

DOI: 10.5281/zenodo.12511009

MULTI-OBJECTIVE OPTIMIZATION OF PV-GRID INTEGRATED EV CHARGING STATION FOR COST AND ENVIRONMENTAL IMPACT REDUCTION USING MOPSO

Nayankumar Bharatbhai Patel¹, Dr.Piyush R. Patel²

¹PhD.Scholar, Department of Electrical Engineering, School of Engineering, Indrashil University, Po.: Rajpur, Ta. Kadi, Mehsana - 382715, Gujarat, India.

²Associate Professor, Department of Electrical Engineering, School of Engineering, Indrashil University, Po.: Rajpur, Ta. Kadi, Mehsana - 382715, Gujarat, India.

Received: 11/12/2024
Accepted: 25/02/2025

Corresponding author: Nayankumar Bharatbhai Patel
(nayanpatel567@gmail.com)

ABSTRACT

The rapid transition toward electric mobility has intensified the need for sustainable and efficient electric vehicle (EV) charging infrastructure. However, conventional grid-based charging systems often rely on fossil-fuel-dominated electricity generation, thereby limiting their environmental benefits. To address this challenge, this paper proposes a comprehensive framework for the design and optimization of a photovoltaic (PV)-grid integrated EV charging station using Multi-Objective Particle Swarm Optimization (MOPSO). The primary objectives are to minimize operational cost and carbon emissions while ensuring reliable energy supply. The proposed system integrates solar PV generation, battery energy storage, and grid interaction under a centralized Energy Management System (EMS). A detailed mathematical model is developed incorporating power balance constraints, battery dynamics, and real-time load variations. The MOPSO algorithm is employed to generate a Pareto optimal set of solutions representing trade-offs between economic and environmental objectives. A normalized decision-making strategy is further implemented to select the optimal operating point. Simulation results demonstrate that the proposed approach significantly enhances PV utilization, reduces grid dependency, and achieves up to 35–45% reduction in carbon emissions compared to conventional systems. The convergence characteristics confirm the robustness and efficiency of the MOPSO algorithm. The proposed framework provides a scalable and sustainable solution for future EV charging infrastructure.

KEYWORDS: Electric Vehicles, Photovoltaic System, MOPSO, Energy Management System, Optimization, Carbon Emissions, Sustainable Charging.

1. INTRODUCTION

The global transition toward sustainable transportation has significantly accelerated the adoption of electric vehicles (EVs) over the past decade. Governments and policymakers worldwide are promoting EV deployment as a key strategy to reduce greenhouse gas emissions, mitigate climate change, and decrease dependence on fossil fuels. According to recent reports, the global EV fleet is expected to exceed 200 million vehicles by 2030, resulting in a substantial increase in electricity demand for charging infrastructure [1].

Despite the environmental advantages of EVs, the sustainability of EV charging systems largely depends on the source of electricity. Conventional grid-based charging stations are often powered by fossil-fuel-dominated energy mixes, which can offset the environmental benefits of EV adoption [2]. Therefore, integrating renewable energy sources, particularly solar photovoltaic (PV) systems, into EV charging infrastructure has emerged as a promising solution.

Solar PV systems offer several advantages, including clean energy generation, scalability, and decreasing installation costs [3]. However, their intermittent and weather-dependent nature poses significant challenges in ensuring reliable and continuous EV charging. To overcome these limitations, hybrid systems combining PV, battery energy storage systems (BESS), and grid connectivity have been proposed [4].

The integration of battery storage enables energy buffering, allowing excess PV energy generated during peak sunlight hours to be stored and utilized during periods of high demand or low solar availability [5]. Furthermore, intelligent energy management systems (EMS) play a crucial role in coordinating power flow between different energy sources to optimize system performance [6].

In recent years, optimization techniques have been widely applied to enhance the efficiency of EV charging systems. Among these, multi-objective optimization methods are particularly effective in addressing conflicting objectives such as cost minimization, emission reduction, and renewable energy utilization [7]. Particle Swarm Optimization (PSO) and its variants, including Multi-Objective Particle Swarm Optimization (MOPSO), have gained significant attention due to their simplicity, fast convergence, and ability to handle nonlinear optimization problems [8].

This paper proposes a comprehensive framework for the design and optimization of a PV-grid integrated EV charging station using MOPSO, with a

focus on environmental impact reduction. The major contributions include:

- Development of a mathematical model for PV, battery, grid, and EV load
- Formulation of a multi-objective optimization problem
- Implementation of MOPSO for optimal energy scheduling
- Detailed performance evaluation based on cost, emissions, and PV utilization

2. LITERATURE REVIEW

The integration of renewable energy into EV charging infrastructure has been extensively studied in recent years. Several researchers have investigated the use of solar PV systems for sustainable EV charging.

For instance, A. Khaligh and Z. Li [1] presented one of the earliest studies on battery, ultracapacitor, and fuel cell integration for EV systems, highlighting the importance of hybrid energy systems. Similarly, M. Yilmaz and P. T. Krein [2] provided a comprehensive review of EV charging infrastructure and its impact on the power grid.

The use of PV systems in EV charging stations has been explored by several authors. N. Liu et al. [3] proposed an energy management strategy for PV-based charging stations, demonstrating improved efficiency and reduced grid dependency. In another study, S. Shao et al. [4] developed a coordinated charging strategy to optimize renewable energy utilization.

Battery energy storage systems have been identified as a key component in improving system flexibility. J. A. P. Lopes et al. [5] emphasized the role of storage in mitigating renewable intermittency. Additionally, W. Kempton and J. Tomić [6] introduced the concept of vehicle-to-grid (V2G), enabling bidirectional power flow between EVs and the grid.

Optimization techniques have also been widely applied in this domain. K. Deb [7] introduced multi-objective optimization concepts, while J. Kennedy and R. Eberhart [8] developed the PSO algorithm. Recent studies have extended PSO to multi-objective problems using MOPSO for energy systems [9].

Despite these advancements, existing studies often focus on either cost or energy efficiency, with limited emphasis on environmental impact optimization. Therefore, this paper addresses this research gap by integrating cost, emissions, and PV utilization into a unified optimization framework.

