

# Smart Solar Garage with PSO-Based Optimization for Energy and Vehicle Performance

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## Abstract

The swift growth of electric mobility, coupled with a rising global focus on sustainable energy, has propelled the advancement of smart garages that incorporate renewable energy, the Internet of Things (IoT), and sophisticated optimization methods. These systems aim to reduce energy waste, boost operational efficiency, and aid in the development of smart, eco-friendly urban infrastructure. This study outlines the design and execution of a Smart Solar Garage that utilizes Particle Swarm Optimization (PSO), solar energy, and Arduino-based automation to achieve intelligent management of energy flow and vehicle performance. The suggested system employs solar panels as its main energy source, complemented by efficient energy storage units to ensure a steady power supply. PSO, a nature-inspired metaheuristic algorithm, is used to optimize the distribution and use of power among charging modules, lighting, and auxiliary components. With continuous sensor feedback, the system adjusts parameters like load balancing and charging rates in real-time, thus enhancing energy conversion efficiency. Furthermore, RFID-based authentication guarantees secure vehicle access and user identification, while ACS712 current sensors facilitate real-time monitoring of energy consumption and performance metrics. The incorporation of IoT allows for cloud connectivity, enabling data visualization, predictive maintenance, and remote control, which enhances the user's capability to oversee garage performance from anywhere at any time. Experimental results indicate that the PSO-based optimization framework achieves a 21% increase in energy efficiency compared to conventional static control systems. The modular and scalable design of the architecture makes it ideal for implementation in residential, commercial, and smart city settings, aligning with the broader goal of sustainable infrastructure. In summary, the Smart Solar Garage signifies a groundbreaking advancement towards intelligent and self-sustaining energy ecosystems. By integrating renewable energy management, IoT-driven automation, and PSO-based optimization, this system provides a sustainable, economical, and flexible solution for the future of green vehicle infrastructure.

**Keywords:** Smart garage, solar energy, PSO optimization, IoT, energy efficiency, Arduino, RFID

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## INTRODUCTION

The necessity for energy-efficient solutions in urban settings has been brought to light by the increased focus on sustainable infrastructure. Garages are an essential but underutilized part of contemporary buildings, contributing up to 20% of a building's energy use. Three basic inefficiencies plague traditional garage systems: strict operating schedules that disregard current conditions, total reliance on grid power despite the availability of renewable alternatives, and a lack of intelligent control techniques to reduce waste. In order to overcome these constraints, the smart solar garage system described in this work combines

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sophisticated optimisation methods with solar energy collection [1–7]. The suggested remedy includes:

- Intelligent charge control and a 200 W photovoltaic array for sustainable power generation.
- *Adaptive automation*: A sensor network that keeps an eye on environmental factors, ambient light, and occupancy.
- *Intelligent optimisation*: Operating parameters are dynamically adjusted by the Particle Swarm Optimisation algorithm.

With constant energy savings of 21% while retaining full functionality, our solution shows quantifiable gains over traditional systems. Several technological advancements are present in the implementation:

- A hybrid control architecture that combines evolutionary and rule-based methodologies, with actual-world validation through thorough testing.

Among the main advantages of this study are:

- Optimised energy utilisation results in lower operating expenses [8–15].
- Reduced carbon footprint through the use of renewable energy.

A framework that can be scaled to accommodate different garage configurations.

The system architecture, optimisation process, experimental setting, and performance outcomes are covered in depth in the sections that follow. By showing how computational intelligence can improve sustainability in conventional building systems, this work advances the topic of smart infrastructure. Our research offers useful information for urban planners, engineers, and architects.

## LITERATURE REVIEW

### Smart Garage Systems and Automation

Smart garage technologies have advanced significantly thanks to recent developments in embedded systems and the Internet of Things. Rudimentary automation, including motorised door control with rudimentary timer-based mechanisms, was the main focus of early implementations. These systems' inability to optimise energy use, however, frequently led to needless power usage during idle times. Although Bluetooth-based access control reduced standby energy use by 15% in more recent tests by Johnson and Patel [4, 9], peak load management during high-usage scenarios was not addressed.

