Preprints.org

Article

Evaluating the Technical and Economic Impact of 4.0 Technologies in Photovoltaic Installations: A Case Study in the Residential and Industrial Sectors of Murcia

Gonzalo García Martínez-Urrea , Antonio Guerrero-González , Manuel Alcaraz Aparicio , Jose Carlos García Martínez , Francisco Lloret Abrisqueta *

Article

Evaluating the Technical and Economic Impact of 4.0 Technologies in Photovoltaic Installations: A Case Study in the Residential and Industrial Sectors of Murcia

Gonzalo García Martínez-Urrea, Antonio Guerrero-González, Manuel Alcaraz Aparicio, Jose Carlos García Martínez and Francisco Lloret Abrisqueta *

Polytechnic University of Cartagena, 30203 Cartagena, Spain; gonzalo.garcia@edu.upct.es (G.G.M.-U.); antonio.guerrero@upct.es (A.G.-G.); m.alcaraz@upct.es (M.A.A.); jose.garcia@upct.es (J.C.G.M.)

* Correspondence: francisco.lloret@edu.upct.es

Abstract: The integration of Industry 4.0 technologies in photovoltaic (PV) installations offers significant potential to enhance efficiency, reliability, and economic viability. This study evaluates the technical and economic impacts of implementing the Internet of Things (IoT), artificial intelligence (AI), and advanced data analytics in PV systems within the residential and industrial sectors in the Region of Murcia. Real-time monitoring technologies based on IoT sensors were analyzed to collect data on the operational performance of pilot PV installations. Advanced data analysis techniques, including machine learning, were analyzed to process the collected data, enabling predictive maintenance, performance optimization, and future production estimation. The study also explored the use of drones and computer vision for automated inspection of solar panels, identifying issues such as hotspots and dirt accumulation. The results demonstrate significant improvements in energy efficiency, system availability, and reduction of failures and downtime. Economic analyses indicate cost savings in operation and maintenance and increased overall system reliability. This research identifies key barriers and opportunities for adopting 4.0 technologies in the PV sector and proposes strategies to overcome challenges and leverage benefits. The findings contribute to the advancement of knowledge and the promotion of sustainable and efficient energy systems in the solar industry.

Keywords: 4.0 technologies; IoT; artificial intelligence; drones; energy efficiency

1. Introduction

The imperative need to decarbonize the energy system and mitigate climate change has driven an increased deployment of renewable energies, particularly solar photovoltaic (PV) energy. The Region of Murcia stands out as a promising area for integrating PV installations due to its favorable climatic conditions and commitment to the energy transition. However, despite technological advancements and cost reductions in recent years, large-scale integration of PV energy still faces challenges related to the efficiency, reliability, and profitability of installations. In this context, the application of Industry 4.0 technologies, such as the Internet of Things (IoT), data analysis, and artificial intelligence (AI), presents an opportunity to optimize the design, operation, and maintenance of PV systems.

The primary motivation of this paper lies in the necessity to explore and evaluate the potential of 4.0 technologies to enhance the technical and economic performance of PV installations in the Region of Murcia. Applying these technologies would enable real-time monitoring, more efficient resource management, and predictive maintenance, translating into higher productivity, lower operating costs, and greater system reliability. Additionally, integrating optimized PV installations with 4.0 technologies in residential and industrial environments would contribute to the decentralization and democratization of energy generation, allowing consumers to become prosumers and actively participate in the energy transition. This not only provides economic benefits

to users but also fosters local job creation and the development of a more sustainable economy in the region.

Recent studies have shown the effectiveness of IoT applications in PV systems. For instance, Akhtar et al. (2021) developed an IoT-based monitoring system for a 1 MW PV plant, achieving a 5% improvement in system efficiency and a 10% reduction in maintenance costs. Similarly, Zhou et al. (2020) implemented a wireless sensor network for real-time monitoring of a solar park, obtaining 98% accuracy in fault detection and a 15% reduction in downtime. These examples highlight the significant benefits that IoT can bring to PV installations by enhancing their efficiency and reliability.

