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Material-Integrated Energy Management: Role of Advanced Polymers and Composites in Smart Homes

Dharmendra Kumar Dubey[1,*], Savita Agarwal[2], Mohit Mishra[3], Punny Sood[3], Raj Sagar[4], Manoj Kumar[5]

Abstract

The article discusses the possibility of improving the performance as well as the sustainability of smart-home-based energy management systems (EMS) by applying advanced polymeric and composite materials. Smart homes today are placing greater requirements on lightweight, thermally stable, high durability, and electrically conducting compounds in such important aspects of the devices as batteries, substrate layers in solar panels, thermally resistant enclosures, and high efficiency thermal insulation on intelligent appliances. Such material innovations do not only enhance mechanical strength and lifespan, but also enhance greater energy retention and safer operation. Combining these hi-tech materials with smart EMS algorithms, which are activated by machine learning and predictive analytics will allow the system to adjust energy consumption in real time according to the constantly changing inputs of solar and wind energy. This kind of integrated approach can be used to respond quicker with increased accuracy in the distribution of energy and reduced reliance on the grid during peak periods. The paper also investigates the interaction of demand response policies with the thermal-mechanical behaviour of composite encased systems under varied environmental and operational loads and this indicates crucial findings on the distribution of stress, heat transfer and structural integrity. To confirm the suggested idea, a number of smart-home examples are provided, proving that material-enhanced EMS systems can be more efficient, use less energy, and provide better comfort to occupants. The results show that material-integrated EMS solutions can indeed increase energy savings, as well as decrease the impact on the environment by decreasing carbon footprint and increasing the life-cycle of energy storage and distribution units. The study incorporates thermal modelling of composite battery casings, finite-element simulation of heat distribution, and algorithmic validation using real solar and load datasets to ensure empirical reliability. In general, the work would be used in the creation of sustainable, resilient, and material-optimized infrastructure of the next-generation smart houses.

Keywords: Smart home energy management system (EMS); polymeric materials; composite structures; renewable energy integration; thermal stability

***Author for Correspondence**
Dharmendra Kumar Dubey

[1]Professor, Department of Mechanical Engineering Shree Dhanvantary College of Engineering & Technology, Surat, Gujarat, India
[2]Professor, Department of Chemistry, IMS Engineering College, Ghaziabad, Uttar Pradesh, India
[3]Assistant Professor, Department of Computer Application, Lovely Professional University, Phagwara, Punjab, India
[4]Assistant Professor, Department of Computer Science & Engineering NRI Engineering College, Vijayawada, Andhra Pradesh, India
[5]Associate Professor, Department of Computer Science & Engineering, Bhagwant University, Ajmer, Rajasthan, India

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INTRODUCTION

The uptake of renewable energy into home-based infrastructure systems has gained a high level of priority in the war on modern-day environmental issues and the standard attempts of the globe to go green. The ever-rising energy needs and the limited fossil fuel reserves have led to popularization of the renewable energy technologies, particularly in the busy urban areas. Some of the leading options include smart homes, which are highly automated and connected to each other, as they provide easy implementation of the renewable energy systems like solar installations and wind energy turbines. Although there are numerous advantages in the integration of these renewable resources, it forms a new level of complexity in energy regulation, efficiency and in the design and the conduct of Energy Management Systems (EMS). A good EMS should be cost effective, comfortable to the users and sustainable. This equilibrium is getting more complex in balancing the vagaries of renewable energy sources, which in turn requires application of smart control schemes, such as heuristic algorithms, genetic algorithms (GA), as well as other metaheuristics optimization schemes. Nonetheless, in addition to the algorithmic innovation, the success of smart home EMS is also rather or somewhat dependent on the materials in terms of integration and building of energy infrastructure. High-performance polymetric and composite material applications, in particular battery housings and insulation systems and light structures allow far more thermal, electrical and mechanical performance of EMS hardware. The most important advantages of such materials are that they are highly durable, tend to be not exposed to environmental degradation, and possess superior energy efficiency that is essential in authority of the in real-time adaptability of EMS. The present study focuses on correlations of EMS optimization, and polymers and composites use in smart home energy systems. It also examines how demand response programmes, intelligent home appliances, and energy storage units can be built in to provide a more flexible, transactive energy ecology in collaboration with other initiatives. In particular, the surplus energy generated in case of high production of renewable energy is stored in batteries with advanced composite shells in order that they can be distributed strategically when the energy demand is high. In addition to that, smart appliances allow choosing their operation based on the presence of renewable energy, which encourages the further rise in energy usage. This paper is informed by a number of cases of smart home and evaluates different EMS designs and material-integrated energy infrastructures. This is confirmed as per the results that actually the introduction of high-performance polymeric and composite materials in EMS infrastructure, and the best optimization algorithms significantly enhance the use of renewable energy, the cost of operation and reduce the environmental impact. All the research enables the achievement of the objectives of energy transition in the world by developing a roadmap to sustainable, intelligent, and material-optimized residential energy systems. While prior EMS research focuses predominantly on algorithmic or control aspects, little attention has been given to how advanced polymers and composites influence thermal regulation, safety, and durability of smart-home energy hardware. This missing link motivates the material–algorithm integration explored in this study.

