International Journal of Energy and Power Engineering
2025, Vol. 14, No. 5, pp. 115-121
https://doi.org/10.11648/j.ijepe.20251405.11

SciencePG
Science Publishing Group

Research Article

Predictive Maintenance and Digital Twins for Greener Power Generation: Case Studies from China, Germany, Norway, and the Netherlands

Agil Mammadov[1, *], Yaroslav Danilov[2]

[1]School of Financial Economics, Moscow State Institute of International Relations (University), Moscow, Russia
[2]MCS School, Moscow, Russia

Abstract

Predictive maintenance (PdM), supported by artificial intelligence (AI) and digital twin methods, is gaining attention as a practical and cost efficient way to manage power generation assets. In the renewable energy sector, where performance, stability, and cost control are central concerns, PdM enables operators to anticipate equipment faults, schedule interventions more effectively, and reduce unplanned downtime. This paper reviews how such approaches are being applied in four different national contexts: China, Germany, Norway, and the Netherlands, and considers their contribution to cleaner and more reliable energy systems. The discussion highlights several patterns that emerge across these countries. In China, the rapid expansion of wind and solar capacity has driven the use of PdM to improve fault detection and optimize turbine and panel performance. Germany demonstrates how PdM can be integrated into broader energy transition policies, using digital twins and AI to balance fluctuating renewable output with grid demands. Norway shows the value of predictive tools in extending the life and efficiency of hydropower equipment, while the Netherlands illustrates the particular benefits of PdM in offshore wind projects, where remote monitoring and early fault recognition are critical. Evidence from these cases points to three consistent outcomes: improved uptime of renewable assets, measurable reductions in maintenance costs, and smoother integration of intermittent power sources through more advanced grid management. Taken together, these findings suggest that PdM is not only a set of technical tools but also a strategic component in building sustainable, resilient, and economically viable energy systems. Its wider adoption may help accelerate the transition toward low carbon power on a global scale.

Keywords

Predictive Maintenance, Digital Twins, Artificial Intelligence, Renewable Energy, Smart Grids, Power Generation

1. Introduction

With the recent introduction of the Internet of Things (IoT) and the rapid development of artificial intelligence (AI) technologies, the maintenance field has undergone a significant transformation. Traditionally, only two forms of maintenance were available: Reactive Maintenance and Preventive Maintenance (PM). Reactive maintenance is performed only after component failure, which limits operational efficiency and increases safety risks and repair costs. Preven-

[*]Corresponding author: agilmsu@gmail.com (Agil Mammadov)

Received: 18 September 2025; **Accepted:** 4 October 2025; **Published:** 3 December 2025

tive maintenance schedules inspections and repairs at fixed intervals to avoid failures but can cause excessive maintenance and operational disruptions.

Recently, Predictive Maintenance (PdM) has been introduced as an innovative approach. Maintenance is applied only when analytical models predict failure or degradation based on data gathered from IoT, analyzed via Big Data techniques and computed with powerful hardware. This approach reduces costs, enhances safety, and extends machinery lifespan by performing only necessary maintenance [1].

The increasing human population drives higher electricity demand, making sustainable and effective energy systems crucial. Renewable sources like photovoltaics, wind turbines, and hydropower present variability and are decentralized, requiring agile management of distributed microgrids. AI algorithms analyze historical weather, wind, and solar data, enhancing renewable system effectiveness. AI-powered smart grids react to real-time disturbances to balance demand and supply, increasing grid stability and energy yield while prolonging machinery life [2, 3].

Traditional preventive maintenance has drawbacks in renewable energy due to downtime during maintenance. PdM combined with machine learning, machine vision, smart sensors, and digital twin technology emerges as the optimal solution. Digital twins represent virtual copies of physical systems with varying functional levels from standalone to autonomous, enabling forecasting, diagnostics, prescriptive recommendations, and closed-loop control. PdM shifts maintenance from time-based to condition-based, enhancing cost-efficiency and reliability.

2. Why This Matters

Predictive maintenance in power generation addresses key factors of clean energy transition: climate impact, grid stability, and economic efficiency. AI-based PdM avoids unplanned outages and inefficient equipment use, lowering fuel consumption and emissions. Maintaining agility in renewable-dependent grids is essential for supply-demand balance without fossil fuel reliance. Economically, extended asset lifespans and optimized maintenance schedules generate significant annual savings. These benefits accelerate the delivery of reliable, affordable, and sustainable electricity toward net-zero goals.