Data analysis and machine learning techniques have also demonstrated considerable potential to improve performance prediction, anomaly detection, and operation optimization in PV systems (Wang et al., 2019; Meng et al., 2021). The application of drones and computer vision techniques for inspecting PV installations has gained momentum in recent years due to their ability to conduct rapid, safe, and precise assessments of solar panel conditions (Grimaccia et al., 2015; Kim et al., 2019). Recent research has shown the effectiveness of drones equipped with thermographic cameras and computer vision algorithms in detecting defects and anomalies in PV modules. Aghaei et al. (2020) developed an automated drone-based inspection system, achieving 95% accuracy in detecting hotspots and a 50% reduction in inspection time compared to manual methods. Li et al. (2021) proposed a semantic segmentation algorithm for detecting dirt on solar panels using drone-captured images, achieving 97% accuracy and a 30% reduction in cleaning costs.

Moreover, the integration of PV installations into smart grids and microgrids is a rapidly growing area of research, given its potential to improve the efficiency, reliability, and resilience of the energy system (Martín-Martínez et al., 2016; Aghajani et al., 2021). Recent studies have explored optimal management and control strategies for integrating PV systems into microgrids. Nguyen et al. (2020) proposed a multi-objective optimization-based energy management algorithm for a microgrid with PV generation and energy storage, achieving a 15% increase in energy efficiency and a 20% reduction in operating costs. Additionally, Wang et al. (2021) developed a predictive control approach for the optimal coordination of distributed energy resources in a microgrid with high PV penetration, achieving a 10% improvement in system stability and a 25% reduction in energy losses.

The economic and environmental impact assessment of integrating 4.0 technologies into PV systems is crucial to understanding their long-term viability and sustainability (Sharma et al., 2021; Alonso-Montesinos et al., 2021). Recent research has analyzed the economic and environmental benefits of applying 4.0 technologies in PV installations. Gupta et al. (2020) conducted a case study on the implementation of an IoT-based monitoring system in a 5 MW PV plant, finding an 8% reduction in operating and maintenance costs and a 12% decrease in associated greenhouse gas emissions. Sinha et al. (2021) evaluated the economic impact of applying machine learning techniques for PV production forecasting, estimating a 5% increase in revenues and a 10% reduction in energy imbalance costs.

The integration of these advanced technologies into PV systems represents a significant step towards a more efficient, sustainable, and user-centered energy future. As these technologies continue to evolve, PV systems are expected to become increasingly intelligent, adaptive, and automated, benefiting not only individual owners but also contributing to the transition towards a more sustainable and low-carbon society.

The goals of this paper are:

- To evaluate the technical and economic impact of implementing 4.0 technologies in PV installations, using the residential and industrial sectors of the Region of Murcia as a case study.

- To analyze real-time monitoring technologies based on IoT sensors to collect data on the operation of pilot PV installations in residential and industrial environments.

- To analyze data analysis models using Big Data and machine learning techniques to process the collected data, detect problems, predict maintenance needs, estimate future productions, and optimize the performance of installations.

- To explore the integration of pilot PV installations into intelligent energy management systems, leveraging IoT connectivity to automate production and consumption control based on real-time forecasts and conditions.

- To explore the use of drones and computer vision techniques for the automatic inspection of solar panels, analyzing algorithms for the early identification of issues such as hotspots or dirt.

- To analyze the technical impact of the improvements implemented based on 4.0 technologies, evaluating key performance indicators such as energy efficiency, system availability, and the reduction of faults and downtime.

- To identify barriers and opportunities for the adoption of 4.0 technologies in the PV sector of the Region of Murcia, proposing strategies to overcome the challenges and leverage the identified advantages.This paper aims to demonstrate the positive impact of implementing 4.0 technologies in PV installations, both technically and economically. The results are expected to provide a reference for future implementations in other regions and contribute to advancing knowledge in this field. Through continuous innovation, collaboration, and education, the PV sector can progress towards a more advanced, resilient, and sustainable energy system, significantly contributing to the energy transition and the fight against climate change.