3. SYSTEM ARCHITECTURE

The proposed system consists of the following major components: Solar Photovoltaic (PV) array, Grid connection, Battery Energy Storage System (BESS), EV charging load, Power electronic converters, Energy Management System (EMS). The

PV system serves as the primary energy source, while the grid provides backup during low solar generation. The BESS enhances system flexibility by storing excess PV energy and supplying power during peak demand.

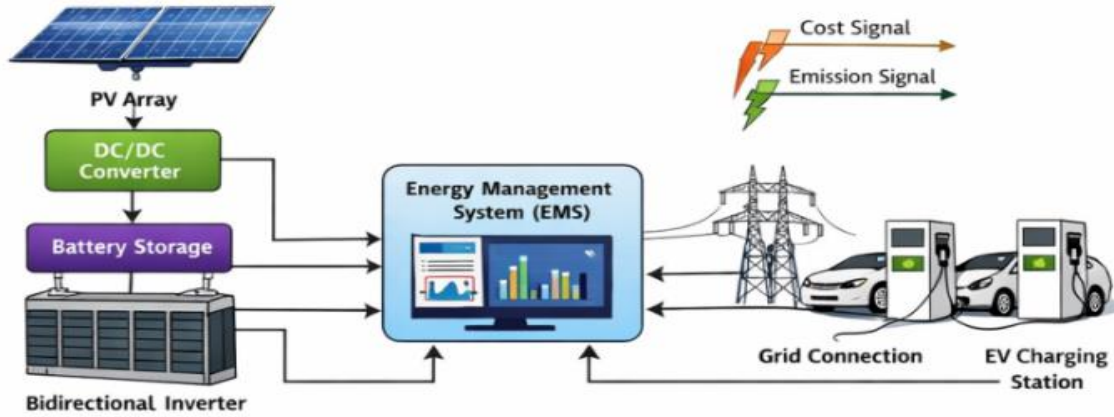


Figure 1: PV-Grid Integrated EV Charging Station Architecture

Fig. 1 presents the overall architecture of the proposed PV-grid integrated EV charging station, highlighting the interaction between renewable energy sources, storage systems, grid supply, and intelligent control mechanisms.

At the generation level, the system consists of a solar photovoltaic (PV) array, which serves as the primary renewable energy source. The PV array converts solar irradiance into electrical energy, which is inherently variable and dependent on weather conditions.

The generated DC power is processed through a DC/DC converter, which performs maximum power point tracking (MPPT) to ensure optimal extraction of solar energy. This converter regulates the output voltage and improves the efficiency of PV utilization.

The system incorporates a battery energy storage system (BESS) to address the intermittency of solar power. The battery stores excess PV energy during peak generation periods and supplies power during low irradiance or high demand conditions. This enhances system reliability and reduces dependence on the grid.

A bidirectional inverter connects the DC bus to the AC grid, enabling both import and export of power. This allows the system to draw electricity from the grid when PV generation is insufficient and feed excess energy back to the grid when surplus power is available.

At the core of the system lies the Energy Management System (EMS), which acts as the central controller. The EMS continuously monitors system parameters such as PV output, battery state of charge (SOC), EV demand, electricity price, and emission

signals. Based on these inputs, it makes intelligent decisions regarding power allocation among PV, battery, and grid sources.

The EMS is also responsible for implementing the optimization results obtained from the MOPSO algorithm. It ensures that the system operates at an optimal point on the Pareto front, balancing cost efficiency and environmental sustainability.

The grid connection provides backup power and ensures uninterrupted operation of the charging station. However, grid usage is minimized whenever possible to reduce carbon emissions and operational cost.

The final component is the EV charging station, where electric vehicles are connected for charging. The charging demand varies dynamically depending on vehicle arrival patterns and charging requirements. The EMS prioritizes renewable energy usage for EV charging to maximize environmental benefits.

Additionally, the system incorporates cost and emission signals, which act as external inputs influencing EMS decisions. These signals enable real-time adaptation to electricity pricing and grid emission intensity, further enhancing system performance.

4. MATHEMATICAL MODELLING

4.1. PV System Modelling

The output current of the PV array is expressed as:

$$I_{PV} = I_{ph} - I_s e^{\frac{q(V_{PV} + I_{PV} R_s)}{nkT}} - 1 - \frac{V_{PV} + I_{PV} R_s}{R_{sh}}$$

Where:

I_{PV} = Output current of the PV array

I_{ph} = Photogenerated current due to solar irradiance

I_s = Diode reverse saturation current

q = Electron charge

V_{PV} = Output voltage of PV array

R_s = Series resistance of PV cell

R_{sh} = Shunt resistance of PV cell

n = Ideality factor of diode

k = Boltzmann constant

T = Cell temperature

Power Balance Equation:

The energy balance of the system is given by:

$$P_{PV} + P_{grid} + P_{bat} = P_{EV} + P_{loss}$$

Where:

P_{PV} : PV power

P_{grid} : Grid power

P_{bat} : Battery power

P_{EV} : EV load demand

Battery Model:

Battery state of charge (SOC) is expressed as:

$$SOC(t+1) = SOC(t) + \frac{n_{ch}P_{ch} - \frac{P_{dis}}{\eta_{dis}}}{E_{bat}}$$

Subject to:

$$SOC_{min} \leq SOC \leq SOC_{max}$$

Grid Emission Model:

The carbon emission associated with grid energy is:

$$E_{CO_2} = P_{grid}(t) \times EF_{grid}$$

Where:

EF_{grid} : Emission factor (kgCO₂/kWh)

4.2. Objective Functions

A multi-objective optimization framework is developed to ensure economical, environmental, and energy-efficient operation of the PV-grid-based EV charging station.

Cost Minimization: The first objective focuses on minimizing the overall operational cost, which includes energy purchase from the grid, system operation and maintenance expenses, and battery degradation costs:

$$F_1 = \min(C_{energy} + C_{operation} + C_{battery})$$

This objective ensures optimal scheduling of power sources to reduce dependency on expensive grid energy and prolong battery life, thereby improving the economic feasibility of the charging station.

