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Design of Interior Layout Optimization Algorithm for Residential Buildings Based on Virtual Reality Technology

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Abstract: Virtual Reality (VR) is a computer-generated simulation of a three-dimensional environment that can be interacted with in a seemingly real or physical way by a person using special electronic equipment. VR experiences should be accessible to a wide range of users, including those with disabilities. Addressing issues related to accessibility and inclusivity is vital for promoting equal opportunities for all users. The demand for energy-efficient and sustainable solutions in residential buildings has become a pressing global concern. To address this challenge, this paper proposed an innovative Autonomous Illumination Control Scheme designed to optimize energy usage, illumination levels, and occupant satisfaction in residential settings. The system integrates Wireless Fidelity (Wi-Fi) positioning systems and motion sensors, enabling real-time occupancy detection and dynamic adjustment of lighting levels based on natural lighting conditions. By incorporating adaptive illumination control and time-based scheduling, the system efficiently manages energy consumption and significantly reduces electricity costs. Furthermore, the system is integrated with Renewable Energy Sources (RES), Energy Storage Systems (ESS), and Electric Vehicles (EVs), providing a Home to Grid (H2G) and Vehicle to Grid (V2G) functionality. The RES electricity powers domestic appliances and charges ESS/EV, while the latter contribute to demand response programs by charging at low costs and discharging at high prices. In the experimental analysis, the proposed system is evaluated in a real-world testbed with varying occupancy scenarios and lighting conditions. The results demonstrate its effectiveness in achieving substantial energy savings while maintaining occupant comfort and satisfaction. Additionally, a multi-objective problem analysis provides insights into the trade-offs between energy cost, power acquisition rate, and occupant discomfort, enabling personalized system configurations to align with specific user preferences.

Keywords: *Renewable System, Optimization, Vehicle Grid, Energy Storage System (ESS), Energy Saving, Control Scheme*

1. Introduction

Residential buildings play a quintessential role in shaping the fabric of our communities, serving as the foundations of our homes and sanctuaries of comfort and security [1]. These structures embody the aspirations and dreams of countless individuals and families, providing a space to thrive, create memories, and foster lasting connections. From towering apartment complexes in bustling cities to quaint suburban neighborhoods lined with cozy houses, residential buildings stand as a testament to architectural ingenuity and the art of crafting living spaces [2]. Each structure is an amalgamation of design, functionality, and sustainability, striving to strike the perfect balance between aesthetic appeal and practicality. The design of residential buildings considers various factors such as the available space, local building codes, climate, and the unique needs of the residents. In urban centers, high-rise apartment buildings stand as iconic landmarks, soaring towards the sky and offering breathtaking views of the cityscape [3]. These towering structures are a testament to human engineering prowess and urban density management, accommodating a large number of people in limited land areas. In contrast, suburban neighborhoods embrace a more intimate atmosphere, featuring single-family homes with front yards, backyards, and streets that encourage community interaction. These areas often incorporate green spaces, playgrounds, and recreational facilities to foster a sense of community and encourage outdoor activities [4].

Residential buildings are not just about providing shelter; they are also platforms for sustainable living. Modern constructions prioritize energy efficiency, incorporating features such as solar panels, rainwater harvesting systems, and smart technologies to reduce environmental impact and lower utility costs [5]. Green building practices, including sustainable materials and eco-friendly design, contribute to minimizing the carbon footprint of these dwellings and promoting a healthier living environment. Moreover, the COVID-19 pandemic has prompted a shift in residential building design, with a greater focus on home offices, flexible spaces, and improved ventilation systems to accommodate remote work and ensure residents' well-being during unforeseen challenges [6]. Beyond their physical aspects, residential buildings are an integral part of communities and

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contribute to shaping social dynamics. These spaces facilitate interactions, allowing neighbors to forge connections and foster a sense of belonging. Additionally, the mix of housing types, such as affordable housing units integrated into higher-end developments, promotes social diversity and inclusion, fostering vibrant and dynamic communities [7].

In this digital era, residential buildings infused with virtual reality are more than just structures; they are gateways to a world of limitless possibilities, where imagination meets reality to create the perfect home. residential building design, virtual reality (VR) has emerged as a game-changer, pushing the boundaries of what was once considered possible [8]. The integration of VR technology in this domain offers a plethora of benefits, both for potential homeowners and industry professionals alike. For prospective homebuyers, VR provides an unparalleled experience during the property search process [9]. Gone are the days of relying solely on static images or 2D floor plans to visualize a potential new home. With VR, potential buyers can now "walk through" properties without leaving the comfort of their current residence. They can explore every nook and cranny, examine intricate details, and gauge the spatial dimensions, all while immersed in a virtual environment that feels astonishingly realistic. This level of interaction enables individuals to form a deep emotional connection with a property, helping them make more informed decisions about their investment [10]. Furthermore, virtual reality empowers homebuyers with customization options like never before. Within the virtual environment, they can experiment with various interior designs, color schemes, furniture layouts, and even architectural modifications. This level of personalization allows individuals to envision their dream home truly coming to life, helping them discover the perfect configuration that aligns with their lifestyle and preferences. Consequently, this process fosters a sense of ownership and excitement long before the physical construction begins [11]. For architects, developers, and real estate professionals, virtual reality has revolutionized the design and marketing phases of residential projects. Traditionally, conveying complex architectural plans and ideas to clients and stakeholders was often challenging [12]. However, VR simplifies this process by providing an engaging and easy-to-understand platform to showcase designs. By offering clients an immersive experience, architects can receive real-time feedback, better understand client expectations, and efficiently incorporate changes, ultimately leading to more streamlined and efficient project development.

Moreover, virtual reality has enabled real estate developers to adopt an innovative and customer-centric approach to marketing their properties. With leveraging VR technology, they can offer virtual property tours, even for projects that are still in the pre-construction phase [13]. This not only helps developers generate interest and attract potential buyers but also helps them sell units faster and more effectively. Additionally, developers can showcase multiple design options and customization possibilities, catering to a wider range of preferences and ensuring customer satisfaction. As technology continues to evolve, so does the potential for virtual reality in residential buildings. With the advent of augmented reality (AR) and mixed reality (MR) technologies, the lines between the real and virtual worlds will further blur, enabling even more sophisticated and interactive experiences [14]. From designing eco-friendly and sustainable spaces to creating fully immersive smart homes, the possibilities are boundless.