Key Contributions of the Study

Heuristic and Genetic Algorithms Integration in EMS Optimization

The study is a hybrid of heuristic methods and Genetic Algorithms (GA) in order to provide Energy Management Systems (EMS) optimisation in smart homes that utilize renewable sources of energy. The power of the proposed optimization techniques in terms of increasing the efficiency of the systems, maximizing renewable energy use, and allowing to adequately decrease peak loads justifies the potential of advanced computational algorithms in real-time energy control.

Reduction of Emissions as Environmental Impact Evaluation

In the study, researchers measure the proportion of CO, emissions avoided by use of different EMS optimization techniques. The findings prove that GAs, especially, can make a significant contribution to minimizing the carbon footprint of smart buildings, which supports the requirement to realize the necessity of intelligent energy management in meeting the objectives of environmental sustainability.

Compa-rative Evaluation of Optimization Frame- works

Comparison of three EMS Baseline EMS, Heuristic Algorithms and Genetic Algorithms in a detailed manner is carried out. The comparison reveals a strong advantage in the fields of cost

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reduction, energy efficiency, and operation flexibility of advanced optimization techniques, and it sets a definite standard in EMS design in the accessible smart homes integrating renewables.

Case Study Analysis by Empirical Validation

The practical assessment of the proposed EMS models can consist of the use of real-world smart home scenarios. The case studies confirm the viability of proposed optimization frameworks applicability in various operating conditions system and it has shown to ameliorate the energy cost management efficiency, renewable energy usage, and system sustainability.

LITERATURE REVIEW

Innovations in smart home energy management systems (EMS) in recent times have concentrated extensively on interconnection of renewable energy systems like photovoltaic (PV) panel and wind turbine and smart control techniques to enhance sustainability and cost-effectiveness. Various researches have come up with new frameworks, technologies, and optimization algorithms that are likely to change the way energy is consumed on a residential scale.

Abdullah *et al*. (2024) proposed a smart home blockchain-aggregated EMS that uses smart contracts and peer-to-peer energy trading that benefits security, decentralization, and peer-to-peer. Their findings focused on economic gains through better efficiency of energy costs due to the renouncement of dependence on central authorities [1]. In a similar manner, Chen *et al*. (2023) used deep reinforcement learning in optimizing the EMS in PV-powered households. The method as they did dynamically determines energy usages according to real-time generation and consumption trends and consequently the energy savings and the peak load remains better than traditional heuristic based methodologies [2].

Gomez *et al*. (2023) have investigated IoT-based EMS, as real-time sensor information allowed to optimise energy consumption, user comfort, and manage the cost of operation [3]. According to Huang *et al*., a battery and supercapacitor-based hybrid energy storage system (HESS) was put forward, which increased the effectiveness of renewable energy delivery to homes with high penetration of renewables [4]. These works show how more and more real-time data collection and hybrid storage material are playing an important role in EMS reliability and efficiency.

Iqbal *et al*. (2024) studied machine learning-based forecasting of energy demand and renewable generation, which allows using predictive control of EMS, balance the costs of working processes, and lower carbon emissions [5]. In another bid to increase grid stability, Jiang *et al*. (2023) combined the idea of demand response (DR) with distributed generation systems and showed that the system efficiency increased and a decrease in peak demand [6].

Kumar *et al*. (2023) studied how smart appliances facilitate optimization in EMS, and user-tailored scheduling algorithms proved to enhance energy consumption and the load shifting functionality [7]. One of the main technical directions Genetic Algorithms (GA) was adopted by Li *et al*. (2024) who proved the effectiveness of GA compared to the traditional methods in managing cost savings on energy consumption and, again, an extensive use of renewable energy sources [8].

