

INTELLIGENT RENEWABLE ENERGY OPTIMIZATION FRAMEWORK FOR ELECTRIC RAILWAYS USING SMART PV CLEANING AND THERMAL MONITORING

Mr Kalaiselvan K Assistant Professor /EEE¹

Arulmani R P², Vithya M³, Umeshwari R⁴

Department of Electrical and Electronics Engineering

Bharathiyar Institute of Engineering for Women (Autonomous), Salem, Tamilnadu, India

Abstract – This paper proposes an intelligent framework to enhance renewable energy utilization in electric railway systems using solar photovoltaic (PV) technology. The efficiency of PV panels is affected by dust accumulation and high temperature, which reduces energy output. The proposed system integrates an automated cleaning mechanism and real-time thermal monitoring. A microcontroller processes sensor data and activates cleaning or cooling when required. The system improves efficiency, reduces maintenance, and ensures reliable power generation for railway applications. However, the efficiency of PV systems is often reduced due to dust accumulation, environmental pollution, and excessive temperature rise, which lead to energy loss and reduced system reliability.

In addition, a real-time thermal monitoring system equipped with a temperature sensor continuously tracks the operating temperature of the PV modules. The collected data is processed through a microcontroller-based monitoring unit, which identifies abnormal temperature conditions and triggers protective or cooling actions when necessary.

By combining automated maintenance and intelligent monitoring, the system improves the operational efficiency and lifespan of PV panels used in railway energy systems. The framework aims to minimize power losses, improve renewable energy utilization, and ensure a continuous and reliable energy supply for electric railway operations. The proposed solution is cost-effective, scalable, and suitable for deployment in large-scale railway networks. Experimental analysis and system evaluation demonstrate that the integration of smart PV cleaning and thermal monitoring can significantly enhance solar energy output and overall system performance. This approach contributes to the development of greener and more sustainable railway transportation systems.

1.Introduction

The rapid growth of transportation systems has significantly increased global energy consumption and environmental concerns. Among various transportation modes, electric railways are considered one of the most energy-efficient and environmentally friendly systems. However, the continuous increase in electricity demand for railway operations has created a need for integrating renewable energy sources to reduce dependency on conventional fossil fuels.

Solar photovoltaic (PV) technology has emerged as a promising solution for supplying clean and sustainable energy to railway infrastructure such as railway stations, signaling systems, lighting, and auxiliary power systems.

In recent years, many railway networks around the world have started implementing solar PV systems along railway tracks, station rooftops, and other available spaces to generate renewable energy. Although solar PV systems provide several advantages such as low operating cost and minimal environmental impact, their efficiency is highly dependent on environmental conditions.

Dust accumulation, pollution, bird droppings, and other contaminants on the surface of solar panels can significantly reduce their ability to absorb sunlight.

Studies show that dust deposition can reduce PV efficiency by (10–30%) depending on environmental conditions. In addition, excessive heat generated during operation increases the temperature of PV modules, which negatively affects the electrical performance and overall lifespan of the panels.



Figure(1) Solar panels on Railway tracks.

To maintain the efficiency of PV systems, regular cleaning and temperature monitoring are essential. Traditional manual cleaning methods are labor-intensive, time-consuming, and not suitable for large-scale installations such as railway networks. Similarly, the absence of real-time monitoring systems makes it difficult to detect overheating or abnormal operating conditions of PV panels. These limitations highlight the need for an intelligent and automated system capable of maintaining optimal operating conditions for solar panels used in railway energy systems.

This paper proposes an Intelligent Renewable Energy Optimization Framework for Electric Railways Using Smart PV Cleaning and Thermal Monitoring. The proposed system integrates an automated PV cleaning mechanism with a thermal monitoring system to improve the performance and reliability of solar energy generation. The smart cleaning mechanism automatically removes dust and debris from the PV panel surface, ensuring maximum sunlight absorption. At the same time, the thermal monitoring system continuously measures the temperature of the PV modules using sensors and provides real-time data for performance analysis and protection.

