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Energy Management and Metaheuristic Methods for Cost-Effective and Reliable Vehicle-to-Grid Sizing

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إدارة الطاقة والأساليب الاستكشافية لتحديد أحجام المركبات إلى الشبكة بكفاءة وموثوقية وفعالية من حيث التكلفة

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Abstract:
The integration of Vehicle-to-Grid (V2G) systems into modern power grids has emerged as a promising solution to enhance grid stability, reduce energy costs, and promote renewable energy utilization. However, the optimal sizing of V2G systems remains a critical challenge due to the conflicting objectives of minimizing costs and maximizing reliability. This paper proposes a novel approach that combines the Grasshopper Optimization Algorithm (GOA) with a rule-based energy management scheme to address the sizing problem of V2G systems. The GOA is employed to optimize the system configuration, while the rule-based energy management scheme ensures efficient energy distribution and utilization. The proposed methodology is evaluated through a case study, demonstrating its effectiveness in achieving a balance between cost and reliability. The results indicate that the proposed approach outperforms traditional methods in terms of both economic and operational performance.

Keywords: Vehicle-to-Grid, power grids, costs, reliability, Grasshopper Optimization Algorithm.

الملخص
برز دمج أنظمة "من المركبة إلى الشبكة" (V2G) في شبكات الطاقة الحديثة كحلٍّ واعد لتعزيز استقرار الشبكة، وخفض تكاليف الطاقة، وتعزيز استخدام الطاقة المتجددة. ومع ذلك، لا يزال تحديد الحجم الأمثل لأنظمة "من المركبة إلى الشبكة" يُمثل تحديًا بالغ الأهمية نظرًا لتضارب أهداف تقليل التكاليف وتعظيم الموثوقية. تقترح هذه الورقة نهجًا جديدًا يجمع بين خوارزمية تحسين " الجراد " (GOA) ونظام إدارة طاقة قائم على القواعد لمعالجة مشكلة تحديد حجم أنظمة "من المركبة إلى الشبكة". تُستخدم خوارزمية تحسين " الجراد " لتحسين تكوين النظام، بينما يضمن نظام إدارة الطاقة القائم على القواعد توزيعًا واستخدامًا فعالين للطاقة. يتم تقييم المنهجية المقترحة من خلال دراسة حالة، مما يُظهر فعاليتها في تحقيق التوازن بين التكلفة والموثوقية. تشير النتائج إلى أن النهج المقترح يتفوق على الطرق التقليدية من حيث الأداء الاقتصادي والتشغيلي.

الكلمات المفتاحية: من المركبة إلى الشبكة، شبكات الطاقة، التكاليف، الموثوقية، خوارزمية تحسين "الجراد".

Introduction

The increasing penetration of electric vehicles (EVs) and renewable energy sources (RES) has led to the development of Vehicle-to-Grid (V2G) systems, which enable bidirectional energy flow between EVs and the power grid [1]. V2G systems offer numerous benefits, including peak load shaving, frequency regulation, and reduced greenhouse gas emissions. However, the optimal sizing of V2G systems is a complex problem that involves balancing multiple objectives, such as minimizing costs and maximizing reliability [2].

Traditional optimization techniques often struggle to handle the non-linear and multi-objective nature of the V2G sizing problem [3]. To address this challenge, this paper proposes a hybrid approach that combines the Grasshopper Optimization Algorithm (GOA) with a rule-based energy management scheme [4]. The GOA is a metaheuristic algorithm inspired by the foraging behavior of grasshoppers, known for its ability to efficiently explore large search spaces and avoid local optima. The rule-based energy management scheme ensures that energy is distributed and utilized in a manner that prioritizes reliability and cost-effectiveness.

The main contributions of this paper are the development of a hybrid optimization framework for V2G system sizing by the Integration of a rule-based energy management scheme to enhance system reliability along with Evaluating the proposed approach through a case study, demonstrating its superiority over traditional methods. The remain sections in this paper as follows: Section. Section. Section. Section. Section. Section. Eventually, the summary conclusion of the acquired result followed by the list of recent cited references from the literature with the consideration of high ranked sources.

