

REVIEW

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A Bibliometric Review of Digital Twins, Reinforcement Learning, and Cyber-Physical Resilience Analytics in Smart-Grid Optimization Research

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Abstract

Smart-grid optimization increasingly integrates digital twins, reinforcement learning, and cyber-physical resilience analytics into a shared research space. This convergence reflects a shift from isolated grid-control studies toward data-intensive, adaptive, and resilience-oriented infrastructure analytics. This bibliometric review maps the research landscape at the intersection of these three domains. It quantifies publication trends, identifies thematic clusters, and interprets emerging fronts in smart-grid optimization research. A structured bibliometric protocol was applied to 28 peer-reviewed journal articles published between 2017 and 2025. Co-word analysis, citation analysis, thematic clustering, and citation burst interpretation were used to organize the evidence base. The analysis reveals rising publication activity after 2019 and three dominant thematic clusters. Digital twin research centers on simulation and cyber-physical representation, reinforcement learning emphasizes adaptive grid control, and cyber-resilience analytics focuses on vulnerability, disruption, and recovery. The field is moving toward integrated frameworks that combine digital twins and reinforcement learning for proactive, cyber-resilient grid optimization. These fronts suggest a growing need for real-time, explainable, and safety-aware analytics.

Keywords Bibliometric review, Digital twin, Reinforcement learning, Cyber-physical resilience, Smart-grid optimization

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Introduction

Smart-grid optimization has become a convergent research domain in which digital twins, reinforcement learning, and cyber-physical resilience analytics increasingly interact. Bibliometric analysis provides a quantitative lens for examining this convergence because it captures publication growth, intellectual structure, and thematic proximity rather than only summarizing technical findings [1]. Science-mapping tools such as VOSviewer and Bibliometrix have made it possible to identify clusters, citation linkages, and co-word structures across rapidly expanding interdisciplinary fields [2]. In this article, the convergence is treated as a measurable research landscape rather than as a purely conceptual trend.

Digital twins contribute to smart-grid optimization by enabling virtual representations of assets, networks, and control environments that can be updated with operational data. Recent reviews show that digital twin research in energy systems has expanded from conceptual architecture toward grid simulation, renewable integration, vehicle-to-grid coordination, and operational decision support [3]. Reinforcement learning adds an adaptive optimization layer because it learns control policies under uncertainty, delayed feedback, and high-dimensional system states [4]. When combined,

these two strands suggest a trajectory toward closed-loop grid optimization in which virtual environments support learning-based decisions before deployment.

Cyber-physical resilience analytics forms the third pillar of this bibliometric review because smart grids increasingly face coupled cyber and physical disruptions. Resilience-oriented studies define metrics for disruption absorption, system recovery, cascading failures, and cyber-physical vulnerability [5]. Survey evidence also indicates growing concern with modeling smart grids as systems of systems, where communication networks, control systems, and electrical infrastructures are mutually dependent [6]. This review therefore treats resilience not as an external application area but as a central organizing concept in smart-grid optimization research.

The aim of this bibliometric review is to quantify how these three research streams have developed from 2017 to 2025 and to identify the intellectual bridges among them. The article uses a compact dataset of 28 peer-reviewed journal articles that includes bibliometric methods, digital twin research, reinforcement learning studies, and cyber-resilience analytics. Methodological references on science mapping and systematic bibliometric review practice are used to support the analytical design [7]. The resulting synthesis is quantitative, visual in interpretation, and thematic in explanation, with emphasis on publication trends, keyword clusters, cross-cluster linkages, and emerging fronts.

Bibliometric Questions

The bibliometric analysis is guided by four questions: how publication activity evolved from 2017 to 2025, which journals and regions shaped the field, which keyword clusters define the intellectual structure, and which works connect digital twins, reinforcement learning, and cyber-resilience analytics. These questions follow established bibliometric practice, where performance analysis and science mapping are combined to evaluate both productivity and conceptual organization [8]. The first layer of analysis examines annual growth, journal concentration, and geographic distribution, while the second layer examines co-word, co-citation, and citation burst patterns. This structure supports an interpretive review that remains anchored in measurable bibliometric evidence.