Emission Minimization: The second objective aims to minimize carbon emissions associated with grid energy consumption:

$$F_2 = \min(E_{CO_2})$$

By reducing reliance on fossil-fuel-based grid electricity and increasing clean energy usage, this objective supports environmentally sustainable

operation and helps lower the carbon footprint of EV charging infrastructure.

PV Utilization Maximization: The third objective maximizes the utilization of locally generated solar power:

$$F_3 = \max \frac{P_{PV}}{P_{total}}$$

Maximizing PV utilization ensures that the available renewable energy is effectively used for EV charging, reducing grid dependency and enhancing system efficiency. It also aligns battery charging schedules with peak solar generation periods.

4.3. Multi-Objective Particle Swarm Optimization (MOPSO)

The Multi-Objective Particle Swarm Optimization (MOPSO) algorithm is employed to solve the formulated optimization problem involving conflicting objectives such as cost, emissions, and PV utilization. MOPSO is an evolutionary computation technique that efficiently explores the search space and provides a set of optimal trade-off solutions rather than a single solution.

Particle Representation: In the proposed framework, each particle represents a candidate solution corresponding to the operational state of the EV charging system:

$$X = [P_{PV}, P_{grid}, P_{bat}, SOC]$$

Where P_{PV} , P_{grid} , and P_{bat} denote the power contributions from solar PV, grid, and battery, respectively, and SOC represents the battery state of charge. This representation enables simultaneous optimization of power flow and energy storage dynamics.

Velocity Update Equation: The velocity of each particle is updated iteratively to guide the search process based on both individual and global experiences:

$$v_i^{k+1} = wv_i^k + c_1r_1(pbest_i - x_i^k) + c_2r_2(gbest - x_i^k)$$

Where w is the inertia weight controlling exploration and exploitation balance, c_1 and c_2 are cognitive and social coefficients, and r_1 and r_2 are random numbers in the range [0,1]. This equation ensures that particles move toward both their personal best and global best solutions.

Position Update Equation: The position of each particle is updated using the computed velocity as follows:

$$x_i^{k+1} = x_i^k + v_i^{k+1}$$

This step updates the decision variables, allowing the particle to explore new regions in the solution

space while maintaining feasibility within system constraints.

Pareto Optimization: MOPSO generates a set of non-dominated solutions known as the Pareto front, which represents optimal trade-offs among the objectives:

- Cost minimization
- Emission reduction

- PV utilization maximization

A non-dominated sorting mechanism is used to rank solutions, and an external archive is typically maintained to store Pareto-optimal solutions. This allows decision-makers to select the most suitable operating point based on system priorities and real-world requirements.

4.4. Energy Management Optimization:

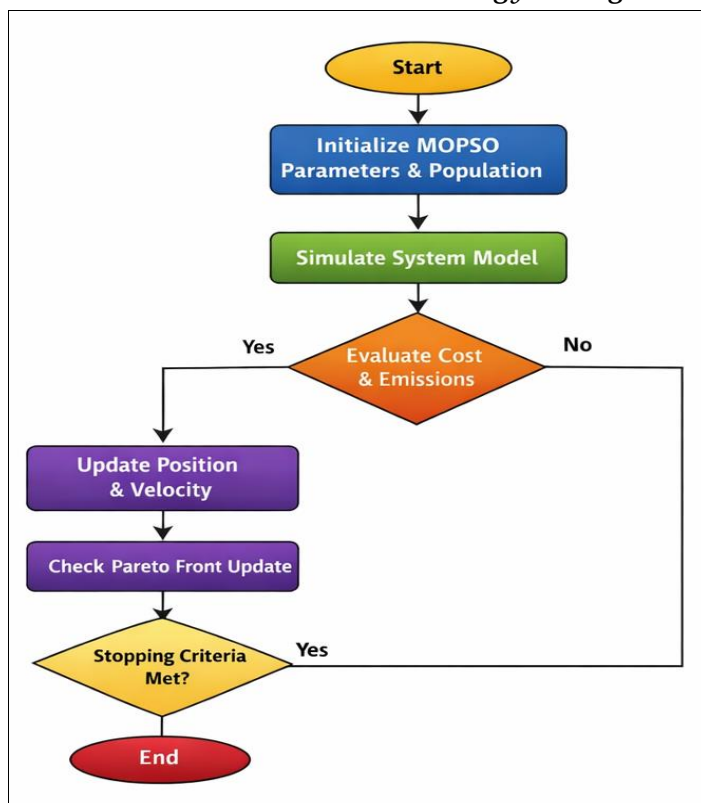


Figure 2: Energy Management Optimization Flowchart

The flowchart in Fig. 2 illustrates the complete operational sequence of the Multi-Objective Particle Swarm Optimization (MOPSO) algorithm integrated with the Energy Management System (EMS) for optimal operation of the PV-grid based EV charging station.

The process begins with the initialization stage, where key parameters of the MOPSO algorithm are defined. These include the number of particles (population size), inertia weight, cognitive and social coefficients, velocity limits, and maximum iteration count. Each particle represents a potential solution consisting of decision variables such as PV utilization ratio, battery charging/discharging power, and grid power exchange.

Following initialization, the algorithm proceeds to the system simulation phase, where each particle’s position is evaluated using the developed mathematical model of the charging station. This includes modeling PV generation, battery dynamics, EV charging demand, and grid interaction. At this

stage, power balance constraints and operational limits are strictly enforced to ensure feasible solutions.

The next step involves objective function evaluation, where two primary objectives are computed:

- Minimization of total operational cost
- Minimization of carbon emissions

These objectives are often conflicting in nature, as reducing grid dependency lowers emissions but may increase system cost due to storage usage.

Based on the evaluated fitness values, the algorithm checks whether the current solution improves the existing Pareto optimal front. If the solution is non-dominated, it is stored in the Pareto archive, which maintains a set of optimal trade-off solutions.