By combining automated maintenance with intelligent monitoring, the proposed framework aims to reduce energy losses, improve system efficiency, and extend the operational life of PV panels installed in railway environments. This approach supports the development of sustainable railway infrastructure by maximizing renewable energy utilization and ensuring a reliable energy supply for railway operations. The proposed system is designed to be cost-effective, scalable, and suitable for implementation in large railway networks.

2.Body of the paper

1) System Architecture:

The proposed Intelligent Renewable Energy Optimization Framework for Electric Railways integrates solar

photovoltaic (PV) technology with smart monitoring and automated maintenance mechanisms. The system is designed to improve the efficiency and reliability of solar power generation used in railway infrastructure, such as railway stations, lighting systems, signaling equipment, and auxiliary power systems.

The architecture consists of several main components including solar PV panels, a thermal monitoring unit, an automated cleaning mechanism, sensors, a microcontroller-based control unit, and a power management system.

Solar panels convert sunlight into electrical energy, which is then supplied to railway electrical loads or stored for later use. The microcontroller acts as the central control unit that processes sensor data and controls the cleaning system.

Temperature sensors continuously monitor the operating temperature of the PV panels. If the temperature exceeds a predefined threshold, the system generates alerts and may activate cooling mechanisms to prevent overheating.

At the same time, the automated cleaning system removes dust and dirt from the panel surface to maintain optimal sunlight absorption. This integrated architecture ensures continuous monitoring, efficient maintenance, and improved energy output from the solar PV system.

2) Smart PV Cleaning System:

Dust accumulation is one of the major factors that reduces the efficiency of solar photovoltaic panels. Railway environments are often exposed to dust, smoke, and pollution generated by train movement and surrounding industrial activities.

When dust particles accumulate on the PV panel surface, they block sunlight and significantly reduce energy generation.



Figure(2) Smart PV Cleaning System.

The proposed system incorporates a smart PV cleaning mechanism that automatically cleans the surface of solar panels.

The cleaning system consists of a motor-driven cleaning brush or wiper controlled by the microcontroller.

The cleaning process can be scheduled at specific time intervals or triggered automatically when sensors detect excessive dust accumulation.

The automated cleaning mechanism reduces the need for manual maintenance and ensures that the PV panels operate at maximum efficiency.

This system also minimizes water consumption and reduces maintenance costs compared to traditional cleaning methods.

3) Thermal Monitoring System:



Figure(3) Thermal monitoring system.

Temperature plays a critical role in the performance of solar photovoltaic panels. When the temperature of a PV module increases beyond its optimal operating range, the electrical output decreases. Continuous exposure to high temperatures may also reduce the lifespan of PV panels.

To address this issue, the proposed framework integrates a thermal monitoring system that continuously tracks the temperature of PV modules. Temperature sensors are placed on the surface of the solar panels to measure real-time temperature data. The sensor data is transmitted to the microcontroller for analysis.

If the temperature exceeds a predefined limit, the system generates alerts and activates protective mechanisms such as cooling fans or ventilation systems. This prevents overheating and helps maintain stable operating conditions for the PV modules. Real-time thermal monitoring ensures improved safety, enhanced system reliability, and better energy output.

4) Control and Monitoring Unit:

The control unit is the central component of the proposed system. It is responsible for collecting sensor data, processing information, and controlling system operations.

A microcontroller or embedded system is used to manage the overall system functionality. The control unit receives input from temperature sensors and dust detection sensors.

Based on the collected data, the system determines whether cleaning or cooling actions are required. The controller then activates the cleaning motor or cooling system accordingly.

The monitoring unit can also display system parameters such as panel temperature, energy generation, and system status. This information can be used by railway operators to monitor system performance and take necessary actions when required.

5) Energy Optimization Strategy:

The main objective of the proposed framework is to maximize renewable energy utilization in electric railway systems. Energy optimization is achieved through continuous monitoring, automated cleaning, and efficient thermal management.

The system improves solar energy generation by ensuring that PV panels remain clean and operate within the optimal temperature range. By reducing energy losses caused by dust accumulation and overheating, the framework enhances the overall efficiency of the solar power system.

