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Cyber-Physical Power System Digital Twins—A Study on the State of the Art

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Abstract

This study explores the transformative role of Cyber-Physical Power System (CPPS) Digital Twins (DTs) in enhancing the operational resilience, flexibility, and intelligence of modern power grids. By integrating physical system models with real-time cyber elements, CPPS DTs provide a synchronized framework for real-time monitoring, predictive maintenance, energy management, and cybersecurity. A structured literature review was conducted using the ProKnow-C methodology, yielding a curated portfolio of 74 publications from 2017 to 2025. This corpus was analyzed to identify key application areas, enabling technologies, simulation methods, and conceptual maturity levels of CPPS DTs. The study highlights seven primary application domains, including real-time decision support and cybersecurity, while emphasizing essential enablers such as data acquisition systems, cloud/edge computing, and advanced simulation techniques like co-simulation and hardware-in-the-loop testing. Despite significant academic interest, real-world implementations remain limited due to interoperability and integration challenges. The paper identifies gaps in standard definitions, maturity models, and simulation frameworks, underscoring the need for scalable, secure, and interoperable architectures and highlighting key areas for scientific development and real-life application of CPPS DTs, such as grid predictive maintenance, forecasting, fault handling, and power system cybersecurity.

Keywords: digital twins; cyber-physical power systems

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1. Introduction

The integration of cyber-physical power system (CPPS) digital twins (DT) has emerged as a pivotal area of research, offering transformative potential for enhancing the resilience, efficiency, flexibility, and adaptability of modern power grids. By seamlessly merging physical infrastructure with cyber components, CPPS DTs leverage real-time data, advanced control systems, and predictive analytics to model operational states and dynamically respond to system changes [1]. These DTs are underpinned by computational models that encompass a wide range of elements, from electromechanical equipment such as generators and transmission lines to communication devices like servers and routers, thereby enabling innovative approaches to power system operation and strategic management [2].

Originally conceptualized in the manufacturing sector to optimize product lifecycle management [3], DT technology has recently been adapted to address the growing complexity of modern power systems. This complexity stems from the integration of renewable energy sources, decentralized assets, and advanced communication networks [4]. However, despite their potential, CPPS DTs are not yet widely adopted due to significant technical

and integration challenges in enabling them, mainly in the area of correlation and orchestration between the physical and cyber system DT capabilities. A theoretical, generalist CPPS DT, as presented in Figure 1, would contain models of generation, transmission, distribution and utilization-level system dynamics, elements, processes, and devices while also concerning itself with networking elements such as control algorithms, communication devices and methods, and computing capabilities. This theoretical CPPS DT could be structured as the orchestration of two digital twins—one of the physical system and the other of the cyber system—or as a single monolithic entity, depending on how the simulations, analytics, and communication with the physical twin are implemented. In this figure, the former approach is represented. From a long-term view perspective, the CPPS DT also plays the role of informing CPPS strategy and management with analytics from the operating model, while also providing capabilities for scenario simulation that can aid in managing changes in topology, controls, procedures, and other aspects of a modern CPPS.

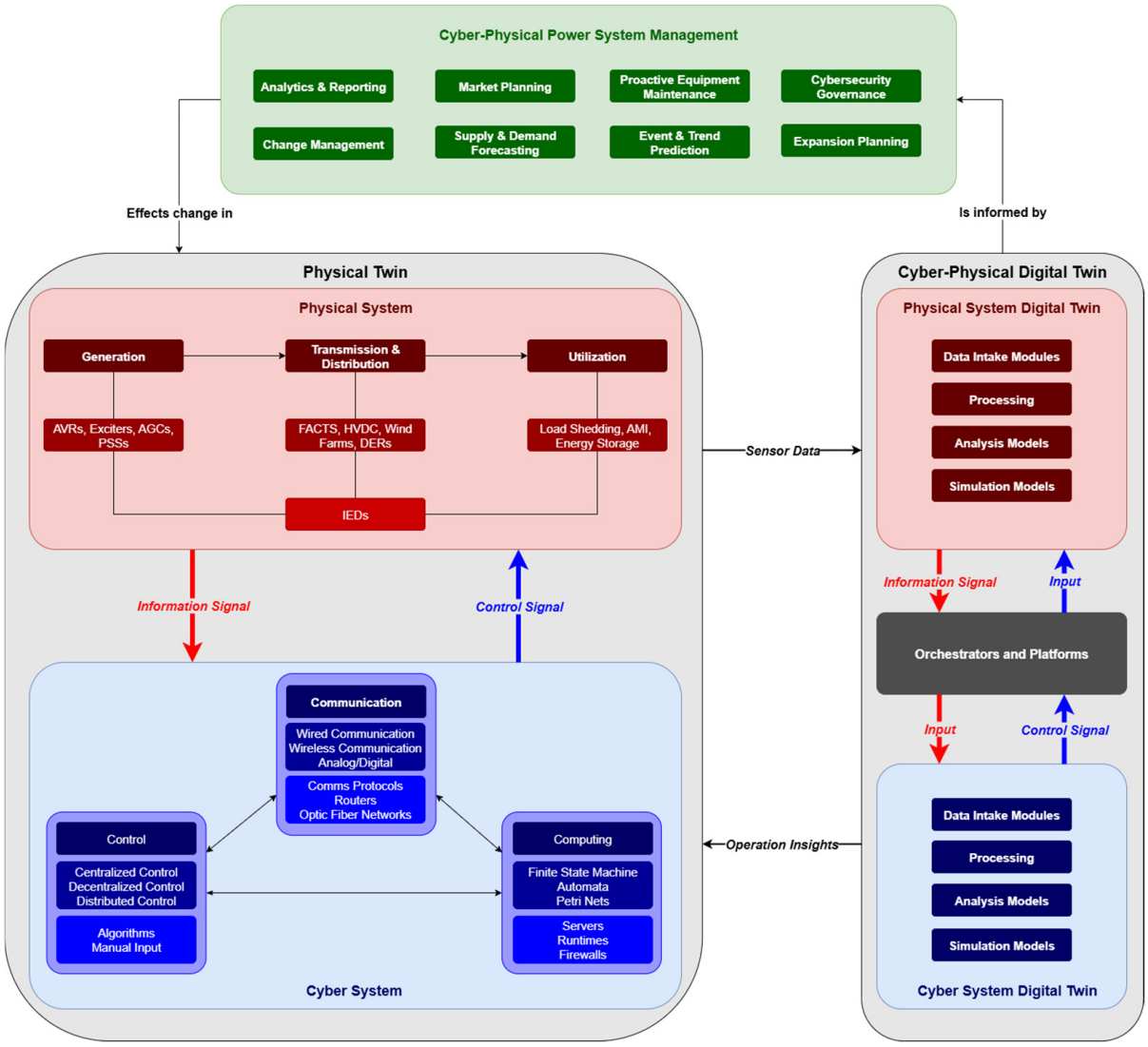

Figure 1. Capability-focused view of a theoretical CPPS DT.

Other key issues include achieving interoperability among diverse data sources and system models, accurately representing grid states, standardizing communication protocols and data models, optimizing computational resources for machine learning integration, and ensuring robust operational security to mitigate risks of malicious interference [5,6].

Despite these challenges, the practical applications of CPPS DTs have garnered substantial research interest. They are increasingly viewed as next-generation solutions to critical issues in contemporary power systems, such as predictive equipment health monitoring, pre-fault alarm systems, real-time decision-making support during faults, post-fault analysis, grid expansion planning, integration of distributed energy resources (DERs), cybersecurity frameworks, and load dispatch management [7,8].