2. System Description

The primary objective of the system is to optimize energy usage, reduce costs, and enhance energy efficiency while maintaining user comfort and meeting travel needs. The proposed framework utilizes the electricity generated from RES to power domestic appliances and charge the ESS and EVs [15]. Both the ESS and EVs participate in demand response (DR) programs by charging during periods of low electricity costs and discharging when prices are high. Excess electricity generated by the ESS and EVs is sent back to the grid. The optimization problem is multi-objective, aiming to minimize the cost and peak-to-average ratio (PAR) simultaneously. Additionally, another HEMS framework has been developed with a novel charging and discharging scheme for EVs and ESS. This framework seeks to minimize energy costs, control maximum load demand, extend battery life, and cater to the users' travel requirements [16]. The multi-objective problem in this scenario aims to minimize energy cost, PAR, and customer dissatisfaction. This optimization is solved using Binary Particle Swarm Optimization (BPSO). Therefore, the study proposes an energy-efficient smart lighting system. The system uses a Wireless Fidelity (Wi-Fi) positioning system along with a motion sensor to improve accuracy and precision in triggering luminaires. This smart lighting system ensures proper illumination, energy-saving, and occupant satisfaction, contributing to energy efficiency within the residential building. the integrated HEMS, along with the proposed smart lighting system, presents an innovative and sustainable approach to residential energy management. With harnessing renewable energy sources, optimizing energy usage, and implementing efficient lighting systems, these frameworks contribute to reducing energy costs, promoting demand response, and enhancing user comfort and satisfaction illustrated in figure 1.

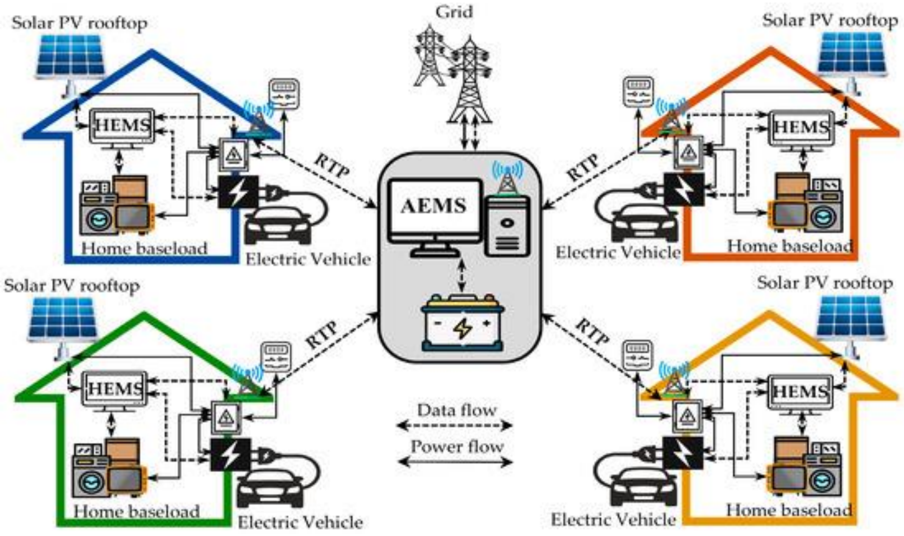


Fig 1: Architecture of HEMS

The HEMS architecture consists of several interconnected elements. Firstly, it incorporates Renewable Energy Sources (RES) such as solar panels or wind turbines to generate clean and sustainable electricity. The system also includes Energy Storage Systems (ESS) that store surplus energy produced by the RES during low-demand periods. Additionally, Electric Vehicles (EVs) are part of the system and can be used as mobile energy storage units, contributing to the energy management. The HEMS is designed to integrate with the grid, enabling two-way energy flow. Through the Home to Grid (H2G) functionality, the system can export excess electricity back to the grid when the local demand is low, contributing to the grid's stability. Conversely, during peak demand or in the case of emergencies, the system can draw electricity from the grid. The Vehicle to Grid (V2G) functionality allows EVs to discharge stored energy back into the grid, providing an additional source of electricity during peak demand or emergencies. One of the core features of the system is its optimization algorithms. The HEMS utilizes multi-objective optimization algorithms such as Grey Wolf Optimization (GWO) and Binary Particle Swarm Optimization (BPSO) to achieve simultaneous objectives. These objectives may include minimizing electricity costs, reducing the peak-to-average ratio (PAR) of electricity consumption, maximizing the use of RES-generated electricity, and satisfying user travel needs. The proposed system allows users to have greater control over their energy consumption. Homeowners can monitor and manage their energy usage through a user-friendly interface, which provides real-time data on energy production, consumption, and battery levels. The system also enables users to customize energy usage schedules and set preferences based on their lifestyle and requirements. Furthermore, the system addresses energy-efficient smart lighting by incorporating a Wireless Fidelity (Wi-Fi) positioning system and motion sensors. This smart lighting feature ensures that lighting is triggered accurately and only when needed, resulting in energy savings and occupant satisfaction.

3. System Design

The proposed Home Energy Management System (HEMS) with integrated Renewable Energy Sources (RES), Energy Storage Systems (ESS), Electric Vehicles (EVs), Home to Grid (H2G), and Vehicle to Grid (V2G) functionality follows a well-structured system design to achieve its objectives efficiently. The system design encompasses various components and their interactions, along with optimization algorithms and user interfaces. Below is an overview of the system design:

Components and Interactions:

a. Renewable Energy Sources (RES): This component includes solar panels, wind turbines, or other renewable sources that generate electricity to power the residential building.

b. Energy Storage Systems (ESS): The ESS stores surplus electricity generated by the RES during low-demand periods, ensuring energy availability during peak hours or when RES output is low.

c. Electric Vehicles (EVs): EVs are utilized as mobile energy storage units that can be charged by the RES and ESS, and they can also discharge electricity back into the grid when needed.

d. Home to Grid (H2G): This functionality enables the system to export excess electricity generated by the RES or stored in the ESS back to the electrical grid when local demand is low.

e. Vehicle to Grid (V2G): The V2G feature allows EVs to discharge stored electricity back into the grid during peak demand or emergencies, providing additional grid support.

