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ARTICLE

Intelligent Energy Management Strategies for New Energy Vehicles to Enhance Environmentally Sustainable Transportation Systems

***N. Nagabhooshanam* [1*], *Aman sharma* [2], *KDV Prasad* [3], *Kommula Bapayya Naidu* [4], *BEVL Naidu* [5]**

[1]*Department of Research Analytics, Saveetha Dental College and Hospitals, Saveetha Institute of Medical and Technical Sciences, Saveetha University, Chennai 602105, India*

[2]*Department of Mechanical Engineering,GLA University, Mathura 281406, India*

[3]*Department of Research, Symbiosis Institute of Business Management, Symbiosis International (Deemed University), Bengaluru 560100, Karnataka, India*

[4]*Department of Electrical and Electronics Engineering, Aditya University, Surampalem 533437, Andhra Pradesh, India*

[5]*Department of Management Studies, Aditya Degree & PG College, Kakinada 533003, Andhra Pradesh, India*

ABSTRACT

As the demands for environmental sustainability and the requirements to lower carbon emissions have escalated, New Energy Vehicles (NEVs) have emerged as a compelling substitute for fossil-fuel-run automobiles. Hence, a smart energy management strategy has been developed to enhance the performance of NEVs, maximizing the sustainability of transportation systems and minimizing environmental impacts. The system combines different power reserves, including a photovoltaic (PV) generator, fuel cell (FC), and battery system, to provide a continuous energy supply, even when the vehicle is running. The Multi-Directional Power Transfer converter for the battery provides the required energy adaptation between the input and output. The FC and PV systems are all connected through a direct current/direct current converter to effectively charge the battery whenever excess energy is present. The new energy management technique called Optimized Ant Colony Algorithm is proposed to dynamically allocate power among the different power sources, improving system efficiency. Unlike traditional methods, the suggested approach actively optimizes energy flow according to actual demand and availability, minimizing energy losses and enhancing sustainability. The MATLAB/Simulink

*CORRESPONDING AUTHOR:

N. Nagabhooshanam, Department of Research Analytics,Saveetha Dental College and Hospitals Saveetha Institute of Medical and Technical Sciences, Saveetha University, Chennai, India; Email: sainaga90@gmail.com

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tool was used to simulate the energetic performance of an electric car utilizing the suggested approach. The performance of this multi-source power system is assessed by contrasting the energy the PV and FC generating devices offer, and the energy generation of each recharge system. Additionally, the battery power comparison validates the cost-effectiveness and sustainability of the proposed model in NEVs. Results designate a significant improvement in energy efficiency and overall NEV environmental sustainability within contemporary transportation networks.

Keywords: Electrical Vehicles (EV); Photovoltaic (PV); Environment; Fuel Cells (FC); Optimized Ant Colony Algorithm (OACA); Energy Efficiency

1. Introduction

The demand for clean, efficient, and eco-friendly means of transportation is driving the rapid expansion of intelligent transport systems, assuming a critical role in the development of future mobility solutions [1]. The advent of Electric Vehicles (EVs) has enormous potential to restrict greenhouse gas emissions and enhance the quality of urban environment, making them a green alternative to conventional fossil fuel-based vehicles. Smart energy management is not just the setting up of charging stations but also the integration of renewable energy sources like solar and wind in a smooth manner to provide a greener and sustainable power supply for EVs [2]. Transportation infrastructures have to be maximized to realize economic and social objectives, maximize traffic mobility, reduce congestion, and protect people through improved road safety via minimized road crashes while, at the same time, managing environment-related issues such as air emissions and carbon production [3]. Plug-in Electric Vehicles (PEVs) have come out strongly as an economical option for reduced carbon dioxide output with the additional benefit of cleaner, more environmentally friendly and less-dependence-on-oil-based solutions. Intelligent transportation systems have revolutionized traditional gasoline and diesel-powered transport networks into new-age, low-cost, and highly sustainable transport solutions that provide efficient and quiet transport services, rendering them increasingly applicable to urban environment [4]. However, with better energy density and performance, lithium-ion battery cells high cost and weight remain the main barrier to the prolongation of the driving range of EVs and hence their universal use [5]. To achieve a future-proofed transportation infrastructure, current systems need to have EVs interconnected with electric grids to facilitate efficient distribution of energy, conservation of resources, and better grid reliability. Smart charging systems are essential in resolving these challenges by way of recharging infrastructure management, grid demand balancing, and the use of renewable energy sources to reduce the reliance on fossil fuels [6]. PEVs, hybrid electric vehicles, and hydrogen fuel cell vehicles are prime examples of EV technology, each with its respective advantages in terms of efficiency, environmental sustainability, and energy consumption. These vehicles utilize various modes of propulsion like electric motors, fuel cells, and regenerative braking to offer better performance and extend battery life [7]. The increasing number of EVs places significant strain on the energy supply infrastructure because charging these cars requires a lot of energy. Bi-directional charging networks such as V2G and high-power chargers can further alleviate grid tension by allowing EVs to supply power back into the grid in peak demand periods. Intelligent power management techniques combined with predictive analytics based on AI can also streamline EV charging schedules and energy allocation for uninterrupted and seamless power delivery to EV users [8]. The research aims to establish smarter power management technologies for New Energy Vehicles (NEVs) to develop power consumption efficacy and transport sustainability while minimizing environmental impact. It aims to integrate different energies and maximize the efficiency of power via enhanced conversion and management. A smart energy management strategy is present to maximize energy use in NEVs through the combination of various energy sources, such as photovoltaic (PV) generators, fuel cells (FC), and batteries.