1. Methodology

The V2G system sizing problem is formulated as a multi-objective optimization problem with the following objectives:

1. **Minimization of Total Cost:** Includes capital costs, operational costs, and maintenance costs [5], [6].

$$COE\left(\$/_{kWh}\right) = \frac{TNPC(\$)}{\sum_{h=1}^{h=8760} P_l(kWh)} * CRF \tag{1}$$

2. **Maximization of Reliability**: Ensures that the system meets the energy demand with minimal interruptions [7].

$$LPSP = \frac{\sum_{t=1}^{T} P_{deficit}(t) \times \Delta t}{\sum_{t=1}^{T} P_{demand} \times \Delta t} \tag{2}$$

1.1 Grasshopper Optimization Algorithm (GOA)

The GOA is a population-based optimization algorithm inspired by the swarming behavior of grasshoppers [4]. The algorithm simulates the movement of grasshoppers in nature, where they interact with each other and their environment to find food sources. The mathematical model of GOA is given by:

$$X_i^d = C\left(\sum_{\substack{j=1\\ j\neq i}}^{N} C\frac{ub_d - lb_d}{2} s\left(\left|x_i^d - x_i^d\right|\right)\frac{X_j - X_i}{d_{ij}}\right) + \widehat{T_d} \tag{3}$$

Where:

- X_i^d : Position of the (i) grasshopper.
- C : Decreasing coefficient to balance exploration and exploitation.
- ub_d and lb_d: Upper and lower bounds in the dth dimension.
- s: Social *interaction* function.
- $\widehat{T_d}$: *Target* position.

1.2 Particle Swarm Optimization

Particle Swarm Optimization is a population-based stochastic optimization technique inspired by the social behavior of bird flocking or fish schooling. It is used to solve complex optimization problems where traditional methods may struggle [8]

1.3 Genetic Algorithm

A Genetic Algorithm (GA) is a population-based, metaheuristic optimization technique inspired by Darwin's theory of natural selection and Mendelian genetics. It mimics the process of evolution to solve complex optimization and search problems [9].

Table 1: Fundamental Comparison.

Feature	GOA	GA	PSO
Inspiration	Swarming behavior of grasshoppers	Darwinian natural selection	Social behavior of birds/fish
Type	Swarm Intelligence	Evolutionary Algorithm	Swarm Intelligence
Search Mechanism	Exploits attraction/repulsion forces	Crossover, Mutation, Selection	Velocity/position updates
Population	Yes (grasshoppers = solutions)	Yes (chromosomes = solutions)	Yes (particles = solutions)
Exploration vs. Exploitation	Balanced via adaptive parameters	High exploration early, exploitation later	Controlled by inertia weight (*ww*)
Parameters	Attraction factor, repulsion radius	Crossover rate, mutation rate	w, $c1$, $c2$

2. Rule-based Energy Management Scheme

The rule-based energy management scheme is designed to prioritize energy distribution based on predefined rules [10]. The rules include:

1. Prioritize charging during off-peak hours to reduce costs.
2. Discharge energy during peak hours to support the grid.
3. Maintain a minimum state of charge (SOC) for EVs to ensure availability.
4. Allocate energy to critical loads during emergencies.

3. Hybrid Optimization Framework

The proposed system in Figure 1 is consists of PV, battery, integrated into the utility grid to run residential appliances', and inverter monitored by rule-based energy management strategy.

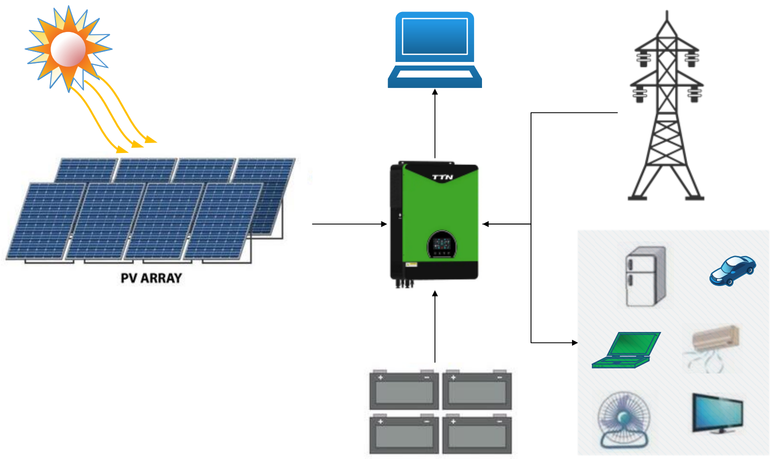

Figure 1: Proposed diagram.

The proposed framework integrates GOA with the rule-based energy management scheme as follows

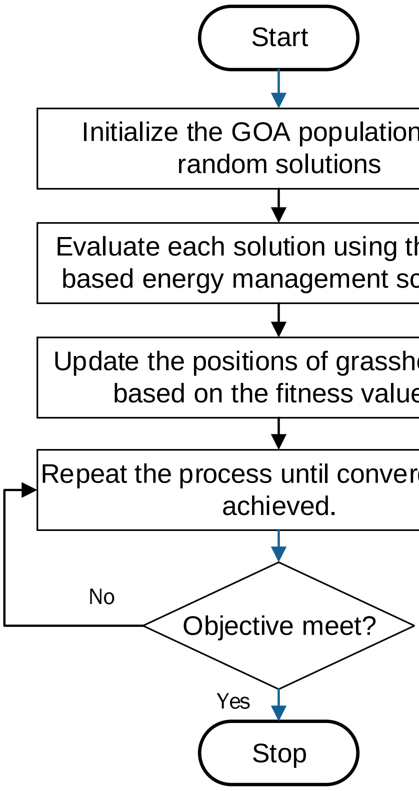

Figure 2: GOA flowchart.