Leveraging the categorizations and theory presented in [1,9,10], it can be said that the study of CPPS DTs is comprised of understanding their potential applications and figuring out the integration complexity for the multiple technology enablers spanning across different fields of computer science and engineering, while making use of advanced simulation techniques to achieve lifelike representations of power system processes and infrastructure. It is also clear that there are still steps to be taken when it comes to maturity level definitions and categorizations and that field studies, tests, and implementations have yet to be rolled out. To illustrate and complement this understanding, Figure 2 provides a tree view of the CPPS DT area of research while also expanding into specific applications, technologies, simulation techniques, maturity definitions, and case study types.

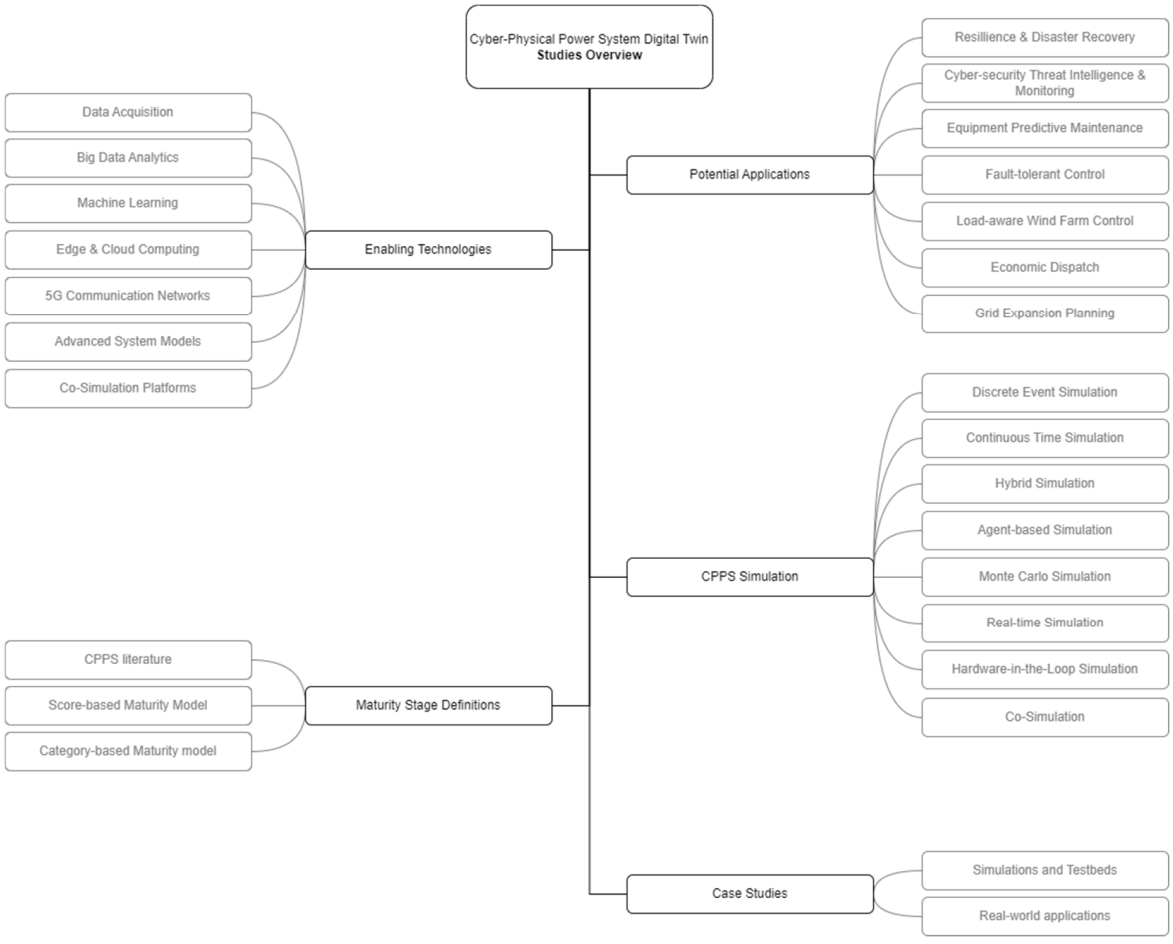

Figure 2. Map of foundational concepts for CPPS DTs.

As such, considering their capabilities and recent trends in technology with data-driven Large Language Models and Machine Learning algorithms, CPPS DTs hold significant promise for advancing the operational and strategic capabilities of modern energy infrastructure, provided that scalability, viability, and security concerns are adequately addressed, and have been increasingly studied and assessed for the past 5 years (2020–February 2025), with a noticeable increase in research interest from 2022, as can be

seen on the graph presented in Figure 3. This figure also presents the number of publications on the Power System DT area, indicating that around 20–25% of all publications involving Power Systems and Digital Twins address the CPPS area. These include magazine articles, patents, books, and journal papers, among other forms of publication.

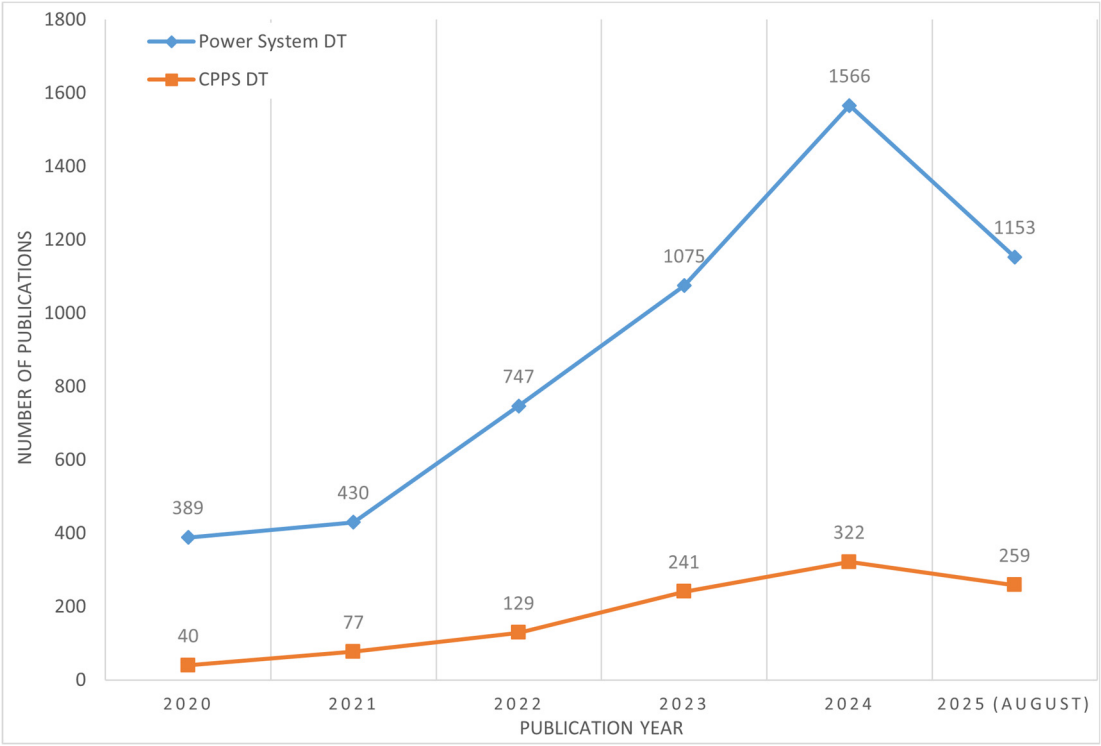

Figure 3. Search results for publications related to DT in power system applications during the 2020–August 2025 period, using Scopus, ScienceDirect, and Google Scholar.

This paper, therefore, presents a comprehensive overview of the key topics and technical enablers in the CPPS DT research area. It conducts in-depth reviews of the existing literature to identify relevant use-cases and examines both the conceptual evolution and the current state of CPPS DT implementation in simulated and real-world environments. This work also sheds light onto cross-disciplinary research gaps at the core of the broader DT area and also in the specific CPPS context, thus paving the way forward for other works to study and address them.

