1. Integrating Digital Twin Technology in Energy Management: A
2. Review of Smart Building Solutions

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1. Abstract
2. Digital Twins (DTs) represent a transformative approach to managing smart building

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| systems, particularly in optimizing energy consumption and integrating renewable energy |
| sources. This review examines the evolution and application of DT technology in smart |
| buildings, highlighting how real-time data synchronization and predictive modeling enhance |
| energy management strategies. By creating virtual replicas of physical structures, DTs allow for |
| precise monitoring and analysis of energy flows, facilitating proactive responses to changing |
| demands and improving operational efficiency. The integration of renewable energy sources, |
| such as solar panels and wind turbines, is explored, displaying how DTs can manage variability |
| and optimize use based on predictive analytics. This review also addresses challenges and |
| future directions in the deployment of Digital Twins in energy management, emphasizing the |
| need for robust data management, cyber security measures, and interdisciplinary collaboration |
| to fully realize their potential. Overall, the application of Digital Twins in smart building systems |
| promises significant advancements in energy efficiency and sustainability. This study explores |
| the integration of digital twin technology in smart building energy management, highlighting its |
| potential to enhance efficiency, optimize energy consumption, and improve overall |
| sustainability. By reviewing recent advancements, this research provides valuable insights into |
| how digital twins can revolutionize energy management strategies, paving the way for smarter |

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1. and more adaptive building solutions.
2. **Keywords**: Digital Twins, Energy Management, Smart Buildings, Renewable Energy Integration, Energy
3. Optimization Building Information Modeling (BIM).

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# 1. INTRODUCTION

1. As urbanization accelerates and the demand for sustainable energy solutions intensifies, the need for
2. innovative technologies in building management has never been more pressing. Smart buildings,
3. equipped with intelligent systems that enhance operational efficiency and reduce environmental impact,
4. have emerged as a key solution to these challenges . Among the various technological advancements,
5. Digital Twins (DTs) stand out as a revolutionary concept that leverages real-time data to create virtual
6. replicas of physical assets. This review focuses on the integration of Digital Twin technology within smart
7. building systems, particularly in the context of renewable energy management. Digital Twins enable the
8. continuous monitoring and analysis of energy consumption patterns, allowing for dynamic adjustments
9. that optimize performance. By simulating various scenarios and incorporating renewable energy sources
10. such as solar and wind, DTs facilitate a more sustainable and resilient approach to energy management.
11. Furthermore, the use of Digital Twins allows building managers to assess the impact of integrating
12. renewables on overall energy systems, leading to improved decision-making and enhanced operational
13. strategies. This introduction outlines the significance of DTs in addressing the complexities of energy
14. consumption and renewable integration, setting the stage for a detailed exploration of their applications,
15. benefits, and challenges in smart building systems. The subsequent sections will delve into technological
16. advancements, and future directions to emphasize the pivotal role of Digital Twins in revolutionizing
17. energy management in the built environment.With the rapid advancement of smart building technologies,
18. the need for innovative energy management solutions has become more critical, making the integration of
19. digital twin technology essential for enhancing efficiency and sustainability.This research highlights the
20. role of digital twin technology in optimizing energy consumption in smart buildings, improving their
21. adaptability to operational changes and reducing energy waste. By reviewing the latest developments in
22. this field, this study provides a comprehensive insight into how digital twin technology can be leveraged
23. for intelligent energy management, paving the way for more efficient and sustainable strategies.
24. ***2. RELATED WORK***
25. The concept of Digital Twins has gained traction in various fields, with significant applications
26. emerging in energy management and smart building systems. Numerous studies have explored the
27. integration of Digital Twin technology in enhancing operational efficiency and sustainability in built
28. environments. Recent research has proposed several of implementing Digital Twins in smart buildings to
29. improve decision-making capabilities and enhance energy efficiency by dynamically adjusting energy
30. usage based on predictive models.