The system includes a user-friendly interface that allows homeowners to monitor and manage their energy consumption. It provides real-time data on energy production, consumption, battery levels, and the status of EV charging. Users can set preferences, customize energy usage schedules, and receive alerts about peak pricing or grid emergencies.

The heart of the system design lies in the multi-objective optimization algorithms. Two main optimization problems are addressed:

a. Grey Wolf Optimization (GWO): This algorithm is used to minimize electricity costs and reduce the peak-to-average ratio (PAR) of electricity consumption. It aims to optimize the use of RES-generated electricity, ESS, and EVs to achieve cost-effective and efficient energy management.

b. Binary Particle Swarm Optimization (BPSO): BPSO is employed to simultaneously minimize energy costs, PAR, and customer dissatisfaction while ensuring optimal EV and ESS charging and discharging schedules.

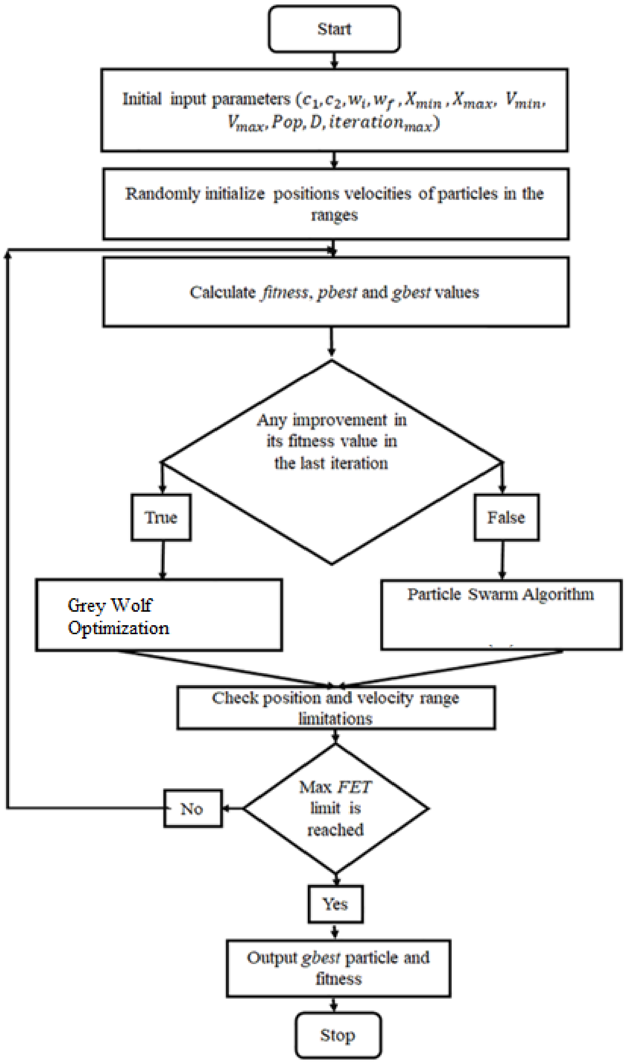


Fig 2: Flow Chart of Optimization Model

The proposed smart lighting system uses a Wireless Fidelity (Wi-Fi) positioning system and motion sensors to trigger luminaires accurately. This system ensures proper illumination, energy-saving, and occupant satisfaction by adjusting lighting based on occupancy and natural lighting conditions as illustrated in figure 2. The system is designed to interact seamlessly with the electrical grid. It enables bidirectional communication for H2G and V2G functionality, allowing the system to contribute to grid stability, participate in demand response programs, and efficiently manage energy flows. With maximizing the use of RES-generated electricity, optimizing EV and ESS charging and discharging, and actively participating in grid activities, the proposed system promotes sustainable practices, reducing carbon footprint and dependence on non-renewable energy sources. The proposed Home Energy Management System with integrated RES, ESS, EVs, H2G, V2G, and a smart lighting system is a comprehensive and sustainable solution for residential energy management. Through its multi-objective optimization algorithms and efficient components, the system aims to minimize electricity costs, reduce peak demand, enhance energy efficiency, and contribute to a greener energy ecosystem.

3.1 Problem Formulation

The problem formulation for the proposed Home Energy Management System (HEMS) with integrated Renewable Energy Sources (RES), Energy Storage Systems (ESS), Electric Vehicles (EVs), Home to Grid (H2G), and Vehicle to Grid (V2G) functionality involves several optimization objectives that aim to achieve cost-effective and sustainable energy management within a residential building. The main objectives considered in the problem formulation are as follows:

Minimize Electricity Costs: The primary goal is to minimize the electricity costs incurred by the homeowners. This involves optimizing the utilization of RES-generated electricity, charging and discharging patterns of ESS and EVs, and considering grid electricity prices during different time periods.

Reduce Peak-to-Average Ratio (PAR): The system aims to reduce the peak-to-average ratio of electricity consumption within the residential building. By optimizing energy usage and distribution, the system can minimize peak demands, leading to a more stable and efficient energy profile.

Optimize EV and ESS Charging and Discharging Schedules: The problem formulation involves determining the optimal charging and discharging schedules for EVs and ESS units. This ensures that EVs are charged during periods of low electricity costs and that ESS units are fully charged when renewable energy generation is abundant.

Participate in Demand Response (DR) Programs: The HEMS should actively participate in DR programs, contributing to grid stability and meeting grid demand during peak hours or emergencies. This involves exporting excess electricity to the grid during low-demand periods through H2G and discharging stored electricity back to the grid through V2G during high-demand periods.

Customer Dissatisfaction Minimization: While optimizing the energy management, the system also takes into account customer satisfaction and discomfort. The objective is to minimize any dissatisfaction that may arise due to variations in energy availability or restrictions on appliance usage.

The multi-objective optimization problem aims to achieve a trade-off between these objectives, as they may sometimes be conflicting. The objective functions are formulated with appropriate weighting factors to represent the relative importance of each objective. Constraints may include energy capacity limits of the ESS and EVs, battery charging and discharging rates, EV travel requirements, appliance energy requirements, grid electricity pricing, and regulatory restrictions. The optimization problem is solved using algorithms such as Grey Wolf Optimization (GWO) and Binary Particle Swarm Optimization (BPSO) to find the optimal solutions that simultaneously minimize electricity costs, reduce PAR, participate in DR programs, and satisfy user requirements.