The paper is organized as follows: a deep dive into the methodology for finding the underlying scientific corpus for this work is provided in Section 2. Section 3 discusses the applications of industry interest for CPPS DT, while Section 4 provides an analysis of the core technical enablement challenges, and Section 5 addresses case studies executed in the past 5 years. Section 6 discusses the results and presents research findings and unaddressed gaps in this field. Finally, Section 7 concludes with the main findings and presents recommendations for future work.

2. Research Methodology

This state-of-the-art study was executed in order to gain an improved understanding of the applications of DTs in power systems, with a particular focus on advancements related to CPPS.

The structured Knowledge Development Process—Constructivist (ProKnow-C) methodology [11] was adopted to ensure a rigorous and reproducible bibliographic selection process. This process essentially goes through two major stages:

1. Definition of search axes, keywords, and databases;
2. Aggregation and filtering of the original database through removal of duplicates, books and patents, scientific relevancy/impact analysis, and manual inspection of titles and summaries to determine a final bibliographic portfolio.

2.1. Research Scope and Initial Database Creation

In order the optimally search in databases such as Scopus and Google Scholar, pertinent keywords must be defined. The authors relied upon the Institute of Electrical and Electronics Engineers (IEEE) Taxonomy to do so, interlocking it with other keywords identified in previously read papers from major sources by using "OR" logic connectors.

The Publish or Perish 8 (PoP) software tool [12] was used to query the aforementioned databases, retrieving metadata for up to 1000 entries per search (a PoP limitation). The keyword combinations, presented in Table 1 together with the papers found per combination, targeted DTs in the power systems context and simulation methods for general cyber-physical systems—both with a focus on CPPS. This effort yielded an initial gross of 2207 documents.

Table 1. Keywords and number of papers found on each search.

Keyword Axis 1	Keyword Axis 2	Keyword Axis 3	Papers Found
Digital Twins	Power Systems	-	817
Digital Twins	Substations	-	192
Digital Twins	Microgrids	-	144
Digital Twins	Cyber-physical Systems	Power Systems	212
Cyber-physical Systems	Co-Simulation	Power Systems	493
Cyber-physical Systems	Hardware-in-the-Loop Simulation	Power Systems	145
Cyber-physical Systems	Monte Carlo Simulation	Power Systems	85
Cyber-physical Systems	Dynamic State Simulation	Power Systems	90
Cyber-physical Systems	Hybrid Simulation	Power Systems	29

This effort yielded an initial gross of 2207 documents.

2.2. Database Refinement and Selection Criteria

In order to achieve a corpus that can be the foundation for the study, the gross database (2207 papers) was refined through the following steps:

- Step 1: Duplicate removal and exclusion of patents and books, reducing the corpus to 1847 documents;
- Step 2: Filter based on historical scientific relevancy, only retaining papers with more than 3 citations per year or published post-2021, resulting in 703 papers;
- Step 3: Title screening, resulting in 164 papers;
- Step 4: Abstract and contribution analysis, achieving the final curated database of 74 key publications

The refined database's earlier works mostly touch the subject of advanced simulation techniques, with the more recent years seeing an increase in publications touching on the subject of CPPS DTs—especially in the last two and a half years, as shown by the temporal distribution presented in Figure 4. This, together with the bibliometric analysis of the refined database presented in Table 2, is an indicator of the rising interest and increasing importance of the CPPS DT research area.

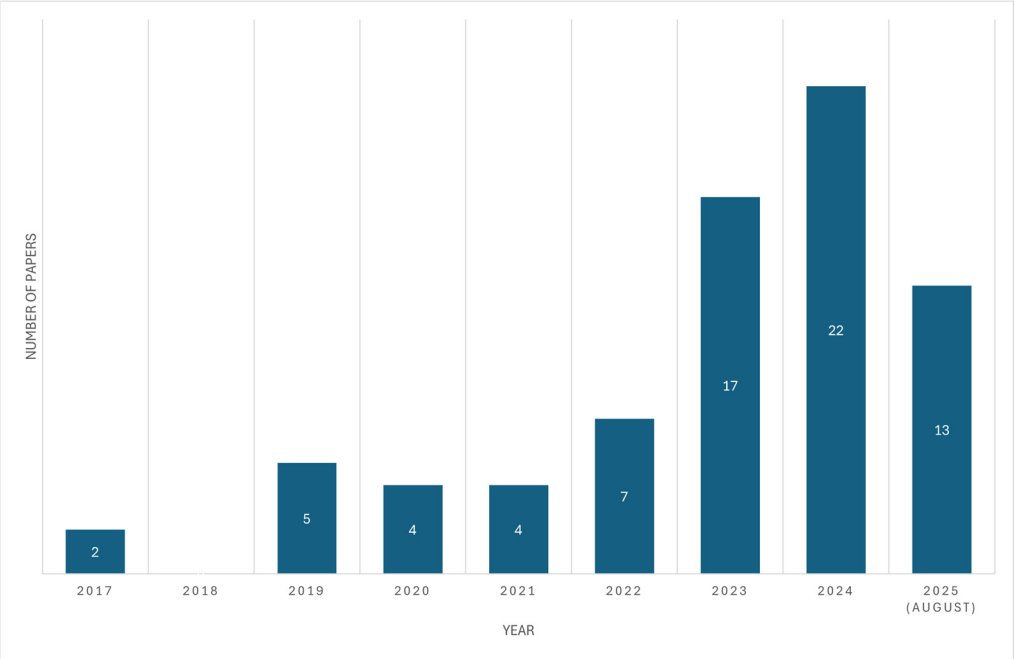

Figure 4. Distribution of papers in the final database over the years.

Table 2. Bibliometric analysis of the refined database.

Metric	Result
Papers	74
Total Citations	954
Time Span (Years)	9
Citations/Year	106
Citations/Paper	13
Citations/Author	5
Paper/Author	0.71
Authors/Paper	3.18
h-index	12

Not all 74 papers in the resulting corpus are cited in this paper, as some of them were of contextual importance to the authors or had similar contributions to other selected papers. Attaining a variety of topics and scope breadths/depths in this final database was the priority, with [4,9,13,14] addressing terms of general reviews, frameworks, and overviews on CPPS and DTs, [2,15] elaborating on DT applications for grid equipment monitoring, [6,16–29] touching on the subject of grid cybersecurity with some works already pointing toward a CPPS DT-based solution, [8,30,31] analyzing the methodologies to improve the grid resilience of CPPS under natural disasters and other types of contingencies and highlighting DTs as a potential option, [32–56] exploring PS/grid-level and communication network DT applications on both simulated and real-world environments, and [57–70] studying simulation techniques for CPPS.

2.3. Key Observations

Through an inspection of the bibliography's metrics and temporal distribution, it can be said that the field has gained increasing attention since 2022, with a notable rise in real-world applications on the physical domain of CPPS in 2024.

Earlier works in the corpus (2017–2022) focused on the introduction and strategic vision of simulation techniques used in the literature's more recent works, which have seen a significant shift toward practical implementations and cybersecurity.

The h-index of 12 and citation/paper of 15 indicate a growing but still emerging research domain. Industry trends and modern needs, such as system integrability and cybersecurity, are also expected to drive future developments.

Table 3 presents an evolution of research themes within the curated literature over time.

Table 3. Research theme evolution over time in the curated bibliography.