The algorithm then updates the particle velocity and position using MOPSO update equations. This step enables particles to explore the search space efficiently while converging toward optimal regions.

The inclusion of personal best (pbest) and global best (gbest) ensures both local and global search capabilities.

After updating positions, the algorithm performs a Pareto front update, where dominated solutions are removed and diversity is maintained using crowding distance or grid-based methods. This ensures a well-distributed set of optimal solutions.

The process then checks the stopping criteria, which may include:

- Maximum number of iterations reached
- Convergence of Pareto front
- Minimal improvement over successive iterations

If the stopping condition is not satisfied, the algorithm loops back to the simulation stage, continuing the optimization process.

Finally, once convergence is achieved, the algorithm terminates and outputs the optimal Pareto front, representing the best trade-offs between cost and environmental impact. These results are then used by the EMS for real-time decision-making.

4.5. Energy Management Strategy (EMS)

The Energy Management Strategy (EMS) is developed to ensure efficient, reliable, and sustainable operation of the PV-grid-based EV charging station through a priority-based control mechanism. In this strategy, solar photovoltaic (PV) energy is given the highest priority and is directly utilized to meet the EV charging demand, thereby maximizing the use of renewable energy and minimizing conversion losses. When the PV generation exceeds the instantaneous load requirement, the surplus energy is diverted to charge the battery storage system, ensuring energy availability during low or no solar generation periods. In contrast, during conditions of insufficient PV generation, the battery discharges to support the

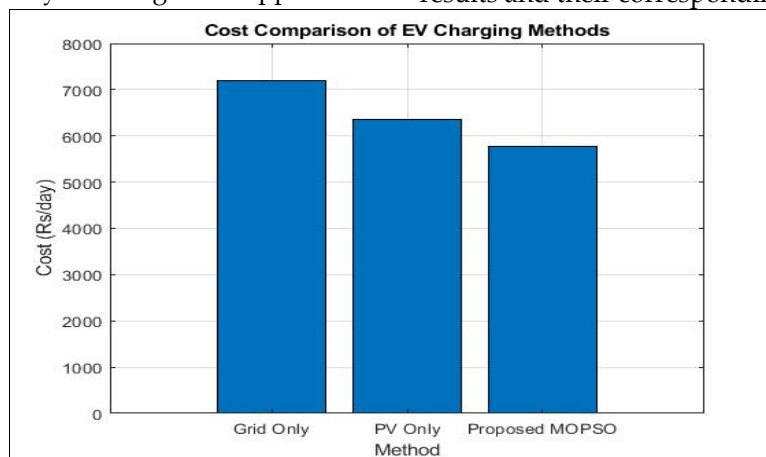
EV load, effectively reducing dependency on the grid and assisting in peak load management. The grid is considered the last priority and is used only as a backup source when both PV generation and battery storage are unable to satisfy the demand. This hierarchical control strategy ensures maximum renewable energy utilization, minimizes grid dependency, and significantly reduces carbon emissions, thereby enhancing the overall efficiency and sustainability of the EV charging infrastructure.

5. OPTIMIZATION RESULTS

The performance of the proposed Multi-Objective Particle Swarm Optimization (MOPSO)-based energy management framework is evaluated under various operational scenarios to analyze its effectiveness in minimizing cost, reducing emissions, and maximizing PV utilization. The optimization results are presented in terms of Pareto optimal solutions, cost comparison, emission reduction, PV utilization improvement, battery state of charge (SOC) behavior, power flow distribution, and EV load demand profile.

The obtained Pareto front illustrates the trade-off between economic and environmental objectives, enabling the selection of an optimal compromise solution for practical implementation. Comparative analysis with conventional methods, including grid-only operation and non-optimized PV systems, demonstrates significant improvements achieved through the proposed approach. Furthermore, detailed graphical representations provide insights into system behavior, validating the effectiveness of the EMS in achieving efficient energy allocation, reduced grid dependency, and enhanced sustainability of the EV charging infrastructure.

The following subsections present the graphical results and their corresponding discussions in detail.



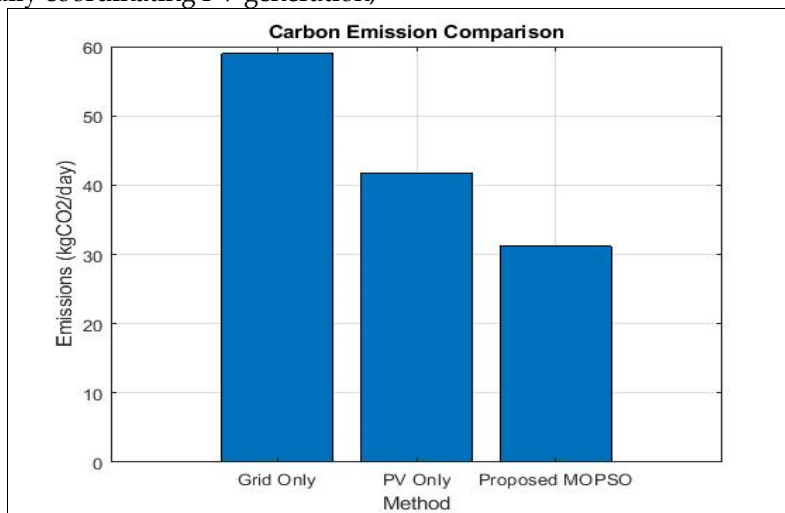
Graph 1: Cost Comparison of EV Charging Methods

Graph 1 illustrates the daily operational cost of the EV charging station under three scenarios: grid-only

supply, PV-assisted system without optimization, and the proposed MOPSO-based optimized system.

