly dependent on specific situations that are difficult to predict and impacted by various economic, technological, and societal factors.

2. Literature Review

Ma et al., have investigated how modern technology affect people's daily lives. A smart network control system that combines electricity production, use, and administration is called a HEMS. It seeks to enhance consumers' energy use and streamline communications with the grid in order to promote two-way energy flow. The first countries to use HEMS applications were the following: the Netherlands, China, the United States, Italy, Denmark, Japan, Germany, and Britain. Most of them were installed using smart meter technology [12]. According to Michael et al., a HEMS's primary advantages include its ability to lower energy expenses and bills as well as provide grid services including demand flexibility and peak energy saving. However, a significant issue that may reduce the benefits of a HEMS for both customers and grid operators is uncertainty in home energy systems [13]. However, it is essential that HEMSs complement the goal of making residents comfortable and at peace. Jin., have proposed that HEMSs keep an eye on the energy usage trends in their homes. Establishing a model to efficiently regulate and manage energy usage was the researchers' impact on the field of HEMSs. In order to calculate the overall power and load, a home EM system must first get data from the power source. Only then can it determine the most cost-effective scheduling. Using a variety of sensors, smart electricity meters in the age of smart power grids gather information from home appliances and send it to the EM centre via communication devices [14]. Wang and Chen., have described that the conventional data transmission method necessitates installing numerous connections for home appliances, which not only detracts from the building's appearance but also adds to the burden and new power lines design expenses. Zigbee wireless transmission technology's affordable price, minimal energy consumption, and excellent dependability have disrupted the traditional practice of domestic appliances transmitting data via wire. Through wireless data transfer, Zigbee links the actual index gathering device to the data centre, increasing the flexibility of information gathering for HVAC, heating, and other equipment dispersed throughout the house and encouraging smart device monitoring [15]. Both retrofit initiatives and flexible energy contracts are now of more importance to consumers. Utility companies are now turning to clean energy sources and novel Demand Response (DR) strategies as a result of the Covid-19 pandemic's intermittent energy demand and subsequent gas problems in Eastern Europe. These, along with the general objective of a clean and equitable energy transition, have forced policymakers to give households' behaviour, energy cues, and financial incentives for extensive retrofitting more careful thought. For instance, the EU "Save Energy" plan, part of the Repower EU program, emphasises the significance of immediate as well as long-term steps to decrease the energy usage of both homes and businesses by encouraging voluntary a routine modification and upgrading structural measures in combination: behavioural and lifestyle changes can help drastically reduce energy usage. Making the decision to lower heating conditions, utilise cooling systems and home appliances more effectively, and turn off the lights can result in significant instant savings [16]. Gaspari et al., have conducted more research is being done on user energy profiles and energy saving alternatives in order to better inform the creation of tools, policies, and initiatives. The literature still shows a lot of ambiguity regarding the true role and importance of residence occupants in energy conservation, though, in part because of the determinants of user behavioural change and in part because of the behaviours that are taken into account (e.g., only routine-dependent behaviours or single investments in energy-saving appliances). Additionally, there is also disagreement on the efficacy of electrical energy tracking and control techniques, which have long been thought of as a solution to this problem [17]. According to Zand et al., SG auxiliary services have presented a new EM approach for PV-based electric vehicles. However, wireless solar energy monitoring and control are not covered in this study [18]. Wei et al., have presented a novel reinforcement learning method for EM that capitalises on the growth of electric vehicles and wind. Nevertheless, the system's hardware implementation was not shown. Moreover, there is no coverage for load management and tracking directed by wind power. The energy transaction behaviour between regular residential users and the power system under various electricity prices is examined in this study based on the previously described issues. Additionally, a pertinent hardware circuit is created and evaluated while taking the household EM system's data connection interference into account [19]. The study's contributions are summed up as follows:

- Under the conditions of time-of-use electricity tariffs, a household EM framework is constructed that consists of photovoltaics, energy storage, household loads, and the power grid. The most cost-effective energy dispatch mode is chosen based on the actual power generated and utilised of the consumers' families.
- The Zigbee network is constructed, and hardware devices are used to simulate user energy scheduling. The water wave effect's cost fluctuation is determined by setting transmission interference at various times.