Year	Main Research Themes
2017	Hardware-in-the-Loop simulation, co-simulation, cyber/physical system single-domain testbeds [16,57].
2019	Early power system digital twin concept introduction [13,70] and long-term vision on its potential, cross-disciplinary strategic vision.
2020	HiL/co-simulation integration ideation [4,71,72], early experimentation of digital twins in benchmarking power systems (virtual-to-virtual) [27].
2021	Expansion into substation digital twins [55] in the virtual-to-virtual domain, initial applications on specific grid elements being studied [2].
2022	Investigation on generation and transmission grid applications [5,73,74] still in the virtual-to-virtual space, coupled with the start of the growth in interest in CPPS [75].
2023	IEC61850 substation twins [26], initial assessments on DTs for cybersecurity [17,18], strategic roadmaps for practical implementations [15,18,47,49,54,62,76], studies merging leveraging HiL simulation in order to shift from virtual-to-virtual DTs [62].
2024	First real-world power system DT implementations on small-scale systems and microgrids [44], assessments on CPPS DT as a tool to enhance systemic cybersecurity and operations [6,9,20,21,23,25,30,45,58], and initial proofs-of-concept on practical CPPS DT applications on microgrids [43,45,53,77].
2025 (as of August)	Framework proposals and real-life case studies on generation plants [32,33,37,39], machine learning algorithm integration to DT ecosystems [41], increasing diversity and scale of applications [34–36,42], with some studies focusing on early implementations of DT-powered cybersecurity frameworks for the grid [40].

3. Applications of Interest in the Literature

The emergence of CPPS DTs as a research topic comes from the versatility, analytics, and situational awareness that they can offer to multiple actors within the power system while providing optimized solutions for some of the core problems of the contemporaneous grid—representing a potential paradigm shift in strategic infrastructure planning, management of change, and operations.

Drawing upon an extensive analysis of the curated literature (as detailed in Section 2), this section provides a thorough examination of seven key application domains where CPPS DTs present significant value in real-world implementations.

3.1. Real-Time Monitoring

The modern power grid generates staggering volumes of data, with recent estimates suggesting that a typical transmission substation can produce over 5 TB of operational data annually [78]. However, extracting insights and analytics from these high-volume data sources is still a challenge when it comes to real-time execution, given that there is a need for historical processed data points for most algorithms to determine specific patterns/events and highlight them/or issue warnings when required.

DTs, by creating digital replicas of these systems and accepting real datasets as input, can be used to monitor the status of grid and network components and to track what the theoretical operation metrics would have been under the same conditions—essentially, they can provide dynamic baseline comparisons. As such, the need for storing high volumes of historical data or for highly complex algorithms (which also consume extended computational processing power) is diminished. Additionally, this benefit can be reaped at other levels in the CPPS, considering the nuances of substations, microgrids, DERs, and other grid-composing blocks.

The work presented in [15], for example, explores this idea by creating a simulation of a 345 kV substation and comparing its phasor measurement unit (PMU) data against it, reaching a 72% reduction in false alarms in comparison to a machine learning algorithm trained in a historical dataset for the same entity, taking roughly 40% less time to do so. In this particular study, a live data stream was not implemented, and the event datasets were fed to the simulation and comparison algorithm in a single, decoupled batch.

3.2. Assistance to Proactive Maintenance

Grid equipment maintenance is also one of the core topics of discussion as an immediate application of DTs, given how these elements can also be separately modeled for specific insights and how their output data can be analyzed and mined for information on their performance, which can then be used to prompt maintenance teams to act. As such, DTs represent a shift from time-based to condition-based maintenance approaches in the grid.

In [79], the idea of using DTs to calculate reliability probability density of relay protection statuses, addressing issues related to fuzziness and randomness, is presented as a follow-up to a probabilistic model that improved relay protection system availability from 99.2% to 99.8% in a 12-month field trial across 18 substations.

Similarly, networking equipment maintenance can also benefit from DTs by using different sets of output data (e.g., response times, network throughput), as ideated in [54], where a study on network architectures, topologies, traffic, resource usage, and detection schemes for dynamic changes within a network was executed to create an intelligent network maintenance schedule by creating a simulation of a given network and feeding it the inputs of its real-world counterpart.

Additionally, [56] presents a virtual domain application where a three-dimensional model of a substation was created using Building Information Modeling (BIM) with component parameters being made available. This 3D model is then fed with sensor outputs for each modeled component, creating a visual aid for the substation's operational and maintenance teams to run periodic checks and extract analytics and insights from. Essentially, the DT is built using the models from the BIM by creating a data ingestion layer that can map properties to the BIM's components (e.g., the temperature on a transformer, the rotational speed of a generator). While there is no simulated component to this DT proposal, there is a digital model of the substation's physical assets (3D, from the BIM), and there is a proper data stream into this model, which could be enhanced to run simulations behind the visual layer to then support the real-time monitoring capability and enter the realm of dynamic baseline comparisons.

3.3. Decision Support Systems

Given the real-time analytics capabilities imbued within the DT concept and its extensibility and fit with machine learning algorithms, another area of scientific attention is support to decision-making in operation and strategic planning scenarios. One primary

advantage of DTs is their ability to simulate diverse scenarios for system planning and contingency management.

For example, by modeling the effect of integrating new renewable sources, a PS DT can inform decisions about where to position assets to minimize curtailment and balance demand, as ideated in [60].

An example of DT assistance in decision-making at a grid planning level can be seen in [49], where the authors propose a framework that optimized microgrid operations with a focus on minimizing power losses and enhancing voltage levels at various nodes—achieving results of 15.7% reduction in power losses in a 42-node microgrid model.

Another such example can be seen in [80], where a hierarchical DT architecture is proposed, utilizing real-time HiL simulation to emulate a physical grid, performing dynamic behavior analysis on top of the physical twin data, and implementing observer algorithms for situational awareness—ultimately serving as a possible support tool in grid planning and operation.

Outside the power systems domain, in [81], an autonomous decision-making framework for a cyber-physical is proposed for gas-lift (a method used to lift oil from wells using gas) using techniques such as Bayesian inference, Monte Carlo simulations, transfer learning, online learning, and model hyperdimensional reduction—displaying possibilities for the integration of cyber and physical DTs.

3.4. Resilience and Risk Management

Other core components of modern power systems operation in which digital twins can be viable solutions are resilience and risk management, considering the comprehensive, data-driven approach enabled by the new technology. In similar fashion to the last section, the DT's simulation capabilities play a key role in the solution, given that they can simulate potential disruptions ad hoc and continuously monitor system conditions via their data acquisition capabilities—thus helping operators proactively identify vulnerabilities and implement risk-mitigating actions before issues escalate [73].

One of the research area's earlier publications, [55], establishes that a substation DT can also assist in digital inspections, personnel positioning, path planning and navigation, safety risk analysis and early warning, real-time alarm for safety events, and panoramic monitoring.

More recently, the authors of [82] have leveraged DTs for risk assessments on benchmark, simulated substations, by using the Markov chain and Gibbs sampling methods.

Additionally, the work presented in [83] looks at power system vulnerabilities during cascading failures and blackouts, with an outlook to improve grid resiliency by establishing a DT-based real-time analysis framework that allows for real-time monitoring and analysis of vulnerability data from the grid's physical twin, essentially creating vulnerability indices that are used for impact assessments on various grid elements. The authors reported a 39% reduction in blackout risk in a 500-bus test system through real-time vulnerability indexing in a simulated validation step, as presented in their paper.

3.5. Energy Management Optimization

PS DTs can also provide a framework for balancing supply and demand while maximizing the efficiency of energy resources through the usage of historical and real-time data, thus helping operators manage power flow, coordinate DERs, and reduce inefficiencies across the system in multiple situations such as floating demands, changing weather conditions, and equipment performance variations [46].

This application is particularly relevant in the context of energy trading with prosumer behaviors involved, as explored in [50] where a digital twin model-based approach was

used to propose a cost optimization framework for residential community microgrids with DERs.

3.6. Renewable Energy and Decentralized Resource Integration

As stated in [31], the digital twin of a smart grid emerges as a transformative tool for decentralized resource integration into the broader distribution grid, as it optimizes operations and helps enhance grid resilience by providing insights to the planning and expansion phases.

For example, works like [84] discuss the integration of energy systems, emphasizing the importance of combining various technologies and sectors to enhance resiliency and support decarbonization efforts, citing digital twins as one of the key enablers for developing an infrastructure capable of being the foundation for the power system of the future, given their potential multidisciplinary nature that effectively allows for each part of the grid to be represented in detail.

