

Classification of Photovoltaic Panel Materials using Machine Learning

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ABSTRACT: The rapid increase in end-of-life (EOL) photovoltaic (PV) panels necessitates accurate and reliable techniques for fault detection, material classification, and sustainable recycling. Spectral and electrical signal analysis offer non-destructive approaches for identifying PV conditions and constituent materials such as glass, silicon, polymers, and metals. However, conventional methods suffer from limitations due to sensor noise, spectral distortions, degradation variability, and high-dimensional data complexity, leading to reduced robustness and poor generalization in real-world conditions. To overcome these challenges, this study proposes a two-stage photovoltaic fault prediction framework integrating simulation and machine learning. In the first stage, a detailed PV system is modeled in MATLAB, incorporating a PV array, perturb and observe (P&O) based maximum power point tracking (MPPT) controller, pulse width modulation (PWM) generator, and DC–DC boost converter to generate realistic operational data. In the second stage, the generated data are processed using a Python-based digital twin framework combined with advanced machine learning techniques. A comprehensive preprocessing pipeline is applied, including data cleaning, noise reduction through filtering, and normalization to ensure consistent inputs. Data visualization methods such as heatmaps, univariate and bivariate analysis, and t-SNE projections are used to explore correlations and feature separability. Discriminative features are then extracted using scaling, transformation, and physics-aware spectral descriptors. Finally, a digital twin-guided, physics-aware spectral graph kernel Bayesian model is developed, with parameters optimized using the African Vultures Optimization Algorithm, enabling adaptive, robust, and uncertainty-aware fault prediction and classification in PV systems.

KEYWORDS: Photovoltaic (PV) fault prediction, End-of-life (EOL) panels, Spectral analysis, Digital twin, Machine learning, MATLAB simulation, MPPT, DC–DC boost converter, Feature extraction, Bayesian model, African Vultures Optimization Algorithm, Signal processing.

I. INTRODUCTION

The rapid expansion of solar energy has established photovoltaic (PV) panels as a key component of clean and renewable power generation. With millions of installations worldwide across residential, commercial, and utility sectors, PV systems typically operate efficiently for 20–30 years before reaching their end-of-life (EOL) stage due to performance degradation. As early generations of panels retire, managing EOL photovoltaic materials has become a significant environmental, technological, and policy challenge. While solar energy reduces greenhouse gas emissions, its long-term sustainability depends on addressing the impacts of disposal, recycling, and material recovery from decommissioned panels. PV panels are complex, multi-layered systems composed of materials such as glass, aluminum, silicon, polymers, and trace metals like silver, copper, and lead. Improper disposal can contribute to growing electronic waste (e-waste), leading to landfill pressure and potential soil and water contamination. With the increasing volume of PV waste expected in the coming decades, there is an urgent need for efficient recycling systems, regulatory frameworks, and innovative recovery technologies. At the same time, EOL PV waste presents economic opportunities, as many materials can be recovered and reused, supporting circular economy principles and reducing reliance on virgin resources.

Effective EOL management also contributes to resource conservation and energy security by reducing the need for energy-intensive extraction of critical materials such as silicon and silver. Advanced recycling techniques—including mechanical, thermal, and chemical processes—enable the recovery of high-purity materials, minimizing waste and enhancing sustainability in the solar industry. Public awareness and stakeholder involvement further strengthen these efforts. Aligning with global sustainability goals, EOL PV management promotes green manufacturing and waste

minimization. Innovations in material design and recyclability are improving future panel recovery processes. Overall, integrating advanced recycling, strong regulations, and lifecycle thinking ensures that photovoltaic technology remains environmentally sustainable while supporting long-term energy and economic resilience.