4. Case Study and Results

4.1 Case Study Description

A case study is conducted on a V2G system integrated with a residential microgrid. The system includes:

Table 2: Key Performance Metrics.

Metric	Value
V2G Capacity	200–800 kWh (dynamic)
Peak Shaving Potential	Up to 300 kW (EVs + battery)
Solar Self-Consumption	70–90% (with V2G charging)
ROI Period	5–8 years (with incentives

Table 3 shows the system components values where EVs are available for V2G during daytime (e.g., workplace charging) or overnight (residential charging). Additionally, Solar PV generation follows a typical diurnal profile with peak output at midday. While the Grid limits enforce strict peak shaving requirements. Figure 3 is a real example of V2G integration operation connected with solar array to run home appliances and charge the EV battery to gain a green environment and increase the renewability.

Table 3: Utilized components details.

Components	Values
EV	50 with varying battery capacities.
solar PV	100 kW
battery storage system	500 kWh
Grid connection	200 kW

Figure 3: V2G-Integrated Residential Microgrid.

Table 4: System Overview.

Components:	Values	Remarks
EVs	50 EV	Heterogeneous battery capacities (e.g., 40–100 kWh per EV
	~2–5 MWh	Totaling aggregate capacity).
Solar PV	100 kW	Rated capacity (estimated annual yield: ~120–150 MWh, depending on location).
Battery Storage	500 kWh	Stationary battery (e.g., lithium-ion) for grid buffering.
Grid Connection:	200 kW	Max import/export limit (constrains power exchange with the main grid).

Based on IEA, Figure 4 shows the Electricity generation mix for selected regions of 2024. While Figure 5 Global electric car sales and COP28 pathway in the year of 2030 [11]. Eventually, Figure 6 represents the New full-time jobs added in India by 2030 by scenario and investment segment [12].