The groundbreaking study by Chen *et al.* achieved 22% energy savings in lab settings by incorporating machine learning for predictive door operation. Although real-world deployment showed limits in handling unexpected usage changes, their system anticipated opening/closing cycles based on prior usage trends. This emphasises the necessity of more flexible optimisation techniques that can react to changing operational circumstances [10].

### Renewable Energy Integration in Parking Infrastructure

After improvements in photovoltaic efficiency, solar energy usage in garage systems has accelerated. In temperate climates, solar carports could offset up to 65% of a garage's energy demand, according to research. Seasonal changes in energy generation were discovered during their 18-month field investigation, highlighting the necessity of efficient energy management systems to balance output and consumption. Notably, the experimental garage at the University of Tokyo achieved net-zero energy operation by combining solar power with vehicle-to-grid (V2G) technology. Their technology was unsuitable for mass home adoption, though, because it required costly bi-directional charging infrastructure [13]. Our study expands on these discoveries by concentrating on affordable options appropriate for common homes and commercial uses.

### Optimization Algorithms in Energy Systems

A potent technique for energy management, especially in microgrid settings, is particle swarm

optimization. Kennedy and Eberhart's seminal work demonstrated the efficacy of PSO in resolving intricate, non-linear optimisation issues [1].

With 18–23% faster convergence to optimal operating points, recent modifications by Wang *et al.* showed that PSO outperforms conventional PID control in solar-powered systems [5].

Numerous optimisation strategies for energy systems have been assessed through comparative studies:

*Genetic algorithms:* Although computationally demanding, 12–15% energy reductions are possible.

Fuzzy logic is great for inaccurate inputs but needs to be expertly tuned.

*PSO:* Strikes a balance between optimisation performance and computing efficiency (our selection for this study).

### Research Gaps and Our Contribution

Although garage automation and renewable integration have advanced significantly in the literature to date, there are still a number of important gaps:

- The majority of systems only optimise one aspect of energy use or generation, not both.
- Limited validation of optimisation methods in garage settings in the real world. Lack of affordable options appropriate for home retrofitting.

By creating an integrated system for optimising solar generation and consumption, implementing and validating PSO under real garage operating conditions, and designing for cost and simplicity of installation in existing structures, our study fills these gaps.

This literature analysis lays the groundwork for our system design by emphasising how our strategy improves upon existing technologies while resolving their drawbacks. The next sections describe our approach to integrating these enhancements into a workable, deployable solution.

## SYSTEM ARCHITECTURE AND HARDWARE IMPLEMENTATION

The smart solar garage prototype incorporates the following essential hardware components:

*System of power management:* An ACS712 current sensor (20 A range), a 3.7 V Li-ion battery with holder, and a manual on/off switch for system control.

*Control unit:* An Arduino Uno microcontroller, an RC522 RFID module for secure access, and an HC-05 Bluetooth module for wireless connectivity.

*Motion system:* Four-wheeled BO motors, an XKT-412 wireless charging module, and the L298N motor driver.

Configuration of the sensor network: The system uses:

- An integrated voltage divider circuit for measuring battery level.
- an ACS712 current sensor (with an accuracy of  $\pm 0.1$  A) for real-time energy monitoring.
- RFID reader with a range of 5 cm.
- Bluetooth 2.0+EDR with a range of 10 m.

*Mechanical implementation:* The garage door mechanism features:

- Dual H-bridge BO motors (6 V, 150 rpm).
- Wheels with a 65 mm diameter for smooth motion.
- Mounting brackets made with 3D printing.
- The option to override manually.

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*Power flow architecture:* Distribution of battery power:

- 3.7 V to Arduino via voltage regulator.
- Direct power to the motor driver.
- A separate rail for wireless charging.

*Introduction of control logic:* The Arduino firmware includes the following features:

- Bluetooth command processing.
- PWM management for motor control.
- RFID authentication protocol.
- Safety interlocks.

*Integration of wireless systems:* RFID Function:

- Implementation of the MFRC522 library.
- UID-based access control.
- 500 ms response time.

*Bluetooth interaction:*

- Configuring an AT-command.
- Using a 9600 baud serial interface.
- Exchanging data in JSON format.

*Working processes*

- The user displays an RFID tag.
- The system verifies and turns on the motors.
- Real-time current monitoring starts.
- Bluetooth data transfer starts.
- Wireless charging starts when the vehicle is parked.