II. PROBLEM STATEMENT

The rapid increase in end-of-life (EOL) photovoltaic (PV) panels has created significant challenges in efficient material identification and fault detection, which are essential for effective recycling and sustainable waste management. As large volumes of PV modules reach the end of their operational lifespan, accurately distinguishing between reusable, recyclable, and hazardous components becomes increasingly complex. Traditional fault detection and spectral classification techniques, which rely on electrical and optical signal analysis, often suffer from limitations such as sensor noise, spectral distortions, and variability caused by long-term degradation. These factors reduce the reliability and consistency of analysis, particularly under real-world operating conditions where environmental and aging effects are prominent.

In addition, PV systems generate high-dimensional electrical and spectral data, making it difficult for conventional analytical methods to extract meaningful patterns and features efficiently. The complexity of such data often leads to poor classification accuracy, limited fault diagnosis capability, and reduced generalization across different panel conditions. As a result, existing approaches are inadequate for handling large-scale, heterogeneous EOL PV datasets. Furthermore, the lack of intelligent, automated, and integrated analysis frameworks limits the efficiency of recycling processes and delays decision-making in waste management systems.

To address these issues, there is a critical need for advanced data-driven methodologies that combine signal processing, machine learning, and physics-based insights. Such approaches can enhance feature extraction, improve classification accuracy, and provide robust fault prediction capabilities. Developing reliable and scalable analytical frameworks is essential to support efficient PV panel recycling, minimize environmental impact, and ensure the long-term sustainability of solar energy systems.

III. PHYSICALLY FEASIBLE FEATURE SPACE FORMULATION

The physically feasible feature space formulation in this study is designed to ensure accurate and reliable photovoltaic (PV) material classification by integrating domain-specific knowledge with data-driven preprocessing techniques. The dataset consists of 3,258 records with 15 features, representing PV panel measurements collected under diverse environmental and operational conditions. It includes key environmental parameters such as temperature, humidity, illumination level, incident angle, and sensor distance, which significantly influence the spectral response of PV materials. In addition, spectral reflectance values are recorded at multiple wavelengths—450 nm, 550 nm, 650 nm, 850 nm, 1100 nm, 1450 nm, and 1950 nm—capturing distinct material characteristics across the visible and infrared spectrum. Each record is uniquely identified using `sample_id` and `panel_id`, while the target variable, material label, denotes the type of PV material, such as glass, silicon, polymers, or metals.

To ensure data quality and consistency, a comprehensive preprocessing pipeline is implemented. Data cleaning is first performed to remove inconsistencies, correct structural errors, and handle missing or noisy values. Subsequently, spectral signal-to-noise ratio (SNR) enhancement techniques are applied to improve the quality of reflectance measurements, reducing the impact of sensor noise and external disturbances. Environmental parameters are then normalized to maintain uniformity across all samples, ensuring that variations in measurement conditions do not bias the learning process.

Feature engineering further refines the dataset into a physically meaningful representation suitable for machine learning. Min–Max scaling is applied to standardize all numerical features into a consistent range, improving model convergence and stability. To analyze high-dimensional relationships and class separability, t-distributed stochastic neighbor embedding (t-SNE) is used for dimensionality reduction and visualization. Additionally, physics-aware spectral descriptors are derived to capture wavelength-dependent patterns and intrinsic material properties embedded in the reflectance data. These engineered features enhance the discriminative power of the dataset, enabling the model to learn more effectively and achieve higher classification accuracy while maintaining physical interpretability.