An optimum EV charging preparation algorithm based on Grey Sail Fish Optimization (GSFO), which fuses GWO and SFO, was examined by Rajamoorthy et al. [9]. It enhanced traffic efficiency and power optimization, although scalability with rising vehicles required more examination. An environmentally conscious optimization method for planning when to charge electric vehicles was observed using Exponential Harris Hawks Optimization (EHHO) algorithm [10]. Using this, EVs spend less time charging in the Charging Station and the finest EV charging stations were suggested. For multi-connection DC networks, the characteristics of the top and bottom energy management levels were obtained using an Ant Colony Optimization (ACO) technology [11]. It was demonstrated that the ACO algorithm did not break electric power limitations, fluctuations in voltage, or oscillations. However, shifting periods were greatly decreased while ensuring environment-friendly operational practices The history and advantages of EVs were analyzed, and the results found were better charging infrastructure and battery technology [12], despite the challenges such as the expense of high infrastructure and range anxiety. Furthermore, a cloud-supported IoT-centered Intelligent Transportation System (CIoT-ITS) for traffic flow optimization and congestion management was examined by Liu and Ke [13]. Simulation proved its efficiency in vehicle flow control, although it was limited in its scalability and practical applicability of the system in real-world environmental settings. The acceptance of EVs and the complexities of deploying effective fast-charging structures, particularly integrating with the renewable energy sector and electrical grid, were addressed by Mohammed et al. [14]. They discussed planning strategies, simulation models, and optimization techniques for the increasing need for environmentally sustainable EV fast-charging points. A power managing algorithm for a solar and biogas hybrid EV recharging center that minimized power generation and costs and environmental impacts was presented by Karmaker et al. [15]. It showed a decrease in the cost of energy and lower emissions, with station owners experiencing short payback periods. A new power managing strategy for plug-in hybrid EVs with the aid of fuzzy logic and neural fuzzy logic regulators was discussed to improve the efficiency of batteries [16]. The results indicated that more sophisticated control strategies increased fuel economy, while promoting environmental efficient operations. However, the optimal system to be adopted by different vehicle profiles and operating conditions needs further evaluation. The contributions of EVs and the V2G method to renewable energy resource integration, environmental sustainability and demand management on the grid were summarized by Dik et al. [17]. The conclusions identified technological innovation and challenges. Limited scalability and practical implementations were its limitations. The influence of 5G technology on Intelligent Transporting Systems (ITS) in smart cities, along with its technological and economic and environment effects, were discussed by Gohar and Nencioni [18]. It detailed how 5G will improve various sectors of a smart city, especially transportation. The practical issues and full integration into current infrastructures were its constraints. Growing need for ecologically friendly transport demands effective management of energy in order to create a stable, reliable power source for NEVs. Fluctuations in power from sources such as PV generators and FC result in power instability and loss of efficiency. Effective energy delivery and conversion are thus essential to ensure high performance and utilization rates even with varied conditions. To mitigate these challenges, this research introduces a MDPT converter and OACA through which energy flow is managed. The proposed system improves energy adaptation, ensures effective power distribution, and boosts overall sustainability in NEVs. High cost of batteries and constraints of lithium-ion batteries, such as low energy density and weight, have a direct impact on NEV's efficiency and travel distance. Such constraints highlight the need for a highly efficient energy management system capable of effectively blending multiple sources of energy to assist in reducing dependence on a single source of power. Poor energy delivery leads to power imbalances, energy losses, and higher operating expenses. To solve this, the research introduces MDPT converter and an OACA to control energy flow. The objectives of the proposed method are as follows:

(1) Maximizes NEV energy management through the incorporation of PV, FC, and battery systems for a steady and uninterrupted power supply.

(2) Employs an MDPT converter for smooth energy flow and a DC/DC converter to charge the battery with surplus renewable energy.

(3) Uses Optimized Ant Colony Algorithm (OACA) to distribute energy in real-time dynamic based on real-time demand.

(4) Greater use of renewable power, reducing dependence on fossil fuels, and increasing environmental sustainability.

(5) Evaluation of the energy output of the FC and PV systems and the efficiency of every method of recharging, point to great gains in energy efficiency and the environmental sustainability of NEVs in today's transportation systems.

Existing research has focused into numerous optimization methods for managing energy for EVs, but there are still constraints on scalability, real-time flexibility, and energy integration from multiple sources. The GSFO and EHHO approaches have been successful in charging efficiency optimization and station choice, but they mostly aim at minimizing waiting times instead of optimizing overall energy allocation. ACO has also been used in multi-connection DC networks to avoid power constraints and voltage variations, but not entirely dynamic energy distribution from various sources such as PV generators, FC, and batteries. The new approach, OACA, improves its capability to dynamically distribute energy according to demand variations, reducing energy losses and enhancing overall sustainability. The comparisons of performance based on metrics like energy output, energy efficiency, cost-effectiveness, and sustainable energy consumption will further confirm the advantage of OACA over current optimization techniques.

1.1. Research Gaps

Existing research on EV charging infrastructure contains some limitations such as scalability issues, inefficient traffic optimization, and utilization of renewable energy sources in an inefficient manner. Existing optimization techniques like GSFO, EHHO, and ACO improve efficiency but are inefficient in handling large-scale EV networks, leading to congestion and scheduling inefficiencies. Traffic flow optimization models are not validated in real-time and do not integrate perfectly with energy management, restricting their applicability in real-world scenarios. Moreover, renewable power sources such as PV and FC are usually isolated, leading to inefficient energy consumption. Energy problems such as overcharging, deep discharge, and power unsteadiness shorten battery life and system stability. High infrastructure cost also prevents widespread fast-charging station adoption and integration with renewable energy sources. Existing researches does not dynamically combine PV, FC, and batteries, resulting in increased energy consumption and inefficiencies. Optimization methods do not have real-time verification, and hence they are not appropriate for large-scale EV networks. Traffic flow and energy distribution are typically handled separately, lowering overall efficiency.

1.2. Possible Solution

To overcome these challenges, the research conducted an optimized, scalable EV charging scheduling system with the Optimized Ant Colony Algorithm (OACA) to dynamically allocate charging slots, avoiding congestion and delay. It is combined with ITS to enable smooth traffic flow with charge ability, preventing wastage of energy. The PV, FC, and battery storage are smoothly integrated based on an MDPT platform, which captures the dynamic energy input and consumption balance. Real-time adaptive energy distribution optimizes the usage of the battery life and smart DC/DC converters ensure voltage adjustment and loss minimization. The platform is also compatible with high-efficiency Vehicle-to-Grid (V2G) interaction to deliver the best demand-side management and grid stability. With more effective power allocation, less dependency on grid power, and lower infrastructure bottlenecks, the proposed model is efficient in terms of cost, scalability, and environmental sustainability for NEV energy management. The suggested OACA-based system maximizes real-time energy distribution with the seamless integration of PV, FC, and batteries, minimizing energy wastage and congestion. The system improves efficiency, prolongs battery life, and provides a stable, scalable energy management system for NEVs.