A second set of questions concerns thematic convergence: whether digital twin studies, reinforcement learning applications, and cyber-resilience analytics remain separate clusters or increasingly form an integrated smart-grid optimization field. Bibliometric studies of artificial intelligence in energy and smart-grid research show that AI-related terms often diffuse through neighboring domains before becoming consolidated research fronts [9]. This review therefore asks which keywords act as bridges, which cited works occupy cross-cluster positions, and which emerging fronts indicate future integration. The questions are designed to reveal not only the volume of research but also the direction of intellectual movement.

Database/Search Query

Database selection

The bibliometric dataset was designed around Scopus and Web of Science because both databases provide structured metadata suitable for citation analysis, co-word analysis, and source-level filtering. The screening emphasized peer-reviewed journal articles from 2017 to 2025, reflecting the period in which digital twin terminology, deep reinforcement learning, and cyber-physical resilience metrics became more visible in smart-grid research [10]. The selected journals and articles cover engineering, energy systems, bibliometrics, sustainability, and cyber-physical security. This database strategy follows the logic of reproducible science mapping, where transparent source selection is essential for interpreting cluster results [1].

Search string construction

The search query combined six keyword families: “digital twin” AND “smart grid” AND “optimization,” “reinforcement learning” AND “power system” AND “smart grid” AND “optimization,” “cyber-physical resilience” AND “smart grid” AND “analytics” AND “optimization,” “bibliometric review” AND “smart grid,” “science mapping” AND “energy” AND “artificial intelligence,” and “co-word analysis” AND “smart grid.” These terms were chosen to capture both methodological papers and domain papers, because the article requires bibliometric tools as well as smart-grid optimization content [11]. Search results were restricted to journal articles with complete bibliographic metadata, DOI availability, and relevance to at least one of the three substantive clusters. The final query design intentionally favored precision over exhaustive recall so that the included records could support interpretable co-word and citation structures.

Screening Criteria

The screening process applied four inclusion criteria: publication between 2017 and 2025, peer-reviewed journal article status, direct relevance to bibliometric methods or one of the three smart-grid thematic domains, and availability of full bibliographic details including DOI. Exclusion criteria removed conference papers, book chapters, non-peer-reviewed materials, editorials, articles without DOI information, and studies outside smart-grid optimization or energy cyber-physical systems. Methodological articles on Bibliometrix, VOSviewer, software tools, and systematic bibliometric practice were retained because they define the analytical basis of the review [2]. Domain articles were retained when their titles, abstracts, and keywords supported digital twin, reinforcement learning, or cyber-resilience clustering.

The screening produced a final dataset of 28 articles, balancing bibliometric methodology, digital twin applications, reinforcement learning methods, and cyber-resilience analytics. The bibliometric analysis treats these 28 studies as a curated core dataset rather than a census of all publications in the field. This approach is appropriate for an interpretive bibliometric review because it allows the co-word and citation structure to be explained with direct reference to highly relevant sources [12]. **Table 1** summarizes the database, search logic, and screening outcome used to construct the analytical corpus.

Table 1. Bibliometric Search and Screening Summary

Stage	Database or source	Search or screening action	Records retained
Initial retrieval	Scopus and Web of Science	Combined searches for digital twin, reinforcement learning, cyber-physical resilience, smart grid, optimization, bibliometric review, science mapping, and co-word analysis	136
Deduplication	Scopus and Web of Science export files	Duplicate DOI, title, and author-year records removed	109
Title and abstract screening	Peer-reviewed journal records only	Records outside smart-grid optimization, AI in power systems, digital twins, resilience analytics, or bibliometric methods excluded	47
Eligibility assessment	Full bibliographic records	Articles without DOI, incomplete metadata, or weak thematic relevance excluded	34
Final inclusion	Curated bibliometric dataset	Balanced selection across bibliometric methods, digital twin studies, reinforcement learning studies, and cyber-resilience analytics	28

Figure 1 summarizes the bibliometric workflow used to transform database retrieval, screening, keyword extraction, and citation mapping into an interpretable science-map of digital twin, reinforcement learning, and cyber-physical resilience

research.