It is notable that other works in sources such as the IEEE Power & Energy Magazine and IEEE Electrification Magazine also stress the need for accelerated and increased volume in scientific representation of digital twins in the context of renewable energy and DER integration.

3.7. Cybersecurity

Cybersecurity is one of the key areas of potential CPPS DT application being studied nowadays, with a variety of works exploring potential use-cases [19,21–23,75] and elaborating on industry gaps, highlighting the increasing need for high-quality digital representation of communication infrastructure and operational technology networks in power systems [16,28,29].

Considering events in the recent past, such as blackouts in Kyiv being caused by malware attacks on Ukraine's power system infrastructure [85], and the fact that modern grid equipment is accessible via a communication network, there is waning oversight of the grid's resources in favor of decentralization on the grid's edge [86].

As a matter of fact, this concern has existed for a considerable amount of time now, with works such as [16] that look to create cyber-physical test beds of highly digitized systems with the aim of developing cybersecurity frameworks being published.

Through modeling communication networks and their protocols/gateways/access points in tandem with the physical elements of a power system, it is possible to identify false data injection attacks [23] and establish frameworks to enhance the resiliency of microgrid control systems under denial-of-service (DoS) attacks [25], among other potential use-cases.

4. Enabling Technologies

The successful implementation of CPPS DTs relies on a sophisticated integration of hardware, software, and computational frameworks. While certain segments of the electrical energy sector have already met some of the requirements, others require substantial modernization to fully leverage their benefits [1]. There are also parts of the networking infrastructure that need optimization, as high-velocity communication frameworks are essential for a CPPS DT to receive and transmit data in timely fashion to its physical counterpart, and the software/firmware assets of all elements in the chain must be cyber-safe to prevent any malicious actors from tampering with the DT's structure and performance [9].

This section examines the core enabling technologies highlighted in the curated literature, focusing on their roles, current implementations, and associated challenges.

4.1. Data Acquisition Systems

Data acquisition forms the fundamental bridge between physical power systems and their digital counterparts, enabling real-time state representation that distinguishes digital twins from conventional simulations. The fidelity of a CPPS DT directly depends on the sensor infrastructure deployed across the physical system, with varying requirements across grid hierarchies. Transmission systems rely on high-speed phasor measurements, distribution networks utilize granular smart meter data, and generation assets depend on equipment-specific monitoring [52]. Examples of data acquisition system patterns for the physical layer of CPPS across areas of the power system are phasor measurement unit (PMU)-based wide area measurement systems (WAMS) on the transmission side, which provide operators with a high volume of data from multiple buses on the grid with high sampling rates, and advanced metering infrastructure (AMI) on the distribution level which relies on smart meters, micro-PMUs, and other sensors capable of ethernet connectivity to make measurement data available for other applications on the grid's edge.

The cyber layer of CPPS DT relies on native logging capabilities embedded in modern communication protocols and network devices, enabling real-time monitoring of cyber–physical interactions. Network switches, routers, and controllers generate various types of logs at configurable intervals, capturing metrics such as latency, packet loss, and throughput. For security, an IEC 62351-compliant system encrypts logs via TLS 1.3 and implements role-based access control to prevent tampering, together with protocols that have embedded audit trails to enable forensic analysis after cyberattacks [87].

4.2. 5G Communication Networks

Merely acquiring data is not enough, as they need to be transmitted over to concentrators and other servers in the network, and that must happen in the fastest way possible in order to avoid problems related to latency and out-of-step processing [6]. The integration of 5G communication networks to the grid's measurement units is one of the key enablers of CPPS DT—especially since they also complement edge computing by adding enhanced responsiveness in comparison to other types of networks and incorporate advanced security features, ensuring data encryption at rest and in transit in isolated channels for critical data flows to further protect the grid from cyber threats [52].

The work presented in [72], for example, explores the construction of a CPPS laboratory and has an explicit focus on the criticality of high-speed communications to transmit data to simulation and processing modules, displaying degraded and out-of-sync performance when using non-5G alternatives.

4.3. Cloud and Edge Computing

The integration of cloud and edge computing technologies addresses the computational demands of CPPS DT, since the former provides scalable storage and processing power for analyzing large datasets, running complex simulations, and hosting machine learning models and the latter enables localized data processing close to the source, which greatly reduces latency and enhances the ability of digital twins to respond to real-time grid changes such as fluctuating renewable energy generation of sudden load shifts [88]. As such, combining the two creates a hybrid framework that balances the need for centralized analytics with real-time, localized decision-making capabilities—all of which are core tenets of PS and CPPS digital twins.

Furthermore, cloud computing has the added benefit of server-side security and dynamic application hosting, reducing risks and costs typically associated with on-premise computing.

The work in [89], for example, proposes a novel approach for realizing coordinated control of DERs based on cloud-hosted and edge-hosted DT, using different modules of the PS DT in different scenarios and coordinating them over cloud and edge computing to achieve an aggregated, real-time analytics hub that can potentially support the grid during contingency events.

4.4. Data Analytics and Machine Learning

One of the core capabilities of DTs is their ability to process the acquired data and generate insights and analytics on top of them. The main engines behind this are big data analytics methods and machine learning algorithms, as stated in the previous subsection, which can run on cloud servers and on the grid's edge [1].

Being able to handle large datasets using minimal computational processing power is core to making digital twins operate in synchronicity with their physical counterparts, and big data frameworks such as Hadoop and Spark facilitate the storage and accessibility of such datasets [90], thus enabling algorithms based on machine learning and statistical models to forecast grid behavior, recognize certain patterns and scenarios, or recommend certain changes to grid topology for energy management optimization.

Works that explore digital twins' machine learning capabilities are plenty, as using such techniques is already a staple of the scientific community. More recently, for example, in [51], a tool based on a digital twin that has an embedded set of augmented state extended Kalman filters (ASEKF) within it was proposed for forecasting power consumption in industrial systems, deploying the ASEKFs to optimize energy management and planning.

4.5. Advanced Simulation Techniques and Platforms

The simulation of CPPS presents unique challenges, requiring the integration of fundamentally different modeling approaches from the power systems and communication networks domains [19]. As such, effective CPPS DTs demand not only accurate simulation of each domain individually but also their seamless interaction through coordinated simulation techniques and a correlation model between domains.

This subsection will discuss the main simulation methods noted in the curated literature established in Section 2, some of which are best suited to particular domains of CPPS and some of which are key enablers for the aforementioned domain interactions. These techniques name the sub-subsections within this subsection.

These approaches are implemented through established tools such as OpenDSS, GridLAB-D, PowerFactory, PSCAD, and RTDS for physical power grid-related elements and NS-3, GNS-3, and OMNET++ for the cyber domain elements and their respective behaviors [91].

The evolution from pure power system to CPPS digital twins has driven the development of co-simulation platforms capable of synchronizing these disparate simulation approaches. While Dynamic State Estimators (DSE) have shown promise for representing CPPS dynamics [43], this subsection focuses specifically on formal simulation methods for CPPS, favoring those that touch upon the DT subject.

4.5.1. Discrete Event Simulation

Discrete Event Simulation (DES) models systems through discrete state changes triggered by sequential events, making it ideal for analyzing complex CPPS dynamics [92]. As shown in Figure 5's algorithm diagram, and according to [93], DES comprises five core components:

- Statistical Counters, which are variables used for storing statistical information about system performance;

- Initialization Routine, which is a subprogram/method that initializes the simulation model at time zero (first iteration);
- Event List, which is a list containing all information about all scheduled events, such as when each type of event will occur;
- Simulation Clock, which is a variable containing the current value of simulated time;
- System State, which is a collection of state variables necessary to describe the system at a particular stamp in time.