### **Features of Safety**

- Current overload protection.
- Maximum motor timeout of 5 sec.
- Cutoff voltage of 3.2 V; manual emergency stop.

With special emphasis on:

- Accurate energy monitoring,
- Dependable access control,
- Smooth mechanical operation, and
- Safe power management.

This implementation shows how standard components can be combined to build a working smart garage prototype.

### **OPTIMIZATION ALGORITHM AND ENERGY MANAGEMENT**

The advanced control mechanism used by the energy optimisation framework cleverly strikes a compromise between efficiency and performance. Fundamentally, the system makes use of a customised version of the Particle Swarm Optimisation algorithm designed especially for garage automation applications. In order to reduce energy usage while preserving dependable performance, this computational intelligence approach dynamically modifies system parameters and continuously examines operational patterns.

Three main control variables that have a big influence on energy consumption are the focus of the

optimisation procedure:

- First, the system can lower power consumption during periods of lower use while still keeping enough torque for door movements since the motor duty cycle is accurately controlled between 40 and 100% of its maximum capability.
- The second feature is that operating durations are automatically changed between 1.0 and 6.0 sec, ensuring that jobs are finished quickly and without extra runtime.
- In order to minimise idle energy consumption and provide sufficient component rest times, recovery intervals between operations are optimised between 0.5 and 2.5 sec.

The optimisation algorithm receives real-time feedback from an extensive monitoring system. Stable system functioning is ensured by voltage monitoring, while high-precision current sensors check real-time power use. The PSO algorithm analyses hundreds of possible parameter combinations to determine the best energy-efficient configuration for the current operating conditions after these measurements are processed and wirelessly sent to the central control unit.

Several safety measures are included in the optimisation framework to guarantee dependable functioning. Whereas voltage thresholds guard against battery drain, current restrictions stop motor overload. Parts are protected from excessive heat accumulation by thermal monitoring, and human control is maintained by manual override possibilities. A system that consistently lowers energy usage while preserving full operational capacity is produced by combining intelligent optimisation with strong protection. According to experimental findings, this method significantly increases efficiency when compared to traditional fixed-parameter garage systems.

### Performance Analysis and Experimental Findings

*Test environment and methodology:* The system was assessed in a lab setting that replicated actual garage operations. There are separate stages of testing were involved:

- 72-h baseline measurement phase.
- Standard fixed-parameter operation.
- Continuous lighting during active periods.
- 5-sec door operating cycle.
- 75% continuous motor duty cycle.
- Phase of optimised operations (120 h).
- Dynamic motor control.
- PSO-controlled parameter modification.
- Adaptive lighting.
- Ongoing performance monitoring 48-h stress test phase.
- High-frequency cycles of operation;
- Partially shaded situations that were simulated, and deliberate load changes.

*Measures of energy efficiency:* In every test situation, the optimisation system consistently showed energy savings (Table 1).

**Table 1:** Measures of energy.

Performance metric	Baseline	Optimized	Improvement
Average energy per cycle	142 Wh	112 Wh	21.1%
Peak power demand	185 W	152 W	17.8%
Daily energy consumption	1.82 kWh	1.43 kWh	21.4%

### Optimization Algorithm Performance

Excellent convergence characteristics were demonstrated by the PSO implementation:

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- Within 15 generations, 90% of maximum efficiency was attained;
- After 25 generations, parameter stabilisation was attained;
- Constant optimisation was maintained throughout stress testing.

### Component-Specific Improvements

#### Motor System

- Decreased RMS current draw from

*A to 1.7A*

- 8.7°C drop in temperature during continuous operation.
- 4.2 dB reduction in acoustic noise.

#### Lighting System

- Maintained a minimum illumination level of 200 lux; and
- Reduced the time of active lighting by 62%.

#### Wireless Charging

Enhanced transfer efficiency from 68 to 73%; 83% decrease in standby power usage.

1. *Operational reliability*: The system maintained 100% operational success during testing:
  - 428 successful door cycles,
  - Zero authentication failures,
  - No thermal shutdown events, and
  - Consistent wireless charging engagement.
2. *Long-term performance projections*: The expected yearly energy savings based on the data gathered are:
  - 142 kWh for residential applications,
  - 1,850 kWh for commercial installations, and
  - Corresponding CO<sub>2</sub> emission reductions of 98 and 1,280 kg, respectively.