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1. ***2.1. Integration of BIM and IoT in Smart Building***
2. BIM and DT, when integrated with BAS and MS, enhance building management by improving
3. energy efficiency assessment through multi-factor modeling. This leads to better decision-making and
4. significant energy savings.[1]. Digital twins, leveraging IoT data and BIM, revolutionize energy
5. management by optimizing consumption, integrating renewables, and influencing user behavior, as
6. demonstrated by real-world applications.[2]. Digital twins, powered by IoT, optimize energy management
7. for diverse sources like solar, wind, and hydro. They gather real-time data to predict faults, plan
8. maintenance, and improve overall performance, despite challenges in data quality and model complexity
9. [3].
10. BIM and IoT integration, facilitated by tools like Revit DB Link, Grasshopper, and Dynamo,
11. creates a comprehensive building model. This integrated model enhances monitoring, control, and
12. optimization, leveraging real-time sensor data and building information. However, challenges like data
13. quality and security must be addressed.[4]. Digital twins, enhanced by machine learning, optimize energy
14. systems by predicting demand, detecting anomalies, and improving efficiency. However, challenges in
15. data quality and security must be addressed for successful implementation.[5]. Design Builder optimizes
16. building design by simulating energy performance and integrating with digital twins. This leads to more
17. efficient, comfortable, and sustainable buildings. [6]. Digital twins optimize BIPV systems by enabling real-
18. time monitoring, performance simulation, and predictive maintenance, leading to improved efficiency and
19. reduced costs.[7] . Product Lifecycle Management (PLM) streamlines product development by managing
20. data, improving collaboration, and optimizing processes, resulting in faster time-to-market, higher quality,
21. and reduced costs.[8].
22. Digital twins simulate real-world city scenarios to analyze air quality, identify pollution sources,
23. and evaluate mitigation strategies. This technology aids in developing sustainable urban management
24. practices and improving public health. [9]. The research aims to address the challenge of estimating solar
25. radiation on building facades in urban areas by developing an algorithm that leverages LiDAR data and
26. solar irradiance measurements. This will improve energy efficiency and sustainable urban planning.[10].
27. The research aims to optimize solar energy utilization by integrating LiDAR with BIM. This approach
28. creates accurate building models, enabling the optimal placement and sizing of solar panels for maximum
29. energy generation [11].
30. The research develops an automated design tool for distributed PV systems using BIM and
31. optimization techniques. This tool improves design efficiency, increases power output, and reduces costs
32. by considering complex environmental factors.[12]. The research aims to streamline BIPV system design
33. by creating a unified platform that integrates multiple design elements. This platform improves efficiency
34. and accuracy, reducing time and costs. [13]. The research aims to optimize solar panel installation in
35. tropical areas by using BIM to analyze solar radiation on building surfaces. This approach identifies
36. optimal locations for solar panels, maximizing energy generation and addressing energy needs.[14].
37. The research develops an ANN-based forecasting model for BIPV systems using satellite
38. imagery. This model improves energy production management and grid stability by accurately predicting
39. solar radiation fluctuations.[15]. The research optimizes BIPV system design in complex building
40. geometries to mitigate partial shading effects. Using BIM and genetic algorithms, the study identifies the
41. optimal layout for solar panels, maximizing energy production while considering shading factors [16].

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## 2.2. Exploring Digital Twins Technology