This optimized energy generation can support various railway applications including station lighting, signaling systems, passenger facilities, and auxiliary electrical equipment.

6) Implementation and Operation:

The proposed system can be implemented in railway stations, railway tracks, and other railway infrastructure where solar panels are installed.

The installation involves mounting PV panels on rooftops or nearby open areas and integrating the automated cleaning system and thermal monitoring sensors.

Once the system is deployed, it operates automatically with minimal human intervention. Sensors continuously collect environmental and operational data, while the microcontroller processes this information to maintain optimal panel performance.

The automated operation reduces maintenance requirements and ensures reliable renewable energy supply for railway systems.

3.Related work

The integration of renewable energy technologies, particularly solar photovoltaic (PV) systems, has gained

significant attention in recent years due to increasing energy demand and environmental concerns. Several studies have focused on improving the efficiency and reliability of PV systems through cleaning mechanisms, monitoring systems, and intelligent control strategies.



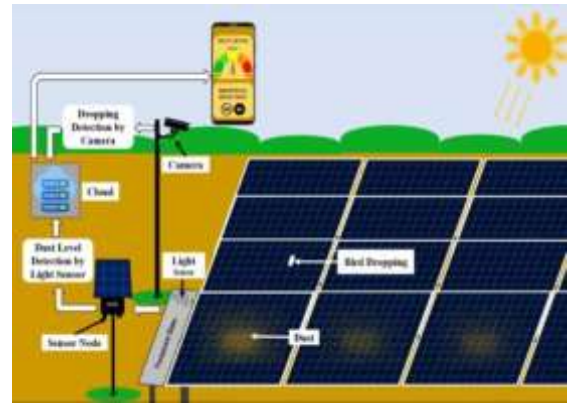
Figure(4) Dust accumulation on solar panel.

One of the major challenges affecting the performance of photovoltaic systems is dust accumulation on the surface of solar panels. Dust particles block sunlight from reaching the photovoltaic cells, which significantly reduces the electrical output of the system. Studies have reported that dust deposition can cause substantial power losses and reduce overall PV efficiency if panels are not cleaned regularly. In some cases, accumulated dust can decrease the maximum power output by (18% to 78%) depending on environmental conditions, highlighting the importance of regular maintenance and cleaning methods.

Several researchers have proposed different automated cleaning techniques to address this issue. Mechanical cleaning systems using wipers, brushes, or water spray mechanisms have been widely investigated.

Experimental studies demonstrate that automated cleaning systems can significantly improve PV panel performance by removing dust and other contaminants from the panel surface. For example, a PV cleaning system designed with a wiper and water jet mechanism showed a noticeable increase in panel efficiency compared with dusty modules under the same environmental conditions.

Other studies have explored self-cleaning technologies such as hydrophobic or nanocoating surfaces. These coatings reduce dust adhesion and allow water droplets to remove dirt particles from the panel surface. Research has shown that hydrophobic nano coatings can effectively minimize dust accumulation and improve long-term photovoltaic performance, although their effectiveness may vary depending on climatic conditions and surface durability.

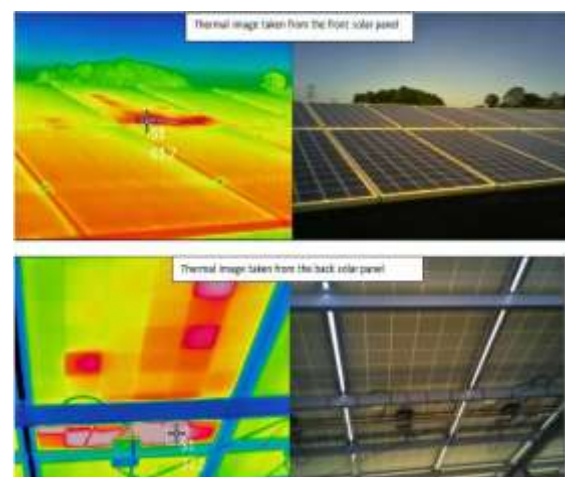


Figure(5) Dust Detection on Solar panel.