3. Research Methodology

Energy losses and restricted real-time optimisation are two issues with conventional PV systems that are identified as part of the research technique. To identify gaps and support the suggested strategy, a comprehensive evaluation of the literature is carried out. Continuous surveillance and adaptive decision-making are the main features of this innovative system that combines wireless connectivity and smart energy management. To guarantee compatibility, every part of the system— PV panels, storage facilities, wireless modules, and control algorithms—is described in full. While a strong wireless communication protocol is put in place for smooth data flow, sophisticated algorithms are created for predicted EM under various circumstances. To assess performance in various scenarios, the system is emulated in controlled conditions. Efficiency is increased by optimising critical characteristics like latency and energy flow. To verify its practical application, a scalable model is built and its performance is evaluated in a variety of operating scenarios. Reliability and energy efficiency metrics are examined, and the outcomes are contrasted with those of conventional systems. To improve the framework, experimental and simulation data are evaluated. To address shortcomings and call attention to changes, insights are presented. The process culminates with the documenting of results to direct future investigations into improving PV-storage systems via wireless connectivity and intelligent energy management.

Domestic PV energy storage management system modelling

As illustrated in figure 1, the smart home with reserve capacity and energy generation has effectively implemented a connected data network through the use of the ZigBee device. Wireless communication device arrangement significantly increases the household electrical power reserve control system's intelligence. In addition to classifying household energy flow, this section defines four different EM designs: selling power, balance power purchase, and reserve power. Furthermore, feed-in pricing circumstances and time-of-use price are taken into account while determining the household energy system's ideal financial objective function. This study splits the day into 24-hour time slots, each of which is denoted by $t \in H = \{1, \ldots, 24\}$an indicator to clearly illustrate the system's operating conditions at various periods. When electricity prices are low, users can store excess power generation in their homes by installing energy storage devices. Users have the option to sell a certain quantity of electricity for a profit at this point as the power grid's selling price of electricity rises in tandem with the peak load. Allow the user's power storage in time slot t to be des[t], thus a reserve energy is limited by

$$0 \leq des[t] \leq DE\ S,\ \forall t \in H, \quad (1)$$

The energy storage device's maximum capacity for storage is denoted by DE S. In addition, as consumers are impacted by variable loads, electricity usage is ever-changing. An unfixed load is introduced when the air conditioning system modifies the temperature within based on the user's preferences while the user is indoors. Consequently, the user must buy electric energy from the power grid when their energy is insufficient to offset this portion of the demand. Assume that the user's power purchase during time slot t is b[t], meaning that the power consumed is limited by

$$0 \leq b[t] \leq L[t],\ \forall t \in H, \quad (2)$$

In the time slot, the load is denoted by L[t].