1. BIM and DT, when combined, enhance building sustainability by enabling datadriven design,
2. optimizing energy efficiency, and integrating renewable energy sources. This approach leads to more
3. environmentally friendly and cost-effective buildings.[17]. The research addresses the challenge of
4. accurately predicting BIPV and BAPV system performance by using AI techniques to analyze various
5. factors like weather and shading patterns. This leads to improved system design and performance
6. evaluation.[18]. Digital twins, created using drone data, provide a 3D virtual replica of large-scale solar
7. power systems. This technology enables efficient fault detection and maintenance planning, increasing
8. system efficiency and reducing costs.[19]. The research proposes a new solution combining digital twin
9. technology and big data to improve energy management in energyintensive industries. This approach
10. enables continuous process improvement, leading to increased efficiency and reduced environmental
11. impact .[20].
12. The research proposes integrating PCM into smart buildings and using digital twin technology to
13. optimize energy consumption. This approach improves energy efficiency and reduces environmental and
14. economic costs.[21]. The research proposes using digital twin technology and AI to optimize energy
15. consumption in residential areas. By analyzing energy data and predicting needs, this approach promotes
16. sustainable and efficient energy management. [22].The research explores the feasibility of NZEBs in
17. existing buildings. By combining technical and financial analysis, it evaluates various NZEB options using
18. a novel approach involving hierarchy-flow charts and BIM. This approach demonstrates the potential for
19. significant energy savings and reduced environmental impact.[23].
20. The research develops a digital twin model integrated with a convolutional mixer and LoRa
21. notification system for efficient fault diagnosis in PV systems. This approach improves system reliability
22. and maintenance by enabling real-time fault detection and notification.[24]. Digital-PV is a digital twin
23. platform that simulates autonomous aerial monitoring of PV power plants. It enables testing and
24. optimization of various monitoring strategies, including fault detection and path planning. The platform
25. also generates data for training AI models to improve PV plant monitoring efficiency.[25].

# 2.3. Integrating Digital Twins with PV and Solar Systems

1. The research develops a digital twin model for fault diagnosis in distributed solar energy
2. systems. By comparing estimated and measured outputs, the model accurately detects faults, improving
3. system performance and reliability.[26]. The research develops a lightweight digital twin for real-time
4. temperature monitoring in PV boost converters. This model, based on FEM simulations and a lookup
5. table, accurately predicts temperatures, enabling optimized performance and risk mitigation.[27]. The
6. research develops a simulation platform to study BIPV system behavior under various conditions,
7. including faults. By analyzing I-V curves, the platform enables accurate fault diagnosis, improving system
8. maintenance and reliability.[28]. The research proposes an intelligent system to manage energy
9. consumption in commercial buildings, focusing on HVAC systems. By leveraging predictive control and
10. building thermal mass, the system reduces peak demand, optimizes energy use, and provides demand
11. response services to the grid.[29].
12. The research proposes a smart home system that combines solar panels, energy storage, and
13. machine learning to reduce electricity costs and improve grid stability. This system optimizes energy
14. consumption by intelligently scheduling appliances and participating in energy-saving programs.[30]. The
15. research proposes smart energy management systems that use machine learning to optimize appliance
16. scheduling and participate in energy-saving programs. This approach reduces household electricity bills
17. and improves grid performance.[31]. This study explores the use of demand response (DR) and
18. reinforcement learning (RL) to optimize residential load scheduling in smart micro grids with renewable
19. energy, considering user preferences and costeffectiveness.[32]. The research proposes an advanced
20. control system to optimize energy consumption and distribution in a smart building integrated with a micro
21. grid and electric vehicles. This system aims to reduce costs and enhance sustainability by coordinating
22. energy flows between the building and vehicles.[33].
23. This research introduces a novel method for Maximum Power Point Tracking (MPPT) in solar
24. cells using an improved intelligent algorithm. This method outperforms traditional tracking methods and
25. current optimization algorithms in terms of speed, accuracy, and stability, especially under varying
26. environmental conditions.[34]. This study introduces an ANFIS-based maximum power point tracker
27. (MPPT) to optimize solar photovoltaic systems. It enhances a DC-DC converter connected to a 400 W PV
28. array, evaluated using MATLAB/SIMULINK. The controller demonstrates effective tracking speed and
29. dynamic response under varying conditions.[35]. The research employs a neural network (BPNN) to train
30. a solar system to determine the optimal voltage under varying conditions. This innovative technique
31. enables the system to generate the maximum possible electrical power from each solar panel. [36].
32. An improved MPPT algorithm is proposed that combines PI controllers for voltage and current
33. regulation with an incremental conductance (INC) method for duty cycle control.[37]. This research aims
34. to maximize power output from PV systems by integrating a novel control approach that addresses
35. weather fluctuations. This approach combines a modified fuzzy logic controller, a DC-DC boost converter,
36. and a battery management system for optimized performance.[38]. This research optimizes photovoltaic
37. (PV) array performance in shaded conditions. It achieves this by employing a modified Sudoku-based
38. panel arrangement within a Total-Cross-Tied (T-C-T) system, resulting in enhanced power output,
39. efficiency, and reduced losses. [39].
40. This research enhances grid-tied PV system performance by optimizing its design. Key
41. advancements include a rapid and efficient MPPT algorithm and optimized component selection, resulting
42. in improved power extraction and reduced complexity.[40]. The research introduces a new FLC-based
43. MPPT algorithm for photovoltaic systems. By incorporating a third variable, the algorithm improves
44. tracking accuracy and reduces oscillations, leading to higher efficiency and faster response times
45. compared to traditional methods.[41]. The research employs a genetic algorithm to analyze solar energy
46. production data, leading to accurate parameter determination. This enables the creation of a precise
47. digital model, improving system performance and maintenance planning for large-scale solar power
48. systems. [42].
49. The research addresses the limitations of BIPV systems in Asian countries by proposing
50. colored BIPV solutions. Using BIM, the study demonstrates the potential of colored PV systems to
51. generate significant clean energy while preserving architectural aesthetics.[43]. The research proposes a
52. novel approach combining RF and LSTM networks to predict energy consumption in public buildings. By
53. applying this method during early design stages, energy efficiency and sustainability can be significantly
54. improved. [44].