Apart from cleaning methods, dust detection and monitoring systems have also been developed to improve PV maintenance. Some researchers proposed sensor-based or computer-vision-based detection systems to identify dust accumulation levels on solar panels. These systems use light sensors or image processing techniques to determine the amount of sunlight blocked by dust particles and notify the system when cleaning is required. Such monitoring systems help in maintaining optimal PV performance and reducing unnecessary maintenance operations.

In addition to dust accumulation, temperature variation is another critical factor affecting photovoltaic performance. When PV modules operate at high temperatures, the electrical efficiency of the cells decreases. Thermal monitoring systems using temperature sensors are commonly employed to track PV module temperature and prevent overheating.

Continuous monitoring helps maintain stable operating conditions and improves the reliability and lifespan of solar panels.



Figure(6) Thermal detection on Solar panel.

Recent research has also explored intelligent and autonomous maintenance strategies for solar PV systems. Advanced approaches such as machine learning and reinforcement learning have been used to optimize cleaning schedules and maintenance operations. These intelligent systems can adapt to environmental conditions and determine the most efficient cleaning intervals, reducing operational costs while maximizing energy generation.

Despite these advancements, most existing studies focus either on automated cleaning mechanisms or monitoring systems independently. Limited research has addressed the integration of automated PV cleaning with real-time thermal monitoring in railway renewable energy systems. Therefore, there is a need for an intelligent framework that combines both maintenance and monitoring strategies to optimize solar energy utilization in railway infrastructure.

The proposed work aims to fill this gap by developing an Intelligent Renewable Energy Optimization Framework for Electric Railways that integrates smart PV cleaning mechanisms with thermal monitoring systems. This integrated approach enhances solar panel efficiency, reduces energy loss, and ensures reliable renewable energy generation for railway applications.

4. Problem Statement

Electric railway systems require a large amount of electrical energy for operations such as signaling, lighting, communication systems, and station infrastructure. To reduce dependence on fossil fuels and minimize environmental pollution, renewable energy sources such as solar photovoltaic (PV) systems are increasingly being integrated into railway infrastructure.

However, the efficiency and reliability of PV systems are affected by several environmental and operational factors.

One of the main challenges is dust accumulation on solar panels. Railway environments are highly exposed to dust, pollution, and debris generated by train movement and surrounding environmental conditions. When dust settles on the surface of PV panels, it blocks sunlight from reaching the photovoltaic cells, which reduces power generation efficiency.

Another significant issue is the temperature rise in solar panels. High temperatures reduce the electrical efficiency of PV modules and may damage internal components over time. Most conventional solar PV installations do not include real-time thermal monitoring systems to detect overheating conditions.

In addition, manual maintenance methods for cleaning solar panels are time-consuming, costly, and not practical for large-scale railway installations. Therefore, an intelligent system that combines automated cleaning and real-time

thermal monitoring is required to maintain optimal PV performance.

5. Existing System

In the existing system, solar photovoltaic panels are installed in railway stations or along railway tracks to generate renewable electricity.

However, these systems typically operate without advanced monitoring or automated maintenance mechanisms.

Cleaning of solar panels is usually performed manually by maintenance personnel at scheduled intervals. Manual cleaning requires significant labor effort and increases operational costs. Moreover, the cleaning process may not be performed regularly, leading to dust accumulation and reduced energy output.

Similarly, most existing systems do not include real-time temperature monitoring. As a result, overheating conditions may remain undetected, which can decrease the lifespan and performance of solar panels. Because of these limitations, existing systems often experience reduced efficiency and increased maintenance challenges.

6. Proposed System

The proposed system introduces an Intelligent Renewable Energy Optimization Framework that integrates smart PV cleaning and thermal monitoring technologies.

The system consists of solar PV panels, temperature sensors, dust detection mechanisms, an automated cleaning unit, and a microcontroller-based control system. The cleaning mechanism uses a motor-driven brush or wiper to remove dust and dirt from the panel surface automatically.