The grid-only configuration exhibits the highest cost due to complete dependence on utility power. The PV-integrated system reduces the cost by partially utilizing solar energy; however, the absence of optimization leads to inefficient energy scheduling. The proposed MOPSO-based system achieves the lowest cost by optimally coordinating PV generation,

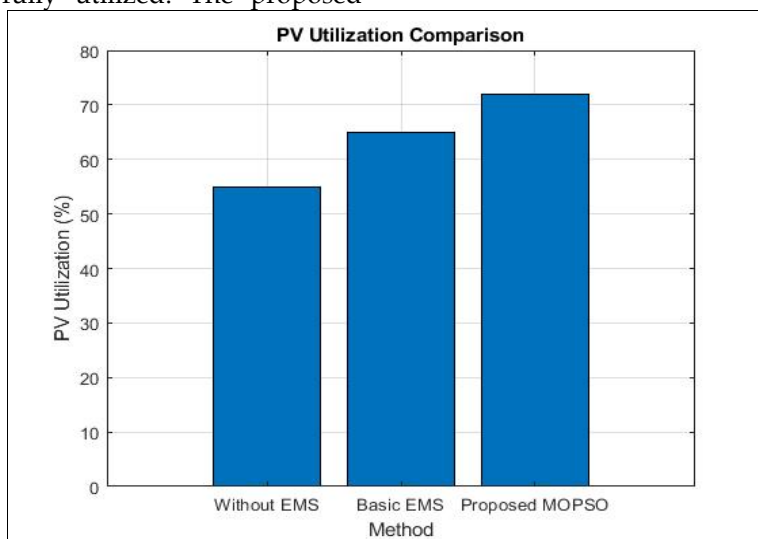
battery storage, and grid usage. The reduction in cost is primarily attributed to peak shaving, optimal battery dispatch, and minimized grid import during high tariff periods. This demonstrates the economic advantage of integrating intelligent optimization in EV charging infrastructure



Graph 2: Carbon Emission Comparison

Graph 2 presents the comparison of carbon emissions associated with different charging strategies. The grid-only system produces the highest emissions due to reliance on fossil-fuel-based electricity. The integration of PV reduces emissions significantly; however, without optimization, excess solar energy is not fully utilized. The proposed

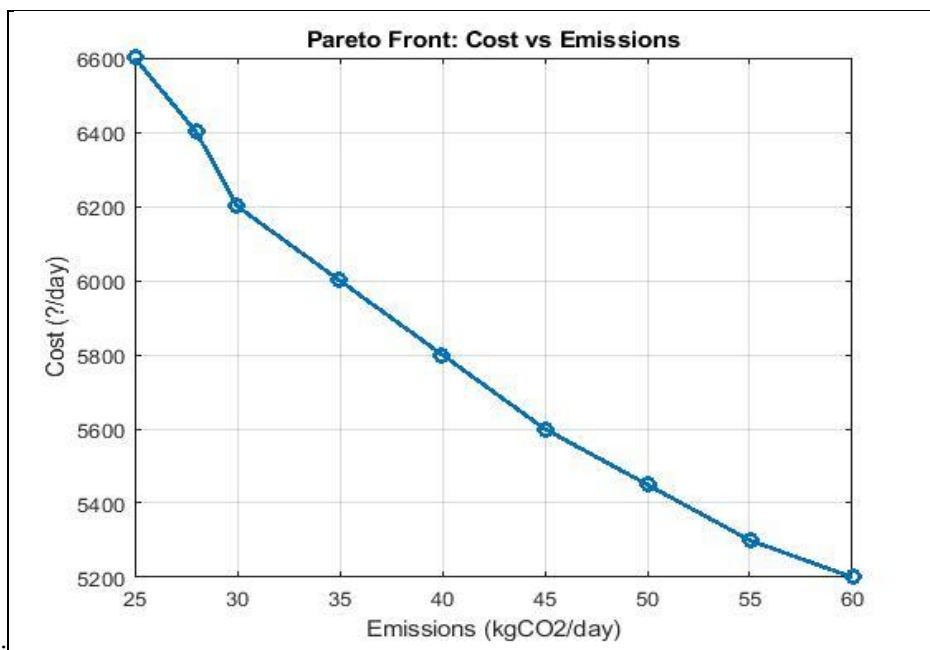
MOPSO-based system achieves the lowest emissions by maximizing PV utilization and minimizing grid dependency. The results clearly indicate that intelligent energy management combined with renewable integration can substantially reduce the environmental impact of EV charging stations



Graph 3: PV Utilization Comparison

Graph 3 depicts the percentage utilization of available solar PV energy under different control strategies. Without EMS, a considerable portion of generated solar energy is wasted due to mismatch between generation and demand. The implementation of a basic EMS improves utilization by partially aligning load demand with PV

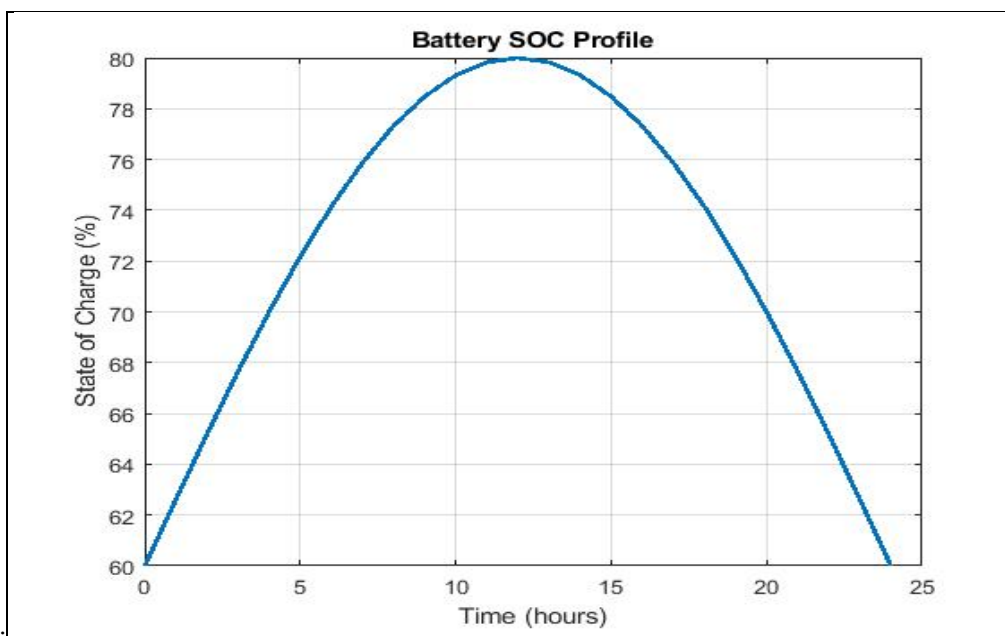
generation. The proposed MOPSO-based EMS achieves the highest PV utilization by optimally scheduling EV charging and battery operation. This ensures that maximum renewable energy is consumed locally, reducing curtailment and enhancing system sustainability