3. Methodology

This study reviews specialized technical studies and corporate reports to synthesize conclusions about PdM and AI analytics impacts. It compiles data from governmental and corporate sources, examining current PdM achievements and statistics across selected countries. A cross-country comparison contrasts experiences of industry leaders to identify challenges and lessons learned.

This table summarizes the methodology applied in the research project. Each case study is presented with its source, type of source, method of analysis, and relevance to research:

Table 1. *General Sources and Analytical Methods Used in the Study.*

Source	Type of Source	Method of Analysis	Relevance to Research
A Survey of Predictive Maintenance: Systems, Purposes and Approaches	Academic preprint	Literature review of PdM and IoT integration	Foundational theoretical basis for predictive vs preventive maintenance.
IJSRA 2024	Peer-reviewed article	Critical reading, synthesis of AI & Big Data in grids	Shows how AI improves grid stability and CO_2 reduction.
Siemens AI overview	Corporate site	General review	Provides general industry framing for AI in energy.
Stadtmann F, et al. *Digital Twins in Wind Energy: Emerging Technologies and Industry-Informed Future Directions*. IEEE Access. 2023.	Academic review	Literature synthesis of digital twin applications in wind energy, including classification of maturity levels, survey of AI/ML techniques, and case study references from industry	Supports predictive maintenance framework by detailing current digital twin technologies in wind farms (sensor fusion, SCADA integration, AI for anomaly detection). Provides maturity scale useful for cross-country comparison of implementations.

Table 2. *China: Sources and Case Study Methods for Predictive Maintenance in Power Generation.*

Source	Type of Source	Method of Analysis	Relevance to Research
CREA 2025 China coal power	NGO/Think tank	Data/statistical analysis	Provides baseline on fossil-heavy energy

Source	Type of Source	Method of Analysis	Relevance to Research
report			mix, urgency of renewables.
Ember - China country data	NGO database	Data mining	Tracks share of renewables and growth trends.
China Power company page	Corporate website	Contextual review	Provides company-level energy operations context.
Wuqiangxi hydropower	Corporate report	Case study extraction	Example of predictive maintenance in a hydro plant.
Jinweizhou hydropower	Industry database	Technical profile analysis	Gives capacity and operational data for Chinese hydro PdM.
Hydropower.org case study	NGO/Industry case study	Case review	Documents AI + PdM applications in hydropower globally (China included).
Bentley case - POWERCHINA 80 MW solar	Corporate case	Document analysis	Shows digital twin use in solar farm planning.
Longyuan Power wind PdM	Corporate release	Case-specific analysis	Example of an AI-based wind turbine PdM project (200+ turbines).

Table 3. Germany: Sources and Case Study Methods for Predictive Maintenance in Power Generation.

Source	Type of Source	Method of Analysis	Relevance to Research
IEA Germany 2025	IEA country report	Policy/system analysis	Frame Germany's renewable strategy and maintenance needs.
BASE nuclear phase-out	Government page	Policy context	Context for Germany's energy transition away from nuclear.
IEA France country profile	IEA country report	Comparative analysis	Contextualizes German reliance on French nuclear imports.
BMWi 2024 - Germany & France grid flexibility	Government press release	Policy context	Shows regional interconnection and flexibility agreements.
CEIC - Germany electricity imports	Database	Data analysis	Quantifies German dependence on imports.
Fraunhofer DeepTrack	Research project	Review of technical design	Example of digital twin + deep learning in solar plants.
Siemens/NVIDIA case	Corporate blog	Technology impact analysis	Digital twin PdM in power plants (combined cycle).
Schluchseewerk Flyer (Siemens)	Corporate flyer	Case-specific review	PdM in German pumped-storage hydropower with vibration monitoring.

Table 4. The Netherlands: Sources and Case Study Methods for Predictive Maintenance in Power Generation.

Source	Type of Source	Method of Analysis	Relevance to Research
IEA Netherlands electricity page	IEA database	Statistical analysis	Provides an electricity mix and policy targets.
IEA Netherlands 2024 country report	IEA report	Policy/system review	Comprehensive review of the Dutch grid and renewables.
TenneT website	TSO/corporate site	News analysis	Provides operational updates and real-world PdM examples.

