International Journal
of Discoveries and Innovations in Applied Sciences
Vol. 6 Issue 4 | **pp.** 16-25 | **e-ISSN:** 2792-3983
Available online @ https://oajournals.net/index.php/ijdias

Digital Twin Technology For Power Systems: Researching Virtual Models For Predicting Blackout Scenarios Under Climate Variability

Arman Sabyrzhan[1], Soliev Mukhammadkhon Bobirshoevich[2], Khamraev Mahmud[3], Iliyas Zere[4]

1. Harvard John A. Paulson School Of Engineering And Applied Sciences, USA
2. Director of Innovative Centre, Independent researcher at Samarkand Branch of Tashkent University of Economics, Uzbekistan
3. Senior research Assistant at the International Research Lab , Under Innovative Centre, Uzbekistan
4. Research Assistant at International Research Lab, under Innovative Centre, Uzbekistan

* Correspondence : armansabyrzhan@college.harvard.edu, mukhammadkhon.soliev@innovativecentre.org , makhmudkhamraev@innovativecentre.org , iliyaszere@innovativecentre.org

Citation: Arman Sabyrzhan, Soliev Mukhammadkhon Bobirshoevich, Khamraev Mahmud, Iliyas Zere. Digital Twin Technology For Power Systems: Researching Virtual Models For Predicting Blackout Scenarios Under Climate Variability. International Journal of Discoveries and Innovations in Applied Sciences 2026, 6(4), 16-25.

Received: 10th Apr 2026
Revised: 25th Apr 2026
Accepted: 22th Apr 2026
Published: 3th May 2026

Abstract: This work explores how digital twin tech applies to electrical grids, particularly through simulated models designed to foresee blackouts caused by shifting weather patterns. Through a structured analysis of ten scholarly and industrial publications, it suggests these virtual replicas hold both conceptual depth and practical strength in forecasting grid behavior during unstable climate phases. Evidence shows such twins - which mirror actual infrastructure through live, two-way data flow - allow ongoing tracking, forward-looking modeling, and smart regulation, features highly relevant for spotting faults before they spread. It also becomes clear that changing climates bring layered pressures like intense temperatures, downpours, storms, and fire outbreaks, challenges traditional network designs struggle to handle. One path forward lies in thoughtfully built digital duplicates, combining internet-connected sensors, machine learning tools, and up-to-the-minute environmental inputs, forming a response to today's growing uncertainty. Still, major obstacles persist - lacking uniform frameworks, facing steep setup expenses, exposed to cyber threats, along with difficulties in simulating vast, diverse power systems. For digital replicas to function effectively across a country's electricity network, changes in organizational structure plus funding toward shared technological platforms become essential first steps.

Keywords: Digital Twin, Power Systems, Blackout Prediction, Climate Variability, Smart Grid, IoT, Predictive Analytics, Grid Resilience, Extreme Weather

1. Introduction

Climate shifts unfolding faster now challenge long-held ideas about how energy systems should work. Built expecting steady conditions, electrical networks face rising pressure from wilder storms, intense heat, floods, because nature behaves differently today. Blackouts spreading widely show what happens when old designs meet new realities [1]. During winter 2021, frozen equipment after Storm Uri knocked out supply across Texas, leaving millions in darkness for days on end, lives lost, damage tallied beyond 130 billion dollars later. Heat peaking abnormally high during 2022 strained supplies further, seen sharply in Europe and India alike power stations slowed as cooling sources failed just when people needed most electricity [2]. These moments reveal weak spots hidden within standard planning methods used by those running the grid.

Global assessments show that extreme weather events are becoming more frequent and actually place growing stress on infrastructure systems around the whole globe. As the IPCC notes, “climate-related hazards are increasing in frequency and intensity,” This does put a heavy pressure on the urgency of adapting energy systems to new environmental conditions.

With growing pressure on power systems, experts now ask whether blackouts can be foreseen and avoided. One promising answer comes from digital twin tech is a live model that mirrors actual infrastructure. This replica updates constantly by exchanging information with physical assets [3]. Instead of frozen images or one-off calculations, it shifts as conditions change. Because it reflects ongoing operations, it supports both observation and forecasting. Powered by artificial intelligence, streams from internet-connected sensors, and weather inputs, such models could help utilities act ahead of crises.