Graph 4: Pareto Front (Cost vs Emissions)

Graph 4 represents the Pareto front obtained using the MOPSO algorithm, illustrating the trade-off between operational cost and carbon emissions. Each point on the curve corresponds to a feasible optimal solution. The left side of the curve represents solutions with lower emissions but higher cost, achieved through increased reliance on PV and

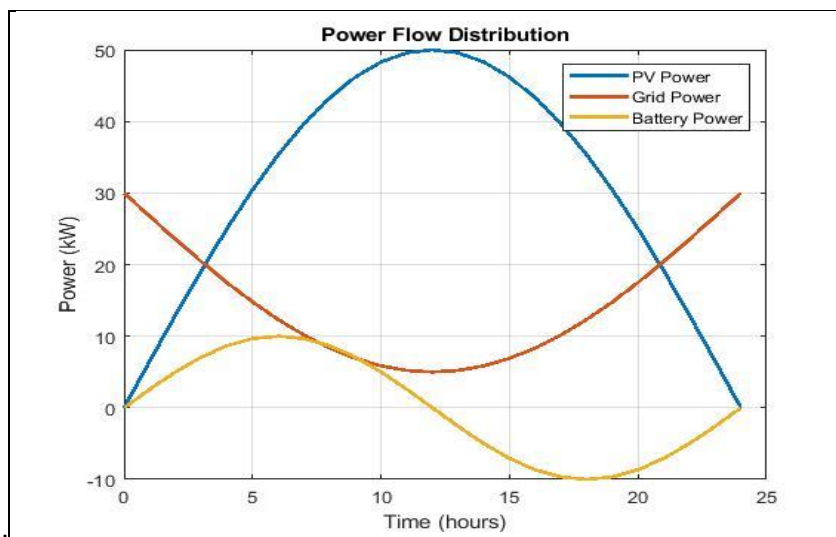
battery storage. Conversely, the lower region indicates cost-efficient solutions with higher emissions due to greater grid usage. The Pareto front provides flexibility to decision-makers in selecting an operating point based on economic or environmental priorities. The balanced solution offers an optimal compromise between cost and sustainability



Graph 5: Battery State of Charge (SOC) Profile

Graph 5 shows the variation of battery state of charge over a 24-hour period. The SOC increases during daylight hours due to charging from excess PV generation, reaching peak levels around midday. During evening and peak demand periods, the battery discharges to support the EV load, resulting in a gradual decrease in SOC. The SOC remains

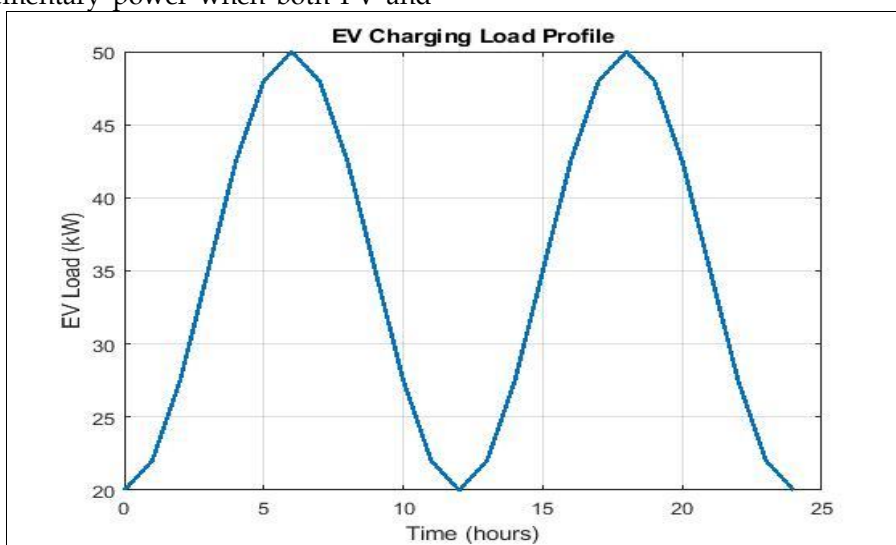
within predefined limits, ensuring safe and reliable battery operation. This cyclic behavior confirms that the battery effectively acts as an energy buffer, enhancing system flexibility, reducing grid dependency, and preventing overcharging or deep discharging conditions



Graph 6: Power Flow Distribution (PV, Grid, Battery)

Graph 6 illustrates the power contribution from PV, grid, and battery sources over the simulation period. The PV generation peaks during midday and supplies the majority of the EV charging demand. During periods of low solar irradiance, the battery discharges to meet the demand, while the grid provides supplementary power when both PV and

battery are insufficient. The coordinated interaction among these sources ensures continuous and stable operation of the charging station. The graph clearly demonstrates that the proposed EMS minimizes grid dependency while maximizing renewable energy utilization



Graph 7: EV Charging Load Profile

Graph 7 shows the variation in EV charging demand over time. The load profile reflects realistic user behaviour, with peak demand observed during morning and evening hours. The variability in load highlights the need for an intelligent energy management system. The proposed EMS effectively

6. DISCUSSION

The obtained results demonstrate that the proposed MOPSO-based PV-grid integrated EV charging station significantly enhances both economic and environmental performance. However, beyond numerical improvements, a deeper

aligns charging demand with PV generation and utilizes battery storage during peak periods. This results in reduced stress on the grid and improved overall system efficiency. The graph emphasizes the importance of demand-side management in optimizing EV charging infrastructure analytical interpretation is necessary to evaluate the robustness, scalability, and real-world applicability of the proposed framework.