Source	Type of Source	Method of Analysis	Relevance to Research
RAP - Transparent Grids toolkit	NGO toolkit	Policy + governance analysis	Explains the importance of grid transparency and AI tools.
em-power.eu - digital twin grids	Industry news	Technology review	Case overview of digital twin applications in grids.
Van Dinter et al. 2023, PHM	Peer-reviewed research paper	Methodological case review	Provides a detailed case study of PdM for Dutch cable joints.

Table 5. *Norway: Sources and Case Study Methods for Predictive Maintenance in Power Generation.*

Source	Type	Method of Analysis	Relevance to Research
IEA Norway country page	Government report	Statistical and policy analysis	Provides energy mix overview and strategic priorities for Norway's energy transition.
IEA Norway 2022 Energy Policy Review	Country review	Policy & system evaluation	Contextualizes national energy strategy and infrastructure challenges.
Business Insider article on Elvia's digital twin	Media report	Case study summarization	Offers insights into AI-enhanced grid resilience and digital twin deployment.
Disruptive Technologies article on Elvia sensors	Industry article	Technology implementation analysis	Highlights IoT-based PdM solutions applied in Norway's distribution network.
Digital Twin for Wind Energy: Latest updates from the NorthWind project	Academic preprint	Conceptual frameworks & technical methods	Supplies digital twin maturity model (0-5) and methods applicable to wind energy.
NorthWind research portal (WP4)	Research center page	Research overview	Delivers strategic direction on predictive maintenance and digital twin innovation in Norway's energy sector.

4. Country Case Studies

4.1. China

China operates the largest number of coal-fired power plants but also leads in renewable generation, accounting for 38% of the country's power from low-carbon sources like hydro, wind, and solar. Electricity demand is rapidly growing due to electrification and AI-driven facilities, necessitating reliable grid infrastructure. Considering the nuances of the renewable sources of electricity, such as dependence on outside factors and the need for regular maintenance, the integration of AI with its outstanding predictive and analytical capabilities into the working processes is an obvious choice for the Chinese energy system [4-6].

Examples of PdM application in China include:

1) *Wuqiangxi and Jinweizhou Hydropower Plants*: Since 2020, these plants employ a Smart Remote O&M system utilizing AI tools, machine vision, sound recognition, and sensors for predictive maintenance. Benefits include 10% maintenance cost savings, 0.5% increase in available generation time, and 0.3% more power output [7-9].
2) *POWERCHINA Hubei Electric Engineering PV Station*: An 80 MW solar plant that used Bentley's digital twin technology during construction to optimize panel placement, minimize shading (<2%), and save 20 working days [10].
3) *Longyuan Power Wind Turbines*: AI-based PdM monitors over 200 turbines continuously for performance and malfunction diagnosis, enabling shift from preventive to predictive maintenance [11].

4.2. Germany

Germany targets net zero by 2045 and phased out nuclear power in 2023. It imports some electricity from France, which relies heavily on nuclear (64.3%). Due to reduced natural gas availability, renewables' demand is increasing, requiring AI deployment for grid stability [12-16].

PdM examples in Germany:

1) Fraunhofer DeepTrack: Digital twins and data-driven algorithms used in the Merdingen solar pilot plant adjust panels dynamically based on weather to maximize output. The project aims to reduce upgrade costs for widespread adoption [17].
2) Siemens Energy & NVIDIA: Physics-infused digital twins simulate real-time steam and water flows in combined cycle power plants, predicting corrosion to reduce planned shutdowns. A 10% reduction in downtime could save $1.7 billion industry wide. [18, 19].

4.3. The Netherlands

Electricity generation in 2023 was 37.9% natural gas, 24% wind, and 16.5% solar PV. The Dutch government plans to expand nuclear capacity and address grid congestion through a "National Grid Congestion Action Programme" focused on grid extensions, smart solutions, and improved grid insight [20-23].

PdM initiatives include:

1) *Alliander and Siemens*: Partnership introduced Gridscale X software combining digital twins and AI analytics to boost grid efficiency by 30%, optimizing energy distribution and managing congestion [24, 25].
2) *Alliander and Wageningen University*: Digital twin framework for model-based systems engineering monitors medium-voltage cable joint degradation in real time, reducing outages and increasing asset lifespan [26].