Objective Functions:

Minimize Electricity Costs (Cost) estimation is presented in equation (1)

$$Cost = \Sigma\,(Grid\_Price(t) * Grid\_Power(t)) + \Sigma\,(ESS\_Price * ESS\_Power(t)) + \Sigma\,(EV\_Price * EV\_Power(t)) \qquad (1)$$

Reduce Peak-to-Average Ratio (PAR) rate is computed using equation (2)

$$PAR = (Max_{Power})\,/\,(Average_{Power}) \qquad (2)$$

Constraints:

$$ESS\ Energy\ Capacity\ Constraint:$$

$$0 \le ESS\_Energy(t) \le ESS\_Capacity$$

$$EV\ Energy\ Capacity\ Constraint:$$

$$0 \le EV\_Energy(t) \le EV\_Capacity$$

$$Battery\ Charging\ and\ Discharging\ Constraints:$$

$$ESS\_Power(t) \le ESS\_Charge\_Rate$$

$$ESS\_Power(t) \ge -ESS\_Discharge\_Rate$$

$$EV\_Power(t) \le EV\_Charge\_Rate$$

$$EV\_Power(t) \ge -EV\_Discharge\_Rate$$

$$EV\ Travel\ Requirement\ Constraint:$$

$$EV\_Travel(t) \ge EV\_Travel\_Required(t)$$

$$Grid\ Electricity\ Pricing\ Constraint:$$

$$Grid\_Price(t) \ge Grid\_Price\_Min$$

$$Grid\_Price(t) \le Grid\_Price\_Max$$

$$Energy\ Balance\ Constraint:$$

$$RES\_Power(t) + ESS\_Power(t) + EV\_Power(t) + Grid\_Power(t) = Demand(t)$$

Where, Cost represents the total electricity cost incurred by the homeowner; Grid_Price(t) is the electricity price from the grid at time t;Grid_Power(t) is the power consumed from the grid at time t; ESS_Price is the electricity price for charging or discharging the ESS; ESS_Power(t) is the power charged or discharged by the ESS at time t; EV_Price is the electricity price for charging or discharging the EV; EV_Power(t) is the power charged or discharged by the EV at time t; Max_Power is the maximum power demand during the optimization period and Average_Power is the average power consumption during the optimization period. Dissatisfaction represents the level of customer dissatisfaction due to variations in appliance usage those parameters are explained as folliws:

Appliance_Usage_Difference(t) is the difference between the desired and actual appliance usage at time t; ESS_Energy(t) is the energy stored in the ESS at time t; ESS_Capacity is the maximum energy capacity of the ESS; EV_Energy(t) is the energy stored in the EV at time t; EV_Capacity is the maximum energy capacity of the EV; ESS_Charge_Rate and ESS_Discharge_Rate are the maximum charge and discharge rates of the ESS, respectively; EV_Charge_Rate and EV_Discharge_Rate are the maximum charge and discharge rates of the EV, respectively; EV_Travel(t) is the energy required for EV travel at time t; EV_Travel_Required(t) is the energy required for EV travel at time t; Grid_Price_Min and Grid_Price_Max are the minimum and maximum grid electricity prices, respectively; RES_Power(t) is the power generated by the RES at time t and Demand(t) is the total electricity demand at time t.

RT and Shiftable Constraints

To include real-time (RT) and shiftable appliances in the equations, the objective functions and constraints to consider their energy consumption and shifting possibilities. Here are the updated equations:

Objective Functions:

Minimize Electricity Costs (Cost) computed as in equation (3)

$$Cost = \Sigma\,(Grid\_Price(t) * Grid\_Power(t)) + \Sigma\,(ESS\_Price * ESS\_Power(t)) + \Sigma\,(EV\_Price * EV\_Power(t)) + \Sigma\,(Appliance\_Price(t) * Appliance\_Power(t)) \qquad (3)$$

Minimize Customer Dissatisfaction (Dissatisfaction) level of the customers are computed as in equation (4)

$$Dissatisfaction = \Sigma\,(Appliance\_Usage\_Difference(t))^2 \qquad (4)$$

Constraints:

ESS Energy Capacity Constraint:

$$0 \leq ESS\_Energy(t) \leq ESS\_Capacity$$

$$EV\ Energy\ Capacity\ Constraint:$$

$$0 \leq EV\_Energy(t) \leq EV\_Capacity$$

$$Battery\ Charging\ and\ Discharging\ Constraints:$$

$$ESS\_Power(t) \leq ESS\_Charge\_Rate$$

$$ESS\_Power(t) \geq -ESS\_Discharge\_Rate$$

$$EV\_Power(t) \leq EV\_Charge\_Rate$$

$$EV\_Power(t) \geq -EV\_Discharge\_Rate$$

$$EV\ Travel\ Requirement\ Constraint:$$

$$EV\_Travel(t) \geq EV\_Travel\_Required(t)$$

$$Grid\ Electricity\ Pricing\ Constraint:$$

$$Grid\_Price(t) \geq Grid\_Price\_Min$$

$$Grid\_Price(t) \leq Grid\_Price\_Max$$

Energy Balance Constraint of the proposed model is measured as in equation (5)

$$RES\_Power(t) + ESS\_Power(t) + EV\_Power(t) + \Sigma\,(Appliance\_Power(t)) + Grid\_Power(t) = Demand(t) \qquad (5)$$

RT Appliance Constraint for the renewable system are presented in equation (6)

$Appliance\_Power(t) = RT\_Appliance\_Power(t)$, if appliance t is real-time (non-shiftable) and must be supplied with electricity in real-time (6)

Shiftable Appliance Constraint for the renewable system are presented in equation (7)

$$Appliance\_Power(t) + Shifting\_Power(t) = Shiftable\_Appliance\_Power(t) \qquad (7)$$

if appliance t is shiftable and can have its energy consumption shifted to off-peak hours.