Though promising in theory, using digital twins to forecast blackouts amid changing climate conditions has seen limited exploration. “Research so far mostly focuses on factories and product design”. The following statement proves that we are leaving energy systems somewhat overlooked. Rarely do studies examine how these models might protect vital power networks. The lack stands out more now, because climate threats are growing fast, yet upgrades to electrical grids take decades to plan and implement [4], [5].

This study examines how well existing digital twin models, according to current engineering standards, can forecast blackouts in power systems facing shifting climate conditions. It also explores the organizational and technological requirements necessary for large-scale deployment. What follows outlines the structure guiding this inquiry. Next comes an overview of relevant scholarship, where key ideas about digital twins are gathered and clarified. Following that, a detailed explanation unfolds regarding how sources were selected and assessed. Later, findings appear grouped by recurring topics across studies. After examining consequences, obstacles, and possible paths ahead in section five, the sixth part collects every source cited [6], [7]. References appear at the end, following analysis of what matters, what blocks progress, and where research might go next.

2. Literature Review

2.1 Defining the Digital Twin

First introduced in 2003 by Michael Grieves at the University of Michigan, the idea of a digital twin took shape slowly - NASA and aerospace teams later brought it into practice. Because of uneven adoption patterns, agreement on what exactly defines such systems remains absent even now. Though time has passed since its inception, clarity is still missing, something Duan noted as a core barrier for broader use across industries [8]. Functionally speaking, many rely on one prevailing description: an evolving simulation linked in real-time to a physical object, mirroring changes throughout every stage, from creation to active service until retirement. This ongoing exchange between actual and modeled forms lasts the entire lifespan, forming a loop maintained constantly behind the scenes.

A key idea in current discussions draws a line among three similar yet distinct notions: digital models, which lack automatic data sharing between real-world objects and their virtual versions; digital shadows, where information moves one way - from actual to simulated - and nothing returns; and genuine digital twins, featuring constant two-way communication happening instantly. According to [9], recognizing these differences matters greatly because only the complete twin setup enables feedback loops needed for self-directed forecasting and response actions. In power networks, this contrast becomes especially relevant when managing electricity grids actively instead of merely observing them.

Although outline several digital twin traits suited to infrastructure uses like mirroring physical systems accurately, updating live status, linking closely with actual devices, storing past performance, forecasting upcoming actions, and combining various twins into broader frameworks - one stands out when applied to large energy networks. Because nationwide electricity grids consist of mixed components including production units, transfer lines, and local delivery segments, their joint modeling becomes essential; only then can complex breakdown patterns, such as spreading outages, emerge clearly through simulation [10].

2.2 Theoretical Basics Formal Traits and System Needs

Though often discussed loosely, digital twins require clear capabilities to be seen as truly intelligent. Starting with awareness of present conditions, one key role involves monitoring each part of a physical setup in real time. Instead of static models, the twin adapts - whenever reality drifts from expectation, it recalibrates its own structure. From such adjustments comes responsiveness: decisions form not just from pre-set logic but from learned patterns. Acting on insights, the system proposes actions that feed back into operations. With learning built in, progress isn’t abrupt. It emerges through steady refinement driven by live inputs. Success hinges less on initial design than ongoing alignment with shifting goals.

Beginning with these structured criteria, the link to power systems becomes clear. Real-time data like voltage, frequency, load levels, line heat, and equipment status feed into state observation through sensor networks tied to digital infrastructure [11]. Instead of just collecting numbers, the setup detects unusual patterns across the grid, refining predictions about potential breakdowns over time. This adaptive learning shapes how parameter identification works in practice. When it comes to decision-making, corrective moves such as rerouting power flows, reducing demand, or adjusting generation output emerge based on forecasts of coming disruptions. Such actions tie back to optimal control mechanisms embedded within the framework. From this angle, a carefully built digital twin might act ahead of blackouts by tracking risks as they evolve.