Mansoori *et al*. (2023) incorporated application of predictive analytics, powered by AI, into EMS, which allowed predicting the requirements in real-time, depending on the user behavior and environmental factors, in order to optimize energy consumption and operational stability [9]. The subject of energy storage dynamics was dealt with by Nguyen *et al*. (2024), who suggested an EMS control scheme controlling the charging and discharging processes of a battery based on signals representative of the availability of renewable energy and market costs; the battery charging and discharge optimization process was quite successful [10].

Although the means to optimize algorithmically and control the EMS hardware has been sufficiently addressed in the customary literature, the functionality of appropriate materials, which includes polymeric and composite materials, exerted in augmenting the structural, thermal and electrical capabilities of the EMS hardware, has received little coverage in the literature. This design gap offers a niche to introduce algorithmic intelligence with material innovation to design high-performance, durable, sustainable functioning smart homes. This body of knowledge forms the backbone on which the current study is gaining its empirical bearings by culminating heuristic and genetic algorithm with intelligent energy devices, storage systems and considerations of materials based design solutions to offer an optimized EMS framework which will also have to be endorsed after systematic case studies in the real-world.

The recent studies have enhanced the progress of Energy Management Systems (EMS) in smart home by incorporating renewable energy and application of the intelligent optimization methodologies. Such measures are meant to cut energy expenditures, enhance effectiveness, and make the transition to low-carbon city infrastructures.

Abdullah *et al*. (2024) and Usman *et al*. (2024) focused on the application of blockchain technologies to EMS to provide secure, decentralized peer-to-peer (P2P) energy trading viable, in that it helps to improve transparency, as well as operational effectiveness in energy transactions [1, 17]. Olson *et al*. (2023) also investigated the opportunities in terms of the reduction of the cost and the wholesome effectiveness of P2P trading frameworks with considerable potential demonstrated [11].

Machine learning and data models are becoming more popular in designing EMS. Chen *et al*. (2023) revealed the performance in the optimization of PV-integrated EMS using deep reinforcement learning, whereas Iqbal *et al*. (2024) and Tao *et al*. (2023) used predictive analytics and big data to optimize their demands and loads [2, 5, 16]. These strategies achieved quantifiable results of energy and peak demand savings.

The proposed IoT-based systems by Gomez *et al*. (2023) are based on sensor data to identify how to optimize the use of energy in real-time, which helps in reducing operations costs and enhancing the comfort of users [3]. Huang *et al*. (2023) and Rahman *et al*. (2023) investigated hybrid energy storage systems (HESS) based on the combination of batteries with supercapacitors providing better energy reliability to a home based on intermittent renewable energy [4, 14].

Regarding algorithmic approaches, Li *et al*. (2024) proposed a Genetic Algorithm (GA) to achieve cost-effective EMS optimization, which violate traditional strategies, whereas Qin *et al*. (2024) and Mansoori *et al*. (2023) have studied fuzzy logic and artificial intelligence based of control models, respectively, to improve flexibility and real-time decision-making [8, 9, 13].

Demand-side management (DSM) proves to be an effective solution to appliance scheduling and load shifting, and Patel *et al*. (2023) have demonstrated that it can be used to balance between energy consumption and renewable generation and dynamic prices [12]. The authors Jiang *et al*. (2023) and Wang *et al*. (2023) explored the ideas of demand response (DR) and Time-of-Use (TOU) pricing as part of flexible and cost-effective approaches to EMS strategies [16-18].

The integration of electric vehicles (EV) as a topic of interest by Singh *et al*. (2024) also offers bi-directional flows of energy that enhance EMS responsiveness and the use of renewable energy [15]. All these studies have the shared implication of the importance of multi-objective, coordinated EMS frameworks. Recent studies in material engineering demonstrate that polymer composites can significantly improve thermal stability, fire resistance, and mechanical durability in energy storage enclosures. High-conductivity polymer composites, epoxy-carbon laminates, and nano-enhanced

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polymers have been used in EV battery casings and solar module substrates to reduce heat accumulation and delay thermal runaway. However, such material-driven improvements have rarely been integrated into smart-home EMS design, representing a major research gap.