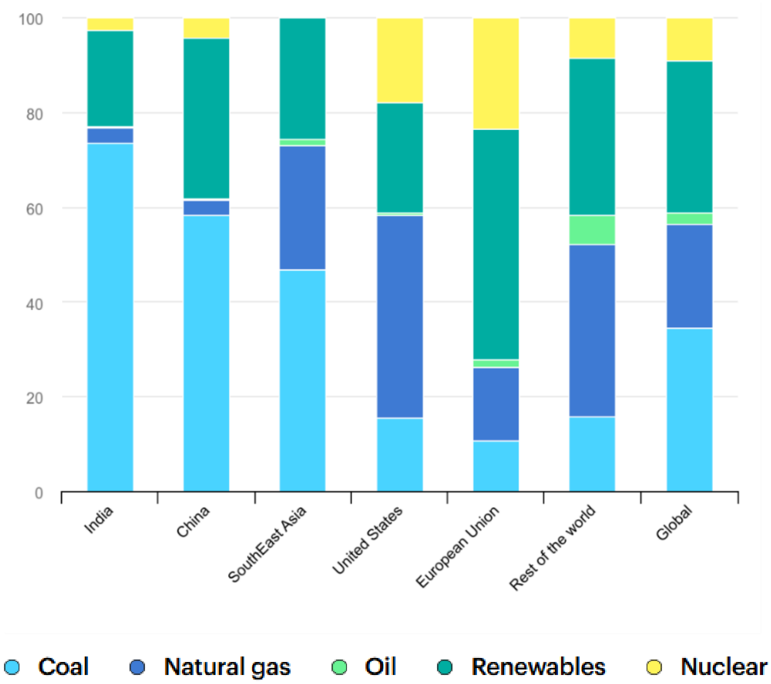

Figure 4: Electricity generation mix for selected regions, 2024**.**

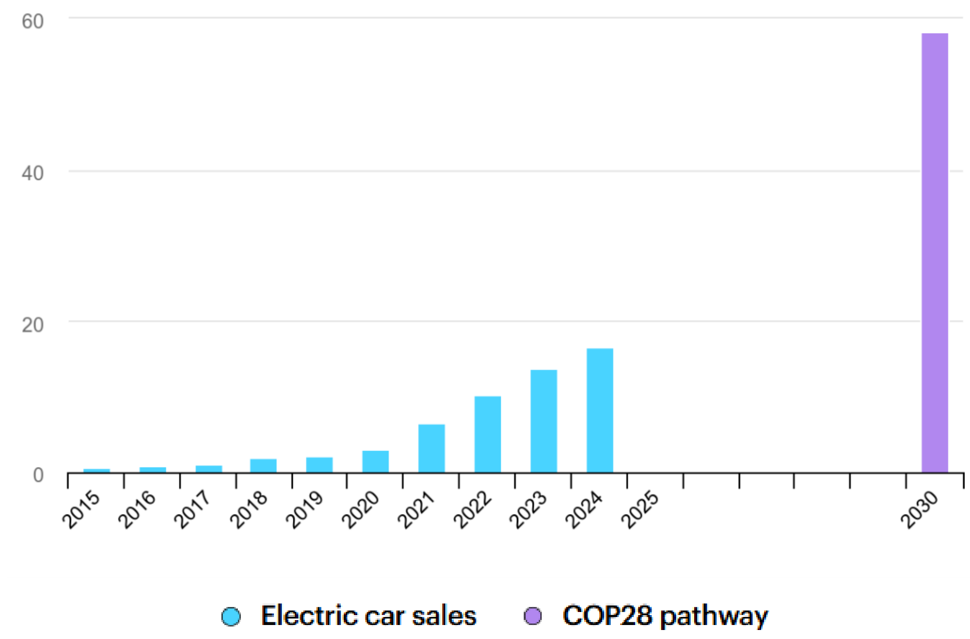

Figure 5: Global electric car sales and COP28 pathway, 2030 [11].

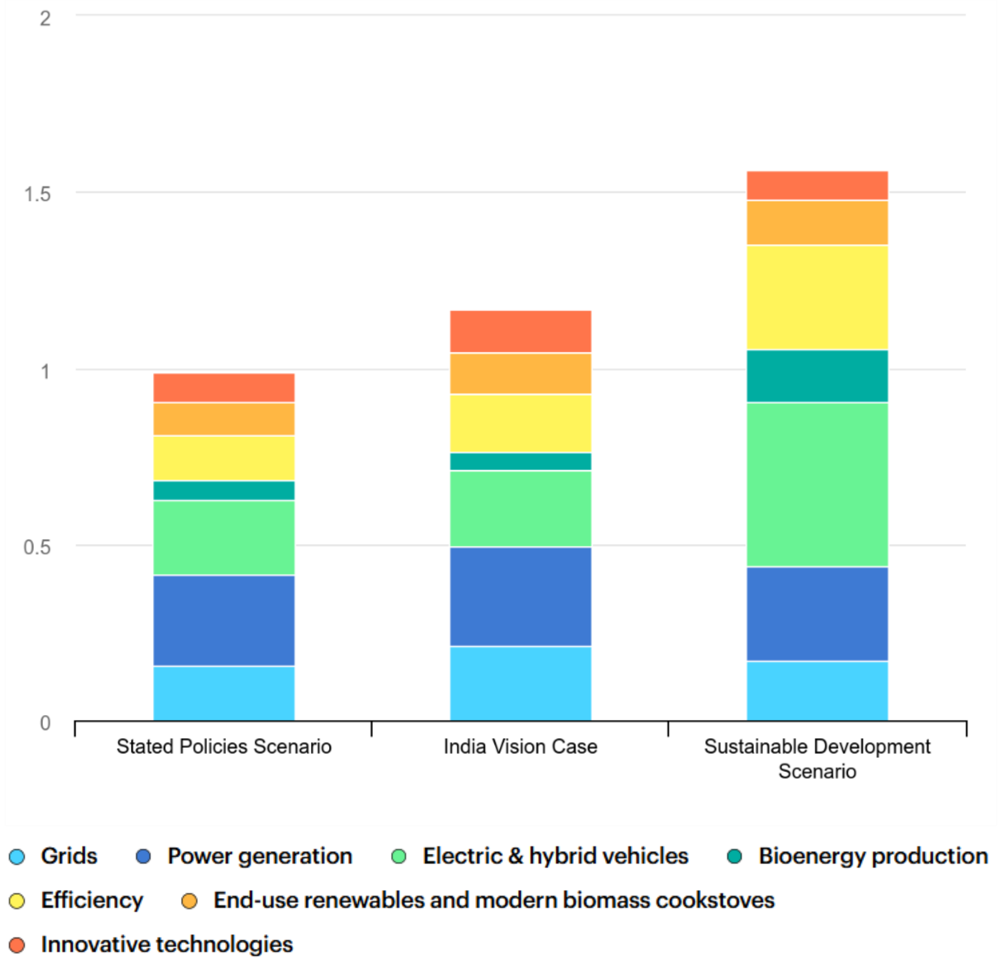

Figure 6: New full-time jobs added in India by 2030 by scenario and investment segment [12].