2.3 Digital Twin Framework and Supporting Technologies

A structure laid out by outlines five levels meant for digital twin setups in power networks. Not just limited to hardware, it begins with real-world components like transmission lines - what they call the physical layer. Above that sits sensor technology: devices such as smart meters and monitoring units feeding live inputs [12]. Instead of blending everything together, their design separates the virtual replica into its own distinct tier - one hosting simulations and analytical tools. Human interaction enters through another level entirely, involving personnel like control room staff or regulatory bodies. Functions cutting across these tiers manage secure data flow, ensure compatibility between systems, and maintain operational continuity. This separation mirrors earlier thinking from, though framed differently. Where those authors stress integration, here the emphasis shifts toward modularity without losing connectivity. Software elements span multiple zones, linking simulated behavior back to actual equipment responses. Communication pathways run throughout, allowing updates to pass smoothly from one zone to the next. Each segment maintains identity yet depends on others for full functionality. Models evolve using incoming measurements while preserving alignment with physical counterparts. Security mechanisms anchor each transition point rather than float independently. No single part operates in isolation, even decision-making relies on upstream signals [13]. Their approach splits complexity into manageable parts without fragmenting purpose.

Among tools highlighted in research, IoT stands out by gathering constant sensor inputs. Instead of relying on isolated measurements, artificial intelligence detects trends through learned behaviors - often spotting irregularities before they escalate. Processing demands get met via cloud platforms, spreading workloads where needed most. When speed matters, fifth-generation networks move information rapidly, shrinking delays dramatically. Simulations grow more accurate when powered by models that mirror intricate interactions within large-scale setups. Power grid digital twins go further. They pull in live updates from atmospheric monitoring sources. Historical climate records like ERA5 add depth to predictions. Weather forecasts delivered instantly help reflect shifting environmental pressures tied to severe breakdown risks.

Recent studies implement digital twin concepts right into the energy infrastructure. As argue, “digital twins enable real-time monitoring, simulation, and optimization of energy systems,”. This is a real showcase of their potential for improving grid responsiveness under dynamic conditions.

2.4 Weather Changes Cause Power Grid Problems

Though the digital twin research reviewed here does not center on electrical grids directly, insights drawn from wider studies on energy and climate point clearly to how shifting weather patterns affect grid stability. Because of intense heat, transmission lines may exceed safe operating limits, a stressor compounded when surrounding air stays hot for long periods. At the same time, power plants relying on water for cooling lose efficiency just as variable renewable output becomes less predictable amid extreme conditions. When severe cold or prolonged heat drives sudden jumps in electricity use, existing supply buffers often fall short. Storms, heavy icing, rising waters, or fire can strike equipment across vast stretches of wiring and substations, disrupting service unexpectedly. Behind each scenario lies a unique mix of measurable environmental factors - factors potentially trackable using sensor data and simulation tools embedded in digital replicas.

These interacting pressures show broader challenges found in power systems literature. Emphasize that “extreme weather events are a major threat to power system resilience,” particularly when multiple stressors affect infrastructure simultaneously.

What makes DT-based forecasting difficult isn’t just mapping individual paths alone instead, it demands showing how they interact at once inside one unified system. When parts of a grid fail and place added strain on nearby elements, the resulting chain reactions unfold unpredictably, shaped strongly by small differences in starting points [14]. Problems like these which are the kind that shift abruptly based on tiny changes are exactly where decision transformers, built around observing states and guiding actions wisely, fit most naturally.

3. METHODOLOGY

3.1 Research Design

Looking into how digital twins might predict blackouts in power grids amid shifting climates forms the core of this work. Instead of gathering new data or running experiments, insights come from combining results across scholarly articles, conference papers, and official documents. The reason? Ideas about digital twins in energy systems are still scattered, separated by field-specific boundaries, with few comprehensive studies yet available. Pulling together existing research offers a solid starting point before deeper investigations begin. Earlier reviews in similar early-stage domains like those by and show that structured analysis brings clarity, openness, and consistency, even without hands-on testing.