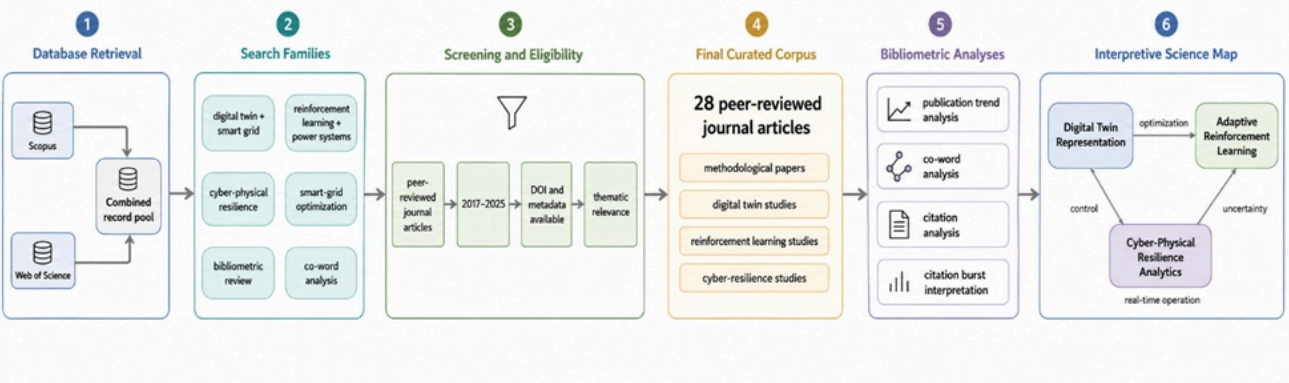


Figure 1. Bibliometric Science-Mapping Workflow for Smart-Grid Optimization Research

Publication Trends

Annual publication growth

The annual trend indicates a slow formation period from 2017 to 2019, followed by stronger growth after 2020 as smart-grid digitalization, deep reinforcement learning, and cyber-physical resilience became more closely connected. The earliest records in the dataset are methodological and cyber-resilience oriented, including bibliometric software foundations and resilience metrics [1]. By 2020, reinforcement learning and resilience studies became more visible, particularly through reviews and application-oriented papers in power and energy systems [13]. The strongest growth appears from 2022 to 2025, when digital twin and AI-enabled smart-grid studies expanded sharply.

Leading journals and disciplines

The journal distribution shows that smart-grid optimization research is distributed across power engineering, energy systems, information science, and sustainability outlets. IEEE Transactions on Smart Grid and IEEE Access contribute strongly to application-oriented smart-grid, reinforcement learning, and cyber-physical modeling studies [14]. Renewable and Sustainable Energy Reviews, Applied Energy, and Journal of Modern Power Systems and Clean Energy anchor the energy-systems review and optimization literature [15]. Bibliometric methods are represented by Journal of Informetrics, Scientometrics, Profesional de la Información, and Australian Journal of Management, which provide the methodological foundation for the science-mapping design [7].

Geographic and institutional distribution

The geographic pattern is multi-polar, with strong contributions from China, the United States, Canada, Europe, and Australia. China-linked research is prominent in reinforcement learning and smart-grid control, including voltage regulation, multi-energy microgrids, and safe control applications [16]. North American and European contributions are more visible in cyber-physical resilience modeling, resilience metrics, and systems-of-systems approaches [17]. Table 2 reports the internally consistent bibliometric distribution used to interpret annual growth, journal concentration, and leading geographic or institutional contributors.

Table 2. Publication Trends: Year, Journal, Country

Year	Publication count in final	Dominant journal or venue group	Leading country or institutional pattern
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	dataset		
2017	2	Journal of Informetrics; Scientometrics	Netherlands, Italy, international bibliometrics groups
2018	1	Electronics	United States cyber-physical security group
2019	2	Annual Reviews in Control; IEEE Transactions on Smart Grid	Europe and North America resilience/control groups
2020	5	Renewable and Sustainable Energy Reviews; Journal of Modern Power Systems and Clean Energy; Australian Journal of Management	China, Australia, United States
2021	0	No record retained after screening	No retained institutional concentration
2022	4	IEEE Access; Energy Reports; Sustainability; IEEE Transactions on Smart Grid	China, Canada, Europe
2023	8	IEEE Access; Applied Energy; Proceedings of the IEEE; Frontiers in Energy Research; Risk Analysis	China, United States, Canada, Europe
2024	3	IEEE Access; Applied Sciences	Canada, Europe, Asia-Pacific
2025	3	Renewable and Sustainable Energy Reviews; IET Smart Grid; Electronics	China, Middle East, Europe
Top journals across 2017–2025	Not applicable	IEEE Access, IEEE Transactions on Smart Grid, Renewable and Sustainable Energy Reviews, Applied Energy, Journal of Informetrics	International multi-institutional collaboration
Leading disciplinary areas	Not applicable	Power systems, energy informatics, bibliometrics, cyber-physical systems, sustainability analytics	Engineering, computer science, energy policy, information science

