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Bibliometric Study of Digital Twins in the Solar Energy Sector

Bibliometric Study Of Digital Twins In The Solar Energy Sector

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Summary

Digital Twins (DTs) represent an emerging technology capable of emulating real systems in virtual environments, offering promising solutions for the energy sector. This work presents a bibliometric analysis of the application of Digital Twins in the solar energy sector, aiming to identify trends, gaps, and main research topics. The methodology was based on data collection from the Web of Science and Scopus databases, covering the period from 2009 to 2024, followed by term correlation processing using the VOSviewer *software* . The results indicate that the topic is recent and growing, with a predominant focus on system management, performance optimization, and intensive use of *Machine Learning* for solar resource and power forecasting.

It can be concluded that research in this area is intrinsically linked to the modernization of power plants and operational efficiency, pointing to a vast field of future investigations.
Keywords: Digital Twins. Solar Energy. Bibliometrics. VOSviewer. Optimization.

Abstract

Digital Twins (DT) represent an emerging technology capable of emulating real systems in virtual environments, offering promising solutions for the energy sector. This paper presents a bibliometric analysis of Digital Twins applications in the solar energy sector, aiming to identify trends, gaps, and main research topics. The methodology relied on data collection from Web of Science and Scopus databases, covering the period from 2009 to 2024, followed by term correlation processing using VOSviewer software. Results indicate that the topic is recent and growing, with a predominant focus on system management, performance optimization, and intensive use of Machine Learning for solar resource and power forecasting. It is concluded that research in the area is intrinsically linked to plant modernization and operational efficiency, pointing to a vast field for future investigations.
Keywords: Digital Twins. SolarEnergy. Bibliometrics. VOSviewer. Optimization.

1. INTRODUCTION

Digital Twins (DTs) are a set of adaptive models that emulate the

The behavior of a real system in a virtual environment, using sensor measurements to...

to monitor the life cycle of equipment (SEMERARO et al., 2021). From the GD, analyses

Effective and more cost-effective solutions can be implemented in areas such as improving...

System, fault detection and maintenance planning.

Digital twins are one of the most impactful current technologies (SLEITI et al., 2022) and

They are a trend in highly complex applications (YAO et al., 2023). The energy sector figures

among the main areas of application of digital twins (TAO et al., 2022), in which will be

fundamental in the modernization of plants, resulting in reduced operating costs and

management improvement (GHENAI et al., 2022).

Given the relevance of the topic to the energy sector and the publications on the subject...

The topics are quite recent, so a survey of the main related areas is a strategy.

This is important for fostering research. It allows for a better understanding of which topics are most important.

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related to the topic. In this sense, this work proposes to be a bibliometric analysis on
Digital twins in the context of the solar energy sector.

Bibliometrics is a research technique that uses statistical methods to analyze and measure data.
the published literature (BROADUS, 1987). It is relevant because it allows quantifying the impact and the
The relevance of a research field, identifying emerging trends, and understanding its structure and...
dynamics of the field (MINGERS and LEYDESDORFF, 2015). In the case of this work, bibliometrics
It will be important to identify and analyze the main trends and topics in the literature on twins.
Digital technologies in the solar energy sector.

2. THEORETICAL FRAMEWORK

In the solar energy sector, the topic of Digital Twins is quite recent and presents several...
research ramifications. Current literature shows that most investigations address the
Development of distributed generation (DG) for specific subsystems.

Artetxe et al. (2023), Gui et al. (2023) and Ullah et al. (2023) focus their studies on inverters,
while Khaled et al. (2020) focus on photovoltaic modules. In addition to the components
In isolated cases, there is a strong focus on the management and control of the plant as a whole.
as explored by several authors (GUO et al., 2023; HUANG et al., 2023; LI et al., 2023;
TUOMIRANTA et al., 2021; YOU et al., 2022; YUAN and XIE, 2023).

Another area of note is performance analysis, investigated by Hong and Pula (2023) and
Natgunanathan et al. (2023). There are also other diverse applications that make up the state of the art.
current (CHENG et al., 2023; RAZO et al., 2020; SEHRAWAT et al., 2023), demonstrating the
The versatility of technology in the photovoltaic field.

3. MATERIALS AND METHODS

For this bibliometric study, information from the following databases was used:
Scopus and Web of Science data were used as primary data sources.