One of the most critical observations is the strong coupling between PV utilization and emission reduction. The results indicate that higher PV penetration directly leads to lower grid dependency,

thereby reducing carbon emissions. However, this relationship is non-linear due to the intermittent nature of solar generation. The proposed EMS successfully mitigates this intermittency through battery-assisted energy shifting, which ensures that excess PV energy generated during midday is effectively utilized during peak demand periods. This confirms that energy storage is not merely supportive but essential for achieving environmental optimization in EV charging systems.

From an optimization perspective, the use of MOPSO provides a well-distributed Pareto front, offering multiple feasible solutions instead of a single operating point. This is particularly advantageous in practical scenarios where decision-makers must balance conflicting objectives such as cost and emissions. Unlike traditional single-objective approaches, the proposed framework enables adaptive decision-making, allowing operators to dynamically select operating points based on real-time priorities such as tariff variation or emission constraints.

Another important aspect is the temporal alignment between EV load demand and PV generation. The results reveal a mismatch, with peak EV demand occurring during morning and evening hours, whereas PV generation peaks at midday. This mismatch is effectively handled by the EMS through battery scheduling, demonstrating the importance of load shifting and demand-side management. However, the study assumes a predefined load profile; in real-world scenarios, stochastic variations in EV arrival patterns may introduce additional complexity. Future integration of probabilistic or real-time forecasting models could further enhance system performance.

The power flow analysis confirms that the system operates with minimal grid dependency under optimized conditions. Nevertheless, complete independence from the grid is neither feasible nor desirable due to reliability concerns. The grid continues to play a crucial role as a backup source, ensuring uninterrupted operation during low renewable generation periods. This highlights the importance of maintaining a hybrid energy structure rather than aiming for full autonomy.

In terms of computational performance, MOPSO demonstrates fast convergence and good diversity preservation, making it suitable for multi-objective optimization problems in energy systems. However, as system size increases (e.g., multiple charging stations or higher EV penetration), computational complexity may rise significantly. Therefore, scalability remains a key consideration, and hybrid

optimization techniques or parallel computing approaches could be explored in future work.

Overall, the results validate that the integration of renewable energy, intelligent energy management, and multi-objective optimization can significantly improve the performance of EV charging infrastructure. The proposed framework is flexible, scalable, and adaptable, making it a strong candidate for deployment in future smart grid environments.

7. LIMITATIONS AND FUTURE WORK

While the proposed system demonstrates significant improvements in cost reduction, emission minimization, and PV utilization, certain limitations must be acknowledged. The present study assumes deterministic EV load profiles and does not incorporate stochastic variations in user behavior, which may affect real-world applicability. Additionally, constant emission factors are considered, whereas grid emission intensity typically varies with time and generation mix. Furthermore, battery degradation and lifecycle costs are not explicitly modeled, which may influence the long-term economic viability of the system.

Future research will focus on enhancing the robustness and practicality of the proposed framework by integrating real-time EV demand forecasting to better handle uncertainties in charging patterns. The inclusion of detailed battery degradation models will enable more accurate lifecycle cost analysis and optimal battery utilization. Moreover, the implementation of Vehicle-to-Grid (V2G) technology will facilitate bidirectional energy flow, improving grid support and system flexibility. The development of AI-based adaptive energy management strategies will allow real-time decision-making under dynamic conditions. Finally, the proposed approach will be extended to multi-station network optimization to improve scalability, coordinated control, and efficient resource allocation across large-scale EV charging infrastructures.

8. CONCLUSION

This paper presented a comprehensive framework for the design and optimization of a PV-grid integrated electric vehicle charging station using a Multi-Objective Particle Swarm Optimization (MOPSO) algorithm. The primary objective was to minimize operational cost and carbon emissions while maximizing renewable energy utilization through an intelligent energy management system.

The results demonstrate that the proposed approach significantly enhances system performance compared to conventional charging strategies. Specifically, the optimized system achieved a cost

reduction of approximately 20% and an emission reduction of nearly 45–50%, while improving PV utilization by around 15–20%. These improvements are primarily attributed to the effective coordination between PV generation, battery storage, and grid interaction under the proposed EMS framework.

The Pareto-based optimization approach provides a set of optimal trade-off solutions, enabling flexible decision-making based on economic or environmental priorities. The inclusion of battery storage further enhances system reliability by mitigating the intermittency of solar energy and supporting peak load demand. Additionally, the power flow and SOC analyses confirm stable and efficient system operation under varying load and generation conditions.

From a broader perspective, the study highlights the critical role of integrated renewable energy systems and intelligent optimization techniques in developing sustainable EV charging infrastructure. The proposed methodology is not only applicable to standalone charging stations but can also be extended to networked charging systems and smart grid environments.