3.2 Data Sources and Literature Search Strategy

Beginning with a broad sweep across scholarly platforms, Google Scholar prominent among them, the search pulled material from IEEE Xplore, ResearchGate, JSTOR, and the ACM Digital Library. Instead of isolated keywords, phrases from dual themes shaped the queries: one rooted in digital twin concepts like virtual model or cyber-physical system, the other tied to how power networks respond to shifting climates, using expressions such as extreme weather power systems or cascading failures. Selection narrowed to ten core studies after weighing each for alignment with both theory and hands-on application of digital twins. These works appeared in reputable journals or recurring conferences, ensuring scrutiny by peers remained central. Age mattered too; only those issued within the past decade and a half qualified. To judge depth and reliability, attention went toward how often they were cited, who authored them, and the standing of their publishing venue. Where gaps emerged, official records detailing actual blackouts or grid stressors helped ground the findings in real-world incidents.

3.3 Grouping Books by Themes

Ten chosen works grouped into three themes, matching the study's guiding theory. One theme covers how digital twins are defined, drawing from who clarify their core traits compared to basic models, showing why two-way prediction matters. Instead of just listing features, these pieces examine what makes such systems distinct when built right. Another section looks at structures behind digital twins, pulling insights from, plus work on tech like sensors, artificial intelligence, fast networks, and remote computing needed for live updates. adds depth here by mapping functional layers within those setups. rounds this part out by emphasizing integration demands across platforms. A third angle focuses on math rules, efficiency needs, challenges during rollout - Rasheed's analysis pairs with Barricelli's field observations and Haag's engineering constraints. Together, they highlight tensions between ideal performance and practical limits in energy grids. Sorting them this way allowed patterns to emerge clearly while exposing mismatches in assumptions among authors. Missing links became visible too, especially where applications fall short despite strong theories.

3.4 Analytical Approach

The process unfolded using two linked approaches. Through internal review, one method uncovered main theories, core evidence, results, and areas of debate across the three topic groups. Following that, connections between clusters helped align ideas with actual needs for predicting blackouts in power systems' digital twins. Insights came by applying concepts like state monitoring, identifying variables, and best control actions - based on - as a guiding structure. Mapping them together led to clear conclusions: some twin functions already hold solid grounding, others need refinement, while certain ones meet deep-rooted obstacles when applied inside today's energy institutions. Focusing on real-world patterns, secondary information about climate and energy networks came from open records like those kept by the U.S. Energy Information Administration, Europe's group of transmission managers, and the global panel studying climate shifts. This background helped shape the model-based exploration using actual signs of how weather changes stress electrical grids.

3.5 Limitations

Findings here face clear boundaries. Because it reviews past work, what can be said depends on what others have already published - much of which focuses on digital twins in factories or broad tech systems, not power grids. Without real-world data from live energy networks using digital twins, some arguments rest on reasoning borrowed from similar areas instead of firsthand evidence. Fast changes in both twin technologies and climate models add another layer; details today might lose relevance before new papers appear. Work ahead would benefit most from hands-on investigation: observing trial runs at major electricity providers, talking systematically with engineers in the field, testing ideas through simulations fed with historical weather patterns - all helping check whether current thinking holds up under practical pressure.

4. Results

4.1 Digital Twins in Power Systems

Studies repeatedly point out five digital twin abilities useful for managing electricity grids and forecasting blackouts. Right at the start, live updates from constant IoT sensor input allow a digital replica to reflect current conditions on every tracked part of the network - including generators, substations, transmission paths, and local distribution units. According to, alongside two years later, staying connected in real time with steady streams of sensor information forms a base requirement; miss this, and what remains is just basic modeling, nothing more [15]. In practice, when applied to energy networks, it means feeding ongoing measurements from SCADA systems, intelligent meters, heat detectors on cables, plus environmental data from climate stations straight into the virtual system representation .

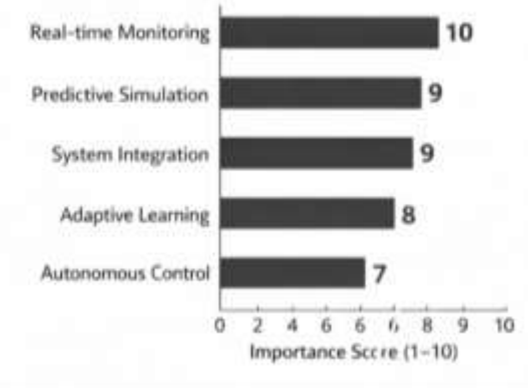
Starting differently, predictive simulations let digital twins forecast upcoming system behaviors using present data along with expected changes. According to, this forecasting forms the central optimization task in how digital twins function - constantly working out what comes next for a system while determining which controls best meet specific goals. When it comes to anticipating blackouts, key targets involve holding steady both voltage and frequency levels, besides staying within safe temperature ranges for every part during anticipated shifts in power demand and supply.