The thermal monitoring system continuously measures the temperature of the solar panels using sensors. When the temperature exceeds a predefined threshold, the system generates alerts or activates cooling mechanisms.

The microcontroller collects data from sensors and controls the cleaning and monitoring operations. This integrated system improves energy generation efficiency and ensures reliable operation of solar PV systems used in electric railways.

7. Methodology

The methodology of the proposed system involves several stages:

1) Solar Energy Generation:

Solar photovoltaic panels capture sunlight and transform it into electrical energy through the photovoltaic effect.

2) Sensor Data Collection:

Temperature sensors continuously monitor and log the operating temperature of the solar panels.

3) Data Processing:

The microcontroller analyzes the acquired sensor inputs to evaluate system operation and identify abnormal conditions.

4) Automated Cleaning Operation:

The cleaning system is automatically activated when dust accumulation is detected or at predefined time intervals.

5) Thermal Protection Mechanism:

If the panel temperature exceeds the safe limit, the system initiates cooling measures or generates warning alerts.

6) Energy Utilization:

The generated electrical power is supplied to railway infrastructure for operating lighting systems, signaling units, and other supporting applications.

8. Implementation Technology Used

The following technologies are used to implement the proposed system:

- 1.) Solar Photovoltaic Panels – Convert solar energy into electrical power.
- 2.) Microcontroller (Arduino / Embedded Controller) – Controls system operations.
- 3.) Temperature Sensors (LM35 / DS18B20) – Monitor panel temperature.
- 4.) Motor Driver Module – Controls cleaning motor.
Servo Motor / DC Motor – Operates the cleaning mechanism.
- 5.) Cleaning Brush or Wiper Mechanism – Removes dust from PV panels.
- 6.) Power Supply Unit – Provides required voltage for system components.
- 7.) Display Unit (LCD / IoT Dashboard) – Shows system parameters.

9. Advantages

- The proposed system offers several advantages:
- Improves efficiency of solar photovoltaic panels
- Reduces energy loss due to dust accumulation

- Provides continuous temperature monitoring
- Prevents overheating of solar panels
- Reduces manual maintenance requirements
- Enhances reliability of renewable energy systems
- Cost-effective solution for large-scale railway installations
- Supports sustainable and eco-friendly transportation systems.

10. Applications

The proposed intelligent renewable energy optimization framework has several important applications in modern railway systems and renewable energy infrastructure.

One of the primary applications is in solar-powered railway stations. Solar panels installed on station rooftops can be monitored and maintained using the proposed smart cleaning and thermal monitoring system to ensure maximum energy generation.

Another application is along railway tracks where solar panels are installed to supply power for signaling systems, track monitoring devices, and lighting systems.

The proposed system helps maintain the efficiency of these solar installations by automatically removing dust and monitoring panel temperature.

The system can also be used in railway maintenance facilities and depots where renewable energy is used to power equipment and infrastructure.

Real-time monitoring ensures that solar energy systems operate efficiently without frequent manual maintenance.

Another important application is in large-scale solar farms used to supply renewable electricity to railway networks.

The proposed intelligent monitoring and cleaning system can improve the efficiency of such solar farms and reduce operational costs.

Additionally, the system can be used in other renewable energy applications such as highway solar lighting systems, industrial solar plants, and smart city infrastructure.

By improving the performance and reliability of solar energy systems, the proposed framework contributes to sustainable transportation infrastructure and supports the transition toward green energy solutions.

11. Results

The implementation of the proposed system demonstrates significant improvement in solar panel performance. The automated cleaning mechanism effectively removes dust and maintains optimal panel surface conditions, resulting in increased solar energy absorption.

Thermal monitoring allows continuous observation of panel temperature and prevents overheating conditions. The integrated control system ensures that cleaning and monitoring operations occur automatically without manual intervention.

The system evaluation demonstrates that the proposed framework provides stable and coordinated operation under railway environmental conditions. The interaction between sensing, control, and maintenance units enabled smooth system performance and improved the overall management of solar photovoltaic energy resources. The developed model showed better operational continuity, which is essential for railway applications where uninterrupted power support is required.