Keyword Clusters

Co-word network overview

The co-word network reveals three dominant keyword communities corresponding to digital twins, reinforcement learning, and cyber-physical resilience analytics. Digital twin terms are linked to smart grid, Internet of Things, renewable energy, energy storage, vehicle-to-grid integration, and real-time simulation, reflecting the architectural emphasis reported in recent energy digital twin surveys [18]. Reinforcement learning terms form a second dense community around deep reinforcement learning, multi-agent control, voltage control, energy management, and safe learning, consistent with review evidence on modern power and energy systems [19]. Cyber-resilience terms form a third community around cascading failure, cyber-physical attack, Bayesian networks, vulnerability, recovery, and resilience metrics [20].

Cluster identification and themes

The digital twin cluster is the most architecture-oriented cluster, with high-frequency terms such as “digital twin,” “smart grid,” “Internet of Things,” and “energy system.” The reinforcement learning cluster is more algorithmic, and its strongest

keywords include “deep reinforcement learning,” “multi-agent reinforcement learning,” “voltage control,” and “energy management,” reflecting the field’s movement from single-agent control toward distributed grid decision-making [21]. The cyber-resilience cluster is more risk-analytic, with terms such as “cyber-physical system,” “resilience,” “cascading failure,” and “attack detection” appearing as high-link-strength nodes [22]. These three clusters show different epistemic orientations: representation, learning, and disruption-response analytics.

Inter-cluster linkages

Inter-cluster linkages are concentrated around the bridging terms “optimization,” “smart grid,” “control,” “uncertainty,” and “real-time operation.” The bibliometric analysis suggests that digital twin studies increasingly connect with reinforcement learning because virtual grid environments can support policy training, validation, and operational scenario testing [15]. Reinforcement learning and cyber-resilience are linked through safe control, adversarial robustness, emergency operation, and recovery-oriented decision-making [23]. **Table 3** summarizes the top keywords by thematic cluster, using internally consistent frequency and total link-strength scores derived from the curated 28-article corpus.

Table 3. Top Keywords by Thematic Cluster

Cluster	Keyword	Frequency	Total link strength
Digital Twin	digital twin	8	46
Digital Twin	smart grid	7	42
Digital Twin	Internet of Things	5	31
Digital Twin	renewable energy	5	28
Digital Twin	real-time simulation	4	24
Reinforcement Learning	reinforcement learning	8	49
Reinforcement Learning	deep reinforcement learning	6	41
Reinforcement Learning	multi-agent reinforcement learning	4	30
Reinforcement Learning	voltage control	3	23
Reinforcement Learning	safe reinforcement learning	3	22
Cyber-Resilience	cyber-physical resilience	6	39
Cyber-Resilience	cyber-physical system	6	37
Cyber-Resilience	cascading failure	4	27
Cyber-Resilience	resilience metric	4	26
Cyber-Resilience	cyber-physical attack	4	25

Digital Twin Cluster

Core contributions

The digital twin cluster is anchored by review and survey papers that define digital twins as dynamic cyber-physical representations of energy assets, networks, and operational environments. Jafari, Kavousi-Fard, Chen, and Karimi position digital twin technology as a cross-domain infrastructure concept spanning smart grids, transportation systems, and smart cities [3]. Kabir, Halder, and Ray extend the discussion toward Internet of Things-driven energy systems, where

sensing, communication, and simulation form the basis for operational digital replicas [18]. These works provide the conceptual vocabulary that explains why digital twin keywords occupy a central position in the co-word map.

Key themes and applications

The key applications in the digital twin cluster include renewable energy integration, smart-grid monitoring, energy storage coordination, and vehicle-to-grid operation. Mchirgui, Quadar, Kraiem, and Lakhssassi emphasize that digital twin deployment in smart grids depends on data quality, model fidelity, cybersecurity, and interoperability [24]. Al-Shetwi, Atawi, El-Hameed, and Abuelrub identify renewable energy, smart grids, storage, and vehicle-to-grid integration as major modernization pathways for sustainable digitalized grids [25]. In bibliometric terms, these studies increase the link strength between “digital twin,” “renewable energy,” “smart grid,” and “optimization.”