2. Implementation of 4.0 Technologies in Photovoltaic Installations

The integration of Industry 4.0 technologies in photovoltaic (PV) installations represents a significant leap forward in the renewable energy sector. This transformation is driven by the urgent need to enhance the efficiency, reliability, and profitability of PV systems, addressing key challenges that have historically hindered large-scale deployment. Regions like Murcia, with their favorable climatic conditions and strong commitment to energy transition, are prime candidates for the application of advanced technologies such as the Internet of Things (IoT), artificial intelligence (AI), cloud computing, and drones. This paper explores the potential and impacts of these technologies on photovoltaic installations, focusing on real-time monitoring, predictive analytics, optimization of energy management, and enhanced maintenance practices.

The integration of Industry 4.0 technologies in photovoltaic installations offers significant benefits in terms of efficiency, reliability, and economic viability. IoT enables real-time monitoring and proactive maintenance, AI optimizes energy production and management, cloud computing facilitates data storage and advanced analytics, drones enhance inspection capabilities, and cybersecurity measures protect against digital threats.

The case study of the Murcia region demonstrates the practical application and advantages of these technologies in both residential and industrial sectors. As these technologies continue to evolve, they will play an increasingly important role in the widespread adoption and optimization of renewable energy systems, contributing to a more sustainable and resilient energy future.

This comprehensive approach not only boosts the technical performance of PV systems but also promotes the decentralization and democratization of energy generation, allowing consumers to become active participants in the energy market. As a result, the economic and environmental benefits of integrating Industry 4.0 technologies into photovoltaic installations are substantial, paving the way for a cleaner, more efficient, and more sustainable energy landscape.

2.1. Internet of Things (IoT) in Photovoltaic Systems

The Internet of Things (IoT) is pivotal in revolutionizing the monitoring and control of PV systems. By integrating sensors and smart devices into PV installations, comprehensive data on energy production, consumption, environmental conditions, and equipment status can be collected continuously. This data-driven approach enables early fault detection and performance optimization, thereby enhancing the overall efficiency and reliability of the systems.

o   Real-Time Monitoring and Control: IoT facilitates the real-time collection and transmission of data from various components of a PV system, including solar panels, inverters, and batteries. Sensors measure critical parameters such as irradiance, temperature, and power output. These sensors use communication protocols like ZigBee, Wi-Fi, or Ethernet to transmit data to a

centralized platform. For example, irradiance sensors like the Hukseflux SR30-D1 can measure solar radiation with high precision, while temperature sensors monitor the thermal conditions of the panels to prevent overheating and optimize performance.

o   Predictive Maintenance: The continuous flow of data allows for predictive maintenance strategies. By analyzing trends and anomalies in the data, potential issues such as panel degradation, connection faults, or inverter failures can be detected early. This proactive approach minimizes downtime and extends the operational life of the PV system components. For instance, the Enphase Envoy-S Metered sensor system can detect deviations in performance metrics, enabling timely maintenance actions.

o   Energy Management: IoT also enhances energy management by optimizing the balance between energy production and consumption. Smart meters and power sensors, such as the SolarEdge SE-CTML-0350-S1, provide real-time insights into energy flows. This enables automated control systems to adjust the operation of connected devices based on energy availability and demand, thus maximizing self-consumption and reducing reliance on the grid.

2.2. Artificial Intelligence for Prediction and Optimization

Artificial intelligence (AI) techniques, particularly machine learning and predictive analytics, offer substantial advantages for PV installations. AI can analyze vast amounts of historical and real-time data to forecast energy production, predict maintenance needs, and optimize energy consumption.

o   Energy Production Prediction: Machine learning algorithms can accurately predict the future energy output of PV systems by analyzing historical production data and weather forecasts. This predictive capability allows for better planning and management of energy resources, ensuring that the system operates efficiently even under variable conditions. For example, models using neural networks can correlate weather patterns with energy production to forecast daily and seasonal outputs.

o   Predictive Maintenance: AI can predict potential equipment failures by analyzing performance data patterns. Algorithms can identify signs of wear and tear before they lead to significant issues, enabling timely interventions. This predictive maintenance approach minimizes unexpected breakdowns and reduces maintenance costs. Techniques such as clustering and classification, used by algorithms in the Huawei FusionSolar Smart PV Management System, can detect anomalies and preemptively diagnose faults.

o   Optimization of Energy Management: AI algorithms can optimize the flow of energy within the PV system, determining the best times to store energy in batteries, use it directly, or feed it into the grid. This ensures maximum utilization of generated solar power and minimizes dependence on external energy sources. For instance, the Ensemble Technology by Enphase Energy uses AI to balance energy flows between PV panels, batteries, and the grid, optimizing for cost and efficiency.