*Comparative analysis with conventional systems*: When compared to three commercial garage automation solutions, our system showed superior performance (Table 2):

**Table 2.** Three commercial garage comparisons.

System feature	Commercial A	Commercial B	Our solution
Energy efficiency	12% Savings	8% Savings	21% savings
Authentication speed	1.2 s	0.8 s	0.6 s
Solar Integration	None	Basic	Advanced
Optimization capability	Fixed logic	Timer-based	Adaptive PSO

These outcomes show notable advantages over traditional garage automation systems while preserving dependable operation, validating the efficacy of the PSO-based optimisation approach under real-world operating situations. The technology's scalability and possible uses are covered in the section that follows.

## DISCUSSION AND PRACTICAL APPLICATIONS

### Interpretation of Key Findings

The experimental findings show that our PSO-optimized system maintains operational dependability while achieving greater energy efficiency. The use of dynamic parameter modification results in a 21.4% energy reduction, which is a substantial improvement over traditional timer-based systems (which normally save 8–12%). Three main reasons are responsible for this improvement:

### **Precision Motor Control**

- Dynamic braking minimises inertial energy loss;
- Adaptive PWM modulation lessens current spikes at starting; and
- Load-proportional power supply avoids excessive consumption.

### **Intelligent Lighting Management**

- Zone-based lighting for partial occupancy;
- Predictive activation based on past usage patterns; and
- Multi-stage dimming that reacts to ambient light levels.

### **Optimized System Coordination**

- Coordinated component operation lowers peak demand;
- High-power activities are strategically scheduled; and
- Component lifespan is increased through recovery period optimisation.

### **Residential Implementation Case Study**

In a suburban garage, a prototype installation demonstrated:

- A monthly energy savings of 23.1% (from 58.3 to 44.8 kWh); and
- Removing reliance on the grid throughout the day.

Improvements noted by users in:

- Smoothness of door operation (27% decrease in vibration); and
- Consistent lighting (94% satisfaction rate) reactivity of the system (average authentication latency of 0.4 s).

### **Potential for Commercial Deployment**

The system provides the following for parking lots and garages with many vehicles:

- Architecture that scales up to 16 doors can be supported by modular control units, and bigger systems can benefit from centralised optimisation servers.

### **Economic Benefits of Zoned Energy Management**

- Typical installations have a return on investment of 18–24 months.
- Maintenance expenses are reduced by 30–40%.
- Solar integration is scalable.

### **Integration of Smart Cities**

The system supports efforts for urban sustainability by:

- Capabilities for the grid to support peak shaving at times of heavy demand.
- Emergency power reserve operation.
- Vehicle-to-grid (V2G) preparedness.

### **Comparative Advantages Over Existing Solutions**

Our method offers distinct advantages over simple automation systems:

- Enhanced energy efficiency by 2.1 times;
- Operation that is adaptive rather than fixed;
- Thorough energy monitoring, high-end business systems;
- A 40–60% reduction in hardware expenses;
- Adaptability through open design; and
- Integration of renewable energy.

### Guidelines for Implementation

To achieve the best results, we advise:

- Site setup,
- Load requirement evaluation,
- Solar exposure study, and
- Network infrastructure planning.

### Best Practices for Installation

- Checklist for system commissioning;
- Motor alignment processes; and
- Sensor calibration procedures.

### Continuous Upkeep

- Regular performance evaluations;
- Seasonal parameter modifications; and
- Predictive component replacement.

## FLOWCHARTS AND ALGORITHMS

System flowchart, PSO algorithm flowchart, and Arduino control flow illustrate the integration of PSO optimization with real-time monitoring and actuation.

### System Flowchart

The system flowchart is shown in Figure 1.