Starting differently each time, adjustment mechanisms inside the digital twin spot mismatches between real-world actions and expected outcomes. When differences appear, information flows into the system, guiding recalibration of built-in settings. According to Barricelli and colleagues from 2019, such ongoing fixes mark the key difference between dynamic twins and fixed simulations. Unlike models reviewed only at intervals, these versions stay accurate despite wear, changes, or environmental shifts over time. For older electrical networks now facing unfamiliar weather pressures, maintaining alignment through continuous updates becomes essential behind the scenes.

Composability lets individual digital twins merge into broader models reflecting whole-grid dynamics. According to, it stands out among essential traits of digital twins; meanwhile, point to scaling up from limited pilots as still unresolved technically. Because cascading failures arise across interconnected parts, isolated device-level simulations fall short - so, within electrical networks, combining representations becomes necessary rather than a choice.

Starting differently each time, control moving both ways marks a real digital twin, unlike simpler models that only observe. This two-way flow means changes can be sent from model to machine. For energy networks, think automatic rerouting, tuning safety devices, adjusting load during peak times. Some researchers insist on this feedback loop as the key trait separating authentic twins from basic copies. One study labels it non-negotiable for legitimacy. Another ranks coordinated regulation among the top tasks every functional twin must handle.

Figure 2. Core Functional Capabilities of Digital Twins in Power Systems



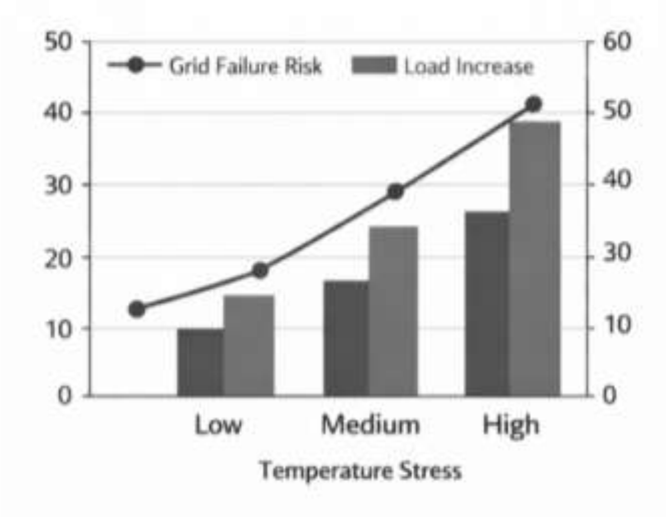
4.2 Climate Changes Add Unpredictable Risks

Looking closer at past studies alongside recent energy data reveals climate shifts strain power systems in multiple connected ways, effects on supply, usage, and physical networks often amplify one another unpredictably. When temperatures soar, electric grids face pressure via several routes: higher air warmth limits how much current power lines can carry due to greater resistance and drooping wires. During hot spells, the need for electricity jumps sharply for air conditioning even as fossil fuel and nuclear plants lose output because their cooling functions weaken. On the flip side, severe cold snaps like what unfolded in Texas during 2021 show how unprepared some power facilities are when freezing conditions hit right when people rely most on heating.

Although rain and dampness shifts open new hazard routes, floods strike substations along with buried cables. When dry spells hit, less water exists to cool thermal plants while hydropower production drops at the same time. Ice building up on wires adds weight until structures fail, knocking out power across wide areas. Strong gusts like those in hurricanes or twisters knock down tall transmission supports and wooden utility poles alike. Fire danger grows where heat, arid conditions, and breezes combine, burning equipment directly and prompting early shutdowns of live wires in vulnerable regions is a step taken often by Pacific Gas and Electric throughout California.