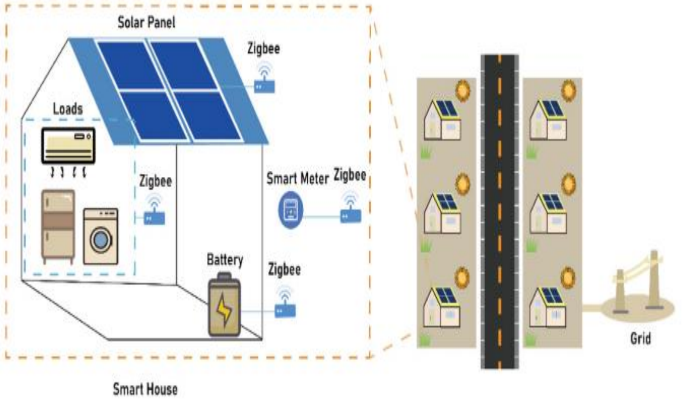

Figure 1. Smart home with reserve capacity and energy generation

Wireless communication network

A wireless communication system that works well in low-power and short-distance situations, Zigbee allows data sharing between any nodes in its network. This component builds the home appliance data transmission network, as seen in figure 2. Energy storage systems, PV equipment, and load all employ Zigbee devices to provide real-time information to smart meters for summarisation. Coordinating the flow of energy both within the house and between the house and the grid, the home EM system analyses the information it receives. The constraint model is determined once the system has processed the data that was uploaded via the Zigbee network. The system transmits commands for control to the Zigbee network after receiving the analysis findings from optimal economic programming. To achieve energy coordination both within the dwelling and among the home and the power grid, this network uses multicast to transmit instructions from the point of coordination to the terminal. In this study, the other machines are designated as terminals, and the point of contact is the Zigbee network's data centre. Through the broadcast, the data centre transmits data packets to the cluster's devices, which digest the information and adjust their operations accordingly. The terminal uses P2P to send data to the data centre at the next time slot. Once the packets have been parsed, the terminal device uses the Zigbee device's I/O port to send data to and from external devices. While the Zigbee network is highly reliable in most settings, it is still challenging to remove the effects of interference from other channels and bit error rate. The entire system could be impacted if the Zigbee network's data transmission fails at time t. In this experiment, the findings of the home EM system are altered after 24 time slots under the greatest PV output, simulating that the data transfer is severely interfered with by connectivity.

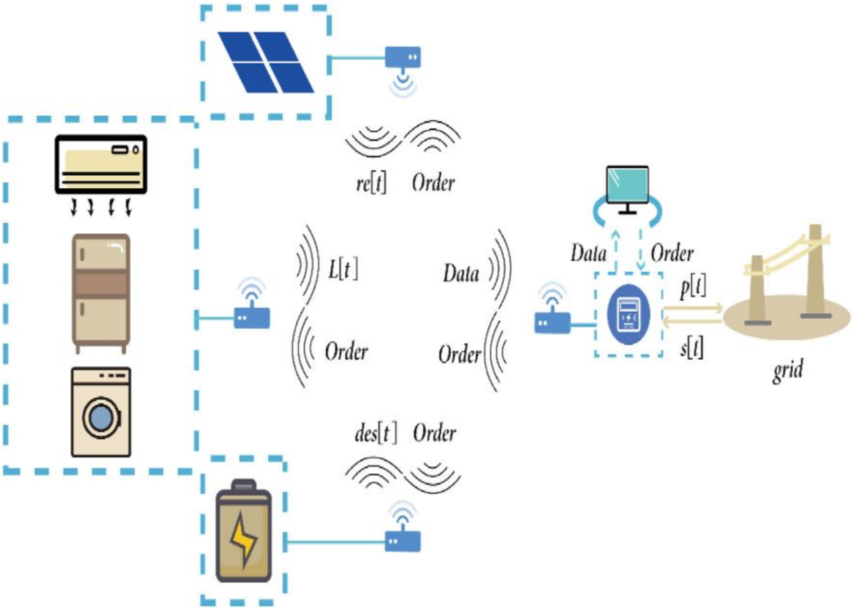

Figure 2. An energy system with a Zigbee network

4. Example analysis

Data on domestic appliance power usage is chosen for the household load. The actual operating data of a user's PV equipment is adopted by the PV output scenario in a single day. The energy storage device's PV output is set at 10 kWh for the purpose of this study. The management system allows for the observation of wheel speed, operating duration, and other parameter data, allowing for real-time monitoring of PV storage flow of energy, storage of energy, and load. The ZigBee network's management system takes action to satisfy load demand before buying electricity from the power grid when a terminal is unable to upload data. When the communication system is functioning regularly, information analysis of the home EM system. PV-generated electricity may readily fulfil residential energy use during the first peak-price period, which runs from 7 to 12. Consequently, surplus energy is sold to the electrical grid by the system. Twelve to nineteen days prior to to the second peak-price period, the system chooses to purchase electricity via the power grid over the valley-price stage. The system now starts to store a significant amount of energy in order to equalise demand during the peak-price phase. To guarantee the economical dispatching of household’s energy, the system starts providing the stored electric energy at 19:00, when the price of power reaches its highest. This lowers the cost of electricity charges at night.