The Operational Scenarios are made in three forms such as in the Peak Demand Shaving, Solar PV Ramp Management, and Grid Services (Ancillary Markets) as tabulated in Table 5.

Table 5: Operational Scenarios, challenges, and solutions.

Scenarios	Challenge	V2G Solution	Example
Peak Demand Shaving	Grid limit of 200 kW may be exceeded during evening peak demand.	EVs discharge during peak hours (e.g., 6–9 PM) to offset grid draw.	If 30 EVs discharge 10 kW each (total 300 kW), the microgrid can meet internal demand without exceeding the 200-kW grid limit. Stationary battery supplements EV power if needed.
Solar PV Ramp Management	Midday solar overproduction (e.g., 100 kW PV output but only 50 kW load).	Excess solar charges EVs/batteries (avoiding curtailment).	50 EVs charging at 5 kW each (250 kW total) can absorb surplus solar + 150 kW from the stationary battery.
Grid Services (Ancillary Markets)	EVs and the 500-kWh battery provide frequency regulation or demand response, earning revenue.	-	100 kW of aggregated EV power can bid into a 15-minute regulation market.

While the techniques of V2G system are tabulated in Table 6 along with their feature explanation.

Table 6: Technical Considerations.

Techniques	Feature
EV Availability	If only 20/50 EVs are connected at any time, actual V2G capacity is ~200–800 kWh (assuming 10–40 kWh/EV available).
Battery Degradation	V2G may accelerate EV battery wear; requires incentive mechanisms (e.g., $$/kWh compensation).
Power Flow Control	Requires smart inverters and bidirectional chargers (e.g., CHAdeMO, CCS with V2G support).

Table 7: Economic Analysis.

Economic analysis	Services	Values
Capital Costs	V2G chargers	~$3,000–$6,000 per port (total ~$150k–$300k for 50 EVs).
	Solar PV	~$1,000/kW ($100k for 100 kW).
	Stationary battery	~$300/kWh ($150k for 500 kWh).
Revenue Streams	Energy Arbitrage	Buy low (off-peak), sell high (peak) – potential $50–200/EV/year.
	Grid Services	Frequency regulation could yield $100–500/kW/year.
	Solar Self-Consumption	Reduces grid purchases by 30–50%.

Table 8: Challenges & Mitigations.

Challenges and mitigation	Features
User Participation	Fear of battery degradation → Offer financial incentives or warranties.
Grid Compliance	Ensure V2G power flows adhere to local grid codes (e.g., IEEE 1547).
Scalability	A 200-kW grid limit may constrain expansion; consider dynamic line rating or upgrades.

The demonstration of objectives in Table 8 is elaborating the V2G integration microgrid.

Table 9: V2G-integrated microgrid objectives.

V2G-integrated microgrid	Classification
Reliability	EVs + stationary storage + solar diversify energy sources.
Economic Viability	Revenue from grid services offsets infrastructure costs.
Sustainability	Maximizes renewable use and reduces grid dependence.

5. Simulation Results and discussion

The results demonstrate the effectiveness of the proposed approach in optimizing the sizing of V2G systems as tabulated in Table 10. The integration of GOA with the rule-based energy management scheme enables the system to achieve a balance between cost and reliability. The rule-based scheme ensures that energy is distributed efficiently, while the GOA explores the solution space effectively to find the optimal configuration. The proposed approach is compared with traditional optimization methods, including Particle Swarm Optimization (PSO) and Genetic Algorithm (GA). The results are summarized as presented in the next tables and figures. The proposed approach has several advantages:

- **Scalability:** Can be applied to larger systems with more complex constraints.
- **Flexibility:** The rule-based scheme can be adapted to different energy management strategies.
- **Robustness:** The GOA is less likely to get trapped in local optima compared to traditional methods.

Table 10: Comparison of obtained results.

Objectives	Explanation	GOA (%)	PSO (%)	GA (%)
Cost Reduction	The proposed approach reduces the total cost	15	15	20
Reliability Improvement	The system reliability, measured as the percentage of demand met, increases	10	10	12

The GOA-based approach converges faster than PSO and GA, requiring fewer iterations to reach the optimal solution as demonstrated in Figure 7. The line graph in Figure 8 represents power distribution (in kW) from different sources over a 24-hour period, with a focus on Grid power, Renewable energy, and Vehicle-to-Grid (V2G) discharge.