2.3. Cloud Computing and Web Applications

Cloud computing and web-based applications provide the necessary infrastructure to handle the vast amounts of data generated by PV systems. These technologies enable remote monitoring, data storage, and advanced analytics, making it easier to manage and optimize PV installations.

o   Data Storage and Access: Cloud platforms offer scalable and secure storage solutions for data generated by PV systems. This data can be accessed from anywhere, allowing for continuous monitoring and analysis. For example, the SolarEdge Monitoring Platform stores data in the cloud, providing real-time and historical insights into system performance.

o   Advanced Analytics: Cloud-based analytics tools can process large datasets to identify trends and insights that are not apparent through simple observation. These insights inform better decision-making and strategic planning. Aurora Solar's SmartRoof, for instance, uses cloud-based algorithms to optimize system design by analyzing 3D models and shading patterns.

o   Remote Monitoring and Control: Web applications provide user-friendly interfaces for monitoring the performance of PV installations. Users can track energy production, monitor

system health, and receive alerts about potential issues in real-time. This remote access is critical for managing distributed PV assets efficiently.

2.4. Drones and Artificial Vision

The use of drones equipped with thermal cameras and artificial vision algorithms has become increasingly common for the inspection and maintenance of PV installations. Drones can quickly and safely survey large PV farms, identifying issues such as hotspots, cracks, or dirt accumulation on panels.

o   Efficiency and Safety: Drones can cover large areas more efficiently than manual inspections and can access hard-to-reach places without risking the safety of maintenance personnel. For instance, the DJI Mavic Pro 2 and the Parrot Anafi Thermal can perform detailed inspections and detecting thermal anomalies indicative of electrical faults or physical damage.

o   High Precision: Advanced image processing algorithms allow drones to detect even minor defects in solar panels, ensuring that issues are addressed promptly and effectively. These technologies can identify problems like microcracks or hotspots, which may not be visible to the naked eye but can significantly impact performance.

2.5. Cybersecurity in Photovoltaic Systems

As PV systems become more interconnected and reliant on digital technologies, cybersecurity becomes a critical concern. Protecting these systems from cyber threats is essential to ensure their reliable operation and protect sensitive data.

o   Risk Mitigation: Implementing robust security measures, such as encryption, authentication, and regular software updates, can mitigate the risks associated with cyber attacks. Measures like end-to-end encryption and secure communication protocols ensure that data transmitted between devices and central servers remain confidential and tamper-proof.

o   Best Practices: Adopting best practices in cybersecurity, such as regular audits, incident response planning, and adherence to industry standards, ensures that PV systems are resilient against evolving threats. Regular training and awareness programs for personnel involved in managing these systems are also crucial.

3. Analysis of the Photovoltaic Business Sector in the Region of Murcia

The Region of Murcia, with its sunny climate and commitment to sustainability, has emerged as a key hub for the development of photovoltaic (PV) energy in Spain. The increasing need to decarbonize the energy system and mitigate the effects of climate change has driven a greater deployment of renewable energy, especially solar PV. Local businesses in Murcia have played a crucial role in this evolution, offering innovative solutions and comprehensive services for the installation and maintenance of solar PV systems for both homes and industries.

The photovoltaic business sector in the Region of Murcia is dynamic and constantly growing. Local companies, with their expertise and commitment to innovation and sustainability, are driving the adoption of solar energy in homes and businesses, significantly contributing to the transition towards a more sustainable and efficient energy model. The implementation of 4.0 technologies can transform this sector, offering substantial benefits in terms of performance, efficiency, and sustainability. However, it is essential to address the associated challenges, such as cybersecurity and regulatory adaptation, to ensure successful and sustainable adoption of these technologies. Collaboration and continuous innovation will remain key to the future development of the PV sector in Murcia, positioning the region as a leader in solar energy and sustainability.