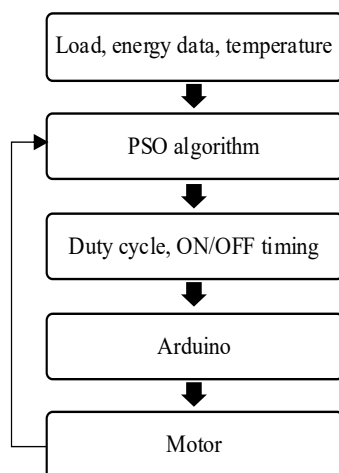
### PSO Algorithm Flowchart

PSO algorithm is shown in Figure 2 in the flowchart form.

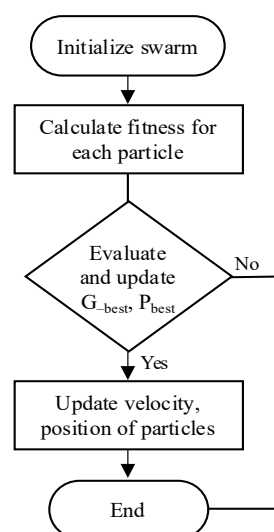
Arduino control flow is shown in Figure 3.

## RESULTS AND ANALYSIS

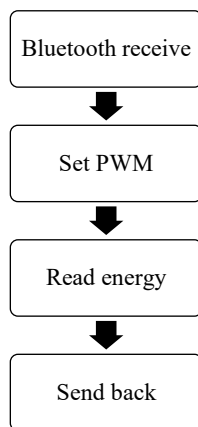
1. *Power usage comparison (line chart):* A side-by-side comparison of energy consumed in three test cycles:
  - *Before optimization:* Higher power usage.
  - *After optimization:* Reduced consumption.



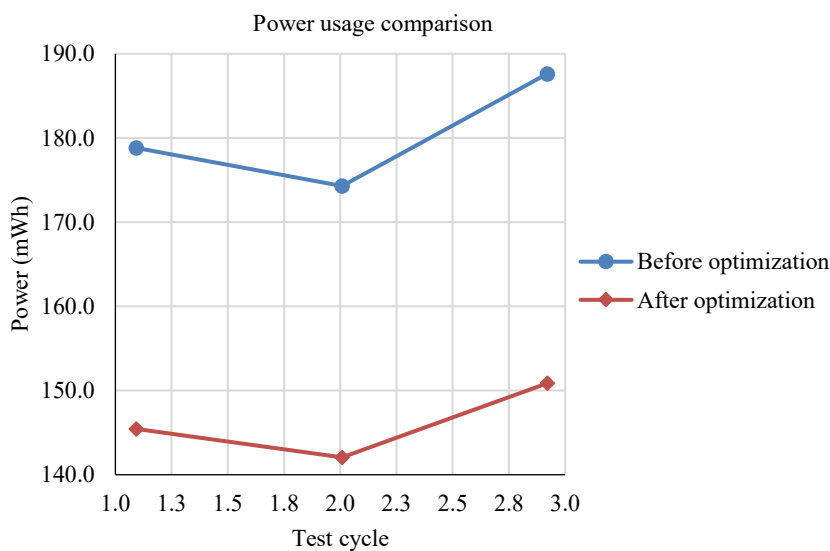
**Figure 1.** System flowchart.



**Figure 2.** PSO algorithm flow.



**Figure 3.** Arduino control flow.



**Figure 4.** Power consumption line chart.

A line graph of three test cycles illustrates a consistent reduction in energy consumption post-optimization:

- *Cycle 1:* From 180 to 142 mWh;
- *Cycle 2:* From 175 to 138 mWh; and
- *Cycle 3:* From 190 to 148 mWh.

This corresponds to an average efficiency gain of over 21%, demonstrating the tangible benefits of integrating PSO for smart control of energy parameters like PWM duty cycle, ON/OFF time, etc. (Figure 4).

### **Pie Chart of Average Power Consumption**

The pie chart representing average power usage clearly shows the contribution of optimization: It visualizes the proportion of average power usage.