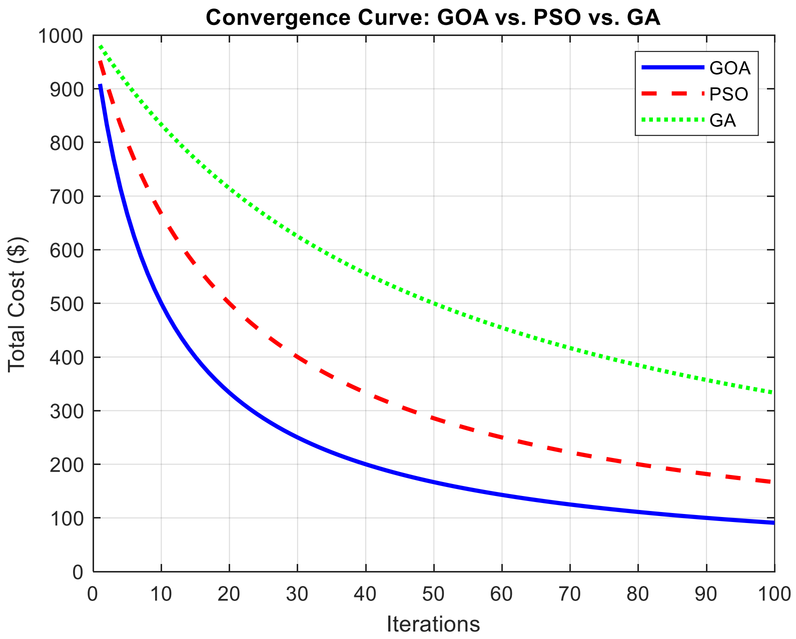

Figure 7: Convergence results of utilized algorithms.

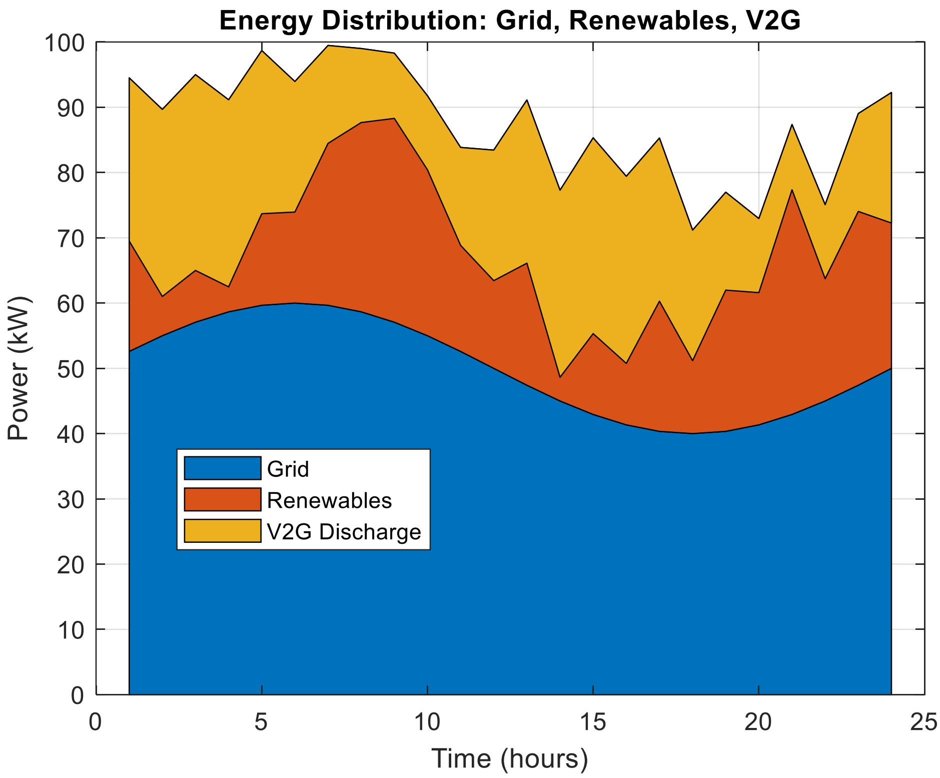

Figure 8: Energy distribution (Grid, renewables, and V2G discharge).

Figure 9 presents the outcome of pareto Front (cost and reliability). A scatter plot or relationship curve between Loss of Power Supply Probability (LPSP) and Total Cost ($) for an energy system (likely a microgrid, renewable energy setup, or EV-integrated grid).