Section 2 offers an explanation of the methodology context. Section 3 delivers the illustrations of the results and findings. The discussion portion is shown in Section 4, while Section 5 provides a description of the conclusion along with the limitations and its future scope.

2. Methodology

The method proposed a new energy management system for NEVs by combining PV, FC, and batteries using design and simulation. The power and DC/DC converters are applied to control the energy transmission efficiently. Power distribution is optimized to reduce losses and enhance the overall performance of the system. Synchronization of the power sources is ensured optimally by implementing smart control algorithms. The system targets real-time adjustment by varying load conditions to stabilize. Simulation models validate the optimal efficiency and sustainability of the system. The approach maximizes the use of NEV energy with ensure of environmentally friendly transportation.

The OACA algorithm maximizes real-time energy distribution through the intelligent coordination of PV, FC, and battery power sources in NEVs. Prior to optimization, energy output, efficiency, and sustainability were constrained through standalone energy usage. With dynamic power allocation and balancing energy resources, the proposed strategy maximizes energy output and efficiency. Intelligent scheduling ensures less wastage and better cost-effectiveness through enhanced renewable energy utilization.

2.1. Electric Vehicle (EV) Architecture

Hybrid electric vehicles (HEVs) are driven with a range of different energy sources, either internally or externally. Classifying this vehicle, it is within two categories: pure EVs and hybrid EVs. The vehicle can run on a battery when driving in a densely populated area or in the heart of the city and switch to an engine when it is farther away since this model is powered by electricity from a different source. In addition, HEVs can further be divided into Fuel cell EVs (FCEVs) and Plug-in HEVs (PHEVs). The research recommends a multi-source technology involving a lithium-ion battery, a PV generator, and an FC system.

EV structure determines the electric and structural arrangement of an EV, including the main parts required for successful performance. It comprises an energy storage system, most commonly a battery, powering the electric motor. A power electronic system, containing inverters and converters, also regulates the exchange of energy from the battery to the motor as well as between ancillary systems. Regenerative braking is also responsible for gaining efficiency through capturing energy while braking. A system that has the capacity to design more than one power source such as FC and PV provides effective energy management. Intelligent energy distribution provides a stable power supply with better performance and sustainability. EV architecture in total provides green, reliable, and efficient mobility. **Figure 1** demonstrates the model of HEV.

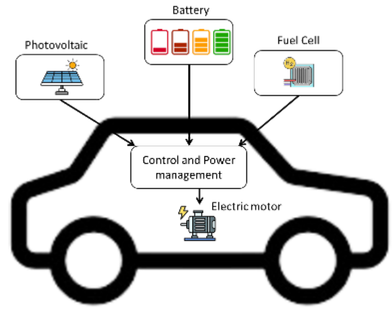

Figure 1. Hybrid Electric Vehicle (HEV) Model.

2.2. Battery Modeling System

Battery Modeling System is important in managing energy flow in NEVs by predicting battery performance. It tracks necessary parameter states of charge to achieve optimal utilization. By making optimal power allocation efficient, it ensures longer battery life and reliability. It dynamically adjusts in accordance with changing loads, avoiding overcharge or deep discharge. It works in tandem with FC and PV to balance energy supply and demand. More sophisticated algorithms enhance precision, which enables effective energy management and sustainability. It maximizes NEV efficiency, providing an optimized and stable power supply.

The battery model's mechanisms need to be understood because the charging method is utilized to recharge a battery. The lithium model has the best power. Voltage in the battery ($U_{batt/cell}$) is defined in

$$U_{batt/cell}=U_{pd}+Q_{batt}J_a+\int \frac{Q_{ks}J_a-U_{ks}}{Q_{ks}D_{ks}}ds+\int \frac{Q_{ts}J_a-U_{ts}}{Q_{ts}D_{ts}}ds \quad (1)$$

Here, Q_{ts} and D_{ts} are the short-term double-layer properties of electromagnetic impedance and inductance respectively. Q_{ks} and D_{ks} are the impedance and inductance of the long-time-interval mass transport effects of electrochemistry and J_a is the load current.

The battery output potential (U_{batt}) and resistive impedance (Q_{bam}) are given in

$$\begin{cases} U_{batt}=\frac{M_{tbatt}}{M_{obatt}}\left(U_{batt/cell}\right) \\ Q_{batt}=\frac{M_{tbatt}}{M_{obatt}}\left(Q_p+Q_{ts}\left(\frac{J_{ts}}{J_s}\right)+Q_{ks}\left(\frac{J_{ks}}{J}\right)\right) \end{cases} \quad (2)$$

Here, M_{tbatt} and M_{obatt} are the number of series and parallel cells. Q_p implies the battery cell impedance when recharging or discharging.

The State of Charge (SOC) of the battery can be stated in relation to time in

$$SOC=-\int_{s-1}^{s}\frac{1}{60}\left(SOC(s-1)N_a-X(U_aJ_a)\right)ds$$
$$SCO(\%)=\frac{R(t)}{R_{max}}\times 100 \quad (3)$$

Here, X represents the coefficient of charging or discharging and N_a is the self-drain of the battery.

The Battery Modeling System maximizes charging and discharging processes. It prevents overcharge and deep discharge, which would result in battery shortening and unreliability. Voltage equations determine power output, while SOC modeling tracks charge levels for efficient energy distribution. By adapting dynamically to changing loads, it balances energy supply and demand in real-time. The system operates in conjunction with MDPT, controlling power transfer between the battery, PV, and FC. The integration predicts energy loss, increases overall efficiency, and moderates power delivery. Consequently, NEVs realize improved energy utilization, cost-effectiveness, and sustainability.