Initially, the databases were consulted using the search query: “Digital Twin AND
(Solar Energy OR Solar PV OR Solar Power). The goal was to find titles that possessed such characteristics.
Keywords in the title or abstract. This approach ensures that the focus is on articles whose theme...
The main focus should be on digital twins in the solar energy sector, avoiding articles that only mention distributed generation (DG).
Briefly, in another context within the solar sector.

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Subsequently, the extracted data served as input for the VOSviewer software.
Used to organize and visualize bibliometric networks and understand which research trends are emerging.
more related to the topic of digital twins in the solar energy sector.

A complementary qualitative analysis of the main problems studied by the titles of
The database analysis was performed using the GPT-4 tool to examine the abstracts of the titles.
found.

4. RESULTS AND DISCUSSION

The results of the consultation are presented in Table 1. It is noteworthy that the literature on the
The topic began to emerge in 2009 in both databases, which highlights how recent it is.
The concept approach. The number of titles found is similar in both databases, with 162 titles.
in Web of Science and 141 in Scopus. Additionally, the total citations per database for the titles.
The number of studies found during the study period is around 1000, with 1018 citations in the Web of Science.
and 892 in Scopus.

Table 1. Results of the Database Query.

Database	Period of Occurrence of Titles	Quotes	Total Titles Found
Web of Science	2009 - 2024	1018	162
Scopus	2009 - 2024	892	141

Source: The authors.

Next, the results of the database queries were used as input for
The analysis of correlated terms was conducted using the VOSViewer software. In the Web of...
In Science, 967 terms were identified, while in Scopus, 1532 terms were found.
Of these, VOSViewer selected 12 terms from Web of Science and 16 terms from Scopus for analysis.

These selected terms meet the relevance criterion, considering the correlation between
They and the minimum frequency of simultaneous occurrences in the title and abstract of the articles. The limits
The minimum occurrence thresholds established were 8 for the Web of Science analysis and 12 for the...
Scopus.

Figures 1 and 2 show the maps of related terms generated by VOSViewer, where
Each color represents a grouping of terms, and the size of the circle indicates the magnitude of the correlation.

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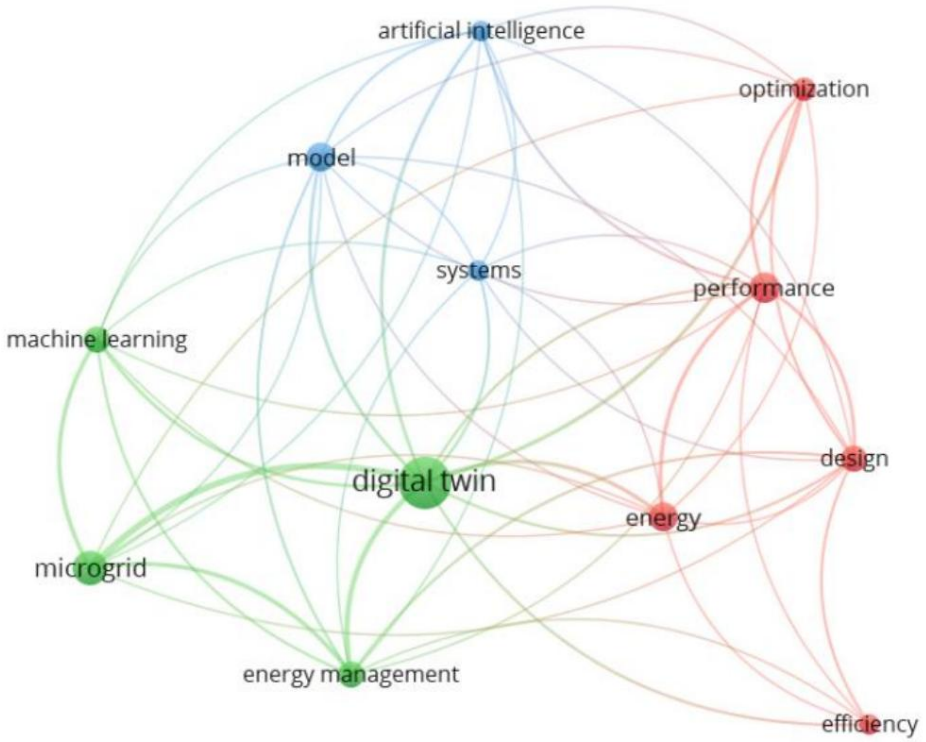

Figure 1. Correlation Map of Terms found from the search for titles on the Web of Science, using a minimum keyword occurrence of 8.