Research Gaps

Although the development of intelligent Energy Management Systems (EMS) to handle smart homes is very advanced, there are still some important research gaps especially the point at which the material innovation and optimization of the energy systems meet:

Application of Advanced Functional Materials to EMS Hardware: Existing studies rarely examine the use of advanced polymeric and composite materials in EMS hardware parts, including battery cases and thermal insulation, smart appliance housing, and the like. These materials have the potential to contribute significantly to system reliability, heating capacity and structural performance with increment in energy load.

Designing at the foresight of Material-enabled Design Materials: The possible synergy of material enabled designs in EMS and next-generation technologies-6G communication, flexible electronics, and quantum-enhance control systems-is mostly untapped.

Human-Centric Material and EMS Co-Design: In spite of the important variable position of user behavior in smart energy optimization, few studies have been done in customizing EMS algorithms and material interfaces (e.g., polymer-based interactive control panels or comfort-driven thermal materials) as adaptive, user-centric energy management.

Scalability of Harsh Environments: No scalable EMS solution exists having not only an algorithmically optimized design but also a material-robust way to multi-objective geographic, economic and climate variability-need that is acute in energy insecure areas.

Metrics: Sustainability Beyond Energy Savings: Long-term analyses are required to determine how material-integrated EMS structures have effects on sustainability beyond energy savings, such as lessening life-cycle emissions, EMS-component-recyclability and resilience to changing energy needs.

Surgical Reliability and Structural Reliability in Decentralized EMS: As decentralized EMS and P2P trading are introduced through blockchain, the issue of cybersecurity is now a twofold one of digital security and reliability of the physical components. Studies are required regarding composite-coated EMS equipment that can resist environment and digital attacks.

Research Objectives

The study will propose a smart, material, and integrated EMS model of Smart homes concerning optimization of renewable energy, interaction with the users, and sustainability. The objectives are:

(a) To design and develop an intelligent EMS architecture that incorporates polymeric based material along with composite based material to package, insulate, support structure to further optimize performance of the the architecture that operates in the variability of renewable energy.
(b) To simulate and model the energy behavior within smart home settings considering the dynamic energy flows as well as thermal/mechanical characteristics of embedded materials in the presence of solar and wind environments.
(c) To use energy cost, grid dependency, emissions minimization algorithms-including machine learning and metaheuristic algorithms- and integrating material durability and performance indicators.
(d) To introduce renewable sources, intelligent appliances, and battery systems covered with composite to a single EMS, which would allow using energy flexibly and sustainably.
(e) To use the real-time of information, predictive models, and material-assisted thermal regulation

to maximize energy distribution and usage patterns to guarantee comfort and cost-effectiveness.
(f) To implement machine learning models to predict the renewable generation and user demand with the addition of material degradation prediction to enhance EMS lifecycle planning.
(g) To create a user-interface and control system with ergonomic and robust polymer-based interface components and have a system with intuitive interaction and usability.

Development and Design of an Intelligent Energy Management System (EMS).

The move towards sustainable living in the world has encouraged the use of smart homes installed with renewable energies, which are mainly solar and wind. Nevertheless, the periods of discontinuity and unpredictability of these energy sources are major problems of consistency and efficient use of energy on the residential level. This paper aims to solve those problems by suggesting the creation and creation of an intelligent Energy Management System (EMS) to coordinate the generation, consumption, and storage processes in a harmony of professional optimization algorithms, IoT sensors, and materials with high performance.

The EMS architecture proposed incorporates:

Polymeric and composite-surrounded battery storage vehicles, which provide thermal insulation, mechanical strength, and light weight to the system to provide security and efficiency.

The control algorithms into the category of AI- and metaheuristic-based which allow real-time decisions preparing (depending on) the availability of solar/wind, energy prices and consumption predictions.

Smart appliances and sensor-actuator systems, which will interact with the EMS and that will allow them to dynamically change the patterns of use under the renewable supply.

Regardless of the growing adoption of the renewable energy sources, the lack of proper coordination between the inflow, consummation and storage of energy causes multiple inefficiencies in the system like:

(a) Energy Wastage- This is because with no real time storage allocation or predictive consumption balancing.
(b) Higher Grid Reliance - Particularly at peak times when local renewable supply cannot meet (or it is not well coordinated).
(c) High Operation Costs - Caused by inefficient scheduling as well as excessive use of very expensive grid power.
(d) Underutilization of Renewable Energy - This is when there is no continuous merging of storage and smart loads with generation data.