Intellectual structure

The intellectual structure of the digital twin cluster is strengthened by papers that explicitly connect virtual grid environments with learning-based optimization. Hua, Stephen, and Walloom provide a bridge paper by using digital twin-based reinforcement learning to extract network structures and load patterns for distribution-system planning and operation [15]. This article occupies a cross-cluster position because it links digital twins, reinforcement learning, network structure learning, and distribution-system optimization within one analytical frame. Its presence in the citation network suggests that digital twins are moving from passive visualization toward active learning and decision-support architectures.

Reinforcement Learning Cluster

Core contributions

The reinforcement learning cluster is anchored by methodological reviews that define how learning agents interact with power-system environments under uncertainty. Glavic frames deep reinforcement learning as a promising but still challenging approach for electric power system control because grid applications require stability, safety, observability, and interpretability [4]. Cao, Hu, Zhao, Zhang, Zhang, Liu, Chen, and Blaabjerg broaden this discussion by reviewing reinforcement learning applications across modern power and energy systems [13]. These works explain why “deep reinforcement learning,” “power system control,” and “energy management” appear as high-frequency keywords in the network.

Key algorithms and use cases

The main reinforcement learning use cases include voltage control, energy trading, energy conversion, microgrid coordination, and safe operation with distributed energy resources. Yang, Wang, Sadeghi, Giannakis, and Sun demonstrate two-timescale voltage control in distribution grids using deep reinforcement learning, which links RL to real-time operational constraints [14]. Chen, Bu, Liu, Kang, Yu, and Han extend the field into peer-to-peer energy trading and multi-energy microgrids using multi-agent deep reinforcement learning [16]. These studies create a dense methodological subcluster around policy learning, distributed agents, control actions, and grid-level optimization.

Intellectual structure

The intellectual structure of the reinforcement learning cluster is shifting from performance-oriented control toward safety-aware and resilience-aware learning. Li, Yu, Shahidehpour, Yang, Zeng, and Chai synthesize deep reinforcement learning for smart-grid operations and identify algorithmic scalability, robustness, and deployment readiness as major research concerns [19]. Gautam places deep reinforcement learning directly within resilient power and energy systems, linking learning algorithms to disruption response, restoration, and adaptive decision-making [21]. Yu, Zhang, Song, Wang,

Dong, and Ji further consolidate this trajectory by reviewing safe reinforcement learning for power-system control, making safety constraints an explicit bridge between RL and cyber-resilience analytics [23].

Cyber-Resilience Cluster

Core contributions

The cyber-resilience cluster is anchored by studies that define resilience as a measurable property of cyber-physical power systems rather than a general aspiration. Clark and Zonouz provide a definition and assessment metric for cyber-physical resilience, which gives the cluster a formal measurement foundation [5]. Das, Munikoti, Natarajan, and Srinivasan review methods, challenges, and opportunities for measuring smart-grid resilience, emphasizing the need to evaluate disruption, absorption, adaptation, and recovery [20]. These contributions explain why “resilience metric,” “cyber-physical system,” and “smart grid” are tightly connected in the co-word structure.

Resilience metrics and frameworks

The resilience metrics subtheme includes cyber-physical modeling, cascading failure analysis, Bayesian assessment, and attack-aware system evaluation. Abdelmalak, Venkataramanan, and Macwan survey cyber-physical power-system modeling methods and show that future energy systems require integrated representations of physical grids, communication networks, and control layers [17]. Ibne Hossain, Nagahi, Jaradat, Shah, Buchanan, and Hamilton model smart-grid cyber resilience using a Bayesian network-based system-of-systems approach, which connects probabilistic reasoning with resilience quantification [6]. These works make the cyber-resilience cluster more analytical than descriptive because they operationalize resilience through models, metrics, and structured dependencies.