In Figure 1, it is noticeable, from the size of the circles, that the terms microgrid, performance, model Machine learning and other technologies are highly correlated with the study of digital twins in the field of Solar energy. This suggests that the development of distributed generation involves the use of various models. including machine learning, aimed at improving system performance.

An interesting observation is that the terms grouped in red suggest digital twins.

They have been applied in solar energy systems with the aim of improving energy performance.

(performance), based on various optimizations that promote efficiency (optimization and efficiency),

And this has been done since the design phase of the project.

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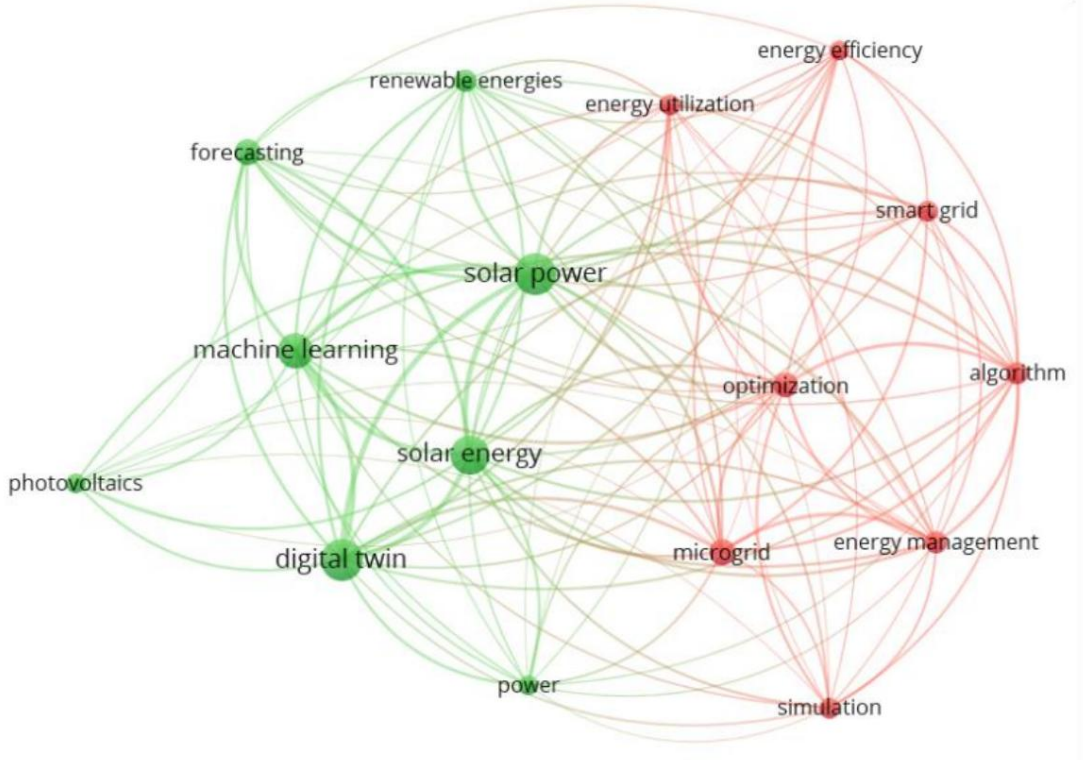

Figure 2. Correlation Map of Terms found from the Scopus title search.
using a minimum keyword occurrence of 12.

On the other hand, in Figure 2, excluding the expected terms *solar power* and *solar energy,* the The terms *machine learning, forecasting, optimization ,* and *energy management* also suggest that Using models to improve system management. Furthermore, a conclusion that...
One takeaway from the green cluster is that the areas of forecasting and *machine learning* are... extremely relevant to the field of digital twins in the solar energy sector, including photovoltaic.

Finally, the results of the qualitative analysis of the abstracts via GPT-4 for the Web of Science. These are presented in Table 2. The predominant themes are associated with the application of Gemini. Digital tools to enhance the management of solar systems, with a particular focus on models. forecasting solar resources and power generation.

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Table 2. Main problems analyzed in the Web of Science titles.