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IV. CONSTRAINT-BASED CLASSIFICATION MODEL

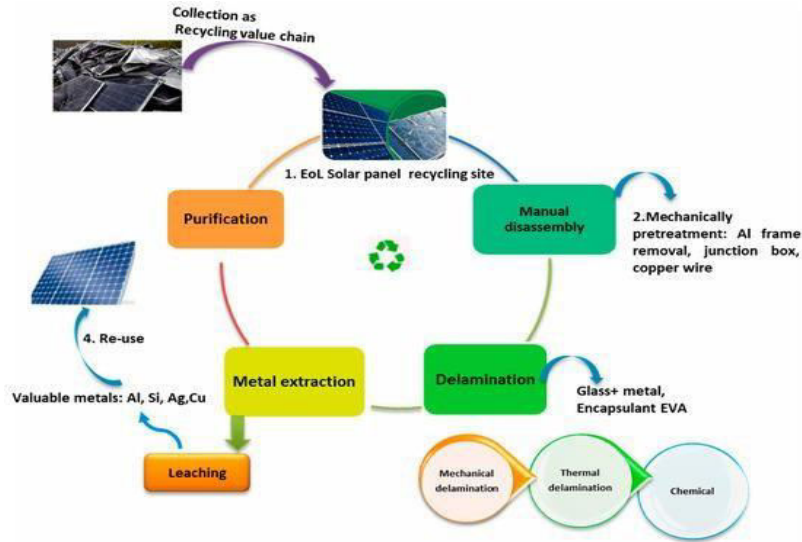
The constraint-based classification model is designed to improve the accuracy and reliability of photovoltaic (PV) material classification by incorporating physical and operational constraints into the learning process. Unlike conventional models that rely purely on statistical patterns, this approach integrates domain knowledge such as spectral consistency, environmental limits, and material-specific characteristics. These constraints ensure that the predicted outputs remain physically meaningful and consistent with real-world PV behavior. The model utilizes engineered features derived from spectral reflectance and environmental parameters, while enforcing bounds on feature relationships to reduce misclassification. Constraint handling also helps in managing noisy and high-dimensional data by restricting the solution space, thereby improving generalization performance. Additionally, optimization techniques are employed to fine-tune model parameters under these constraints, enhancing robustness and interpretability. Overall, the constraint-based classification model provides a more reliable and efficient framework for accurate PV material identification and supports sustainable waste management applications.

V. FUTURE STRATEGIES FOR SUSTAINABLE PV WASTE MANAGEMENT

Future strategies for sustainable photovoltaic (PV) waste management emphasize the integration of eco-friendly design, advanced technologies, and circular economy principles to address the growing volume of end-of-life (EOL) solar panels. A key focus is on designing PV modules for easy disassembly, enabling efficient separation of components such as glass, silicon, and metals. This design-for-recycling approach minimizes material loss and enhances recovery efficiency. The adoption of non-toxic, biodegradable encapsulation materials further reduces environmental risks associated with disposal and recycling processes. Additionally, lightweight and modular panel structures improve transportation, handling, and dismantling at the EOL stage, while reducing reliance on permanent adhesives facilitates easier material separation.

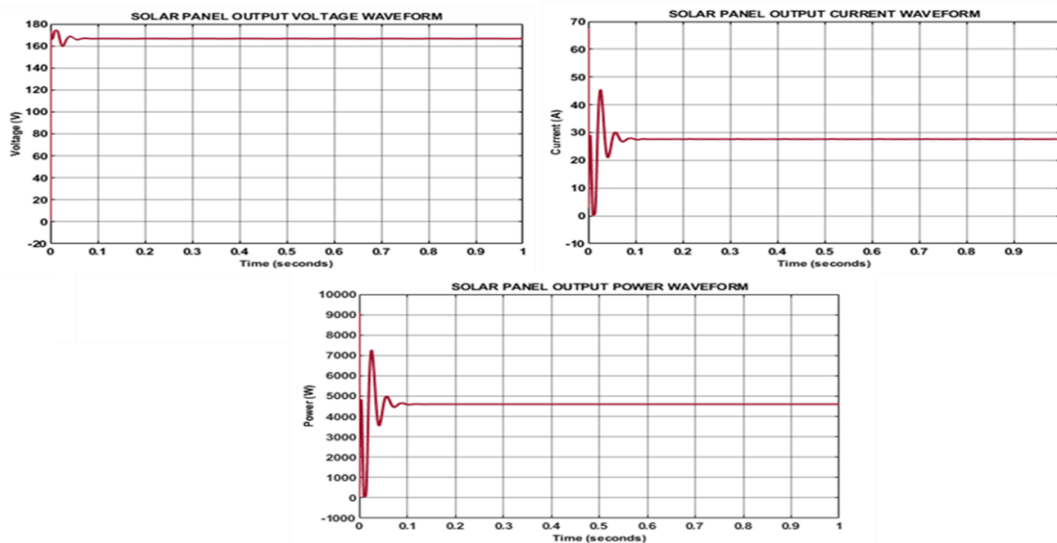
Technological advancements play a crucial role in improving waste management systems. Smart tracking technologies, including digital identification and lifecycle monitoring systems, enable better management of PV panels from installation to disposal. Artificial intelligence (AI) and automation can significantly enhance sorting accuracy and material recovery rates by identifying material types and detecting faults efficiently. Investment in dedicated recycling infrastructure is essential to handle the increasing volume of PV waste and to support large-scale recovery operations. Furthermore, continuous research and innovation in material science are enabling the development of more durable yet recyclable PV components, improving both performance and sustainability.