Automatic Control:

Maximising the usage of clean energy when a home is linked to the grid or preventing battery depletion while the installation is completely detached and is unable to depend upon the grid as an alternative source of energy are two major challenges with these systems. The battery charge level, energy production, and demand from the various appliances, air conditioner, and heat pumps operating in the house must all be taken into consideration when making judgements on this issue. The Raspberry Pi must implement and execute a set of control rules in order to carry out these pertinent judgements. As previously indicated, this method has the benefit of utilising the device's processing power while guaranteeing an offline operation in the event that the network connection is momentarily unavailable. Another significant benefit is the avoidance of using stored in the cloud computational capabilities, which significantly raise the system's overall operating costs. To improve comfort and energy efficiency, our algorithms' control approach is made to maximise the use of PV energy and environmental factors. It effectively replenishes the electrical battery when PV generation is at its peak. By taking advantage of the thermal resistance of building structures, it simultaneously stores thermal storage systems, such as a water tank. To increase heat pump efficiency, this thermal charge is synchronised with times when the outside temperature is higher. Then, when PV generation is minimal or the weather is not at its best, the stored energy is used. The program also arranges heating and cooling tasks to take place during the best periods for energy production and storage use. This guarantees that energy needs are satisfied effectively, even in situations where generation is low or heat pump efficiency is reduced.

Solar panel components

- Solar panels: These panels combine thermal solar energy and PV power generating into one device. These panels come in six different configurations, each with a facing back Sunthalpanel solar thermal panel and a facing the front solar panel with an output power of 405 Wp. A total of 2.43 kWp is delivered by the PV panels when combined, and 9.37 kWp is delivered by the thermal energy component of the panels. The primary circuit of the heat pump can be powered by unconverted PV energy according to this design.
- Electric Battery: The 13.4 kWh Cegasa eBick Ultra 175 battery stores energy while PV production is strong, providing a steady supply of electricity at night and at times when solar radiation is minimal.
- Inverters that convert DC power to AC power and vice versa are known as SMA inverters. An electricity consumption, PV production, and battery status, comprising charging % and charged/discharging power, are all provided by their Modbus TCP connection.
- The Ecoforest AU6 outdoor aid device with Ecogeo 1-6 Pro: With an output range of 1–6 kW, this high-efficiency water-to-water heating system enhances the unit's thermal energy control capabilities and increases its total energy efficiency. Data on compressor speed, electricity consumption, heat source and distribution water networks, and other relevant information are provided by the Modbus RTU connection. Carbon Steel Storage Tank: Featuring firm injected polyurethane foam for thermal insulation and HCFC-free heat storage, this 300-L tank doubles as a buffer. Two NTC temperature sensors are included.

To maximise the use of energy and ensure an adequate amount of heating and cooling, the Integrated Control System, the generator's primary component, regularly evaluates and adjusts the functioning of the components. It is based on the Compute Module 4 (CM4), the commercial version of the well-known Raspberry Pi 4. It features an RS-485 to USB interface for Modbus RTU devices in addition to a gigabit Ethernet connectivity. This is the controller preferred for the entire structure, but it has been difficult to locate material for the various other projects working on due to a recent lack of semiconductors.

5. Conclusion

The EM system used in this study addresses the energy transfer among PV retention, energy storage, load, and the power grid, which is based on the real circumstances of solar energy users. Energy scheduling is used in this system to reduce the operating costs that consumers must pay. Simultaneously, this study creates an electronic network made up of Zigbee connected devices and models how consumers' electricity costs will fluctuate when PV data transmission interferes. The findings indicate that the loss resulting from incomplete user communication is more intolerable as PV power generation increases. As a result, communication hardware needs to be manually repaired as quickly as feasible.