2.3. Multi-Directional Power Transfer (MDPT)

Multi-Directional Power Transfer (MDPT) is a power conversion technology used to regulate energy transfer between different energy sources and loads in a bidirectional power exchange mechanism. MDPT allows power transfer in different directions, ensuring energy utilization to its maximum and promoting system efficiency. In NEVs, MDPT plays an important role in achieving energy generation, storage, and utilization balance. Multi-Directional Power Transfer allows efficient energy transfer between battery, FC, and PV in NEVs. MDPT controls power transfer dynamically as per demand, optimizing energy utilization. It optimizes overall system performance and efficiency by minimizing losses. The system offers a constant supply of energy regardless of variation in generation or consumption. It also enables the regenerative recovery of energy, making it more sustainable. MDPT adapts to varying load conditions, ensuring stable and consistent operation. It renders NEV more efficient, more sustainable, and energy-efficient.

The MDPT converter dynamically balances energy distribution among multiple sources like PV cells, FCs, and batteries, to maximize the power utilization in NEVs. It operates on a bidirectional energy flow mechanism with the capability to efficiently exchange energy based on demand and availability. In the event of excess power generated by PV or FC, MDPT sends it to charge the battery or provide vehicle load. Under conditions of limited generation, the battery supplies energy to ensure stability. By regulating voltage and current in real time through DC/DC converters, MDPT avoids power oscillations, reduces losses, and facilitates seamless energy transfer. This improves system efficiency, extends battery life, and enables grid integration for renewable energy management.

For instance, in a system where various energy sources are involved (such as photovoltaic, fuel cells, and batteries), MDPT facilitates:

Energy Flow Control: It controls power from sources and the battery, and directs energy from the battery to the grid or be used by the car when needed. The total power generated and consumed should be balanced, as expressed in

$$P_t = P_s + P_b + P_l \quad (4)$$

Here, P_t is total power output, P_s is power generated from renewable sources, P_b is power exchanged between battery and other components and, P_l is power required by the load (vehicle).

Bidirectional Power Transfer: MDPT makes sure that excess power from sources (like solar panels or fuel cells) is stored in the battery or sent back to the grid, and power can be drawn from the battery when the sources are not providing sufficient power. The power transfer from the source to the battery and vice-versa can be expressed as

$$P_s = P_b \text{ (Charging the battery)} \quad (5)$$

$$P_b = P_l \text{ (Discharging the battery)} \quad (6)$$

Efficiency Enhancement: Through enabling multi-directional energy transfer, MDPT optimizes the utilization of available energy, minimizes wastage, and enhances the total efficacy of the energy management structure. Efficiency is determined by

$$Efficiency=\frac{P_u}{P_t} \quad (7)$$

Here, P_u is useful power provided to the load.

Energy Flow Optimization in Multi-Directional Systems: In a multi-source hybrid system (e.g., solar power, fuel cells), MDPT can optimize energy flow according to availability. A typical optimization goal is to reduce energy loss and utilize renewable energy as much as possible, as given in

$$minimize \ \sum_i EL_i+EW_i \quad (8)$$

Here, EL_i is loss due to conversion inefficiencies, and EW_i is excess energy not used.

2.4. Renewable Hybrid Power Systems for Electric Vehicles (EV)

Renewable hybrid electric power systems for EVs integrate various renewable energy sources, including fuel cells, solar power, and batteries, to maximize the use of energy and improve environmental sustainability. The systems are intended to minimize the use of non-renewable energy sources, providing a cleaner and more efficient means of powering EVs. The combination of various energy components enables them to deliver a consistent flow of energy and enhance vehicle performance in general. Smart energy management strategies, aid in balancing and optimizing the energy flow between the sources. Generally, these hybrid systems contribute to developing more cost-efficient, sustainable, and environmentally friendly transportation systems.

PV cells and FC motors are the two types of sources of power used in the recharge method. To introduce this hybrid recharge tool, each of these capabilities must be modeled. The DC/DC converter is critical to accommodating, regulating, and controlling the various sources of energy to enable the NEV to operate most efficiently by making use of the synergy of PV, FC, and battery towards efficient utilization of energy. The DC/DC converter plays a key role in optimizing NEV energy management efficiency by smoothly integrating various power sources. The converter regulates and controls energy transmission from the PV generator, FC, and battery to ensure constant operation. With dynamic source balancing, the converter optimizes energy use, minimizes energy loss, and maximizes overall efficiency. Such cooperation makes it possible to adapt instantly to different energy needs, thereby maximizing the environmental impact and sustainability of NEVs. Eventually, the DC/DC converter plays a major role in implementing a stable, efficient, and smart power supply system for future environmentally friendly transportation. **Table 1** demonstrates the comparison of FCs and PV cells.

Table 1. Contrast of FCs and PV Cells.

Characteristic	Fuel Cells (FCs)	Photovoltaic (PV) Cells
Energy Source	Chemical energy	Solar energy
Energy Conversion	Electrochemical conversion	Photovoltaic effect
Maintenance	Requires regular maintenance	Low maintenance, especially in sunny areas
Reliability	High with controlled conditions	Moderate, affected by weather conditions
Environment Impact	Low, but depends on the fuel used	Very low
Power Retention	Requires ongoing hydrogen storage or fuel supply	Capable of storing energy in batteries for later application
Service Life	5,000–10,000 hours (system type dependent)	20–30 years with negligible degradation
Capital Investment	High due to infrastructure and technology for fuel cells	Moderate to high but decreasing
Reaction Time	Fast response to changing loads	Slow response due to reliance on sunlight and energy storage
Mobility Viability	Best for transportation applications	Best for stationary or hybrid applications

2.4.1. Photovoltaic (PV)-Based Energy Generator Model

In EVs, solar cells are utilized as electrical components that convert renewable energy from the sun into electrical energy. The current (J_d) is given as

$$J_d = J_{og} + J_{tg} + J_c \quad (9)$$

The PV cell's current (J_{og}) can be evaluated by

$$\begin{cases} J_{og}=\frac{H}{H_{raf}}\left(J_{qt-ref}+\left[L_{SCT}\left(S_d-S_{d-ref}\right)\right]\right) \\ J_c=J_{qt}\left(f^{\frac{r(U_d+Q_tJ_d)}{\alpha lS}}-1\right) \\ J_{tg}=\frac{1}{Q_o}\left(U_d+Q_tJ_d\right) \end{cases} \quad (10)$$

The PV generating model is subjected to many parallel (M_o) and series (M_t) cells whose current is given in

$$J_o=M_oJ_{og}-\left[M_oJ_{qt}\left(f^{\left(\frac{U_d+Q_tJ_t}{\alpha lS}\right)}-1\right)-\frac{M_o}{Q_o}\left(\frac{U_o}{m_tM_t}+\frac{Q_tJ_o}{M_o}\right)\right] \quad (11)$$