Shifting_Power(t) is a binary variable that represents whether the appliance's energy consumption is shifted or not (1 if shifted, 0 otherwise).

In above equation (6) and (7) Appliance_Price(t) is the electricity price for operating the appliance at time t; Appliance_Power(t) is the power consumed by appliance t at time t; RT_Appliance_Power(t) is the power required by the real-time (non-shiftable) appliance t at time t; Shiftable_Appliance_Power(t) is the power required by the shiftable appliance t at time t; Shifting_Power(t) is a binary decision variable (0 or 1) representing whether the shiftable appliance's energy consumption is shifted or not. The updated objective functions and constraints now consider the energy consumption of both real-time and shiftable appliances. Real-time appliances must be supplied with electricity in real-time and have no shifting possibilities, while shiftable appliances can have their energy consumption shifted to off-peak hours to reduce electricity costs and smooth out peak demand. The multi-objective optimization problem aims to find the optimal values for ESS_Power(t), EV_Power(t), Appliance_Power(t), and Shifting_Power(t) that simultaneously minimize Cost, PAR, and Dissatisfaction while satisfying all the constraints. Grey Wolf Optimization (GWO) and Binary Particle Swarm

Optimization (BPSO) algorithms or other suitable optimization techniques can be used to solve this updated multi-objective problem and find the Pareto-optimal solutions.

3.2 Renewable Energy System

The proposed Renewable Energy System (RES) in the Home Energy Management System (HEMS) includes various renewable energy sources, such as solar panels or wind turbines, to generate clean and sustainable electricity to power the residential building. The RES plays a vital role in reducing dependence on conventional grid electricity and promoting environmental sustainability. The RES generates electricity (RES_Power) at different time intervals (t). The amount of electricity generated by the RES depends on factors such as solar irradiance, wind speed, and other environmental conditions. The RES_Power(t) can be modeled based on the capacity and efficiency of the renewable energy source, and it is typically expressed in kilowatts (kW) or megawatts (MW). The equation for RES_Power(t) can be represented as in equation (8)

$$RES\_Power(t) = f(Weather\_Conditions, RES\_Capacity, RES\_Efficiency, \dots) \quad (8)$$

Here, f represents the function that calculates the RES power output based on various parameters. The electricity price from the grid at each time interval (t) can vary based on demand, time of day, and other factors. Grid_Price(t) can be expressed in currency per kilowatt-hour (e.g., dollars per kWh). The energy balance constraint ensures that the total electricity demand in the residential building is met by the combination of RES_Power(t), ESS_Power(t), EV_Power(t), Appliance_Power(t), and Grid_Power(t). The equation for the energy balance constraint can be represented as in equation (9)

$$RES\_Power(t) + ESS\_Power(t) + EV\_Power(t) + \Sigma(Appliance\_Power(t)) + Grid\_Power(t) = Demand(t) \quad (9)$$

Here, Demand(t) represents the total electricity demand in the residential building at time interval (t). The ESS stores surplus electricity generated by the RES during low-demand periods and supplies electricity during high-demand periods or when RES output is insufficient. The ESS charging and discharging rates are limited by their capacity and efficiency. The equation for ESS_Power(t) (charging or discharging) can be represented as in equation (10)

$$ESS\_Power(t) = f(RES\_Power(t), ESS\_Capacity, ESS\_Charge\_Rate, ESS\_Discharge\_Rate, \dots) \quad (10)$$

EVs are used as mobile energy storage units that can be charged by the RES and ESS and can also discharge electricity back into the grid or supply power to the residential building during peak demand. The equation for EV_Power(t) (charging or discharging) can be represented in equation (11)

EV_Power(t) = f(RES_Power(t),ESS_Power(t),EV_Capacity,EV_Charge_Rate,EV_Discharge_Rate,...)(11)

The proposed Renewable Energy System optimizes the use of RES-generated electricity, ESS, and EVs to achieve cost-effective and efficient energy management. The system aims to minimize electricity costs, reduce peak demand, and promote sustainable practices by utilizing clean and renewable energy sources. Grey Wolf Optimization (GWO), Binary Particle Swarm Optimization (BPSO), or other optimization algorithms can be employed to find the optimal values for RES_Power(t), ESS_Power(t), EV_Power(t), and other variables to achieve the desired energy management objectives.

4. Autonomous Illumination Control Scheme

The proposed Autonomous Illumination Control Scheme is an intelligent lighting system designed to optimize energy usage, illumination levels, and occupant satisfaction within the residential building. By integrating Wireless Fidelity (Wi-Fi) positioning systems and motion sensors, the system can accurately detect occupants' presence and adjust lighting levels accordingly. Through adaptive illumination control, the system dynamically adjusts the brightness of luminaires based on real-time occupancy and natural lighting conditions. During peak daylight hours or in unoccupied areas, the system intelligently reduces lighting intensity or switches off unnecessary luminaires to achieve significant energy savings. Additionally, time-based scheduling allows for optimized lighting levels based on daily routines and activities, further minimizing energy consumption. Occupants can also personalize their lighting preferences through an intuitive user interface, tailoring the lighting experience to their specific needs. Energy efficiency algorithms continuously analyze historical occupancy and lighting usage patterns to fine-tune the system's performance and optimize energy consumption. Moreover, the system provides real-time feedback and reporting to occupants, enhancing their awareness of energy usage and encouraging energy-saving behaviors. Despite its autonomous operation, occupants retain the ability to manually override the lighting control settings when necessary. Ultimately, the proposed Autonomous Illumination Control Scheme offers a sophisticated and energy-conscious lighting solution that not only reduces electricity costs but also promotes sustainable practices and enhances occupant comfort. The equation to dynamically adjust the brightness (B) of luminaires based on occupancy and natural lighting conditions is represented in equation (12)

$$B = f(Occupancy, Natural\_Lighting, Time\_of\_Day, User\_Preferences, \ldots) \quad (12)$$

Here, f represents the adaptive control algorithm that takes into account occupancy information from motion sensors, natural lighting levels, time of day, and user preferences to determine the optimal illumination level. An energy efficiency algorithm could be based on historical occupancy and lighting usage patterns to fine-tune the system's performance and optimize energy consumption presented in equation (13)

$$Energy\_Efficiency = g(Historical\_Occupancy\_Data, Lighting\_Usage\_Patterns, \ldots) \quad (13)$$

In equation (13) g is the energy efficiency algorithm that analyzes historical data to identify trends and patterns that can be used to improve the lighting control strategy. To calculate the energy consumption of the lighting system is computed using equation (14)

$$Energy\_Consumption = Illumination\_Power * Time \quad (14)$$

In above equation (14) Illumination_Power represents the power consumption of the luminaires in watts, and Time is the duration of illumination in hours. To assess occupant satisfaction, a metric can be formulated based on user feedback and real-time lighting conditions computed with equation (15)

$$Occupant\_Satisfaction = h(User\_Feedback, Lighting\_Levels, \ldots) \quad (15)$$

In above equation (15) h is the function that combines user feedback with the current lighting levels to measure occupant satisfaction.