Public awareness and policy support are equally important in ensuring responsible disposal practices. Educational initiatives encourage users to adopt proper recycling methods, while collaboration between industries, governments, and research institutions strengthens regulatory frameworks and promotes sustainable practices. Circular economy models transform PV waste into valuable resources, reducing dependence on virgin raw materials and lowering overall environmental impact. Tools such as life-cycle assessment (LCA) guide sustainable design and decision-making processes. Overall, these future strategies aim to create a closed-loop system that maximizes resource recovery, minimizes waste generation, and ensures the long-term environmental and economic sustainability of solar energy systems.



VI. RESULTS AND DISCUSSION

POWER TRACKING PERFORMANCE COMPARISON



VII. CONCLUSION

In conclusion, the proposed framework provides a robust and efficient solution for the accurate spectral classification of end-of-life (EOL) photovoltaic (PV) panel materials, effectively addressing challenges associated with complex, noisy, and high-dimensional data. By integrating PV system simulation with advanced data preprocessing and feature engineering techniques, the framework ensures the generation of high-quality, physically consistent input data. This integration enables a more precise representation of spectral and environmental characteristics, thereby enhancing the overall analytical performance and reliability of the system. A key strength of the framework lies in the incorporation of a Digital Twin-guided Spectral Graph Kernel Bayesian Model, which combines data-driven learning with physics-aware insights. This hybrid approach allows the model to capture intricate relationships within spectral features while maintaining consistency with real-world physical behavior. As a result, the model achieves improved classification accuracy and better generalization across varying PV conditions. Furthermore, the application of the African Vultures

Optimization Algorithm for parameter tuning significantly enhances model robustness, adaptability, and convergence efficiency. This optimization technique enables effective handling of uncertainties, noise, and variability, ensuring stable and reliable prediction outcomes. The framework not only delivers high classification performance but also facilitates precise identification of key PV materials such as glass, silicon, polymers, and metals. This capability is essential for enabling efficient recycling, material recovery, and sustainable waste management practices. By supporting accurate material segregation, the system contributes to reducing environmental impact and improving resource utilization. Overall, the proposed approach aligns with circular economy principles by transforming PV waste into valuable resources. Its combination of simulation, machine learning, and optimization makes it a scalable and practical solution for real-world deployment. Ultimately, this framework strengthens the sustainability of the solar energy sector by ensuring environmentally responsible management of EOL PV panels while promoting resource efficiency and long-term ecological balance.