## CONCLUSION

1. This review highlights the transformative potential of Digital Twin technology in enhancing energy
2. management within smart building solutions. Digital Twins bridge the gap between physical and digital
3. environments, enabling real-time monitoring, predictive analytics, and informed decision-making. By
4. integrating IoT sensors and data analytics, Digital Twins facilitate improved energy efficiency, operational
5. optimization, and sustainability in building management. The literature demonstrates that the application
6. of Digital Twins can lead to significant reductions in energy consumption and costs while ensuring
7. occupant comfort and safety. Case studies reveal successful implementations in various settings,
8. underscoring the versatility and adaptability of this technology across diverse building types. However,
9. challenges remain in the broader adoption of Digital Twins, including data interoperability, cyber security,
10. and the need for standardized frameworks. To fully realize the benefits of Digital Twin technology, further
11. research is essential to address these obstacles and to enhance the integration strategies within existing
12. building infrastructure. In conclusion, Digital Twin technology represents a promising advancement in the
13. field of energy management for smart buildings. Continued exploration of its capabilities and innovations
14. will be crucial in paving the way for more efficient, sustainable, and intelligent built environments.

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207 **REFERENCES**

208 Walczyk, G. and A. Ożadowicz, Building Information Modeling and Digital Twins for Functional and Technical

209 Design of Smart Buildings with Distributed IoT Networks—Review and New Challenges Discussion.

210 Future Internet, 2024. 16(7): p. 225.

211 Ahmadi, M., Building Information Modeling and Internet of Thing for supporting Energy Management in Digital

212 twin. 2021.

213 Kavousi-Fard, A., et al., Digital Twin for mitigating solar energy resources challenges: A Perspective Review. Solar

214 Energy, 2024. 274: p. 112561.

215 Eneyew, D.D., M.A. Capretz, and G.T. Bitsuamlak, Toward smart-building digital twins: BIM and IoT data

216 integration. IEEE access, 2022. 10: p. 130487-130506.