Across every route described, timing and location link outcomes - storms frequently strike several parts of the power network at once over wide regions, removing varied breakdown patterns that usually contain disruptions before they spread. Because of this, a digital twin meant to forecast outage likelihood during shifting climate conditions needs more than component-level monitoring; it requires simulation of overlapping stresses on many elements brought by severe weather.

Figure 2. Relationship Between Temperature Stress and Power Grid Failure Risk



4.3 Technology and Institutions Have Boundaries

Research highlights repeated hurdles in applying digital twin technology to large-scale power grids. A lack of common frameworks is key), stressing that inconsistent data formats block system interoperability, leaving individual models disconnected when predicting regional blackouts. From a different angle, describe this as a fieldwide misalignment; instead, they propose a framework built on four linked levels to steer progress. Still, even their approach concedes one fact: global alignment has yet to emerge.

Figure 3. Barriers to Digital Twin Implementation

One big challenge comes from what computers can handle. As Rasheed and team noted in 2020, difficulties show up when systems grow too large, require real-time adjustments, or rely on parts that behave unpredictably. If a network stretches across an entire nation tying together countless nodes the volume of information it generates quickly piles up. These kinds of models push hardware to its limits. Running detailed simulations based on physical laws faster than real time passes turns out especially demanding, yet doing so is key to delivering timely insights.

Unexpected risks surface due to flaws in cyber defenses, especially where digital replicas support bidirectional data flow. Because such platforms transmit directives to real-world machinery, vulnerabilities multiply. If compromised, a replica could dispatch altered signals - intentionally provoking system disruption. Evidence gathered by Fuller and colleagues converges with findings from, revealing ongoing shortcomings in security design. Outages triggered by malicious software in Ukraine's electricity systems back in 2015 and again in 2016 reveal just how severe cyber intrusions might turn. Where digital simulations interact directly with physical operations, dangers tend to multiply.

A single obstacle stands in the way: the inner workings of institutions and financial pathways. As noted by, deploying digital twins requires deep investment, reshaping operational layers - employee habits transform, processes adjust, IT frameworks advance, equipment upgrades, programs renew - all while legacy power networks lag without substantial capital paired with regulatory backing. Building a comprehensive digital model of an electric grid depends on expansive sensor deployment, high-speed communication channels, and powerful computing hubs; this kind of infrastructure involves costs exceeding current budgets available to numerous utility firms, particularly those active in areas with limited industrial development.

These risks align with some of the findings in smart grid research note that “the smart grid introduces new vulnerabilities due to increased connectivity,”. It is a clear trade-off between intelligence and security in digital twin systems.

5. Discussion

A closer look at existing studies suggests guarded agreement - digital twins could predict blackouts tied to shifting climate patterns due to their underlying design strengths, though moving beyond concept into real-world use faces tangled hurdles spanning tech limits, organizational resistance, and cost issues that research still struggles to untangle. Despite promise, practical application lags behind theory.

What stands out in this analysis is how closely the core traits of a genuine digital twin - observing state, identifying parameters, while enabling optimal control - match what a climate-responsive power grid needs to function. Grounded in established research, especially the structured approach laid out by, there’s solid reasoning behind why such twins go beyond fixed grid models; instead of staying rigid, they adjust their internal picture of grid status whenever fresh inputs arrive. Because of this adaptability, future states can be forecast under specific environmental pressures, so actions may emerge ahead of critical tipping points. When extreme weather threatens blackouts, the outcome becomes a responsive setup: live meteorological feeds merge with infrastructure signals, launching predictive runs that spotlight clusters of equipment likely to fail together when stresses pile up.

Because cascading blackouts arise from how strained parts interact, not just one piece failing alone, modeling each part separately falls short. The usefulness of digital twins grows when they capture whole-system behaviors, something, along with, have shown through composability traits. When past operating patterns are stored, the model begins recognizing early signs of breakdown before collapse happens. Instead of focusing on standalone pieces, such systems compare live performance to known danger markers drawn from earlier events. Without linking component behavior across the network, even detailed tracking cannot predict wide failures. What matters emerges only when connections matter too.