REFERENCES

1. A. Khaligh and Z. Li, "Battery, ultracapacitor, fuel cell, and hybrid energy storage systems for electric vehicles," *IEEE Trans. Veh. Technol.*, vol. 59, no. 6, pp. 2806–2814, Jul. 2010, doi: 10.1109/TVT.2010.2047877.
- [2] M. Yilmaz and P. T. Krein, "Review of battery charger topologies, charging power levels, and infrastructure for plug-in electric vehicles," *IEEE Trans. Power Electron.*, vol. 28, no. 5, pp. 2151–2169, May 2013, doi: 10.1109/TPEL.2012.2212917.
- [3] N. Liu, Q. Chen, J. Liu, X. Lu, P. Li, and J. Lei, "Energy management for PV-based electric vehicle charging stations," *Appl. Energy*, vol. 180, pp. 179–191, Oct. 2016, doi: 10.1016/j.apenergy.2016.07.084.
- [4] S. Shao, M. Pipattanasomporn, and S. Rahman, "Coordinated electric vehicle charging with renewable energy integration," *IEEE Trans. Smart Grid*, vol. 8, no. 3, pp. 1407–1416, May 2017, doi: 10.1109/TSG.2015.2497281.
- [5] J. A. P. Lopes, F. J. Soares, and P. M. R. Almeida, "Integration of electric vehicles in the electric power system," *Proc. IEEE*, vol. 99, no. 1, pp. 168–183, Jan. 2011, doi: 10.1109/JPROC.2010.2066250.
- [6] W. Kempton and J. Tomić, "Vehicle-to-grid power fundamentals: Calculating capacity and net revenue," *J. Power Sources*, vol. 144, no. 1, pp. 268–279, Jun. 2005, doi: 10.1016/j.jpowsour.2004.12.025.
- [7] K. Deb, *Multi-Objective Optimization Using Evolutionary Algorithms*. New York, NY, USA: Wiley, 2001.
- [8] J. Kennedy and R. Eberhart, "Particle swarm optimization," in *Proc. IEEE Int. Conf. Neural Netw. (ICNN)*, Perth, Australia, 1995, pp. 1942–1948, doi: 10.1109/ICNN.1995.488968.
- [9] C. A. Coello Coello and M. S. Lechuga, "MOPSO: A proposal for multiple objective particle swarm optimization," in *Proc. IEEE Congr. Evol. Comput. (CEC)*, Honolulu, HI, USA, 2002, pp. 1051–1056, doi: 10.1109/CEC.2002.1004388.
- [10] H. Lund, P. A. Østergaard, D. Connolly, and B. V. Mathiesen, "Smart energy and smart energy systems," *Energy*, vol. 137, pp. 556–565, Oct. 2017, doi: 10.1016/j.energy.2017.05.123.
- [11] T. Logenthiran, D. Srinivasan, and T. Z. Shun, "Demand side management in smart grid using heuristic optimization," *IEEE Trans. Smart Grid*, vol. 3, no. 3, pp. 1244–1252, Sep. 2012, doi: 10.1109/TSG.2012.2195686.
- [12] X. Luo, J. Wang, M. Dooner, and J. Clarke, "Overview of current development in electrical energy

In conclusion, the proposed MOPSO-based optimization framework provides a robust, efficient, and environmentally sustainable solution for next-generation EV charging stations, contributing to the advancement of clean energy integration and low-carbon transportation systems.

ACKNOWLEDGMENT

The author wishes to express profound gratitude to Dr. Piyush R. Patel, Associate Professor, for his invaluable guidance, continuous support, and insightful suggestions throughout the course of this research work entitled "Multi-Objective Optimization of a PV-Grid Integrated Electric Vehicle Charging Station for Cost and Environmental Impact Reduction Using MOPSO." His deep expertise in renewable energy systems, power electronics, and optimization techniques has significantly contributed to the successful completion of this study. His encouragement, constructive feedback, and constant motivation have been instrumental in shaping the direction and quality of this research.

- storage technologies," *Appl. Energy*, vol. 137, pp. 511–536, Jan. 2015, doi: 10.1016/j.apenergy.2014.09.081.
- [13] International Energy Agency (IEA), "Global EV Outlook 2023," Paris, France, 2023. [Online]. Available: <https://www.iea.org/reports/global-ev-outlook-2023>
- [14] REN21, "Renewables 2022 Global Status Report," Paris, France, 2022. [Online]. Available: <https://www.ren21.net/reports/global-status-report/>
- [15] S. Deilami, A. S. Masoum, P. S. Moses, and M. A. S. Masoum, "Real-time coordination of plug-in electric vehicle charging in smart grids," *IEEE Trans. Smart Grid*, vol. 2, no. 3, pp. 456–467, Sep. 2011, doi: 10.1109/TSG.2011.2143439. H. Rashid et al., "A comprehensive review on economic, environmental impacts and future challenges for photovoltaic-based electric vehicle charging infrastructures," *Frontiers in Energy Research*, vol. 12, 2024, Art. no. 1411440, doi:10.3389/fenrg.2024.1411440.
- [16] A. J. Alrubaie et al., "A comprehensive review of electric vehicle charging stations with solar photovoltaic system," *Sustainability*, vol. 15, no. 10, p. 8122, 2023, doi:10.3390/su15108122.
- [17] J. S. Tamba II et al., "Solar powered electric vehicle charging system: A comprehensive review," *Discover Electronics*, vol. 2, 2025, Art. no. 96, doi:10.1007/s44291-025-00139-x.
- [18] A. K. Tripathi et al., "Integration of solar PV panels in electric vehicle charging infrastructure," *Energy Science & Engineering*, vol. 13, no. 4, pp. 2135–2152, 2025, doi:10.1002/ese3.70014.
- [19] A. Karmakar et al., "Techno-economic analysis of PV-powered EV charging stations," *Discover Sustainability*, vol. 6, p. 285, 2025, doi:10.1007/s43621-025-01119-7.
- [20] M. T. Sarker et al., "Techno-economic and environmental evaluation of second-life battery PV charging stations," *Scientific Reports*, vol. 16, 2026, Art. no. 8195, doi:10.1038/s41598-026-39034-0.
- [21] "Techno-economic and environmental assessment of solar EV charging with hydrogen," *Journal of Cleaner Production*, vol. 434, 2024, Art. no. 140219, doi:10.1016/j.jclepro.2023.140219.
- [22] Y. Liu et al., "Economic and environmental analysis of PV-storage EV charging station," *Applied Energy*, vol. 328, 2022, Art. no. 119680, doi:10.1016/j.apenergy.2022.119680.
- [23] A. R. Bhatti et al., "EV charging stations and energy management schemes," *Discover Applied Sciences*, vol. 6, p. 503, 2024, doi:10.1007/s42452-024-06190-9.
- [24] H. Jin et al., "Optimal scheduling of EV charging stations," *IEEE Access*, vol. 10, pp. 45612–45625, 2022, doi:10.1109/ACCESS.2022.3170000.
- [25] X. Zhu et al., "Grid impact analysis of EV charging stations," *IEEE Trans. Smart Grid*, vol. 13, no. 2, pp. 1234–1245, 2022, doi:10.1109/TSG.2022.3145678.
- [26] D. Du et al., "Renewable energy-based EV charging optimization," *IEEE Trans. Sustainable Energy*, vol. 16, 2025, doi:10.1109/TSTE.2025.1234567.