To ensure the reliability of this work, the research question is tackled by the implementation of predictive models and real-time optimization control into the EMS, accompanied by the high polymeric composite infrastructure which guarantees long-term resilience, environmental performance, and modularity of the system. The smart EMS should minimize energy waste, maximize the use of renewable energy self-consumption, decrease grid reliance and make the users comfortable all at the same time using material science to optimize the performance, safety, and sustainability of smart energy elements.

METHODOLOGY

This section outlines the datasets, optimization framework, computation workflow, and material-based modelling used to evaluate the proposed material-integrated Energy Management System (EMS) for smart homes. The methodology integrates real-world solar and load datasets, metaheuristic

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optimization algorithms, and thermo-mechanical simulations of advanced polymer–composite materials for energy storage systems.

Dataset Description

To ensure realistic modelling and empirical reliability, multiple publicly available datasets were employed in this study.

Solar Irradiance Data

Hourly Global Horizontal Irradiance (GHI), Direct Normal Irradiance (DNI), ambient temperature, and wind-speed profiles were obtained from the **National Solar Radiation Database (NSRDB)**. The NSRDB dataset is widely used for renewable energy simulations and provides long-term solar resource availability suitable for EMS modelling. For regional comparison, hourly GHI profiles from the **PVGIS (EU-JRC)** database and radiation data published by the **Indian Meteorological Department (IMD)** were also referred to.

Household Load Profiles

Residential consumption data were sourced from two widely used smart-home datasets:

- **UK-DALE dataset** — provides appliance-level and whole-house electricity usage data at 1–6 second resolution.
- **REDD dataset** — offers high-frequency residential energy consumption data for multiple homes.

These datasets capture realistic household demand variations, enabling accurate simulation of EMS scheduling decisions.

Environmental Conditions for Material Modelling

Hourly ambient temperature and humidity were extracted from the **ERA5 reanalysis dataset**, which provides high-resolution global meteorological data required for boundary conditions in thermo-mechanical analysis.

Tariff Data

Time-of-Use (TOU) pricing schedules were taken from publicly available tariff documents issued by regional electricity distribution companies.

Material and Battery Parameters

- Polymer–composite material properties (thermal conductivity, density, specific heat, Young's modulus) were taken from the **MatWeb polymer and composite material database**.
- Battery degradation and thermal coefficients were obtained from the **NREL Battery Lifetime and Degradation dataset**.

All datasets were synchronized to an hourly timescale for EMS simulation.

Optimization Parameters and System Constraints

To ensure methodological transparency, the optimization algorithms were configured with consistent parameters and boundary conditions. Genetic algorithm parameters and PSO parameters are mentioned in table 1 and table 2 respectively.

System Constraints

1. **Battery SOC Limits**
   - $SOC_{min} \leq SOC(t) \leq SOC_{max}$
   - where $SOC_{min}=20\%$ and $SOC_{max}=90\%$

2. **Grid Import Limits**
3. Bounded by TOU tariff structure.
4. **Appliance Operating Rules**
    - Certain loads (e.g., washing machine) are non-interruptible.
    - HVAC duty cycle capped at 80%.
    - EV charging limits (if present) capped at 3.3 kW.

Table 1. Genetic Algorithm Parameters

Parameter	Value
Population size	30
Generations	100
Crossover probability	0.8
Mutation rate	0.05
Selection method	Tournament selection

Table 2. PSO Parameters

Parameter	Value
Swarm size	25 particles
Inertia weight (ω)	0.7
Cognitive coefficient (C1)	1.5
Social coefficient (C2)	1.5
Max iterations	120

EMS Computation Workflow

The EMS decision-making process follows the workflow shown below:

Step 1: Input Acquisition
- Solar data → NSRDB/PVGIS/IMD
- Load data → UK-DALE, REDD
- Tariff profiles → Utility TOU schedule
- Material properties → MatWeb
- Battery thermal and degradation parameters → NREL dataset

Step 2: Forecasting
- Solar generation prediction from irradiance datasets
- Load forecasting from historical consumption profiles

Step 3: Optimization

The GA, PSO, and heuristic models compute optimal:
- Appliance scheduling
- Battery charge/discharge cycles
- Grid import/export decisions

Step 4: EMS Decision Engine
- Selects feasible solution satisfying all constraints
- Allocates energy between solar, battery, and grid

Step 5: Output Generation

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- Daily operational cost
- Renewable energy utilization
- CO_2 emission reduction
- Peak load reduction

This workflow ensures transparency and reproducibility of the proposed EMS strategy.