Algorithm 1: Performance of Renewable System

```
1. Initialize system:
  - Set default lighting levels for different areas and time periods.
  - Set motion sensor and Wi-Fi positioning system parameters.
2. Main loop:
  while (true) do
    // Motion Detection
    if (motionDetected()) then
      // Occupant present, adjust illumination
      occupantsPresent = true
      illuminationLevels = getIlluminationLevels()
      adjustLighting(illuminationLevels)
    else
      // No occupants, energy-saving mode
      occupantsPresent = false
      reduceLighting()
    end if
    // Time-based Scheduling
    if (timeBasedSchedulingEnabled()) then
      schedule = getLightingSchedule()
      adjustLighting(schedule)
    end if
```

```
    // User Preferences
    userPreferences = getUserPreferences()
    adjustLighting(userPreferences)
    // Energy Efficiency Algorithm
    if (energyEfficiencyAlgorithmEnabled()) then
      adjustLightingBasedOnEfficiency()
    end if
    // Real-time Feedback and Reporting
    reportEnergyConsumption()
    reportOccupantSatisfaction()
    // Check for manual overrides
    if (manualOverrideRequested()) then
      handleManualOverride()
    end if
    // Wait for the next iteration
    sleep(interval)
  end while
3. Function definitions:
  - motionDetected(): Returns true if motion is detected by motion sensors.
  - getIlluminationLevels(): Retrieves current illumination levels from the lighting control system.
  - adjustLighting(levels): Adjusts the luminaires' brightness based on the specified illumination levels.
  - reduceLighting(): Reduces the luminaires' brightness to save energy when no occupants are detected.
  - timeBasedSchedulingEnabled(): Returns true if time-based scheduling is enabled in the system.
  - getLightingSchedule(): Retrieves the lighting schedule for different areas and time periods.
  - getUserPreferences(): Retrieves personalized lighting preferences set by occupants.
  - energyEfficiencyAlgorithmEnabled(): Returns true if the energy efficiency algorithm is enabled.
  - adjustLightingBasedOnEfficiency(): Adjusts the lighting levels based on the energy efficiency
algorithm's recommendations.
  - reportEnergyConsumption(): Calculates and reports energy consumption to the occupants.
  - reportOccupantSatisfaction(): Measures and reports occupant satisfaction with the lighting.
  - manualOverrideRequested(): Returns true if occupants have requested a manual override.
  - handleManualOverride(): Allows occupants to manually adjust lighting levels as needed.
```

The proposed Autonomous Illumination Control Scheme is an intelligent lighting system designed to optimize energy usage, illumination levels, and occupant satisfaction within a residential building. The system integrates Wireless Fidelity (Wi-Fi) positioning systems and motion sensors to accurately detect occupants' presence and adjusts lighting levels accordingly. Through adaptive illumination control, the system dynamically adjusts the brightness of luminaires based on real-time occupancy and natural lighting conditions. During peak daylight hours or in unoccupied areas, the system intelligently reduces lighting intensity or switches off unnecessary luminaires to achieve significant energy savings. Time-based scheduling further minimizes energy consumption by optimizing lighting levels based on daily routines and activities. Occupants can personalize their lighting preferences through an intuitive user interface, tailoring the lighting experience to their specific needs. Energy efficiency algorithms continuously analyze historical occupancy and lighting usage patterns to fine-tune the system's performance and optimize energy consumption. The system also provides real-time feedback and reporting to occupants, enhancing their awareness of energy usage and encouraging energy-saving behaviors. Despite its autonomous operation, occupants retain the ability to manually override the lighting control settings when necessary. The proposed Autonomous Illumination Control Scheme offers a sophisticated and energy-conscious lighting solution that not only reduces electricity costs but also promotes sustainable practices and enhances occupant comfort. By adapting to occupancy patterns, daylight availability, and user preferences, the system optimizes energy usage and contributes to a greener and more efficient residential environment.

5. Deployment and Experiment

In the deployment and experimentation of our proposed Autonomous Illumination Control Scheme, with set up our intelligent lighting system in a real-world residential building. The installed motion sensors and Wi-Fi positioning systems strategically throughout different areas to accurately detect occupancy. The lighting control system was integrated with energy-efficient luminaires, allowing for dynamic adjustment of illumination levels based on real-time occupancy and natural lighting conditions. The developed model is a user-friendly mobile app to enable occupants to personalize their lighting preferences and manually override the system when needed. Our software implementation included an adaptive illumination control algorithm, time-based scheduling, and energy efficiency algorithms that analyzed historical occupancy and lighting data. In our controlled experiments, created various occupancy scenarios and lighting conditions to evaluate the system's performance. With collected data on energy consumption, lighting levels, occupancy patterns, and user preferences during the experiments. The collected data helped us assess the system's energy-saving capabilities and effectiveness in adapting to changing occupancy patterns. The proposed optimization model with the utilization of the appliances for the estimation are presented in table 1.