1. Peldon, D., et al., Navigating urban complexity: The transformative role of digital twins in smart city development.
2. Sustainable Cities and Society, 2024. 111: p. 105583.
3. Zhao, L., et al., Digital‐Twin‐Based Evaluation of Nearly Zero‐Energy Building for Existing Buildings Based on
4. Scan‐to‐BIM. Advances in Civil Engineering, 2021. 2021(1): p. 6638897.
5. Wang, W., et al., From BIM to digital twin in BIPV: A review of current knowledge. Sustainable Energy
6. Technologies and Assessments, 2024. 67: p. 103855.
7. Tchana, Y., G. Ducellier, and S. Remy, Designing a unique Digital Twin for linear infrastructures lifecycle
8. management. Procedia CIRP, 2019. 84: p. 545-549.
9. Ariansyah, D., et al., Digital Twin (DT) Smart City for Air Quality Management. Procedia Computer Science, 2023.

226 227: p. 524-533.

1. Martínez-Rubio, A., et al., Evaluating solar irradiance over facades in high building cities, based on LiDAR
2. technology. Applied energy, 2016. 183: p. 133-147.
3. Salimzadeh, N. and A. Hammad. High-level framework for GIS-based optimization of building photovoltaic
4. potential at urban scale using BIM and LiDAR. in International Conference on Sustainable Infrastructure
5. 2017. 2017.
6. Ning, G., et al., BIM-based PV system optimization and deployment. Energy and Buildings, 2017. 150: p. 13-22.
7. Ning, G., et al., e-BIM: a BIM-centric design and analysis software for Building Integrated Photovoltaics.
8. Automation in Construction, 2018. 87: p. 127-137.
9. Fitriaty, P. and Z. Shen, Predicting energy generation from residential building attached Photovoltaic Cells in a
10. tropical area using 3D modeling analysis. Journal of cleaner production, 2018. 195: p. 1422-1436.
11. Rosiek, S., J. Alonso-Montesinos, and F. Batlles, Online 3-h forecasting of the power output from a BIPV system
12. using satellite observations and ANN. International Journal of Electrical Power & Energy Systems, 2018.
13. 99: p. 261-272.
14. Al-Janahi, S.A., O. Ellabban, and S.G. Al-Ghamdi, A novel BIPV reconfiguration algorithm for maximum power
15. generation under partial shading. Energies, 2020. 13(17): p. 4470.
16. Boje, C., et al., A framework using BIM and digital twins in facilitating LCSA for buildings.Journal of Building

243 Engineering, 2023. 76: p. 107232.

1. Polo, J., N. Martín-Chivelet, and C. Sanz-Saiz, BIPV Modeling with Artificial Neural Networks: Towards a BIPV
2. Digital Twin. Energies, 2022. 15(11): p. 4173.
3. Starkey, J., et al., Digital Twinning Proof of Concept for Utility-Scale Solar: Benefits, Issues, and Enablers. The
4. International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, 2022.
5. 46: p. 231-237.
6. Ma, S., et al., Digital twin and big data-driven sustainable smart manufacturing based on information management
7. systems for energy-intensive industries. Applied energy, 2022. 326: p. 119986.
8. Lv, Z., C. Cheng, and H. Lv, Digital twins for secure thermal energy storage in building. Applied Energy, 2023.

252 338: p. 120907.

1. Agostinelli, S., et al., Cyber-physical systems improving building energy management: Digital twin and artificial
2. intelligence. Energies, 2021. 14(8): p. 2338.
3. Kaewunruen, S., P. Rungskunroch, and J. Welsh, A digital-twin evaluation of net zero energy building for existing
4. buildings. Sustainability 11 (1): 159. 2018.
5. Hong, Y.-Y. and R.A. Pula, Diagnosis of PV faults using digital twin and convolutional mixer with LoRa
6. notification system. Energy Reports, 2023. 9: p. 1963-1976.
7. Kolahi, M., et al., Digital-PV: A digital twin-based platform for autonomous aerial monitoring of large-scale
8. photovoltaic power plants. Energy Conversion and Management, 2024. 321: p. 118963.
9. Jain, P., et al., A digital twin approach for fault diagnosis in distributed photovoltaic systems.IEEE Transactions on