2.4.2. Fuel Cells (FC)-Based Energy Generator Model

Fuel cells use air and hydrogen as the fuel sources. The conversion rates between hydrogen (V_{fH2}) and oxygen (V_{fO2}) are defined in

$$\begin{cases} V_{fO_2}=\frac{m^q_{O_2}}{n^{jm}_{O_2}}=\frac{60000*Q*S*j_{fc}}{2*r*E*O_{air}*U_{air}*z\%} \\ V_{fH_2}=\frac{m^q_{H_2}}{n^{jm}_{H_2}}=\frac{60000*Q*S*j_{fc}}{2*r*E*O_{fuel}*U_{fuel}*w\%} \end{cases} \quad (12)$$

The partial pressures of hydrogen and oxygen can be obtained by

$$\begin{cases} O_{H_2}=\left(1-V_{fH_2}\right)w\%O_{fuel} \\ O_{H_2o}=\left(x_{fc}+2z\%V_{fO_2}\right)O_{air} \\ O_{O_2}=\left(1-V_{fO_2}\right)z\%O_{air} \end{cases} \quad (13)$$

The voltage source (F) can be determined by

$$\begin{cases} F=F_{od}-\left(M*A*km\left(\frac{j_{ed}}{j_p}\right)*\left(\frac{1}{1+t^{S_c/3}}\right)\right) \\ U_{ed}=F-Q_{ed}*j_{ed} \end{cases} \quad (14)$$

2.5. Proposed Energy Distribution Plan Using Optimized Ant Colony Algorithm (OACA)

The efficiency of Ant Colony Optimization (ACO) for solving graph-related navigation problems has been widely recognized. The drawback of classical ACO is, however, that it struggles to overcome the added complicating factors involving charging time option selection, queues, and infusing user taste into decisions. These variables mean more advanced tactics are needed for modifying ACO to suit the real world. Thus, conventional ACO methods may be limited in providing optimum solutions in dynamic situations where multiple causative factors are present. To overcome these limitations, better algorithms like the OACA are used to incorporate all such complexities effectively.

Optimized Ant Colony Algorithm (OACA) is a nature-inspired optimization algorithm that has been developed to assist in improved energy management of NEVs. The algorithm imitates the foraging process of ants to follow the most efficient routes for energy transmission between different sources of energy, including PV generators, FC, and batteries. The algorithm adapts dynamically according to changes in energy demand, ensuring that energy flow is optimized in real time. OACA optimizes the use of renewable energy to a higher extent, reducing the usage of non-renewable energy and increasing the efficiency of the system. It continuously assesses energy demand and corrects the allocation to ensure optimal energy balance within the system. Through the integration of the smart optimization technique, OACA guarantees that the energy management system has minimal wastage and maximum performance. This leads to enhanced sustainability, energy efficiency, and cost-effectiveness for NEVs in modern transportation systems. It combines a number of methods to improve charging time optimization and routing operations. **Figure 2** shows the architecture of the Optimized Ant Colony Algorithm (OACA).

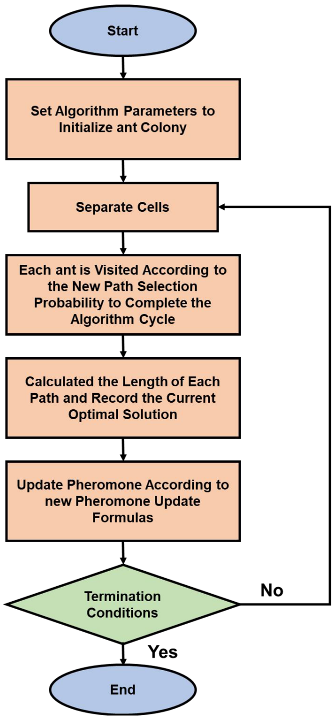

Figure 2. Flow Chart of Optimized Ant Colony Algorithm (OACA).

(1) Initialization Phase: The parameters associated with the ACO algorithm for initialization are applied at time $t = 0$, for instance, the number of ants and the pheromone factor. Ants all originate from the location of EV, and the initial concentrations of pheromone between nodes are expressed in

$$\tau_{u_j,u_i}(0)=\tau 0 \tag{15}$$

(2) Heuristic Evaluation: The heuristic value is calculated to assist ants in choosing charging points depending on the distance to the destination and the power available. It employs path deviation, destination distance, and power of charging to assess the best charging points for ants to travel. The heuristic factor can be expressed as

$$\eta_{u_i,u_i}(s)=\begin{cases}[dev(u_j,u_i)]^b.[o(u_i)]^a.[c_{end}(u_j,u_i)]^d, & u_j\neq u_f\\ \eta^n_{u_j},I(u_j)-u_f(s) & ,u_j=u_f\end{cases} \tag{16}$$

(3) Select Pathway: Ants choose the next node by considering the heuristic factor and concentration of the pheromone. They prefer paths with greater concentrations of pheromone and good conditions for the problem and apply a pseudorandom proportional rule. Starting from u_j, the probability weight of the l th ant choosing the next node as i at moment s is as follows:

$$X^l_{u_j,u_i}(s)=\begin{cases}\left[\tau_{u_j,u_b}(s)\right]^\alpha\left[\eta_{u_j,u_b}(s)\right]^\beta,u_i\in I_l(u_j)-u_f\\ exp^{max[f0](n-m,1)}\left[\tau_{u_j,u_b}(s)\right]^\alpha\left[\eta_{u_j,u_b}(s)\right]^\beta,u_i-u_f\\ 0,otheres\end{cases} \tag{17}$$

(4) Compute Charging Duration and Overall Time: Once the route is determined, the waiting and charging time at every charging station is computed. Nonlinear programming is used to minimize the overall time, in terms of charging time at every station, under given constraints on charging times and energy levels. The entire amount of electricity needed to get from the starting point to the endpoint is expressed as

$$D_m=Max(d(q_0,q_n)+F_f-F_0,\ 0) \tag{18}$$

Each part's electrical size is given in

$$D_K = D_m/K \tag{19}$$

(5) Transition and Update Process: The state transition is computed through different equations to find the levels of electricity at every charging station, the charging time, and the waiting times. The state transition equation computes the charging times and waiting times from past states to obtain the optimal solution for the charging and waiting times for every route. The scent found on the universally optimum route is updated as follows

$$\tau_{u_j,u_i}(s+1)=(1-\rho).\tau_{u_j,u_i}(s)+\rho.\Delta\tau_{u_j,u_i}(s)$$

$$\Delta\tau_{u_j,u_i}=\begin{cases}\frac{R}{S_{best}}, & f_{u_j,u_i}\ \ belongs\ to\ optimal\ path\\ 0, & other\end{cases} \tag{20}$$

when the whole ant colony has finished searching.