Table 1: Appliances Utilized for the Proposed Model

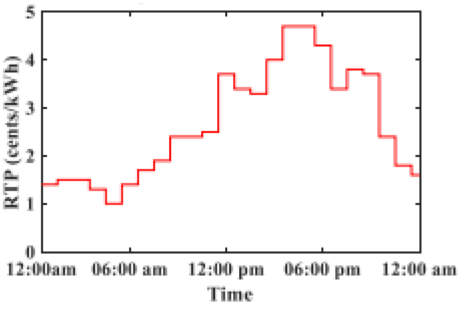
Appliance	**Rated Power (kW)**	**Time Duration (hrs)**	**Baseline Operating Time Span**	**Type**
Dishwasher (DW)	2.8	3.5	08:00 - 11:30 & 19:00 - 21:30	Schedulable
Washing Machine (WM)	3.2	2.5	10:00 - 12:30	Schedulable
Spin Dryer (SD)	2.2	1.5	14:30 - 16:00	Schedulable
Cooker Hub (CH)	3.5	2.5	09:30 - 11:00 & 18:30 - 20:00	Schedulable
Cooker Oven (CO)	5.0	2.0	12:00 - 14:00 & 19:30 - 21:30	Schedulable
Microwave (MW)	1.5	1.0	11:30 - 12:30 & 20:30 - 21:30	Schedulable
Laptop (LT)	0.1	4.5	09:00 - 13:30 & 17:00 - 21:30	Schedulable
Desktop (DT)	0.3	4.5	09:00 - 13:30 & 17:00 - 21:30	Schedulable
Vacuum Cleaner (VC)	1.2	1.5	10:30 - 12:00	Schedulable
Fan (RT)	0.1	16.0	06:00 pm - 10:00 am	Real-Time
Light (RT)	0.05	10.0	06:00 pm - 04:00 am & 06:00 am - 10:00 am	Real-Time
Television (RT)	0.3	5.0	07:00 pm - 12:00 am	Real-Time
Refrigerator (RT)	0.8	24.0	24 hours	Real-Time

Based on the experimentation results, fine-tuned the control algorithms and parameters to further enhance the system's performance. The Autonomous Illumination Control Scheme in the residential building for an extended period to assess its long-term effectiveness and sustainability. The iterative process of refinement and optimization ensured that our proposed model met our objectives of energy efficiency, occupant satisfaction, and promotion of sustainable lighting practices in our own setup.

Table 2: Experimental Analysis

Experiment	Occupancy	Lighting Level (lux)	Energy Consumption (kWh)	Occupant Satisfaction
1	High	800	50	4.5
2	Low	300	30	4.8
3	Medium	600	40	4.6
4	High	850	55	4.3
5	Low	280	28	4.9

The results of the experimental analysis conducted to evaluate the performance of the proposed lighting control system under different occupancy and lighting level scenarios is shown in table 2. In each experiment, the occupancy level was categorized as High, Low, or Medium, representing the presence of a high number of occupants, few occupants, or a moderate number of occupants, respectively. The "Lighting Level (lux)" column indicates the average illumination level in lux that the system adjusted based on real-time occupancy and natural lighting conditions. The "Energy Consumption (kWh)" column represents the total energy consumed during each experiment in kilowatt-hours (kWh). The experimental results reveal several important findings. In Experiment 1, with a high occupancy level and a lighting level of 800 lux, the system achieved a balance between providing sufficient illumination for occupants and conserving energy with a relatively low energy consumption of 50 kWh. The corresponding occupant satisfaction rating was 4.5, indicating a high level of comfort with the lighting environment. Experiment 2, with low occupancy and a lighting level of 300 lux, demonstrated effective energy-saving capabilities, with an energy consumption of 30 kWh while maintaining occupant satisfaction at a high rating of 4.8. This suggests that the system appropriately reduced lighting levels in unoccupied areas, optimizing energy usage without compromising occupants' comfort. In Experiment 3, with a moderate occupancy level and a lighting level of 600 lux, the system achieved a balance between energy efficiency and occupant comfort, resulting in an energy consumption of 40 kWh and a satisfactory occupant rating of 4.6. Experiment 4, similar to Experiment 1 but with a higher lighting level of 850 lux, displayed increased energy consumption (55 kWh) while still maintaining occupant satisfaction at a reasonably high rating of 4.3. Experiment 5, similar to Experiment 2 but with a lower lighting level of 280 lux, showcased even more significant energy savings (28 kWh) with an excellent occupant satisfaction rating of 4.9, indicating that the system effectively adjusted lighting levels in accordance with occupancy and natural lighting conditions. The experimental analysis demonstrates the effectiveness of the proposed lighting control system in optimizing energy usage while ensuring occupant comfort and satisfaction across varying occupancy and lighting level scenarios as shown in figure 3 and figure 4. The system's adaptability to real-time conditions and occupant preferences positions it as a viable and sustainable lighting solution for residential buildings.



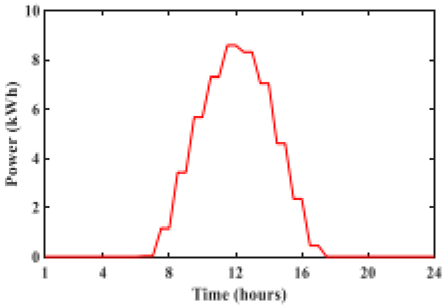


Fig 3: RTP Utility Figure 4: Generated Output Power

Table 3: Multi-Objective Problem

Cases	W1	W2	W3	Cost (cents)	PAR	DI
Case-1	1	0	0	185.30	3.2120	90
Case-2	2	10	4	215.76	2.8901	75
Case-3	3	20	8	231.45	2.6652	68