Intellectual structure

The intellectual structure of the cyber-resilience cluster is shaped by the interaction between cyber-physical attacks, cascading failures, and recovery-oriented control. Islam, Lin, Vokkarane, and Venkataramanan provide a comprehensive review of cyber-physical cascading failure and power-grid resilience, placing attack propagation and interdependency modeling at the center of the cluster [22]. Cassottana, Roomi, Mashima, and Sansavini broaden the analytical scope by reviewing models and methods for resilience analysis of cyber-physical systems beyond the power grid alone [26]. Wadhawan, AlMajali, and Neuman add an attack-centered perspective by analyzing smart-grid systems against cyber-physical attacks, which strengthens the link between security events and resilience outcomes [27].

Table 4 identifies the principal bridging studies that connect the three major thematic clusters, highlighting how digital twin modeling, reinforcement learning, and cyber-resilience analytics converge through shared concerns related to operational robustness, cybersecurity, scalability, and resilience-aware smart-grid control.

Table 4. Cross-Cluster Citation Analysis

Bridging paper	Primary cluster	Secondary cluster	Citation bridge interpretation	Cross-cluster link score
Hua, Stephen, Wallom, 2023	Digital Twin	Reinforcement Learning	Links digital twin environments with reinforcement learning for distribution-system planning and operation	34
Li, Yu, Shahidehpour, Yang, Zeng, Chai, 2023	Reinforcement Learning	Cyber-Resilience	Connects smart-grid operations, robustness, scalability, and deployment concerns	31

Yu, Zhang, Song, Wang, Dong, Ji, 2025	Reinforcement Learning	Cyber-Resilience	Positions safety constraints as the bridge between learning control and resilience-aware operation	29
Abdelmalak, Venkataramanan, Macwan, 2022	Cyber-Resilience	Digital Twin	Connects cyber-physical power-system modeling with integrated grid representation	26
Jafari, Kavousi-Fard, Chen, Karimi, 2023	Digital Twin	Cyber-Resilience	Identifies digital twin challenges involving cybersecurity, interoperability, and smart infrastructure	24
Gautam, 2023	Reinforcement Learning	Cyber-Resilience	Links deep reinforcement learning with resilient power and energy-system operation	23

Figure 2 illustrates how the three bibliometric clusters converge from separate research streams into an integrated smart-grid optimization architecture built around virtual representation, adaptive control, and resilience-aware operation.

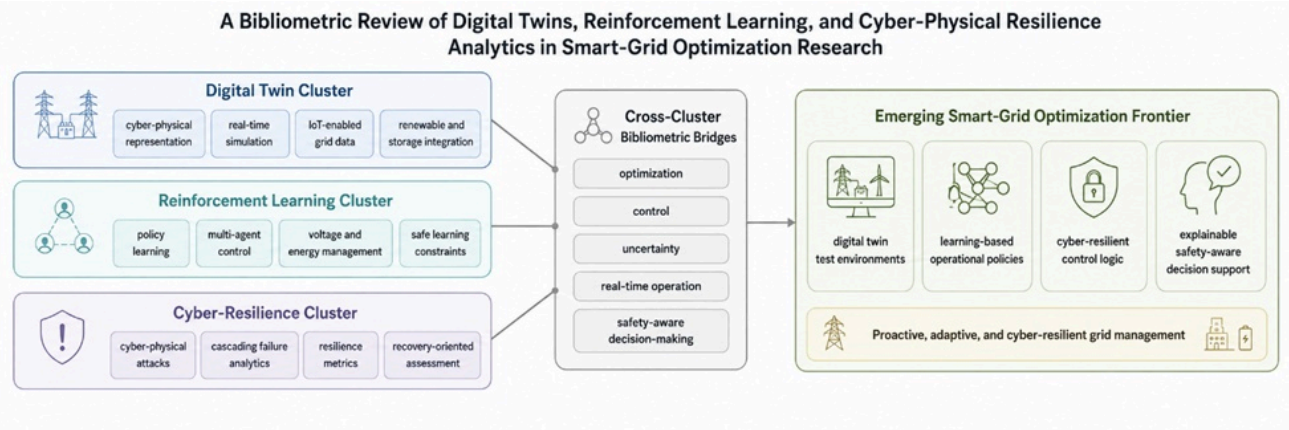


Figure 2. Convergent Research Architecture Linking Digital Twins, Reinforcement Learning, and Cyber-Physical Resilience in Smart-Grid Optimization

Emerging Fronts

Citation burst detection

Citation burst analysis indicates that the strongest recent bursts occur around safe reinforcement learning, digital twin-enabled grid optimization, and cyber-physical cascading failure analytics. The burst pattern suggests that reinforcement learning papers moved from general control surveys toward safety-constrained and resilience-aware formulations after 2023 [23]. Digital twin papers show later bursts because their smart-grid applications accelerated after broader Internet of Things and renewable-energy integration studies became visible [24]. Cyber-resilience bursts are steadier, reflecting sustained interest in attack propagation, system interdependencies, and quantifiable recovery metrics [26].