Algorithm 1 shows the pseudocode for the OACA for EV charge route planning.

Algorithm 1. Optimized Ant Colony Algorithm (OACA) for EV Charge Route Planning.

```
Initialization
Initialize pheromone τ(u_j, u_i) = τ0 for all paths
Initialize ants with positions, power, and destinations
Set parameters: N (ants), max_iter (iterations), α, β, ρ
Main Loop: Iterate through all ants for max_iter
for iteration in range(max_iter):
Step 1: Heuristic Evaluation (for each ant)
    for ant in ants:
        for path in possible_paths:
            Calculate heuristic η(u_j, u_i) based on path deviation, power, and distance
ant.heuristic[path] = calculate_heuristic(path)
Step 2: Path Selection (Choose next node)
    for ant in ants:
current_node = ant.position
next_node = select_next_node(current_node, ant.heuristic, pheromone)
ant.move_to(next_node)
Step 3: Compute Charging Time & Total Time
    for ant in ants:
total_time = calculate_total_time(ant.route)   Minimize charging time at stations
Step 4: Update Pheromone Levels (after ants complete their routes)
    for ant in ants:
        if ant.route == optimal_route:
pheromone_update = calculate_pheromone_update(ant.route)
update_pheromone(ant.route, pheromone_update)
Step 5: Transition Process (update energy and times)
    for ant in ants:
update_ant_state(ant)
Return the optimal route and time
return optimal_route, total_time
```

3. Results and Findings

The efficiency of the suggested smart energy management systems for NEVs is evaluated to analyze the efficiency improvements. The enhancements in energy efficiency, environmental sustainability, and cost-effectiveness are emphasized by integrating PV generators, FC, and batteries. The performance of the system is analyzed based on key factors such as energy output, efficacy, sustainable energy consumption, and cost-effectiveness. The findings show the significant impact of OACA on optimizing energy flow. The findings present significant insights into the future of the proposed system in terms of maximizing NEV operation.

3.1. Experimental Setup

The research utilized a computational experimental setup with a PC that contained an Intel i7 processor and Python libraries for simulating the energy management system. The setup assisted in simulating and analyzing the performance of the NEV in terms of energy efficiency and environmental sustainability. The system was run in simulation and included the PV, FC, and battery systems, all of which were managed by the OACA algorithm for evaluation of performance in real environments in a controlled environment, and thus insight gained into the usability of the system in real terms. Through modelling these components into a controlled system, the research was able to learn about performance and feasibility in the multi-source energy management system.

3.2. Performance Analysis

The performance analysis investigates the combination of renewable energy sources, including PV generators and FC, to render NEVs more energy-efficient and environmentally sustainable. The combination of the energy sources improves the quality of energy production while reducing the reliance on non-renewable energy sources. Through the application of OACA, the energy flow is maximized and efficiently distributed within the system. This optimization leads to system performance and global energy efficiency being dramatically improved. Such results show the prospect for enhanced environmental sustainability and efficiency in NEV operation. **Figure 3** illustrates the graphical representation of the energy provided by the PV and FC.

At slower speeds, the energy output of the hybrid system from the FC and PV components is sufficient to recharge the battery while also driving the engine of the vehicle at the same time. The total energy generation of both sources provides a consistent and stable power output, even during less stressful conditions. The PV system supplies solar radiation energy, while the FC supplies ancillary power as hydrogen to provide maximum overall efficiency. Such cooperation between the two sources of energy reduces the need for the battery, thus making the vehicle more environmentally friendly. As a result, the hybrid system ensures significant improvement in energy efficiency and operating sustainability, particularly under low-speed driving conditions. The performance measures are described through **Table 2**.

Table 2 showcases the system's potential to maximize energy output, efficiency, sustainability, and cost-effectiveness for NEVs. By combining PV, FC, and batteries with OACA, it maximizes power management and minimizes the use of conventional energy sources. This analysis confirms its potential to enhance NEV energy management. **Figure 4** illustrates the comparison of system efficiency and energy consumption for different energy configurations such as PV, FC, and battery.

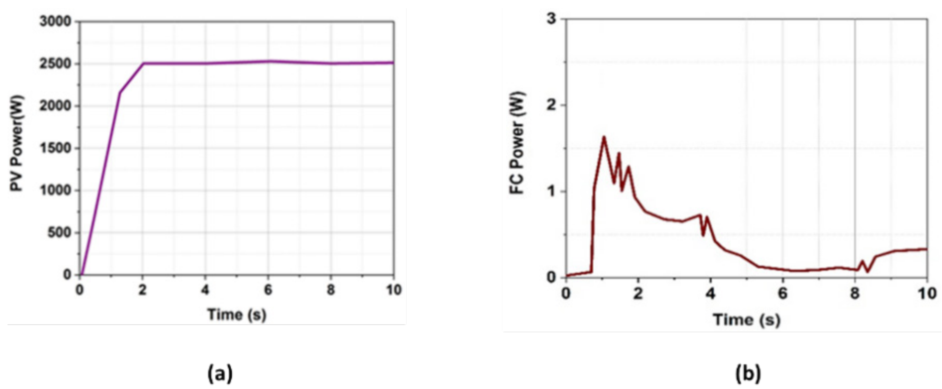

Figure 3. Energy Provided by **(a)** Photovoltaic (PV) and **(b)** Fuel Cells (FCs).

Table 2. Description of the Performance Metrics.