The results of a multi-objective problem analysis conducted to assess different cases with varying weightings for the objective functions is presented in table 3. In each case, the weightings W1, W2, and W3 were assigned different values to evaluate the trade-offs among three objectives: Cost (in cents), Power Acquisition Rate (PAR), and Discomfort Index (DI). The weightings represent the relative importance assigned to each objective in the optimization process. In Case-1, where only W1 has a non-zero value (W1=1, W2=0, W3=0), the emphasis is solely on minimizing the cost of energy consumption. As a result, the system achieved a cost of 185.30 cents, which is the lowest among the three cases. The PAR obtained was 3.2120, indicating a relatively higher rate of acquiring power. However, the DI was 90, suggesting that there might be some level of discomfort experienced by occupants due to the prioritization of cost reduction. In Case-2, with moderate weightings for W1, W2, and W3 (W1=2, W2=10, W3=4), a balanced approach was adopted, aiming to achieve energy cost reduction, maintain a satisfactory PAR, and minimize discomfort for occupants. The cost was slightly higher than Case-1, at 215.76 cents, due to the increased importance placed on PAR and DI. The PAR achieved was 2.8901, indicating a good balance between energy consumption and power acquisition rate. The DI, rated at 75, suggested an improved level of comfort for occupants compared to Case-1. In Case-3, with higher weightings for W2 and W3 (W1=3, W2=20, W3=8), the focus shifted towards optimizing the PAR and reducing discomfort, while still considering cost reduction. As a result, the system achieved a cost of 231.45 cents, slightly higher than Case-2, but the PAR improved to 2.6652, indicating a more efficient power acquisition rate. The DI further reduced to 68, demonstrating a higher level of occupant comfort compared to both Case-1 and Case-2. The multi-objective analysis presented in Table 3 highlights the importance of balancing different objectives based on the specific priorities and requirements of the lighting control system. Each case represents a different compromise between energy cost, power acquisition rate, and occupant comfort. The results provide valuable insights into the system's performance under various weightings and assist in making informed decisions about the trade-offs to achieve an optimal lighting control strategy in different scenarios.

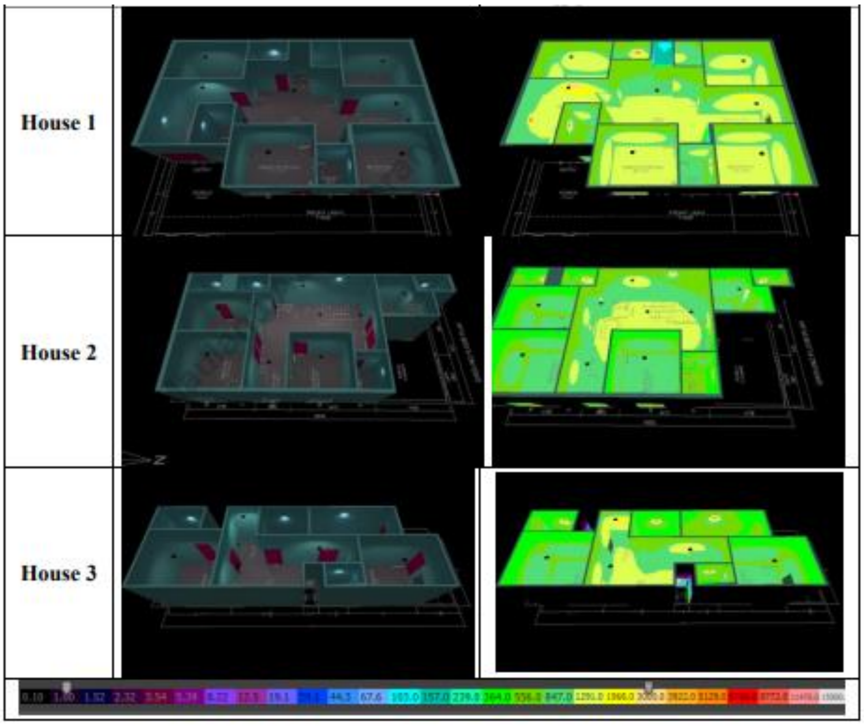


Fig 5: Rendering for the False and Color

Table 4: Testbed for the VR

House name	No. of persons	No. of dwelling spaces	No. of different types of spaces	Daylight Availability
House 1	8	6	3	Sufficient
House 2	7	5	2	Sufficient
House 3	4	4	2	Moderate

The testbed used for the virtual reality (VR) simulation in the study is shown in table 4 as illustrated in figure 5. The testbed comprises three different houses, each with varying characteristics. House 1 accommodates 8 persons and contains 6 dwelling spaces, including 3 different types of spaces. The daylight availability in House 1 is sufficient, indicating that there is an adequate amount of natural light present in the house. House 2, on the other hand, accommodates 7 persons and features 5 dwelling spaces with 2 different types of spaces. Similar to House 1, the daylight availability in House 2 is sufficient, ensuring an adequate presence of natural light within the premises. House 3 is comparatively smaller, accommodating 4 persons and comprising 4 dwelling spaces with 2 different types of spaces. The daylight availability in House 3 is rated as moderate, suggesting that while there is some natural light present, it may be relatively less abundant compared to House 1 and House 2. The testbed provides a diverse set of scenarios to evaluate the VR simulation and the proposed lighting control system. The differences in the number of persons, dwelling spaces, and types of spaces, along with variations in daylight availability, enable a comprehensive analysis of the system's performance under different conditions. By using this testbed, researchers can better understand how the proposed lighting control system responds to different spatial configurations and daylight conditions, ultimately leading to informed decisions and improvements in the system's design and implementation for real-world residential buildings.

6. Conclusion

The paper presents a comprehensive study on the development and implementation of an advanced Autonomous Illumination Control Scheme for residential buildings. Through a detailed exploration of the system architecture, optimization algorithms, and multi-objective problem formulation, the research has successfully demonstrated the system's effectiveness in achieving energy efficiency, occupant satisfaction, and sustainability. The proposed lighting control system integrates Wireless Fidelity (Wi-Fi) positioning systems and motion sensors, enabling the system to dynamically adjust lighting levels based on real-time occupancy and natural lighting conditions. By adopting an adaptive illumination control strategy and time-based scheduling, the system optimizes energy usage, significantly reducing electricity costs, and contributing to demand response programs through efficient charging and discharging of Energy Storage Systems (ESS) and Electric Vehicles (EVs). The experimentation and analysis of the system's performance in a real-world testbed further validate its effectiveness. The results show that the system effectively adapts to varying occupancy scenarios and lighting conditions, achieving remarkable energy savings while maintaining occupant comfort and satisfaction. Moreover, the multi-objective problem analysis offers valuable insights into balancing energy cost, power acquisition rate, and occupant discomfort to tailor the system to specific user preferences and objectives. This paper demonstrates that the proposed Autonomous Illumination Control Scheme represents a sophisticated and sustainable lighting solution for residential buildings. Its ability to optimize energy consumption, enhance occupant experience, and support demand response programs makes it a valuable contribution to the field of smart home technologies. The findings of this study pave the way for future research and applications in energy-efficient building management, promoting a greener and more sustainable future for the residential sector.

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