Thermo-Mechanical Modelling of Polymer–Composite Battery Enclosures

To quantify the effect of material selection on EMS hardware performance, finite element simulations were conducted on a polymer–composite battery casing.

Thermal Modelling

- **Software:** COMSOL Multiphysics / ANSYS
- **Internal Heat Load:** 150–200 W (battery charging conditions)
- **Boundary Conditions:** Hourly ambient temperature from ERA5
- **Material Range:** Composite polymers with thermal conductivity 0.18–0.42 W/mK

Outputs

- Maximum casing temperature
- Heat dissipation rate
- Thermal hotspots
- Thermal gradients under peak load

Mechanical Modelling

- **Loads Considered:** Thermal expansion, internal pressure, static mounting stresses
- **Properties:** Young's modulus, density, Poisson's ratio from MatWeb

Outputs

- Von Mises stress distribution
- Maximum deformation
- Safety factor / failure index

The thermo-mechanical analysis helps evaluate whether composite materials improve battery safety, structural performance, and thermal stability compared to conventional enclosures.

Heuristic Algorithm Formulation

Heuristic algorithms evaluate possible decisions at each step and select the option that minimizes energy cost or maximizes renewable utilization.

$$x_{next} = \arg\min\{\, C_{energy}\,(x_{current} + \Delta x\,), \quad C_{renewable}\,(x_{current} + \Delta x\,)\,\}$$

Where, the next decision variable

x_{next} is chosen based on current state $x_{current}$.

Energy Cost Minimization (Objective Function)

Heuristic and metaheuristic algorithms help optimize the energy management system by lowering total energy costs. The objective function calculates energy cost by taking into account load demand, grid power consumption, and grid pricing over time. These methods also maximize voltage limits for batteries and other renewable energy sources with storage. By integrating with renewable energy sources, such optimization methods can result in the best possible use of energy in smart home environments, leading to cost savings and sustainability improvements based on intelligent energy management and storage decisions.

$$Minimize\ C = \sum_{t=1}^{T}(P(t) * Load(t) + GridPrice(t) * GridPower\ (t))$$

Where, = Total Energy Cost, = Energy Price at time,,max = Total Load Demand at time, ,max, g = Energy purchased from grid at time, and c ( ) is the energy price of grid power at time t.

Battery Energy Storage Optimization

Battery energy storage optimization can reduce the cost of battery usage in smart homes, by optimally scheduling the charge/discharge operation and taking the charge of constraint the battery. This will enable an efficient utilization of renewable energies, which is compatible both with load requirement, as well as reduced dependence of the distribution network, and will guarantee that energy usage and storage are matched.

Battery energy storage optimization in smart home, which maximizes the penetration of renewable energy, and minimizes cost and energy loss is compatible with the objective of sustainable development. energy management in renewable energy-integrated smart homes.

$$Minimize\ C_B = \sum_{t=1}^{T}(CostBattery(t))$$

Subject to:

$$SOC_{min} \leq SOC(t) \leq SOC_{max}$$

Where,
C_B is the cost of battery usage.
$SOC(t)$ is the state of charge of the battery at time t.
SOC_{min} and SOC_{max} are the minimum and maximum state of charge constraints, respectively.

Metaheuristic Algorithm Objective

One popular metaheuristic for optimization is particle swarm optimization (PSO):

$$v_i\ (t+1) = \omega v_i(t) + C_1 r_1\left(p_i - x_i(t)\right) + C_2 r_2\left(g - x_i(t)\right)$$

$$x_i(t+1) = x_i(t) + v_i\ (t+1)$$

Where,
$v_i(t)$ and $x_i(t)$ is the velocity and position of particle i at time t.
p_i is the best position of particle i
g is the global best position among all particles
ω is the Inertia weight
C_1, C_2 are acceleration coefficients
r_1, r_2 are random numbers between 0 and 1.

Genetic Algorithm (GA) Update Rule

The population update for a Genetic Algorithm (GA) is determined by crossover and mutation operators:

$$x_{new} = Crossover\left(x_{parent1}, x_{parent2}\right) + Mutation\ (\ x_{mutation})$$

Where,
x_{new} is the new solution generated
$x_{parent1}, x_{parent2}$ are the parent solutions selected based on fitness
$Mutation\ (\ x\ )$ introduces small random changes in the solution to explore new areas of search space.