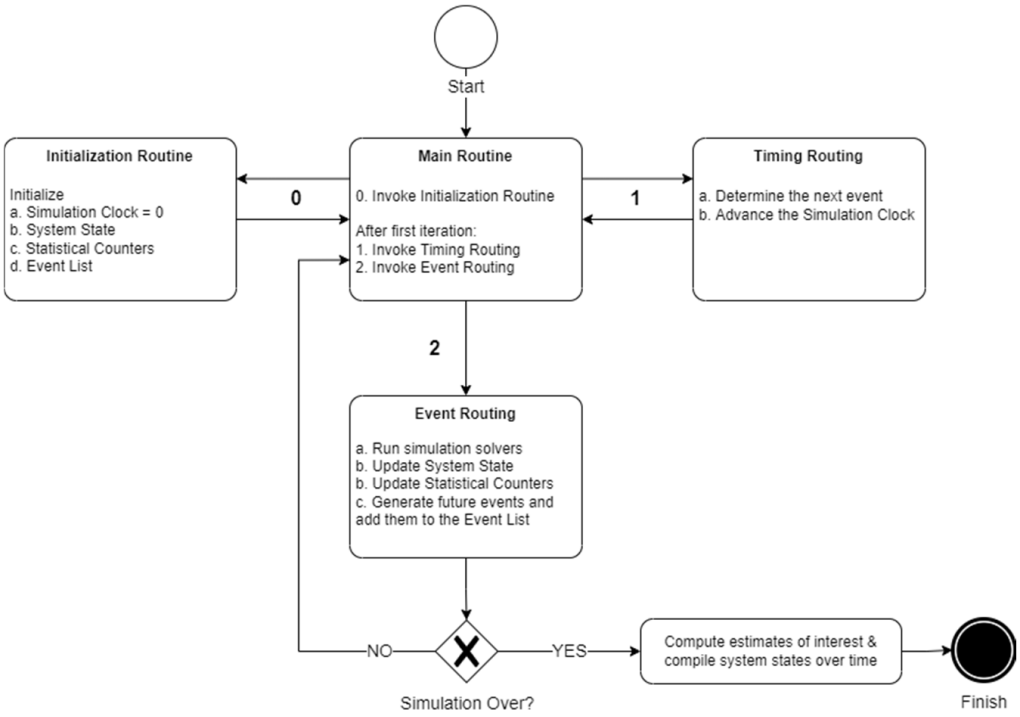

Figure 5. DES high-level structure.

In [58], for example, a new model-based design tool for simulating CPPSs using SystemC-AMS to model both the electromagnetic and the networking events is presented. The tool used in that paper is able to perform cross-domain, monolithic simulations. The authors experimented with two benchmarking cases, one specific to a grid-following inverter and one considering a residential microgrid, demonstrating the tool's capability to perform discrete event-driven, cyber-physical simulation.

4.5.2. Continuous Time Simulation

Continuous Time Simulation (CTS) models power system dynamics through differential equations, enabling analysis at arbitrary time points [94]. While unsuitable for discrete communication networks, CTS provides a critical high-fidelity simulation of electromechanical transients in power grids [4]. The method employs numerical solvers like Euler's and Runge–Kutta methods, typically implemented in tools such as MATLAB Simulink [94].

A representative application, presented in [76] combines CTS grid modeling with hardware-in-the-loop testing of dynamic thermal rating systems. This approach demonstrated how sensor-based CTS models can overcome conservative static loading assumptions while validating physical hardware performance, improving line utilization by 12–15% in benchmark cases.

4.5.3. Agent-Based Simulation

Agent-based Simulation (ABS) models autonomous agents interacting within defined environments to study emergent system behaviors [94]. Particularly suited for smart

grids, ABS captures distributed component interactions and autonomous decision-making processes [95].

A notable application models day-ahead electricity markets, where agent representations of thermal units, DERs, and market operators address congestion and pricing challenges in wind-integrated systems [96].

While ABS applications in CPPS remain unexplored in the literature, adjacent cyber-physical domains demonstrate their potential, particularly in security frameworks where autonomous agent responses enable rapid attack mitigation [22].

4.5.4. Monte Carlo Simulation

Monte Carlo Simulation (MCS) employs random sampling to analyze complex, uncertain systems [94]. For CPPS digital twins, MCS quantifies both physical uncertainties (transmission failures, generator outages) and cyber risks (malware, data breaches) [68]. This enables probabilistic assessment of vulnerability exploitation likelihoods and "what-if" scenario exploration [69].

The work presented in [30] demonstrated MCS's effectiveness for cyber-physical energy hubs, showing how routine reliability analyses of cyber disturbances (packet errors, transmission delays) can mitigate their physical layer impacts. The method proves particularly valuable for identifying high-risk CPPS components requiring reinforced observability in digital twin implementations.

4.5.5. Real-Time Simulation

Real Time Simulation (RTS) synchronizes simulated behavior with actual time, executing each step within strict time constraints [55]. This capability makes RTS fundamental for digital twins, enabling real-time feedback and "what-if" scenario analysis that reduces operational risk [14].

In [47], is the authors demonstrate RTS implementation using OPAL-RT's HYPERSIM to model a 39 kW microgrid with PV generation, EV charging, and battery storage, achieving hardware-in-the-loop integration with utility SCADA systems.

For CPPS applications, Nguyen et al. [17] developed a hybrid platform combining real-time DES (communication networks) and CTS (power grid), successfully validating control and protection systems in an MVAC/DC network.

4.5.6. Hardware-in-the-Loop Simulation

Hardware-in-the-Loop (HiL) simulation integrates physical hardware components with virtual models to validate system performance under realistic operating conditions [63]. The technique fundamentally differs from other simulation methods by requiring specialized infrastructure, including real-time processors, I/O interfaces, and measurement transformers to interface physical components with simulated environments. HiL implementations are typically categorized as either Control HiL (C-HiL), which focuses on testing control devices like protective relays against simulated grid conditions [97], or Power HiL (P-HiL), which evaluates physical power components like converters and batteries under actual power flows [61]. Figure 6 displays a high-level HiL application example, where the hardware under test can be either a control or power element.

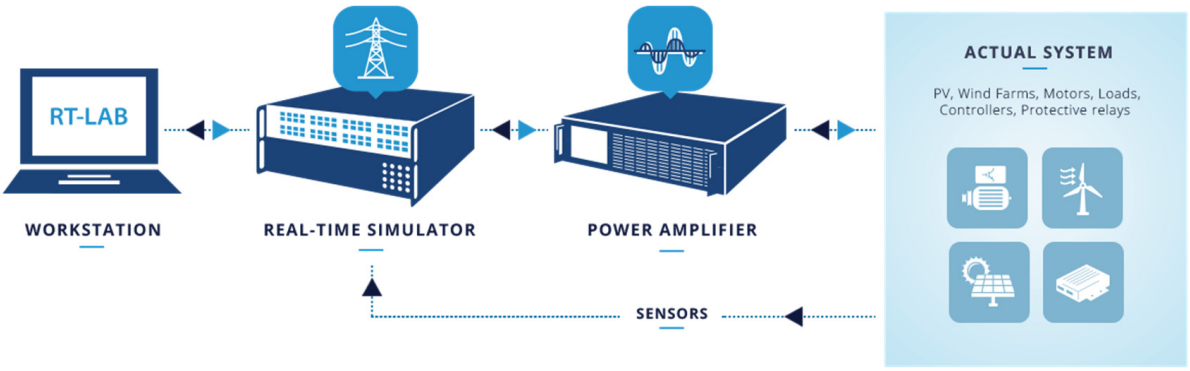

Figure 6. HiL application example with varying hardware devices, configuring in either P-HiL or C-HiL.

Recent research demonstrates HiL's growing importance for CPPS digital twins, such as [62], where a P-HiL platform for power electronic systems that serves as both a testbed and foundation for digital twins, with applications in fault-tolerant converter design and hybrid AC-DC networks, was developed.