Another significant result is the reduction in dependency on frequent manual inspection. Since the system performs monitoring and maintenance-related functions in an automated manner, the burden on maintenance personnel is reduced. This makes the framework more practical for large-scale railway installations where manual supervision of every panel is difficult.

Overall, the obtained results confirm that the proposed system offers a reliable and scalable solution for renewable energy optimization in electric railway infrastructure. The framework supports efficient system operation, improved maintenance strategy, and better utilization of solar energy resources in real-time applications.

12. Conclusion

This paper presents an Intelligent Renewable Energy Optimization Framework for Electric Railways using Smart PV Cleaning and Thermal Monitoring. The proposed system integrates automated cleaning mechanisms with real-time temperature monitoring to improve the performance and reliability of solar photovoltaic panels.

By removing dust accumulation and maintaining optimal temperature conditions, the system enhances solar energy generation efficiency and reduces maintenance requirements. The proposed framework is suitable for large-scale railway renewable energy installations and contributes to the development of sustainable and energy-efficient transportation systems.

The study shows that integrating smart technologies into railway solar infrastructure can improve the consistency of power generation and support dependable operation under varying environmental conditions.

The proposed approach offers a practical solution for railway sectors seeking to strengthen energy sustainability while reducing operational challenges associated with conventional maintenance practices.

In addition, the framework highlights the potential of automation in enhancing the long-term usability of photovoltaic systems installed in railway environments.

Therefore, this work serves as a useful step toward the adoption of smarter and cleaner energy solutions in electric railways, supporting future transportation networks that are both environmentally responsible and technologically advanced.

13. Future Work

Future research can further enhance the proposed system by incorporating advanced technologies such as:

- Internet of Things (IoT) for remote monitoring.
- Artificial Intelligence for predictive maintenance.
- Machine learning algorithms for optimized cleaning schedules.
- Wireless sensor networks for large-scale railway installations.
- Integration with smart grid energy management systems.

14. Reference

- 1.) A. Sayyah, M. N. Horenstein, and M. K. Mazumder, "Energy yield loss caused by dust deposition on photovoltaic panels," *Solar Energy*, vol. 107, pp. 576–604, 2014.
- 2.) A. Kumar Tripathi, M. Aruna, and C. S. N. Murthy, "Performance evaluation of PV panel under dusty condition," *International Journal of Renewable Energy Development*, vol. 6, no. 3, pp. 225–233, 2017.
- 3.) A. Gholami, A. Saboonchi, and A. Alemrajabi, "Experimental study of factors affecting dust accumulation on solar panels," *Renewable Energy*, vol. 92, pp. 239–247, 2016.
- 4.) S. A. Tayel et al., "Enhance the performance of photovoltaic solar panels by a self-cleaning and hydrophobic nanocoating," *Scientific Reports*, vol. 12, 2022
- 5.) A. Sayyah, M. Horenstein, and M. Mazumder, "Mitigation of dust accumulation on solar panels and its

impact on energy yield,” Renewable Energy, vol. 92, pp. 499–505, 2016.

6.) S. R. Anbazhagan, U. Usha, and J. Santhakumar, “Analysis of dust accumulation effects on long-term performance of solar PV panels,” Energy Engineering Journal, 2025.

7.) S. Mekhilef, R. Saidur, and A. Safari, “A review on solar energy use in industries,” Renewable and Sustainable Energy Reviews, vol. 15, pp. 1777–1790, 2011.

8.) J. A. Duffie and W. A. Beckman, Solar Engineering of Thermal Process, 4th ed., Wiley, 2013.

9.) A. A. Kazem and M. T. Chaichan, “Effect of dust on photovoltaic utilization in Oman,” Renewable Energy, vol. 97, pp. 570–580, 2016.

10.) A. Said and H. Walwil, “Fundamental studies on dust fouling effects on PV module performance,” Solar Energy, vol. 107, pp. 328–337, 2014.