4.4. Norway

Norway's electricity system is among the world's cleanest, with 95.6% renewables (89.1% hydropower, 9% wind). Despite fossil fuel exports, domestic electrification is increasing, with some high-energy sectors still fossil-dependent [27, 28].

Examples include:

1) *Elvia Smart Grids*: Collaboration with Siemens and Disruptive Technologies builds a digital twin of the low-voltage network (Gridscale X LV Insights), real-time asset monitoring, and wireless temperature sensors. This shifts maintenance from reactive to predictive, preventing outages [29, 30].
2) *NorthWind Project*: Develops digital twins for wind turbines with a maturity model (0-5), hierarchical asset information models conforming to ISO 81346, and uses reduced-order and fluid dynamics models for simulations. Real-time visualizations and wind farm layout optimization improve predictive maintenance and operational efficiency [31-33].

5. Cross-Country Comparison

AI-driven predictive maintenance (PdM) and digital twin technologies improve renewable integration, grid stability, and cost efficiency across different national contexts. The case studies demonstrate that although China, Germany, the Netherlands, and Norway operate under distinct energy mixes and policy frameworks, similar advantages are consistently achieved. In China, PdM supports the rapid scaling of renewables alongside a still dominant coal sector. Germany uses digital twins to stabilize its grid during the phase-out of nuclear power. The Netherlands applies PdM to ease grid congestion and manage high shares of wind and solar, while Norway employs it to enhance the reliability of its largely hydro-based system.

Despite these differences, common benefits stand out: higher uptime, reduced maintenance costs, and smoother integration of variable renewables. These results confirm that PdM is not limited to a single type of energy system but can be adapted to diverse conditions. The shared outcomes strengthen the case for wider adoption, showing that predictive approaches not only optimize operations but also accelerate progress toward global clean energy goals.

6. Conclusions

This study examined how predictive maintenance supported by artificial intelligence and digital twin technologies is changing asset management in power generation. Shifting from scheduled or reactive maintenance to condition-based strategies makes it possible to improve reliability, reduce costs, and extend the useful life of equipment. These gains are closely tied to the wider goals of efficiency and sustainability that underpin today's energy transition.

The four case studies from China, Germany, the Netherlands, and Norway show that even in very different energy systems, common results appear: reduced downtime, more stable integration of renewables, and stronger grid resilience. This suggests that predictive maintenance is not limited to specific technologies or policy settings but can be applied broadly across diverse national contexts.

At the same time, barriers remain. High initial costs, the need to train personnel, and the lack of shared standards for digital twins all limit wider use. Addressing these issues will be necessary if predictive maintenance is to move from isolated projects to industry wide practice.

Overall, the evidence indicates that predictive maintenance is more than a technical improvement. It should be seen as a strategic instrument for building cleaner, more reliable, and more cost-effective power systems. The lessons from early adopters provide a useful starting point, while future research and cooperation will determine how far and how quickly these approaches can spread.

Abbreviations

AI	Artificial Intelligence
BMWi	Bundesministerium für Wirtschaft und Energie

	(Federal Ministry for Economic Affairs and Energy, Germany)
CO_2	Carbon Dioxide
IEA	International Energy Agency
IoT	Internet of Things
ISO	International Organization for Standardization
MW	Megawatt
NGO	Non-Governmental Organization
O&M	Operation and Maintenance
PdM	Predictive Maintenance
PHM	Prognostics and Health Management
PM	Preventive Maintenance
PV	Photovoltaic
SCADA	Supervisory Control and Data Acquisition
TSO	Transmission System Operator

Author Contributions

Agil Mammadov: Conceptualization , Formal Analysis, Investigation , Methodology, Project administration , Resources , Supervision , Validation , Writing – review & editing

Yaroslav Danilov: Conceptualization , Investigation , Methodology, Visualization, Writing – original draft

Conflicts of Interest

The authorsdeclare no conflicts of interest.