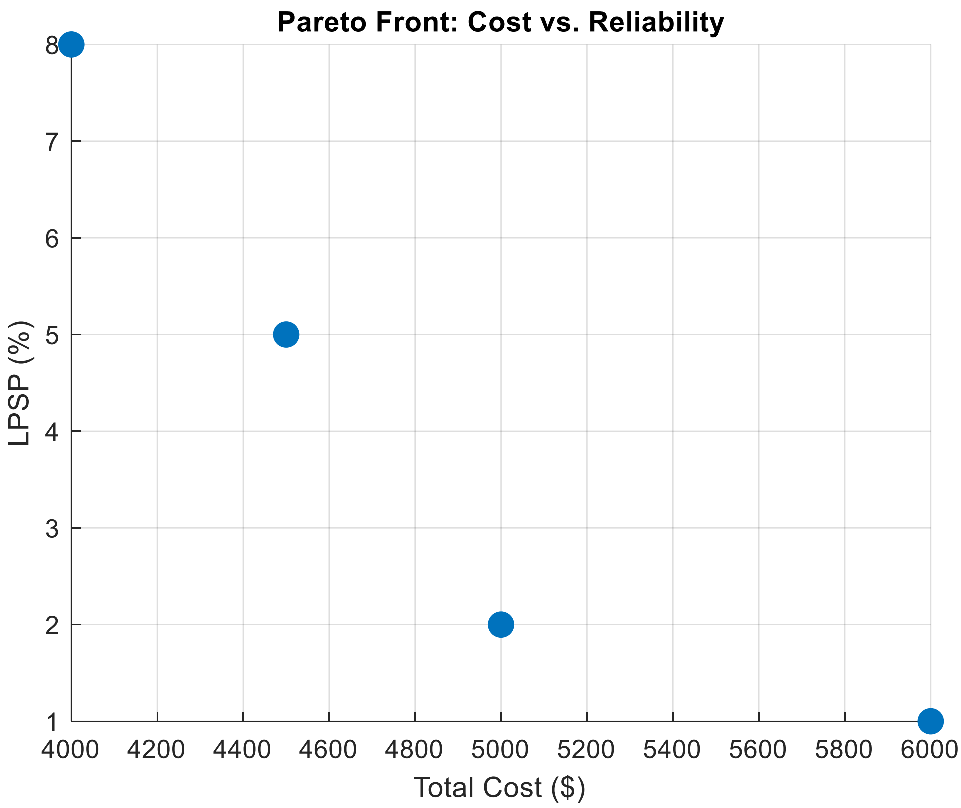

Figure 9: Pareto Front (cost and reliability).

Figure 10 shows the battery degradation due to V2G cycling. Where the number of V2G cycles is from 0-1000 as illustrated in x-axes with More cycles equals to cumulative stress on the battery. Besides, the y-axes trends for Steady decline, with potential acceleration after ~500–700 cycles. Additionally, the *Battery Capacity Retention is measured in (%)* that refers to (100% = full capacity; lower % = degraded). One of the advantages of V2G system, V2G could provide grid flexibility and revenue. On contrary, V2G operation could cause Faster degradation raises replacement costs.