Metrics	Explanation
Energy Output	The combination of three energy sources (PV, FC, and battery) maximizes energy distribution for a stable and continuous power supply of NEVs, regardless of fluctuating operating conditions. The MDPT converter adaptively controls energy adaptation in real time, reducing energy losses and increasing output efficiency.
Efficacy	The suggested OACA-based power management system allocates energy across various sources to maximize the overall NEV efficiency. Through active power flow adjustment relative to demand and availability, the system reduces wastage of energy and optimizes real-time utilization of energy.
Sustainable Energy Consumption	The system focuses on the use of renewable energy, greatly decreasing fossil fuel dependency. Through the use of FC and PV generators, NEVs attain greater sustainability, with lower carbon emissions and a contribution to an environmentally friendly transportation system.
Cost-Effectiveness	By enhancing energy efficiency and less dependence on traditional fuel sources, the system decreases operational costs and enhances NEV affordability. Integration of optimal energy management techniques extends battery lifespan and minimizes maintenance costs, boosting long-term economic feasibility.

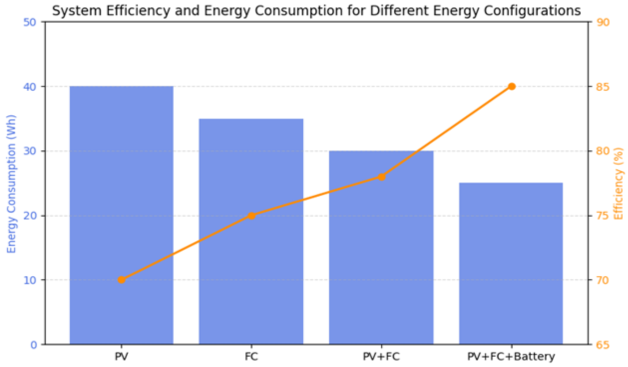

Figure 4. System Efficiency and Energy Consumption Comparison.

The graph shows how the various configurations of energy influence energy consumption and efficiency in the NEV system. The addition of PV and FC increases efficiency along with lower energy consumption as against single-source setups. Addition of a battery (PV+FC+Battery) continues energy flow enhancement further, stabilizing and ensuring it is sustainable. These findings support the efficiency of multiple-energy-source management towards enhancing the NEV's overall performance. The SOC of the battery over time compares the energy management with and without MDPT in NEVs (**Figure 5**).

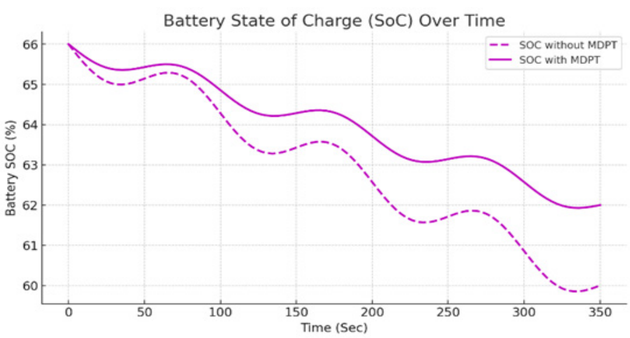

Figure 5. Battery State of Charge (SOC) Over Time.

Optimization of energy management in NEVs aims at maximizing battery efficiency and sustainability through MDPT. Without MDPT, the SoC decreases at a faster rate, which represents poor energy use. The maximized MDPT method maximizes energy flow while minimizing losses and battery unsustainability. These outcomes reflect the competence of smart energy management in producing stable and efficient power supply in NEVs. **Figure 6** shows the power output variations of PV and FC sources in NEVs with and without MDPT for optimized energy sources.

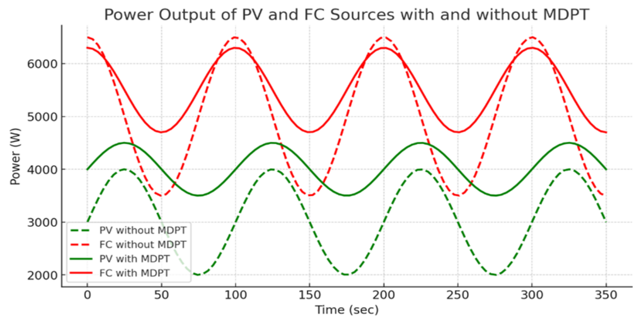

Figure 6. Power Output of PV and FC Sources with and Without MDPT.

The conventional system shows large power delivery fluctuations, impacting overall efficiency. Without MDPT, the power fluctuation is larger, resulting in inefficient energy distribution. With MDPT, the power output becomes smoother, improving energy use and system performance. This proves the efficiency of MDPT in power management optimization for sustainable operation of NEVs. The enhanced power stability renders to improved energy efficiency and lower reliance on additional storage systems.

Table 3 highlights the functioning of the proposed multi-recharger system, combined with Fuel Cells (FC) and Photovoltaic Cells (PV) as power sources.

The optimization process leads to the highest possible rate of energy output from FC as well as PV through improved efficiency of the whole system. This leads to significant improvement in the efficiency of energy and economic viability, making the system more practical for real-world applications. Therefore, the optimized system shows a growth in operating efficiency and cost-effectiveness of NEVs. The optimization method has the highest feasible energy yield rate of both FC and PV with an improvement in overall efficiency of the system. This results in a dramatic improvement in energy efficiency and economic feasibility, making the system more appropriate for real-world applications. The optimized system therefore reflects an improvement in efficiency of operations and the cost-effectiveness of NEVs.

Table 3. Energy Generation of the Proposed Method.

Metrics	Fuel Cell (FC)	Photovoltaic Cell (PV)	PV+FC	After Optimization
Energy Output	Minimal	Average	Average	Maximized
Efficacy	Minimal	Average	Average	Maximized
Sustainable Energy Consumption	Minimal	Average	Average	Maximized
Cost-Effectiveness	Average	Maximized	Maximized	Maximized

3.3. Comparison Phase

The proposed model OACA is compared with the existing methods like Hybrid Optimization of Multiple Energy Resources (HOMER) and Hybrid Recharging System [19,20]. The comparison focuses on the battery power and the integration of the different sources. **Table 4** and **Figure 7** demonstrates the comparison of battery power and energy sources across different models [19,20].

Table 4. Battery Power Comparison of Proposed and Existing Models.