References

1. United Nations (2015). Transforming Our World: The 2030 Agenda for Sustainable Development (A/RES/70/1). Available online: https://www.un.org/en/development/desa/population/migration/generalassembly/docs/globalcompact/A_RES_70_1_E.pdf (accessed on 10 September 2023).
2. Goubran, S. (2019). On the Role of Construction in Achieving the SDGs. J. Sustain. Res., 1, e190020.
3. Guo, Y., Xiang, Y. (2022). Cost–benefit analysis of photovoltaic-storage investment in integrated energy systems. Energy Rep., 8, 66–71.
4. Zhang, T., Chen, Z., Zhao, Q., et al. (2021). Hierarchical optimization strategy for home energy management based on deep reinforcement learning. Autom. Electr. Power. Syst., (21), 1–15.
5. Li, J., Wang, Z., Yan, S., et al. (2020). Optimal control strategy for home energy management systems with comfort in mind. J. Sol. Energy, 41(10), 51–8.
6. Tejero-Gómez, J.A., Bayod-Rújula, A.A. (2021). Energy management system design oriented for energy cost optimization in electric water heaters. Energy Build., 243(15).
7. Lu, Q., Zhang, Z., Lü, S. (2020). Home energy management in smart households: Optimal appliance scheduling model with photovoltaic energy storage system. Energy Rep., 6(2020), 2450–62.
8. De, M., Das, G., Mandal, K.K. (2021). An effective energy flow management in grid-connected solar–wind-microgrid system incorporating economic and environmental generation scheduling using a meta-dynamic approach-based multiobjective flower pollination algorithm. Energy Rep., 7, 2711–26.
9. Al-Ghaili, A.M., Ibrahim, Z.A., Bakar, A.A., Kasim, H., Al-Hada, N.M., Jørgensen, B.N., Hassan, Z., Othman, M., Kasmani, R.M., Shayea, I. (2023). A systematic review on demand response role towards sustainable energy in the smart grids-adopted buildings sector. IEEE Access, 11, 64968–65027.
10. Orlando, M., Estebsari, A., Pons, E., Pau, M., Quer, S., Poncino, M., Bottaccioli, L., Patti, E. (2022). A Smart Meter Infrastructure for Smart Grid IoT Applications. IEEE Internet Things J., 9, 12529–12541.
11. Motta, L., Ferreira, L., Cabral, T., Lemes, D., Cardoso, G., Borchardt, A., Cardieri, P., Fraidenraich, G., de Lima, E., Neto, F.B., et al. (2023). General Overview and Proof of Concept of a Smart Home Energy Management System Architecture. Electronics, 12, 4453.
12. Ma, Y., Chen, X., Wang, L., Yang, J. (2021). Investigation of Smart Home Energy Management System for Demand Response Application. Front. Energy Res., 9, 772027.
13. Michael, B., Killian, M., Jeff, M., Tyrone, V. (2022). Home energy management under realistic and uncertain conditions; A comparison of heuristic, deterministic, and stochastic control methods. Appl. Energy, 325, 119770.
14. Jin, W. (2020). Application of smart electricity meter in smart grid. Electr. Eng. Technol., 18(2020), 53–4+62.
15. Wang, Z., Chen, X. (2019). Research on communication network architecture of smart home. Comput. Technol. Autom., 38(3), 132–5+146.
16. European Commission (2022). COM (2022) 240 Final—EU “Save Energy”; European Commission: Brussels, Belgium.
17. Gaspari, J., Antonini, E., Marchi, L., Vodola, V. (2021). Energy Transition at Home: A Survey on the Data and Practices That Lead to a Change in Household Energy Behavior. Sustainability, 13, 5268.
18. Zand, M., Nasab, M.A., Sanjeevikumar, P., Maroti, P.K., Holm-Nielsen, J.B. (2020). Energy management strategy for solid-state transformer-based solar charging station for electric vehicles in smart grids. IET Renew Power Gener., 14(18), 3843–52. https://doi.org/10.1049/IET-RPG.2020.0399.
19. Wei, L., Yi, C., Yun, J. (2021). Energy drive and management of smart grids with high penetration of renewable sources of wind unit and solar panel. Int. J. Electr. Power Energy Syst., 129, 106846. https://doi.org/10.1016/j.ijepes.2021.106846.