The method has also been adapted for communication networks, where [64] showed that incorporating even a few physical nodes significantly improves protocol simulation accuracy compared to purely software-based approaches. By bridging physical and virtual domains, HiL provides unmatched fidelity for validating cyber-physical interactions in digital twin implementations.

4.5.7. Co-Simulation

Co-simulation enables the synchronized execution of multiple subsystem models using specialized simulation tools, allowing each component to be simulated with its most suitable method while maintaining system-level interactions [59].

This approach is particularly valuable for CPPS, where power grid dynamics and communication networks require fundamentally different simulation techniques. Effective co-simulation requires an orchestration layer to manage interactions between subsystems, preventing siloed execution that fails to capture critical correlations.

Exploring that idea, ref. [71] presents a distributed multi-model platform for smart grid co-simulation, leveraging IoT protocols to enable interoperability between heterogeneous models while incorporating HiL capabilities.

The research conducted in [20], then, advanced this approach through a HiL CPPS co-simulation platform combining RT-LAB (physical dynamics) and OPNET (cyber events), validated through cybersecurity attack scenarios on a 7-bus test system.

Despite efforts like the aforementioned, which do enable co-simulation for PS purposes, the broader scientific community has focused on using Functional Mock-up Interface (FMI) to play the role of orchestrator across multiple simulators and models, given that FMI presents high scalability and is industry-agnostic and tool-agnostic, with its latest version being introduced in [98].

FMI defines three Functional Mock-up Unit (FMU) types:

- Model Exchange (ME): Exposes models as hybrid differential-algebraic equations for external solvers
- Co-Simulation (CS): Couples self-contained simulators at discrete communication points
- Scheduled Execution (SE): Orchestrates model partitions via time-based scheduling

An FMI-based co-simulation structure, as described above, can be seen in Figure 7.

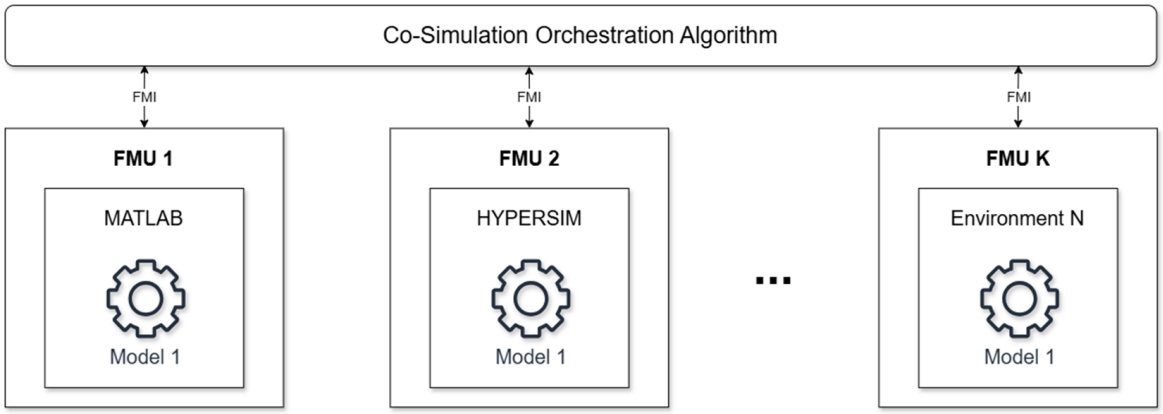

Figure 7. Schematic view of multiple FMUs being orchestrated by a co-simulation algorithm using FMI.

Whilst acknowledging its advantages, FMI implementation presents challenges, including complex system decomposition and connection definition. With the main items noted by the scientific community being that it requires a fair amount of understanding on a system level for each subsystem, it is not straightforward to know where and how to split a system into submodels, and there are difficulties in defining the connections between submodels as well. These and other challenges can be found in [66].

In regard to smart grid co-simulations, there is a framework that is able to handle CPPS co-simulations and that is also compatible with the FMI standard—thus helping researchers in the area circumvent some of the aforementioned problems—called MOSAIK. The framework's defining publication, presented in [67], explores the creation of a CPPS testbed using it through an application case involving virtual power plant control while outlining MOSAIK's architecture and defining a methodology for planning simulation model splits.

5. Case Studies

The validation and proof-of-concept of what is being researched in CPPS DTs has been predominantly carried out in simulation environments, as opposed to real-world implementations or tests, given the logistical and financial complexities of creating data pipelines and management solutions for real-world physical systems.

In these case studies, a usual approach is to simulate the physical system and establish one or two-way communication between it and the virtual environment—essentially creating the digital twin of a simulated system, a virtual-to-virtual implementation.

It's also notable that the maturity stage of these applications might vary based on the applied model, with the term "digital twin" sometimes representing structures with varying degrees of capability—some of them being better categorized as digital models or shadows, following [99]'s proposed maturity model as an example. Even so, some important conclusions and scientific advancements arise from these case studies.

A summary of works with those characteristics, deemed scientifically relevant through the systematic literature review process performed by this study, can be found in Table 4. Note that, for this table, works are presented in chronological order.

On the other hand, there are a few case studies where a real-world physical entity was considered for the implementation of a CPPS DT, also with varying maturity levels. These works do not necessarily reflect CPPS DT real-life implementations, but they model real-world assets and, more importantly, use datasets generated in the real world.

A summary of these works is presented in Table 5, with works being ordered chronologically.

Table 4. Overview of CPPS DT publications with validation or experimentation stages that have no connection to a real-world physical entity.

Year	Paper	Overview
2019	[27]	CPPS digital twin for cybersecurity studies, uses CTS and DES to represent the behaviors of a CPPS and emulate the physical twin.
2023	[24]	Presents a case study based on the deployment of a CPPS digital twin in a simulated medium voltage grid and its OT elements, exploring cyberattack-induced grid events and faults (false data injection).
2023	[48]	Digital twin of a networked microgrid's (modified IEEE 34-bus system) energy management system to study the impact of CPPS digital twins in DER dispatch logic and optimization.
2023	[44]	A CPPS digital twin of a substation, containing machine learning, is proposed to study attacks against a simulation of the GOOSE protocol in a generic IEC618580-based substations. Results demonstrate a 96% F1 Score, showcasing the potential of the approach.
2023	[26]	Digital twin framework used to replicate realistic multi-stage cyberattacks on residential smart grids. Demonstration performed in a digital laboratory.
2023	[19]	Presents a CPPS digital twin-based testbed that allows for assessment of PS operation, network security and reliability, and testing of heterogeneous controllers. Applied in a simulated MVAC/DC system.
2024	[23]	CPPS digital twin topology for a smart grid that facilitates fingerprinting for detecting false data injection attacks at multiple points of the network. A simulated dataset smart grid is used for testing.
2024	[25]	Digital twin of a networked microgrid for tests on their behavior under DoS attacks and development of security frameworks, using data-driven models and a long-short term memory neural network.
2024	[21]	Studies cyberattacks to IEC61850-based substations and the correlation between cyber and physical events through a CPPS digital twin. Uses the IEEE 9-bus system to emulate PMUs and test how the digital twin distinguishes three-phase faults and substation GOOSE cyberattack-induced faults, highlighting correlation as a key parameter.
2024	[45]	Exploration of low earth orbit satellite (LEO) constellation network-enhanced wide-area power systems through the proposal of a real-time CPPS digital twin. Evaluations were run on a wide-area synthetic AC-DC system with a simulated LEO satellite network, exploring the digital twin's accuracy and possible applications and their benefits to the PS area.
2025	[38]	Study on DT for DC microgrids, with its effectiveness being demonstrated through experimental validation using a simplified three-bus DC microgrid testbed. The framework incorporates an electro-thermal DT to manage power flow based on thermal constraints in power distribution cables.
2025	[37]	Proposal of a method for a Smart Generation System's DT with the aim of solving power dispatch problems, relying on the environment as a way to train AI agents to collaborate on centralized decision-making and decentralized control in order to achieve global optima for grid dispatch.