262 Power Electronics, 2019. 35(1): p. 940-956.

1. Van Cappellen, L., et al. A real-time physics based digital twin for online mosfet condition monitoring in pv
2. converter applications. in 2022 28th International Workshop on Thermal Investigations of ICs and Systems
3. (THERMINIC). 2022. IEEE.
4. Lin, W., et al., A dynamic simulation platform for fault modelling and characterisation of building integrated
5. photovoltaics. Renewable Energy, 2021. 179: p. 963-981.
6. Razmara, M., et al., Building-to-grid predictive power flow control for demand response and demand flexibility
7. programs. Applied Energy, 2017. 203: p. 128-141.
8. Zhou, J., et al., Digital twin application for reinforcement learning based optimal scheduling and reliability
9. management enhancement of systems. Solar Energy, 2023. 252: p. 29-38.
10. Huang, J., D.D. Koroteev, and M. Rynkovskaya, Machine learning-based demand response in PV-based smart home
11. considering energy management in digital twin. Solar Energy, 2023. 252: p. 8-19.
12. Yuan, G. and F. Xie, Digital Twin-Based economic assessment of solar energy in smart microgrids using
13. reinforcement learning technique. Solar Energy, 2023. 250: p. 398-408.
14. Dagdougui, Y., A. Ouammi, and R. Benchrifa, High Level controller-based energy management for a smart building
15. integrated microgrid with electric vehicle. Frontiers in Energy Research, 2020. 8: p. 535535.
16. Mo, S., et al., An improved MPPT method for photovoltaic systems based on mayfly optimization algorithm.

279 Energy Reports, 2022. 8: p. 141-150.

1. Revathy, S., et al., Design and analysis of ANFIS–based MPPT method for solar photovoltaic applications.
2. International Journal of Photoenergy, 2022. 2022(1): p. 9625564.
3. Rafeeq Ahmed, K., et al., Maximum power point tracking of PV grids using deep learning.International Journal of

283 Photoenergy, 2022. 2022(1): p. 1123251.

1. Islam, H., et al., Improved proportional-integral coordinated MPPT controller with fast tracking speed for grid-tied
2. PV systems under partially shaded conditions. Sustainability, 2021. 13(2): p. 830.
3. Asif, R.M., et al., Modified fuzzy logic MPPT for PV system under severe climatic profiles.Pakistan Journal of
4. Engineering and Technology, 2021. 4(2): p. 49-55.
5. Rajani, K. and T. Ramesh, Maximum power enhancement under partial shadings using a modified Sudoku
6. reconfiguration. CSEE Journal of Power and Energy Systems, 2020. 7(6): p. 1187-1201.
7. Bakar Siddique, M.A., et al., Implementation of incremental conductance MPPT algorithm with integral regulator
8. by using boost converter in grid-connected PV array. IETE Journal of Research, 2023. 69(6): p. 3822-3835.
9. Li, X., et al., A novel beta parameter based fuzzy-logic controller for photovoltaic MPPT application. Renewable

293 energy, 2019. 130: p. 416-427.

1. Guzman Razo, D.E., et al., A genetic algorithm approach as a self-learning and optimization tool for PV power
2. simulation and digital twinning. Energies, 2020. 13(24): p. 6712.
3. Hamzah, A.H. and Y.I. Go, Design and assessment of building integrated PV (BIPV) system towards net zero
4. energy building for tropical climate. E-Prime-Advances in Electrical Engineering, Electronics and Energy, 2023. 3:
5. p. 100105.
6. Zhou, F., C. Yang, and Z. Wang, Prediction of building energy consumption for public structures utilizing BIM-DB
7. and RF-LSTM. Energy Reports, 2024. 12: p. 4631-4640.