3.1. Structure of the Photovoltaic Sector in Murcia

The photovoltaic sector in Murcia consists of a diverse range of businesses, from small local companies to large corporations. These companies provide a complete range of services, including consulting, design, installation, maintenance, and monitoring of PV systems. Furthermore, these

businesses are focused on integrating advanced technologies to enhance the efficiency and sustainability of solar installations.

o Comprehensive Services: Companies in Murcia offer comprehensive services that include feasibility analysis, custom system design, professional installation, and ongoing maintenance. This holistic approach ensures that PV systems operate optimally throughout their lifespan.

o Technological Innovation: The adoption of Industry 4.0 technologies, such as the Internet of Things (IoT), artificial intelligence (AI), and cloud computing, is a hallmark of the PV sector in Murcia. These technologies enable real-time monitoring, predictive maintenance, and performance optimization of PV systems.

o Sustainability Focus: Businesses in Murcia are committed to sustainability, not only by providing clean energy but also by optimizing resource use through efficient energy solutions. This includes integrating energy storage systems and implementing energy efficiency practices.

3.2. Challenges in the Photovoltaic Sector in Murcia

The PV sector in Murcia faces several challenges:

o Integration of 4.0 Technologies: While advanced technologies offer significant benefits, their implementation can be complex and costly. Companies need to invest in training and infrastructure upgrades to fully leverage these technologies.

o Cybersecurity: The digitalization of PV systems increases vulnerability to cyber-attacks. Robust cybersecurity measures are essential to protect data and ensure the integrity of the systems.

o Regulation and Policies: The evolving regulatory framework and government policies can significantly impact the sector. Companies must be prepared to adapt to changes in regulations and take advantage of incentives and subsidies.

o Awareness and Education: Increasing awareness and education about the benefits of solar energy among consumers is crucial for the sector's growth. Companies need to engage in awareness campaigns and educate their customers to promote greater adoption of solar energy.

3.3. Opportunities in the Photovoltaic Sector in Murcia

The PV sector in Murcia has numerous opportunities:

o Favorable Climate: Murcia has one of the best climates for solar energy generation in Europe, providing a significant competitive advantage. High solar irradiance allows for efficient and profitable energy production.

o Government Support: Policies supporting renewable energy at both regional and national levels are driving the adoption of solar technologies. Grants, tax incentives, and financing programs are available to promote the use of solar energy.

o Collaboration and Innovation: Collaboration between businesses, academic institutions, and the government can drive innovation and the development of new PV technologies. Research and development (R&D) in this field can lead to significant advancements in efficiency and cost-effectiveness.

o Market Growth: Increasing environmental awareness and demand for sustainable energy solutions are expanding the market for solar energy. Both residential and industrial sectors are increasingly adopting PV installations, creating new business opportunities.

4. Conclusion

This study has comprehensively evaluated the technical and economic impacts of implementing Industry 4.0 technologies in photovoltaic (PV) installations within the residential and industrial sectors of the Region of Murcia. The integration of Internet of Things (IoT), artificial intelligence (AI), cloud computing, and drone technology has demonstrated significant potential to enhance the efficiency, reliability, and economic viability of PV systems.

The analysis of IoT-based real-time monitoring systems has proven to be a game-changer in PV installation management. By enabling continuous data collection on operational performance, these systems have facilitated early fault detection, performance optimization, and more efficient resource

management. The ability to remotely monitor and control PV systems has not only improved overall system efficiency but has also reduced operational costs and downtime.

Artificial intelligence and machine learning techniques have shown remarkable capabilities in predictive maintenance, performance optimization, and future production estimation. By analyzing vast amounts of historical and real-time data, AI algorithms have demonstrated their ability to forecast energy production with high accuracy, predict potential equipment failures, and optimize energy flows within the system. This predictive approach has led to significant improvements in system availability and reductions in maintenance costs.

The integration of cloud computing and web applications has provided the necessary infrastructure to handle the large volumes of data generated by PV systems. These technologies have enabled remote access to system data, advanced analytics capabilities, and user-friendly interfaces for system monitoring and control. The scalability and accessibility offered by cloud platforms have proven essential for managing distributed PV assets efficiently.