Problem	Description
Energy Resource Management Distributed	An approach to understanding and managing the dynamic nature of photovoltaic solar power plants due to the variability and uncertainty generated by weather conditions.
Plant Operations Optimization Photovoltaics	Using artificial intelligence methods to create short-term forecasting models to optimize the operations and controls of photovoltaic plants.
Improving Operational Efficiency:	Developing machine learning algorithms to improve the operation and efficiency of photovoltaic plants and detect potential component failures early.
Maximizing the Maximum Point Power (MPPT)	Implementation of reinforcement learning-based control to increase the speed and efficiency of MPPT controllers in solar power systems.

Source: The authors.

In turn, Table 3 reveals the most studied problems in Scopus. Just like on the Web.
In the journal *Of Science*, there is an emphasis on the use of Digital Twins for resource and risk prediction.
power, with an additional focus on load consumption analysis.

Table 3. Main problems analyzed in Scopus titles.

Problem	Description
Load Forecast	Development of short-term load forecasting models for solar-powered smart grids, focusing on quantifying uncertainty and maximizing the modeling of the forecast interval.
Performance Optimization	Using optimization algorithms, such as the *White Shark Optimizer,* to improve the performance of forecasting models.
Solar Resource Analysis	Identifying the most relevant meteorological data for forecasting photovoltaic energy generation.
Improved Forecast Accuracy	Combining parallel convolutional neural networks and bidirectional long-term and short-term memory networks to predict photovoltaic energy generation and use real-time data for correction.

FINAL CONSIDERATIONS

This work carried out a bibliometric study on digital twins in the solar energy sector.
using information extracted from titles in the Web of Science and Scopus databases. It was
It was observed that the presence of titles related to this topic in the databases studied is a
This is a recent phenomenon, beginning in 2009, which highlights its novelty and emerging relevance.

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field of study. This also indicates a need for further research, as there are many
Topics that still need to be studied.

It is worth noting that the bibliometric study presented also provided term maps.
related topics, which serve as a guide to identifying the most relevant topics when it comes to
Distributed generation (DG) in the context of solar energy. From these maps, it was possible to discern that the main...
Applications are primarily focused on systems management, aiming for optimization.
Energy. For this, several models are used, with *machine learning* models being the most common.
highlighted.

It is also important to highlight that, using GPT-4, an analysis was performed of
The main problems studied are listed in the Web of Science and Scopus databases. The main problems, of
In general, they were related to optimizing system management, focusing on
Predictions of solar resources, power generation, and load. For this, primarily using
optimization and *machine learning models.*

These findings suggest that the implementation of digital twins in the solar energy sector...
It is intrinsically linked to the use of advanced modeling and optimization techniques. This highlights the...
The importance of continuous research and the development of new approaches and technologies in this area.
emerging and rapidly growing. The bibliometric analysis carried out in this work, therefore, provides
a basis for future investigations in this promising field of research.

REFERENCES

ARTETXE, E.; URALDE, J.; BARAMBONES, O.; CALVO, I.; MARTIN, I. Maximum Power Point Tracker Controller for Solar Photovoltaic Based on Reinforcement Learning Agent with a Digital Twin. **Mathematics,** vol. 11, 2023. DOI: 10.3390/math11092166.

BROADUS, RN Toward a definition of “bibliometrics.” **Scientometrics,** vol. 12, p. 373–379, 1987. DOI: 10.1007/BF02016680.

CHENG, T.; Zhu, X.; YANG, F.; WANG, W. Machine learning enabled learning-based optimization algorithm in digital twin simulation for management of smart islanded solar-based microgrids. **Solar Energy,** vol. 250, p. 241–247, 2023. DOI: 10.1016/j.solener.2022.12.040.

GHENAI, C.; HUSEIN, LA; AL NAHLAWI, M.; HAMID, AK; BETTAYEB, M. Recent trends of digital twin technologies in the energy sector: A comprehensive review. **Sustainable Energy Technologies and Assessments,** v. 54, 2022. DOI: 10.1016/j.seta.2022.102837.

GUI, Y. et al. Automatic voltage regulation application for PV inverters in low-voltage distribution grids – A digital twin approach. **International Journal of Electrical Power & Energy Systems,** vol. 149, 109022, 2023. DOI: 10.1016/j.ijepes.2023.109022.

GUO, Z. et al. Intelligent Digital Twin Modeling for Hybrid PV-SOFC Power Generation System. **Energies,** vol. 16, 2023. DOI: 10.3390/en16062806.