References

[1] Zhu, T., Ran, Y., Zhou, X. and Wen, Y. (2019). A Survey of Predictive Maintenance: Systems, Purposes and Approaches. https://doi.org/10.48550/arXiv.1912.07383

[2] Javid Montasham (2015). Review Article-Renewable Energies. *Energy Procedia*, 75, pp. 1234-1240. https://doi.org/10.1016/j.egypro.2015.07.774

[3] Hamdan, A., Ibekwe, K. I., Ilojianya, V. I., Sonko, S. and Etukudoh, E. A. (2024). AI in renewable energy: A review of predictive maintenance and energy optimization. *International Journal of Scientific Research and Applications (IJSRA)*, 11(1). https://doi.org/10.30574/ijsra.2024.11.1.0112

[4] CREA (2025). *China Coal Power Report 2025*. Centre for Research on Energy and Clean Air. https://energyandcleanair.org

[5] Ember (2024). *China Country Data*. Ember Climate. https://ember-climate.org

[6] China Power Company (2024). *Energy Operations*. https://www.chinapower.com

[7] Chemtecone (2024). *Wuqiangxi Hydropower*. https://www.chemtecone.com

[8] Power-Technology (2024). *Jinweizhou Hydro Plant Profile*. https://www.power-technology.com

[9] Hydropower.org (2023). *AI in Hydropower: Case Study*. International Hydropower Association. https://www.hydropower.org

[10] Bentley Systems (2022). *POWERCHINA 80 MW Solar Digital Twin*. Bentley Case Studies. https://www.bentley.com

[11] CEIC (2022). *Longyuan Power Wind Turbine Predictive Maintenance*. CEIC Data. https://www.ceicdata.com

[12] IEA (2025). *Germany Energy Report 2025*. International Energy Agency. https://www.iea.org

[13] Federal Government of Germany (2023). *Nuclear Phase-Out Policy*. https://www.bundesregierung.de

[14] IEA (2024). *France Country Profile*. International Energy Agency. https://www.iea.org

[15] BMWi (2024). *Press Release: Germany & France Grid Flexibility*. German Federal Ministry for Economic Affairs and Energy. https://www.bmwi.de

[16] CEIC (2024). *Germany Electricity Imports*. CEIC Data. https://www.ceicdata.com

[17] Fraunhofer ISE (2024). *DeepTrack Solar Project*. Fraunhofer Institute for Solar Energy Systems. https://www.ise.fraunhofer.de

[18] NVIDIA (2023). *Siemens Digital Twin for Energy Systems*. NVIDIA Blog. Available at: https://blogs.nvidia.com

[19] Siemens Energy (2021). *Predictive Maintenance in Hydropower - Flyer*. Siemens Energy.

[20] IEA (2023). *Netherlands Electricity Profile*. International Energy Agency. https://www.iea.org

[21] IEA (2024). *Netherlands Country Report 2024*. International Energy Agency. https://www.iea.org

[22] TenneT (2024). *Corporate Updates on Grid Operations*. TenneT. https://www.tennet.eu

[23] RAP (2023). *Transparent Grids Toolkit*. Regulatory Assistance Project. https://www.raponline.org

[24] em-power.eu (2024). *Digital Twins in Power Grids*. https://www.em-power.eu

[25] Siemens (2024). *AI Solutions for Energy Systems*. Siemens Corporate Publications.

[26] Van Dinter, R., et al. (2023). Architecting a Digital Twin-Based Predictive Maintenance System for Modelling Cable Joint Degradation. *Prognostics and Health Management (PHM)*, 4(1). https://doi.org/10.36001/phmap.2023.v4i1.3753

[27] IEA (2023). *Norway Energy Profile*. International Energy Agency. https://www.iea.org

[28] IEA (2022). *Norway Energy Policy Review*. International Energy Agency. https://www.iea.org

[29] Business Insider (2024). *Elvia Digital Twin Case Study*. https://www.businessinsider.com

[30] Disruptive Technologies (2024). *Smart Sensors for Grid Applications*. https://www.disruptive-technologies.com

[31] Bossert, N., et al. (2024). Digital Twin for Wind Energy: Latest updates from the NorthWind project. arXiv preprint. https://doi.org/10.48550/arXiv.2403.14646

[32] NorthWind Research Centre (2024). *NorthWind Project Portal*. https://northwindresearch.no

[33] IEEE (2024). Digital Twins in Wind Energy: Emerging Technologies and Industry-Informed Future Directions. *IEEE Xplore*. https://doi.org/10.1109/ACCESS.2023.3321320