Though much has been written about digital twins theoretically, gaps remain when linking those ideas to large-scale energy networks. Real-world data on how such models perform amid shifting climates within national grids? Nearly nonexistent. Take production-sector examples - like work on thermal units which showcase controlled environments far less complex than cross-country electricity flows. Moving from factory-level prototypes to continent-wide infrastructure isn’t automatic. Challenges tied to size, integration, and unpredictability pop up, just as noted recently. Jumping across domains demands more than optimism; it needs proof-built step by step.

How unexpected results are handled demands a closer look. At the core of digital twin promises for energy networks lies a contradiction, because these models can react automatically to forecasted disruptions, they gain powerful utility; yet that very responsiveness opens pathways for cyber threats on critical infrastructure. Such dual-use tension remains unresolved across existing studies. Researchers like Fuller and colleagues in 2020, along with Minerva and Crespi the same year, recognize safety risks clearly, still neither maps out how protection could work against advanced attackers targeting entire national grids. So far, evidence implies rollout should happen gradually: start with observation and guidance tools, delay self-governing operations until safeguards evolve sufficiently.

What point out about missing standards affects real-world use of digital twins in power systems, not just the tech side. Though built over many years, today's grids rely on gear from various makers, managed by different public and private operators, sometimes spanning countries and legal zones. To foresee blackouts using digital twins, one must grasp how failures spread across the whole network. This demands shared data across all players. Yet such sharing cannot happen without agreed-upon formats, even if each twin works perfectly in isolation. While their suggested four-part model aims to solve this, it still sits unused, recognized by its creators as unfinished work. Despite promises, no broad agreement exists yet.

One way forward involves rolling out digital twins in phases, tailored to how power grids handle climate stress. Early steps mean focusing on areas at greatest risk. Places like fire-prone forests, river spans vulnerable to flooding, or sections now hitting heat limits with basic monitoring tools that avoid remote-control links, reducing cyber dangers. Such setups stream live data but do not act on it directly. Over time, these feeds gather enough past behavior patterns so later models can spot odd shifts before failures occur. Later, when rules for compatibility tighten and protection methods improve, linking several of these local systems becomes feasible. Connections across different parts allow forecasting how trouble might spread through the network - ability experts often cite as vital for avoiding wide blackouts. This gradual buildup avoids early overreach while laying groundwork others can extend.

Policy insights show grid resilience through digital twins probably won't arise purely from market forces. Because avoiding blackouts benefits everyone, private firms lack strong profit motives to act first. Long waits before returns on power grid upgrades further reduce interest. One utility adopting shared tech standards bears costs while rivals gain free advantages. For progress, rules may need to enforce sensor installation across power networks. Government backing, or assured repayment, could support building digital platforms. Required involvement in setting common protocols might also prove necessary. Without structured ways to involve expatriates, Isaeva's study of Uzbekistan's money transfer trends reveals gaps. In much the same way, funds sent home stay idle without systems to channel them into growth projects. Digital replicas remain an unused possibility unless institutions provide formats, safety rules, and enforced expectations. Structure turns abstract tools into real-world strength.

Looking ahead, one clear need stands out: deeper study of current digital twin experiments within electricity networks. Projects run by National Grid in Britain, Enel in Italy, or researchers at Pacific Northwest Lab across the U.S. could reveal how design decisions shift when moving from factory settings into power infrastructure. Instead of assuming what works, actual performance patterns must emerge through structured comparison. Another path involves testing forecast reliability under realistic conditions. Here, past weather reconstructions like ERA5 might pair with real grid layouts and operations logs to measure how well digital twins anticipate blackouts compared to known breakdowns. Such stress tests would ground claims in evidence rather than theory alone. Beyond modeling, collaboration matters, especially between engineers focused on grids, climatologists tracking extreme events, data specialists shaping information flows, and experts securing critical systems. Together, they could build tailored safeguards where broad guidelines now fall short. Lastly, scaling up poses unanswered questions. While a method proposed by suggests possible gains, whether it functions live across an entire nation's network remains unknown. Processing demands, timing constraints, and integration hurdles have yet to face rigorous scrutiny.

Because of this, a digital twin must be tested for cascading failure dynamics within interconnected systems. As show, "large blackouts can arise from the propagation of small disturbances".