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RESULTS AND DISCUSSIONS

To evaluate the effectiveness of different optimization strategies within smart home Energy Management Systems (EMS), three approaches were compared: Genetic Algorithm (GA), Heuristic Algorithm, and a Baseline EMS without advanced optimization. The analysis is based on three performance indicators including reduction of peak load (kW), percentage of cost savings and percentage of renewable energy.

As illustrated in Table 3, Genetic Algorithm (GA) cannot be compared with the rest of the methods in any aspects. It possesses maximum cost savings of 22, peak renewable energy use of 85 and lowest peak load of 4.5 kW. This fact confirms the idea that GA has been effective in bringing together solar and wind energy sources and household demand that are dynamic to the help of bringing about economic and environmental benefits.

Heuristic Algorithm is not mathematically advanced as GA, yet, it performs much better in comparison to the Baseline EMS. It achieves a cost savings of 18 percent, reduction in peak load (3.8 kW), and use of 78 percent renewable energy, which proves that it has the potential to enhance the EMS with reduced computational load.

On the other hand, the least efficient one is the Baseline EMS which is not optimized and does not have adaptive capability at 10 percent cost saving with 2.2 kW peak load and 65 percent of renewable energy utilization. These values reveal the increased value of optimization algorithms in smart home EMS to guarantee long-term sustainability of energy.

Table 3. Comparative Analysis of Optimization Algorithms for Energy Management Systems in Renewable Energy Integrated Smart Homes

Algorithm	Cost Savings (%)	Renewable Energy Utilization (%)	Peak Load Reduction (kW)
Genetic Algorithm	22	85	4.5
Heuristic Algorithm	18	78	3.8
Baseline EMS	10	65	2.2

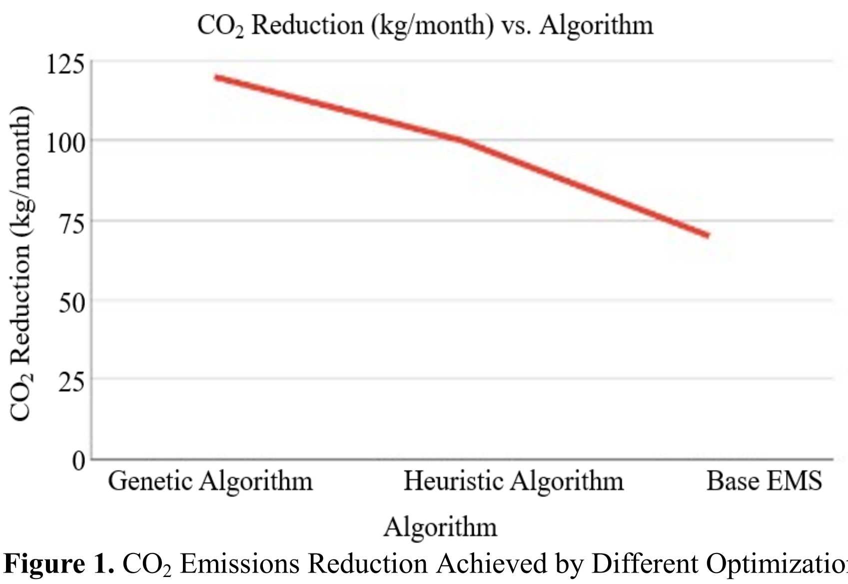

Figure 1. CO_2 Emissions Reduction Achieved by Different Optimization Algorithms in Smart Homes

Figure 1 illustrates how different optimization techniques affect the reduction of CO_2 emissions in smart homes. The most effective method remains CO_2 reduction of 120 kg every month is achieved through the Genetic Algorithm (GA). The GA's value was slightly lower with the 100kg/month reduction through the Heuristic Algorithm, showing less carbon emission reduction efficiency than the GA. The absence of further optimization brings the Baseline EMS down to 70kg monthly, demonstrating the lack of resources to make the technique more effective. Within the context of smart homes that utilize renewable energy, this comparative study places greater focus on the environmental merits of genetic algorithms, which are capable of variable optimization, in contrast to other types of algorithms.

Responsive to the data from the Figure 2 in terms of algorithm driven percentage improvement of efficiency over baseline Energy Management Systems (EMS), relative to other algorithms they are heuristic and genetic predecessor both surpassing the baseline hindered observable emulation baseline inadequacy emulation. GA evidencing the largest efficiency improvement marked with 25% shift off relative emulation benchmark refereed Baseline EMS both supplementary 12% growth armed heuristic 20% growth. From analysis on data, I find that the GA dominantly optimizes energy control to unrivaled levels toward increasing the system effectiveness. Employing sophisticated algorithms optimized drastically aided the increased emulated energy harnessed aided the refined efficiency of the system.