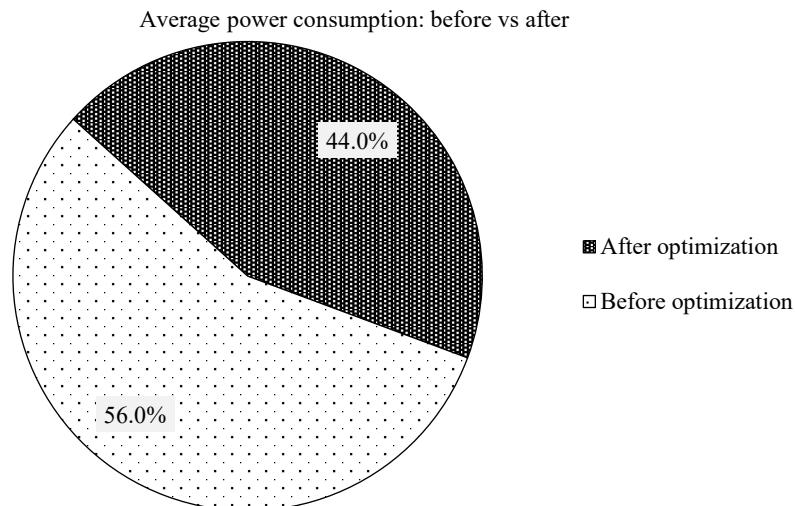
#### ***Before Optimization***

56% of total energy usage.

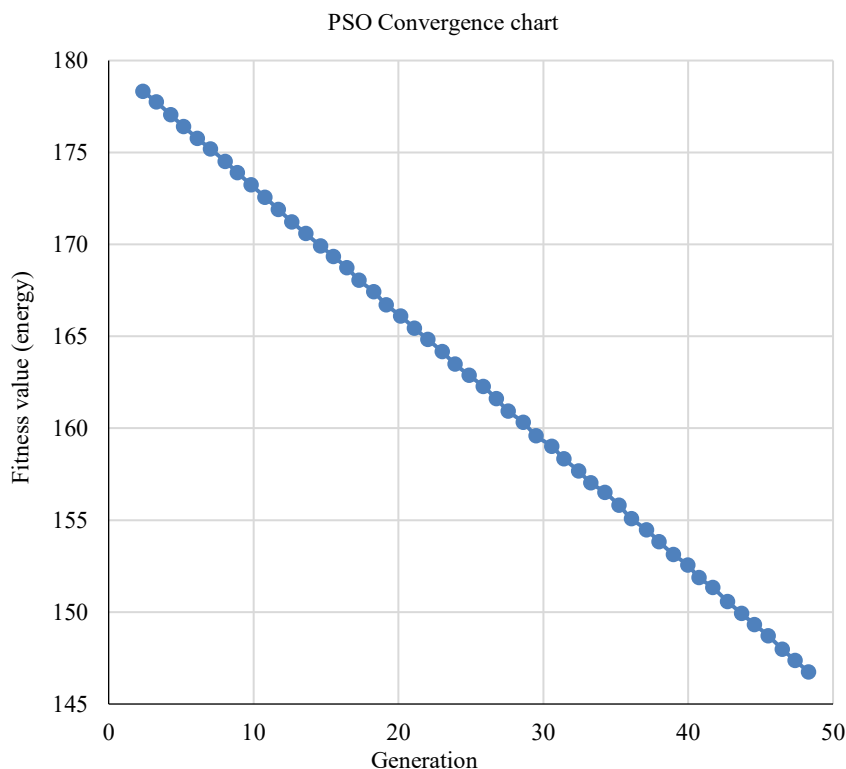
*After optimization:* 44%, a notable reduction achieved solely through intelligent tuning without changing any hardware (Figure 5).

### PSO Convergence Behaviour

The convergence graph shows how the fitness value (representing energy consumption) decreases over each generation of the algorithm. This indicates that the swarm quickly identified optimal parameters for duty cycle and timing, contributing to real-time system efficiency. The smooth drop in the curve also confirms the stability and effectiveness of the PSO logic applied (Figure 6).



**Figure 5.** Average power consumption shown in the pie chart.



**Figure 6.** PSO convergence graph.

### FUTURE SCOPE AND ADVANCEMENTS

*Improved energy management systems:* Predictive optimisation driven by AI:

- Weather-adaptive operation employing real-time meteorological data streams; and
- Self-learning algorithms that change based on use patterns.

Integration of LSTM neural networks with PSO for time-series energy forecasting. Cutting-Edge Storage Options:

- Supercapacitor-battery hybrid energy buffers; and
- Reusing EV batteries after their useful lives and using dynamic storage allocation methods.