Table 4. *Cont.*

Year	Paper	Overview
2025	[40]	Introduction of a DT-based scheme for cyberattack detection and mitigation in DC microgrids, validated through both simulation and experimental results. The study designs an observer-based local DT for each electronic converter interface converter estimates and mitigates simultaneous sensor and actuator attacks by recovering correct signals and a comprehensive centralized DT to estimate and eliminate cyberattacks at the system level in secondary control among multiple converters.
2025	[34]	Demonstration of the high-performing synergy of compiled models and HiL platforms for dynamics emulation, followed by the proposition of a multi-tools simulation methodology to reproduce time-scale dynamics on controlled DC power grids with the aim of creating a high-fidelity DT for a testbed zonal DC shipboard microgrid.
2025	[41]	With a focus on self-healing of islanded microgrids by leveraging a DT that replicates the behavior of physical components, this study creates proactive and reactive maintenance strategies through the orchestration of fuzzy logic and random forest algorithms running on top of the DT. This integrated approach considers multiple health states for lifecycle assessments across various grid elements, presenting the capability of receiving data streams from a physical twin (with no real-world physical twin on the experimentation phase).
2025	[39]	A conceptual framework for a digital twin of the Wały Śląskie hydro power plant, addressing challenges like incomplete documentation and limited real-time data availability. Its novelty lies in integrating computational fluid dynamics and AI-based modeling techniques as essential data inputs for efficiency modeling and operational analysis, thus supporting the DT's conceptualization and development in an environment where real-world data might be scarce.

Table 5. Overview of CPPS digital twin publications with validation or experimentation stages that have varying levels of connection to a real-world physical entity.

Year	Paper	Overview
2023	[65]	Investigation on the role of small computational united in distribution networks as facilitators of intelligent and efficient distribution of sustainable and cyber-safe electricity carried out via a HiL and RTS-based CPPS digital twin. Tests to verify the approach were performed using datasets from a networked distribution grid that was under short-circuit conditions.
2023	[44]	Implementation of a CPPS digital twin for an energy management system as part of the TalTech Campulse Project, which establishes a framework capable of predicting future performance, consumer behavior, and aiding in system maintenance. The approach was tested on a small-scale distributed networked system in Estonia.
2024	[43]	A CPPS digital twin of a non-disclosed English distribution system was developed as one of the deliverables of the UK-based Smart Energy Network Demonstrator project, built upon DSEs and RTSs, and smart meter data acquisition. The study highlights the technical challenge of using DSEs for distribution networks, and its early results show that the approach offers a potential for 54% reduction in solar curtailment via voltage control.

6. Discussion

The analysis of the state-of-the-art corpus reveals that the concept of digital twins in power systems, particularly CPPS digital twins, is gaining significant traction. The recency of the majority of the corpus, with over 75% of publications between 2022 and 2024, underscores the emergent nature of this research area. Despite the promising advancements, several foundational concepts and definitions remain inconsistent across the literature, highlighting the need for standardization.

One of the primary challenges identified is the lack of a universally accepted definition and maturity model for digital twins. The discrepancies in definitions and maturity categorizations, as seen in works like [1,27], complicate the comparison and evaluation of digital twin implementations. While the former proposes a four-level maturity model focusing on communication, adaptability, and intelligence, the latter emphasizes a question-based framework evaluating live data exchange, service multiplicity, and hierarchical structures. This divergence reflects the broader issue within the scientific community, where different research areas adopt varied criteria for defining and assessing digital twins.

Industry-agnostic literature, such as [10,99], offers more generalized maturity models that can be applied across domains. More specifically, in [10] a seven-category model with 31 ranked characteristics, creating a comprehensive yet complex evaluation metric is proposed. On the other hand, [99] presents a five-tier model with clear denominations and expected capabilities at each level, making it more accessible for practical implementation. Both models contribute to the ongoing effort to standardize digital twin definitions and maturity assessments, yet they also highlight the need for periodic reviews and extensions to accommodate new developments.

The practical applications of CPPS digital twins, as discussed in [39,43,44], demonstrate their potential to address critical issues in modern power systems. From real-time monitoring and proactive maintenance to decision support systems and cybersecurity, CPPS digital twins offer innovative solutions that enhance situational awareness, predictability, and operational efficiency. However, the majority of case studies and test beds are confined to simulation environments, with limited real-world implementations. This gap underscores the logistical and financial challenges of deploying CPPS digital twins in large-scale systems.

Other research gaps identified in this study are, in no particular order, as follows:

- There is a pressing need to standardize the ontology of digital twins, encompassing both their definitions and maturity categorizations, in order to establish conceptual clarity in the field, enable researchers to efficiently identify key contributions, and assist journals in distinguishing substantive work from studies employing digital twin terminology primarily as a buzzword.
- The behavior of CPPS digital twins in large-scale systems remains uncertain despite various case studies and test beds.
- The potential of CPPS digital twins in planning for power grid expansion or changes needs further exploration, as the introduction of full-scale grid and communication network simulations can facilitate more varied study types that can be relied on with greater confidence—potentially leading to reductions in design times and better device settings to help protect equipment and grid.
- Integration of CPPS digital twins into operation centers is an open question.
- Structuring digital twins to handle energy trading scenarios with prosumers requires more research.
- Cybersecurity publications focus mainly on false data injection and DoS attacks, but other types of threats need to be addressed.

- Real-world issues in data acquisition and transmission to/from digital twins are not adequately covered in existing papers.
- A broader analysis of edge and cloud computing's impact on CPPS digital twins, particularly regarding performance and security, is needed.
- Current CPPS works do not consistently utilize industry-agnostic simulation frameworks like FMI, highlighting the need for standardized, scalable tools and frameworks to support future developments such as federated and multi-domain digital twins.

7. Conclusions

This study has provided a comprehensive overview of CPPS digital twins, highlighting their transformative potential in modern power systems. By analyzing the motivations, enabling technologies, simulation methods, and maturity level definitions, it is evident that CPPS digital twins represent a paradigm shift in strategic infrastructure planning, management of change, and operations. The emergence of CPPS as a research area offers promising solutions to longstanding issues such as fault detection, energy management optimization, DER integration, proactive maintenance, and real-time monitoring.

A limitation of this paper is that there are a few works from Chinese researchers, published in 2024, whose titles and abstracts pointed toward case studies on simulated environments—but digital versions were only found in their native language, thus precluding any analyses on them as of this study's date of publication. It is important to mention, however, that these papers did not have a significant amount of citations.

Despite the progress, the lack of standardization in digital twin definitions and maturity models remains a core challenge. The divergent approaches in the literature complicate the comparison and evaluation of digital twin implementations, underscoring the need for a universally accepted framework. The contributions of [10] provide valuable insights into creating scalable and accessible maturity models, yet they also highlight the necessity for periodic reviews to accommodate new developments.

The practical applications of CPPS digital twins, while promising, are predominantly confined to simulation environments. The logistical and financial complexities of real-world implementations present significant challenges, yet they also offer opportunities for further research. The identified research gaps, including standardization of digital twin ontology, large-scale system behavior, integration with operation centers, and cybersecurity concerns, point to areas requiring deeper exploration.

Future studies should focus on creating scalable co-simulation frameworks, establishing flexible structures for segregation of duties across modules, and enabling real-time, synchronized communication between digital twins and their physical counterparts. Additionally, the integration of digital twins with edge and cloud computing and distributed artificial intelligence presents opportunities for advancing the operational and strategic capabilities of modern energy infrastructures.

In conclusion, CPPS digital twins hold significant promise for enhancing the resilience, efficiency, and adaptability of power systems. By addressing the identified research gaps and standardizing definitions and maturity models, the scientific community can unlock the full potential of digital twins, contributing to a more stable, reliable, and secure power system.

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