Year V, v.2 2025 | Submission: November 28, 2025 | Accepted: November 30, 2025 | Publication: December 2, 2025

HONG, YY; PULA, RA Diagnosis of PV faults using digital twin and convolutional mixer with LoRa notification system. **Energy Reports,** vol. 9, p. 1963–1976, 2023. DOI: 10.1016/j.egyr.2023.01.011.

HUANG, J.; KOROTEEV, DD; RYNKOVSKAYA, M. Machine learning-based demand response in PV-based smart home considering energy management in digital twin. **Solar Energy,** vol. 252, p. 8–19, 2023. DOI: 10.1016/j.solener.2023.01.044.

KHALED, N.; PATTEL, B.; SIDDIQUI, A. Digital twin model creation of solar panels. In: *Digital Twin Development and Deployment on the Cloud.* Elsevier, 2020. p. 137–162. DOI: 10.1016/b978-0-12-821631-6.00006-2.

LI, Y.; TAO, Q.; GONG, Y. Digital twin simulation for integration of blockchain and internet of things for optimal smart management of PV-based connected microgrids. **Solar Energy,** vol. 251, p. 306–314, 2023. DOI: 10.1016/j.solener.2023.01.013.

MINGERS, J.; LEYDESDORFF, L. A review of theory and practice in scientometrics. **European Journal of Operational Research,** vol. 246, p. 1–19, 2015. DOI: 10.1016/j.ejor.2015.04.002.

NATGUNANATHAN, I. et al. Deakin Microgrid Digital Twin and Analysis of AI Models for Power Generation Prediction. **Energy Conversion and Management:** X, 100370, 2023. DOI: 10.1016/j.ecmx.2023.100370.

RAZO, DEG et al. A genetic algorithm approach as a self-learning and optimization tool for PV power simulation and digital twinning. **Energies,** vol. 13, 2020. DOI: 10.3390/en13246712.

SEHRAWAT, N.; VASHISHT, S.; SINGH, A. Solar irradiance forecasting models using machine learning techniques and digital twin: A case study with comparison. **International Journal of Intelligent Networks,** vol. 4, p. 90–102, 2023. DOI: 10.1016/j.ijin.2023.04.001.

SEMERARO, C.; LEZOCHE, M.; PANETTO, H.; DASSISTI, M. Digital twin paradigm: A systematic literature review. **Computers in Industry,** vol. 130, 2021. DOI: 10.1016/j.compind.2021.103469.

SLEITI, AK; KAPAT, JS; VESELY, L. Digital twin in energy industry: Proposed robust digital twin for power plants and other complex capital-intensive large engineering systems. **Energy Reports,** vol. 8, p. 3704–3726, 2022. DOI: 10.1016/j.egyr.2022.02.305.

TAO, F.; XIAO, B.; IQ, Q.; CHENG, J.; JI, P. Digital twin modeling. **Journal of Manufacturing Systems,** vol. 64, p. 372–389, 2022. DOI: 10.1016/j.jmsy.2022.06.015.

TUOMIRANTA, A. et al. Auto-Parametrizing the Digital Twin of Photovoltaic Power Systems. In: *38th European Photovoltaic Solar Energy Conference and Exhibition,* 2021. p. 1022–1027. DOI: 10.4229/EUPVSEC20212021-5DO.1.4.

ULLAH, SMS et al. Techno-economic impacts of Volt-VAR control on the high penetration of solar PV interconnection. **Cleaner Energy Systems,** vol. 5, 100067, 2023. DOI: 10.1016/j.cles.2023.100067.

YAO, JF et al. Systematic review of digital twin technology and applications. **Visual Computing for Industry, Biomedicine, and Art,** v. 6, 2023. DOI: 10.1186/s42492-023-00137-4.

Year V, v.2 2025 | Submission: November 28, 2025 | Accepted: November 30, 2025 | Publication: December 2, 2025

YOU, M. et al. Digital twins based day-ahead integrated energy system scheduling under load and renewable uncertainties. **Applied Energy,** vol. 305, 2022. DOI: energy 10.1016/ j.apenergy.2021.117899.

YUAN, G.; XIE, F. Digital Twin-Based economic assessment of solar energy in smart microgrids using reinforcement learning technique. **Solar Energy,** vol. 250, p. 398–408, 2023. DOI: 10.1016/j.solener.2022.12.031.