Model	Battery Power (W)	Number of Sources
Hybrid Recharging System [19]	4900	3
HOMER [20]	3200	2
OACA [Proposed]	**5300**	**3**

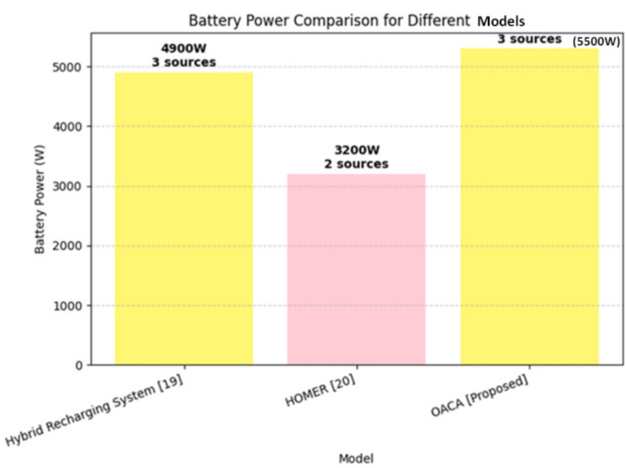

Figure 7. Comparison of Battery Power for Different Models.

HOMER has two power sources, such as PV and FC, and balances energy distribution to be cost-efficient. The three-source (PV, FC and, battery) hybrid recharging system increases charging and availability of energy. The proposed OACA has three energy sources as well but yields a greater battery power output. OACA enhances the overall usage of energy and stability of the system by allocating power dynamically in real-time. In contrast to conventional methods, it provides an adaptive and effective energy flow according to demand and availability. This illustrates the better performance of OACA in achieving maximum energy efficiency for sustainable and cost-efficient NEV operations.

4. Discussion

The goal of the research is to develop the efficiency and environmental sustainability of New Energy Vehicles (NEVs) through the integration of PV generators, FC, and batteries into a multi-source power system. The prevalent energy management technologies of NEVs are restricted particularly the energy output capacity ability, the system performance capability, and the ability to accommodate the sustainable sources of energy in proper terms. Existing systems tend to limit in efficient transmission of energy across numerous energy sources, confining total energy efficiency and elevating dependence on non-renewable resources. Such limitations are addressed using a novel model for managing energy via the OACA when adjusting the dynamic flow of energy. The optimization technique increases energy output, enhances the efficiency of renewable energy resources, and encourages more efficient and cost-saving NEV operations. The performance of the proposed system is assessed based on key parameters such as energy output, efficacy, sustainable energy consumption, and cost-effectiveness. The outcomes demonstrate that the novel model notably promotes NEV efficiency and environmental sustainability through prominent improvement in energy output and economic viability. The battery performance of the proposed system is validated through a comparison with the existing methods. Existing systems such as HOMER and the hybrid recharging system are confronted with dynamic power allocation and maximum energy utilization inefficiencies. The suggested OACA addresses these by providing real-time power distribution, optimal energy efficiency, and improved stability for NEVs. The innovation of energy management not only increases running efficiency in NEVs but is also dedicated to the general target of environmental preservation and more infiltration of renewable power into transport sectors. The system reduces carbon emissions considerably by combining PV and FC as main energy sources, reducing the use of fossil fuels. In comparison to traditional NEV charging systems, which rely on grid electricity from non-renewable energy sources, the system reduces greenhouse gas emissions. The application of FC also increases sustainability since it only produces water as a byproduct, without any harmful pollutants. Also, the optimized energy distribution plan minimizes wastage of energy, hence ensuring a better and environmentally friendly transportation system. Lifecycle analysis of PV and FC parts, factoring in the emissions during manufacturing and disposal, would give the total carbon footprint of the system.

5. Conclusion

The main objective of the research was to design an optimal energy management system that ensured maximum energy flow, enhanced performance, and reduced consumption of non-renewable resources. The OACA was used to optimize the energy management process, ensuring seamless integration between the energy sources and providing maximum output of energy, environmental efficiency, and cost-effectiveness. The research introduces an NEV system that has the potential to enhance performance, as well as environmental sustainability, by incorporating renewable energy sources, such as PV generators, FC, and batteries, into a multi-source power system. The results showed a significant enhancement in all critical performance indicators with the energy output and effectiveness operating at their best levels, while sustainable consumption of energy was appreciably enhanced after optimization. The cost-effectiveness of the system also increased, and its possibilities for large-scale use in today's transportation infrastructure were made possible. Despite these advances, however, the provided system does not deal with real-world environmental variations, such as varying weather conditions, nor does it mitigate the disadvantages of high-density deployment, which pose significant roadblocks to practical application. Research identifies challenges in scalability, as actual deployment in extensive NEV networks needs further confirmation. Environmental aspects such as solar variability and fluctuations in fuel cell efficiency can affect stability. Multiple energy sources need coordination with sophisticated mechanisms to avoid imbalances. Real-time processing of data requires fine-tuning for better accuracy and responsiveness. Future research could include the incorporation of ML techniques to enable the system to learn more about diverse environmental conditions and demand patterns. Research in the future might focus on integrating regenerative braking and wind power to make the system more sustainable and to maximize energy retrieval. Windmills can support PV and FC to provide power under low solar irradiation levels. Regenerative braking will maximize the utilization of energy by capturing kinetic energy at the time of slowing down. Algorithm improvements for real-time optimization will increase the ability of the system to cope with changing levels of energy supply. A roadmap must target large-scale deployment, adaptive energy prediction, and greater grid interaction for broader use.

Author Contributions

Conceptualization, N.N. and A.S.; methodology, A.S.; software, K.P.; validation, A.S., K.P. and K.B.N.; formal analysis, A.S.; investigation, K.B.N.; resources, B.N.; data curation, K.P.; writing—original draft preparation, A.S.; writing—review and editing, N.N.; visualization, K.B.N.; supervision, N.N.; project administration, B.N.; funding acquisition, N.N. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement

Not applicable. The study did not involve human participants or animals and thus did not require ethical review and approval.

Informed Consent Statement

Not applicable.

Data Availability Statement

All data supporting the findings of this study are included in the article.

Conflicts of Interest

The authors declare no conflict of interest.

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