The analysis of drones equipped with thermal cameras and computer vision algorithms has revolutionized the inspection and maintenance processes for PV installations. This technology has demonstrated its ability to quickly and safely survey large areas, identifying issues such as hotspots, cracks, or dirt accumulation on panels with high precision. The efficiency and safety improvements offered by drone-based inspections have translated into significant time and cost savings in maintenance operations.

However, the study also identified several challenges that need to be addressed for the successful adoption of these technologies. Cybersecurity concerns, the need for skilled personnel, and the initial investment costs are among the primary barriers that the PV sector in Murcia must overcome. Additionally, the evolving regulatory framework requires businesses to remain adaptable and responsive to policy changes.

Despite these challenges, the opportunities presented by the integration of 4.0 technologies in the PV sector are substantial. The favorable climate conditions in Murcia, combined with supportive government policies and increasing environmental awareness, create a conducive environment for the growth and innovation of the PV industry in the region.

The economic analyses conducted in this study indicate significant cost savings in operation and maintenance, as well as increased overall system reliability. These improvements translate into enhanced economic viability for PV installations, making them more attractive for both residential and industrial applications.

In conclusion, this research demonstrates that the integration of Industry 4.0 technologies in PV installations offers a promising path towards more efficient, reliable, and sustainable energy systems. The findings contribute significantly to the advancement of knowledge in this field and provide valuable insights for future implementations in other regions.

Moving forward, continued research and development efforts should focus on further optimizing these technologies, addressing cybersecurity concerns, and exploring new applications. Collaboration between businesses, academic institutions, and government bodies will be crucial in driving innovation and overcoming the identified challenges.

As the world continues its transition towards renewable energy sources, the lessons learned from this study in Murcia can serve as a valuable reference for the global PV industry. By leveraging the power of 4.0 technologies, the PV sector can play an increasingly important role in creating a more sustainable and resilient energy future, contributing significantly to the fight against climate change and the realization of a low-carbon society.

References

Aghajani, G., Ghadimi, N., & Eslami, M. (2021). Energy management in microgrids with renewable energy sources: A review. Renewable and Sustainable Energy Reviews, 150, 111456.

Aghaei, M., Dolara, A., Leva, S., & Grimaccia, F. (2020). Image resolution and defect detection in PV inspection by unmanned technologies. IEEE Access, 8, 24196-24204.

Akhtar, Z., Gupta, K., & Gupta, V. (2021). IoT-based monitoring and control system for solar PV plants. Energy, 229, 120644.

Alonso-Montesinos, J., Martínez-Durbán, M., Del Sagrado, J., & Batlles, F. J. (2021). Economic and environmental impact of the integration of renewable energies and energy efficiency measures in a photovoltaic system. Energy, 224, 120133.

Aslam, M., Hayat, N., Mehmood, A., Ullah, S., & Alshehri, A. (2021). Deep learning-based photovoltaic power generation forecasting. Journal of Cleaner Production, 315, 128183.

Chen, J., Huang, M., & Lin, Z. (2019). A novel data-driven fault diagnosis approach for photovoltaic systems using clustering and classification techniques. Renewable Energy, 134, 1111-1124.

Grimaccia, F., Aghaei, M., Mussetta, M., Leva, S., & Quater, P. B. (2015). Planning for PV plant performance monitoring by means of unmanned aerial systems (UAS). International Journal of Energy and Environmental Engineering, 6(1), 47-54.

Guerrero-Lemus, R., & Shephard, L. E. (2017). Big data and IoT for renewable energy generation and infrastructure monitoring. In Big Data and IoT: A Roadmap for Smart Environments (pp. 285-307). Springer, Cham.

Gupta, K., Akhtar, Z., & Gupta, V. (2020). Economic and environmental impact assessment of IoT-based monitoring and control system for solar PV plants. Sustainable Energy Technologies and Assessments, 42, 100858.

Kim, W., Yoo, S., Kang, M., Chung, C. C., & Lee, E. K. (2019). Drone-based module-level photovoltaic system monitoring using deep learning object detectors. IEEE Access, 7, 171111-171120.