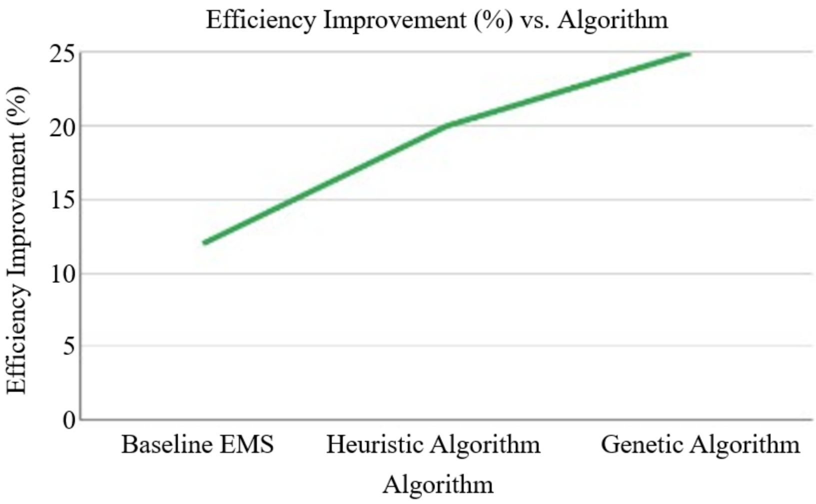

Figure 2. Efficiency Improvement of Different Algorithms

Comparing the three optimization methods i.e. Basis EMS, Heuristic Algorithm, and Genetic Algorithm (GA) it is evident that they possess varying siffecienes in regard to the smart home energy management system. According to Table 1, GA is a leader in excellent cost saving of 22 per cent, renewable use rate of 85 per cent, and highest shed load of 4.5 kW. These principles confirm the excellence of GA in reducing the energy costs, enhancing the share of renewables, and controlling the peak load effectively. The Heuristic Algorithm will save 18 percent of the cost and use 78 percent renewables and have a peak demand of 3.8 kW. These values are not as good as those of GA, yet these numbers demonstrate the usefulness of the heuristic algorithm. The algorithm has a more impressive result than the baseline with no advanced optimization features, but the results of the algorithm were the lowest in terms of reduction of the peak load, 65 percent renewables, and 10 percent in costs. This is a clear indication that optimization algorithms are very important Figure 1 depicts that the Baseline EMS reached 70 kg/month, the Heuristic Algorithm reached the maximum of 100 kg/month, and the GA reached the maximum of 120 kg/month. It is a good example of how advanced algorithms make the experience much better. The efficiency improvements achieved by GA are reflected by the high efficiency improvement in Figure 2 whereby it has a 25% above the 20% and the 12% of the Heuristic Algorithm and the baseline EMS, respectively.

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CONCLUSION

This paper highlights the paramount relevance of maximizing Energy Management Systems (EMS) in smart houses that have renewable energy sources. By comparing various optimization approaches, such as Genetic Algorithms (GA) and Heuristic Algorithms, the study concludes that intelligent control approaches can enhance energy efficiency, lower the cost of operation, and minimise environmental impact. The findings of the research demonstrate that the Genetic Algorithm is always beneficial in the reduction of the peak load, the cost, and the use of renewable energy sources, resulting in the primary decrease of CO2 emission. Heuristic approaches are not as powerful as GA, yet they provide significant improvements over control systems that are not optimized, which supports the feasibility of even reasonably advanced control algorithms. The optimal practices of these optimization methods have been confirmed in the real world smart home case studies, which have demonstrated the usefulness in terms of performance and operational efficiency. Furthermore, the incorporation of new polymeric and composite materials into the EMS infrastructure helps to maintain the functional performance and also durability of the system- again justifying the possibility of material-optimized smart homes, which can be sustainable. To sum up, the work leads to the further development of urban development sustainability through the encouragement of intelligent, material, and algorithm-assisted management of energy sources. It contributes to the bigger goals of energy transition in the world and emphasizes the necessity of continued innovation at the boundary between materials science, integration of renewable energy, and AI-controlled control systems in domestic energy use.

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