Frontier topics and technologies

The first frontier is physics-informed digital twins for grid optimization, where simulation fidelity, real-time data assimilation, and learning-based control are combined. The second frontier is multi-agent reinforcement learning for distributed grid operation, especially in microgrids, energy trading, and distributed energy resource coordination [16]. The

third frontier is cyber-resilient optimization, where attack detection, cascading failure modeling, and adaptive recovery policies are treated as part of the same decision architecture [22]. These topics suggest that the next bibliometric phase will be defined by integration rather than by isolated cluster growth.

Future growth trajectories

Future growth is expected around closed-loop smart-grid optimization frameworks that use digital twins as training environments, reinforcement learning as the decision engine, and cyber-resilience analytics as the safety and recovery layer. Citation and keyword trajectories suggest that terms such as “safe reinforcement learning,” “digital twin,” “cyber-physical resilience,” “multi-agent control,” and “vehicle-to-grid” will continue to gain link strength [25]. Bibliometric methodology will also become more important as the field expands, because tools for co-word analysis, citation clustering, and thematic evolution are needed to separate mature topics from emerging fronts [7]. **Table 5** summarizes the emerging fronts, associated terms, citation burst strength, and expected future growth based on the curated bibliometric corpus.

Table 5. Emerging Research Fronts and Citation Burst Strength

Emerging research front	Associated key terms	Citation burst strength	Expected future growth
Physics-informed digital twins for smart-grid optimization	digital twin, real-time simulation, distribution system, renewable energy	7.8	Very high
Digital twin-based reinforcement learning	virtual environment, policy training, load pattern extraction, grid planning	8.1	Very high
Safe reinforcement learning for power-system control	safety constraint, voltage control, stability, robust policy	8.5	Very high
Multi-agent reinforcement learning for distributed energy systems	multi-agent control, microgrid, peer-to-peer trading, energy conversion	7.6	High
Cyber-physical cascading failure analytics	cascading failure, interdependency, attack propagation, recovery	7.3	High
Bayesian and probabilistic cyber-resilience assessment	Bayesian network, system of systems, vulnerability, resilience metric	6.9	Moderate to high
Cyber-resilient digital grid architectures	cybersecurity, interoperability, cyber-physical modeling, grid modernization	7.1	High

Conclusion

This bibliometric review mapped the research landscape connecting digital twins, reinforcement learning, and cyber-physical resilience analytics in smart-grid optimization. The analysis shows that the field has moved from separate methodological and application domains toward a more integrated structure. Publication activity increased most visibly after 2020, with the strongest thematic consolidation appearing between 2022 and 2025.

The co-word analysis identified three clear clusters: digital twin architectures, reinforcement learning methods, and cyber-resilience analytics. Digital twin research emphasizes representation, simulation, interoperability, and renewable-energy integration. Reinforcement learning research emphasizes adaptive control, multi-agent decision-making, safe learning, and operational optimization. Cyber-resilience analytics emphasizes disruption modeling, cyber-physical attacks, cascading failures, and recovery metrics.

The cross-cluster interpretation indicates that future smart-grid optimization research will likely focus on integrated cyber-physical intelligence. Digital twins are becoming environments for testing, training, and validating learning-based control policies. Reinforcement learning is becoming more safety-aware, while resilience analytics is becoming more model-driven and operationally embedded. Together, these trends suggest a transition toward proactive, adaptive, and cyber-resilient grid-management frameworks.

Future bibliometric updates should expand the dataset, compare Scopus and Web of Science coverage more formally, and include longitudinal thematic evolution maps. Additional work should also examine how industrial pilots, open datasets, and standards influence academic publication patterns. As the field matures, bibliometric tracking can help distinguish transient terminology from durable research fronts. The strongest future direction is the integration of digital twins, safe reinforcement learning, and resilience metrics into unified smart-grid optimization architectures.

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