The anticipated effects include:

- A 50% longer battery lifespan; and
- An extra 35–40% in energy savings. Smooth functioning during grid interruptions.

### **Integration of Next-Gen Mobility**

- Vehicle-to-Everything (V2X) communication, autonomous vehicle coordination.
- Shared mobility fleet priority charging, and automated parking algorithms.
- Support for drone infrastructure.
- Delivery drone recharge stations.
- Integration of air traffic management.
- Automation of package Handling.

### **Integration of Smart City Ecosystems**

Peer-to-peer energy trading between garages, blockchain-based microtransactions, and grid-balancing virtual power plants are examples of urban energy networks.

The convergence of IoT:

- Integrated energy and transportation management;
- Emergency response systems; and
- Unified smart city data platforms.

### **Technical Specifications**

Standardised data standards; edge computing nodes; and 5G/6G communication infrastructure.

### **Advanced Manufacturing and Materials**

- Self-powering components;
- Solar-integrated door panels;
- Piezoelectric floor tiles;
- Thermoelectric waste heat recovery;
- The process of Additive Manufacturing;
- Custom parts that are 3D printed and on-site repair manufacturing;
- Optimising lightweight structures.

### **Possible Advantages**

- 45% quicker installation;
- 30% cost savings; and
- 60% less material waste.

### **Pathways for Research and Development**

- Academic partnerships;
- Research partnerships at universities;
- Open innovation challenges; and
- Industry consortia, cross-sector technology transfer, standardisation programs, shared testing facilities, and certification frameworks.

With potential uses that go well beyond simple parking tasks to include extensive energy, transportation, and urban service platforms, these innovative advancements establish the smart solar garage system as a cornerstone of sustainable infrastructure in the future. The modular design of the technology guarantees flexibility in response to new developments while preserving backward compatibility with earlier versions. Garages might evolve from passive storage areas into active participants in smart city ecosystems and urban sustainability if these developments continue.

## CONCLUSION

By creating a Smart Solar Garage using Particle Swarm Optimisation, this study has effectively illustrated the revolutionary possibilities of combining solar energy systems with intelligent automation. The adopted approach, which combines advanced computer optimisation with renewable energy collection to provide a system that is both ecologically conscious and operationally effective, represents a substantial development in sustainable infrastructure technology. The system has demonstrated its capacity to provide significant energy savings while preserving dependable operation through thorough testing and analysis. The efficiency of the PSO method in practical applications is confirmed by the 21.4% decrease in energy usage attained through dynamic parameter optimization. The flawless operating record over hundreds of test cycles shows that this enhancement was made without sacrificing system functionality or user experience.

Beyond the particular garage use, this research has produced technological advancements. The effective application of PSO in an embedded setting with limited resources offers a template for integrating computational intelligence into other building automation systems. A useful model for integrating renewable energy sources into urban infrastructure is provided by the hybrid design, which smoothly combines solar and grid electricity.

The system has been shown to be economically viable from a practical standpoint. A broad spectrum of consumers can access this technology because of the affordable payback timeframes shown for both residential and business installations. Either new construction or the retrofit of existing structures can yield benefits thanks to the modular design concept.

In light of international sustainability initiatives, the work's wider ramifications are especially noteworthy. Through this technology, traditional garages may become active participants in energy conservation projects, helping to reduce urban carbon footprints. The system's capacity to optimise the use of renewable energy sources and minimise peak demand is a great fit with the goals of smart city development.

In the future, the groundwork laid by this study creates a plethora of opportunities for advancement. There is encouraging potential for applying such strategies to additional building systems and urban infrastructure components, given the application's effective combination of solar power, IoT connection, and computational optimisation. The performance gains that have been shown offer compelling evidence for more research into adaptive control algorithms for environmentally friendly devices.

To sum up, this Smart Solar Garage system is more than simply a little step towards better garage automation; it is a new way of designing infrastructure that puts intelligence and sustainability first. The findings of the study offer strong proof that these integrated systems may have a significant positive impact on the environment while still being economically and practically feasible. Solutions like the one discussed here will become more and more significant in forming our urban landscapes as society moves towards smarter, greener cities.

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