REFERENCES

1. C. He, Y. Zhuo, and Y. Shen, "Improving particle separation and recovery of valuable materials from end-of-life solar panels," *Resources, Conservation and Recycling*, vol. 225, Jan. 15, 2026.
2. O. Khankhoje, H. Bherwani, and R. Biniwale, "Assessing life cycle environmental impacts of solar photovoltaics in India with a focus on end-of-life disposal," *Environ. Sci. Pollut. Res.*, vol. 32, pp. 16098–16119, Jun. 2025.
3. E. Kastanaki, R. Athanasiadou, A. Katsifou, and A. Giannis, "Organic acid-assisted hydrothermal leaching of silver from end-of-life photovoltaic panels," *Appl. Sci.*, vol. 15, no. 12, p. 6383, Jun. 2025.
4. Z. Ma, L. Dong, F. Zhang, J. Liu, Z. Liu, H. Ma, J. Li, and Y. Guo, "Thermal conversion potential of recycled EVA from end-of-life solar panels: Stability assessment, combustion characteristics, and kinetic-thermodynamic profiling," *J. Environ. Chem. Eng.*, vol. 13, no. 5, p. 118087, Oct. 2025.
5. Y. R. Maghraby, A. H. Ibrahim, A. Tayel, H. M. E.-S. Azzazy, and T. Shoeib, "Towards sustainability via recycling solar photovoltaic panels: A review," *Solar Energy*, vol. 285, Jan. 1, 2025.
6. S. Kwon, H. J. Kim, S. Kim, and S. J. Hong, "Sustainability impact evaluation of the recycling of end-of-life crystalline silicon solar photovoltaic panel waste in South Korea," *Sustainability*, vol. 17, no. 2, Jan. 8, 2025.
7. J. Lu, C. Wang, J. Zhu, Y. Wu, and J. Ruan, "Recycling of end-of-life photovoltaic modules: High throughput screening reagents by machine learning and classification of decapsulation mechanisms," *Chemical Engineering Journal*, vol. 521, Oct. 1, 2025.
8. J. Qiu, C. Zhu, B. Ge, Y. Wang, Z. Zhang, J. Han, P. Shi, and Y. Liu, "Manufacturing lithium-ion anodes from silicon recovered from end-of-life solar panels," *Applied Surface Science*, vol. 682, Feb. 15, 2025.
9. Z. Yao, J. Cui, J. Jiang, J. Tong, A. Kumar, P. Romano, F. Vegliò, S. Kumar, J. Liu, and W. Qi, "End-of-life solar panels recycling: Focusing on the kinetic Process Safety and Environmental Protection," vol. 195, Mar. 2025.
10. P. Padhamnath, S. Nalluri, F. Kuśmierczyk, M. Kopyściński, J. Karbowniczek, L. S. Woei, and T. Reindl, "Electrohydraulic fragmentation processing enabling separation and recovery of all components in end-of-life silicon photovoltaic panels," *Solar Energy*, vol. 289, Mar. 15, 2025.
11. F. Almaghrbi, W. Tushar, and R. Sharma, "Stage-wise modelling of energy, emissions, and economic trade-offs in recycling end-of-life photovoltaic panels for circular economy decision-making," *Energy*, vol. 336, Nov. 1, 2025.
12. H. Mumtaz, S. Sobek, M. Sajdak, R. Muzyka, S. Werle, and M. Procek, "Innovative recycling of end-of-life photovoltaic panels with the aim of polymer degradation and valuable chemical production," *Renewable Energy*, vol. 252, Oct. 15, 2025.
13. Z. Yao, J. Tong, R. F. B. Gonçalves, A. Kumar, N. Manić, F. Vegliò, P. Romano, J. Jiang, J. Cui, J. Liu, and W. Qi, "Recycling of end-of-life solar panels: Focusing on the pyrolysis conversion of back sheet from a micro perspective," *Journal of Cleaner Production*, vol. 490, Jan. 20, 2025.
14. L. Q. Luu, T. Q. Nguyen, S. Khakpour, M. Cellura, F. Nocera, N. H. Nguyen, and N. H. Bui, "Material demand and contributions of solar PV end-of-life management to the circular economy: The case of Italy," *Sustainability*, vol. 17, no. 14, Art. no. 6592, Jul. 19, 2025.
15. G. Yan, J. Zhang, S. Liu, X. Song, and Y. Zhang, "An environmentally friendly process for Si recovery from end-of-life photovoltaic panels: Green swelling and mechanical crushing," *Waste Management*, vol. 208, Nov. 2025.



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