What if digital twin technology isn’t just about factories? Its deeper value may lie in managing vital infrastructure amid shifting climate conditions. Engineered systems now face complex risks they were never built to handle. Because past designs relied on stable environmental patterns, today's volatility exposes their limits. Digital twins update themselves constantly unlike rigid legacy methods stuck in older models. They simulate future scenarios while adjusting in real time, offering foresight where it was missing. Power networks could benefit greatly if institutions begin aligning across boundaries. Technical upgrades alone won’t suffice when coordination gaps remain wide. This work aims to open space for such difficult conversations.

6. References

[1] Barricelli, B.R., Casiraghi, E., and Fogli, D. (2019). A Survey on Digital Twin: Definitions, Characteristics, Applications, and Design Implications. IEEE Access, 7, 58727-58745. https://doi.org/10.1109/access.2019.2953499

[2] Duan, H., and Tian, F. (2021). The Development of Standardized Models of Digital Twin. IFAC PapersOnLine, 54(1). https://doi.org/10.1016/j.ifacol.2021.04.164

[3] El Saddik, A. (2018). Digital Twins: The Convergence of Multimedia Technologies. IEEE MultiMedia, 25(2), 87-92. https://doi.org/10.1109/mmul.2018.023121167

[4] Fuller, A., Fan, Z., Day, C., and Barlow, C. (2020). Digital Twin: Enabling Technologies, Challenges and Open Research. IEEE Access, 8, 108952-108971. https://doi.org/10.1109/access.2020.2998358

[5] Haag, S., and Anderl, R. (2020). Conception of a Digital Twin in Mechanical Engineering - A Case Study in Technical Product Development. Proceedings of the Design Society: Design Conference. https://doi.org/10.1017/dsd.2020.23

[6] Liljaniemi, A., and Paavilainen, H. (2020). Using Digital Twin Technology in Engineering Education -Course Concept to Explore Benefits and Barriers. Open Engineering, 10(1), 377–385. https://doi.org/10.1515/eng-2020-0040

[7] Liu, Q., Liu, B., Wang, G., and Zhang, C. (2019). A Comparative Study on Digital Twin Models. AIP Conference Proceedings, 2073, 020091. https://doi.org/10.1063/1.5090745

[8] Minerva, R., and Crespi, N. (2020). Digital Twins: Properties, Software Frameworks, and Application Scenarios. IT Professional, 22(1). https://doi.org/10.1109/mitp.2020.2982896

[9] Rasheed, A., San, O., and Kvamsdal, T. (2020). Formal Properties of the Digital Twin – Implications for Learning, Optimization, and Control. Proceedings of the 2020 IEEE 16th International Conference on Automation Science and Engineering (CASE). https://doi.org/10.1109/case48305.2020.9216822

[10] Trauer, J., Schweigert-Recksiek, S., Engel, C., Spreitzer, K., and Zimmermann, M. (2020). What is a Digital Twin? - Definitions and Insights from an Industrial Case Study in Technical Product Development. Proceedings of the Design Society: Design Conference. https://doi.org/10.1017/dsd.2020.15

[11] Panteli, M., and Mancarella, P. (2015). The Grid: Stronger, Bigger, Smarter? Presenting a Conceptual Framework of Power System Resilience. IEEE Power and Energy Magazine, 13(3), 58–66. https://doi.org/10.1109/MPE.2015.2397334

[12] Zhou, K., Fu, C., and Yang, S. (2020). Digital Twin for Energy Systems: A Review. Applied Energy, 269, 114540. https://doi.org/10.1016/j.apenergy.2020.114540

[13] Dobson, I., Carreras, B.A., Lynch, V.E., and Newman, D.E. (2007). Complex Systems Analysis of Cascading Failures in Power Systems. Chaos: An Interdisciplinary Journal of Nonlinear Science, 17(2), 026103. https://doi.org/10.1063/1.2737822

[14] Yan, Y., Qian, Y., Sharif, H., and Tipper, D. (2012). A Survey on Cybersecurity for Smart Grid Communications. IEEE Communications Surveys & Tutorials, 14(4), 998–1010. https://doi.org/10.1109/SURV.2012.010912.00028

[15] IPCC (2022). Climate Change 2022: Impacts, Adaptation, and Vulnerability. Intergovernmental Panel on Climate Change. https://www.ipcc.ch/report/ar6/wg2/