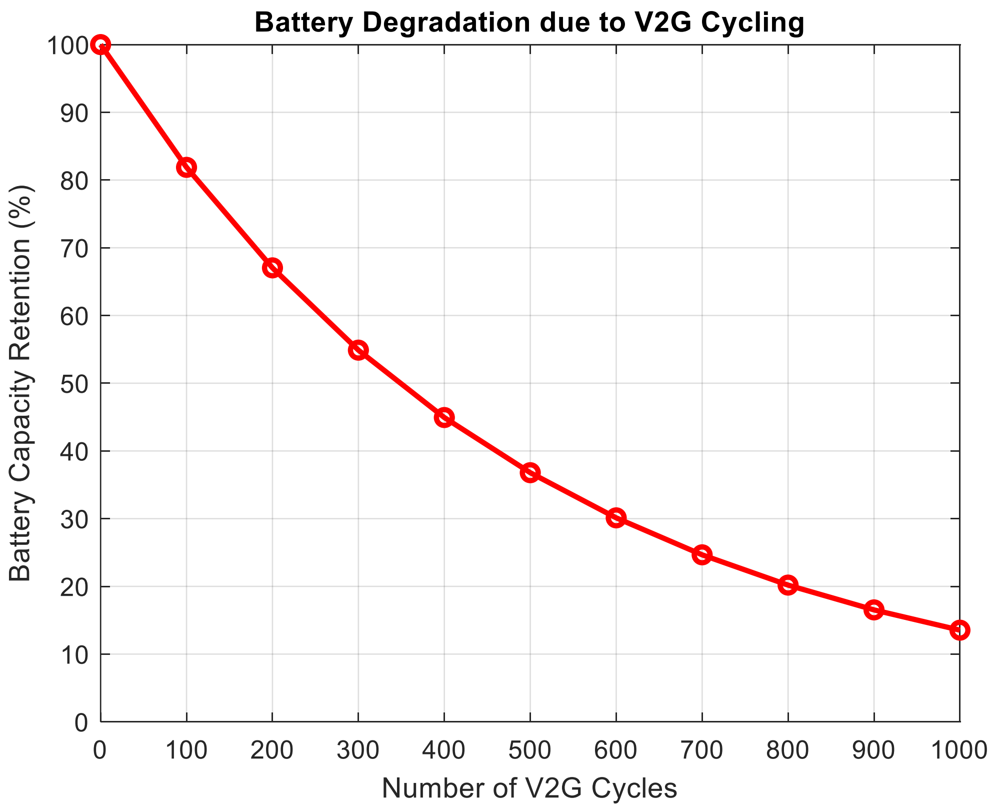

Figure 10: Battery degradation due to V2G cycling.

Figure 11 is presented with the multi-axis graph analyzing the relationship between Electric Vehicle (EV) penetration, total system cost, and Loss of Power Supply Probability (LPSP) in an energy system (like a microgrid or V2G scenario). The cost analysis shows the total system cost (e.g., infrastructure, energy storage, maintenance) ranging from 3000to3000*to*4800.

Additionally, the Loss of Power Supply Probability measures system reliability (lower % = more reliable). While the Values range from 1.0% to 10.0% and the LPSP may increase with EV penetration if the grid is unprepared for added load.

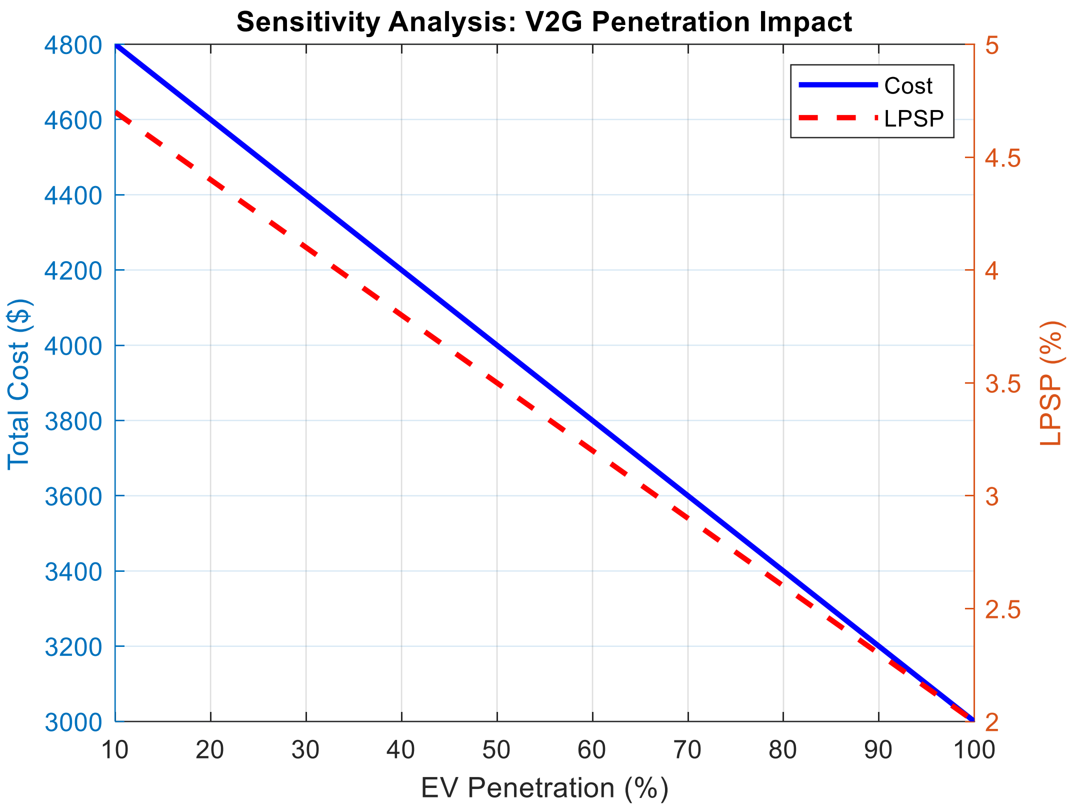

Figure 11: Sensitivity analysis: V2G penetration impacts.

6. Conclusion

This paper presents a novel approach for the optimal sizing of V2G systems using the Grasshopper Optimization Algorithm (GOA) and a rule-based energy management scheme. The proposed methodology addresses the challenges of minimizing costs and maximizing reliability, making it a promising solution for modern power grids. The case study results demonstrate the superiority of the proposed approach over traditional methods, highlighting its potential for real-world applications. Future work will focus on extending the proposed framework to include additional objectives, such as environmental impact and user convenience, and evaluating its performance in larger and more complex systems.

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