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REGULAR CONTRIBUTION

A review on digital twins for power generation and distribution

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Abstract

This paper presents a systematic literature review on the application of digital twins in the energy sector. Initially, we generated an overview through a survey of prior reviews, independent of market vertical, then followed by a more detailed review concentrating on the power production and distribution domains, as per the NIST (National Institute of Standards and Technology) smart grid standard. We implemented a rigorous method, which included seven stages, beginning with the collection of 2238 articles. We observed that the energy sector range was too broad and filtered by generation and distribution during the practical screening, resulting in 275 for further screening. This amount was then condensed to 81 papers that matched the quality screening criteria for synthesis and examination. In summary, digital twin architectures and frameworks include five components: the physical entity, bidirectional communication, the virtual entity (with modeling and simulation), data management, and services. Our study contributed by determining that distribution management is the most pertinent application of digital twins in the distribution domain and fault diagnosis in the generation domain. Furthermore, we found that digital twins involve multiple stakeholders whose role is rarely discussed in studies, and we identified a similar absence of emphasis for security. Research on security often presents the digital twin as an additional layer of protection, yet rarely investigates the security of the digital twin by itself. The potential limitations of our study to answer some of the technical research questions may be because of the criteria for the selection of papers. However, as the emphasis of this study is on the energy sector, it enabled domain-specific findings for generation and distribution.

Keywords Digital twin · Smart grid · Generation · Distribution

1 Introduction

Critical infrastructures are the main sectors that provide means for us to keep our way of life. Their malfunction can debilitate a country's safety and/or security in different forms, reason for which CISA (Cybersecurity Infrastructure and Security Agency) states that from all critical sectors, the energy sector is of unique criticality. Their argument for such uniqueness is that "it provides an 'enabling function' across all critical infrastructure sectors" [1]. Given this context, it is clear the importance of improving the resilience and reliability of the power grid to keep this critical infrastructure functional in adverse situations that may include a wide range of actors, equipment, systems, markets, services, and stakeholders. Moreover, according to the NIST framework for smart grids, investments on this study field are estimated to generate economic benefits that can achieve billions of dollars [2]. Thus, possible technologies that may be suitable to address the energy sector challenges, such as digital twins, are worth exploring. Between the advantages of a digital twin implementation, we can mention real-time simulation to improve decision making, performance, diagnosis, among others. This makes them suitable for addressing common problems of the energy sector, help in the energy transition, and upmost, provide more resilience to the grid. This illustrates the value of exploring current literature to identify the advancements and applications of digital twin technologies within the energy sector.

In light of this, our study seeks to cover the following topics:

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- To identify and classify research papers approaching digital twin concepts and applications in the energy sector;
- To identify design architectures, operational paradigms, current tools, and modeling techniques for the development of digital twins;
- To identify how the digital twin security has been addressed;
- To investigate existing applications and identify use cases that can contribute to foster digital twin application in the energy sector;

By researching these topics, this work will generate fresh insights into some challenges of the power systems, since the identified use cases reflect relevant problems faced by this sector, and the topics that cover digital twin technical aspects are helpful for future implementations. Interestingly, as stated by [3], several governments are planning to incorporate DERs (Distributed Energy Resources) as part of the energy transition strategy, specially from renewable generation, which can be weather dependent resulting in intermittent production. This fact raises even more a challenge that is widely discussed by the scientific community: the growing management complexity of the grid. In a literature review of power systems challenges, besides the distribution management, [4] also pointed climate changes and environmental conditions (that are related to the discussion of DERs incorporation by [3]), disturbances or unexpected events from faults sources, and cyber-attacks. Considering the possible cascading effects of such risks, [5] argued that smart grids naturally leads to decision making by stakeholders that can be assisted by data-driven algorithms, resulting in yet another challenge of "data-driven decision support models." Therefore, we can see that digital twins can be an enabling technology to address the power sector challenges, considering that they would be a virtual replica of an entity of interest, allowing real-time simulations that can guide stakeholders decisions and provide solutions to some of these challenges.

1.1 Background

The reason for naming grids as smart relies on the fact that more and more digital components and services are being applied in the electricity network. The US Department of Energy's Advanced Grid Research [6], states that what makes a grid smart is the "digital technology that allows for two-way communication between the utilities and its customers, and the sensing along the transmission lines." However, the term smart grids is very broad, approaching all domains of the energy sector. The NIST conceptual model of smart grids [2] defines seven main domains: system transmission operators (TSOs); system distribution operators (DSOs); generation (including DERs); customer; markets; operations and service providers. The participants within each domain are named Actors. Therefore, a given power plant, for example, is an actor of the generation domain. Figure 1 summarizes the domains and the communication and electricity flows between them.

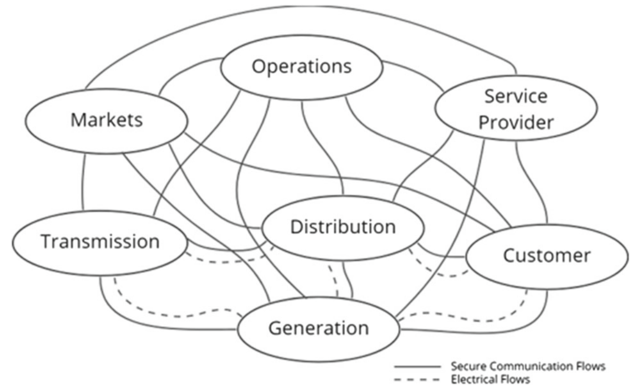

Fig. 1 NIST smart grid conceptual model

Another aspect that this standards highlights is the interoperability, defined as "the capability of two or more networks, systems, devices, applications, or components to work together, and to exchange and readily use information—securely, effectively, and with little or no inconvenience to the user."

Once a smart grid is constituted of an increasing array of interoperable systems, the ability to share information plays a vital role in the continuous digitalization, and the need for the energy transition, requires a consistent understanding of the grid language to improve the communication across stakeholders, including solutions of hardware, software, and services.

From the digitalization perspective, digital twin appeared in many technology trends reports in the last years. A brief way of describing digital twins is that they constitute a virtual replica of a real entity. By doing so, this technology would enable a series of applications that might be helpful for further developments of smart grids. Digital twin has been listed by Gartner as a technology trend for three consecutive years, from 2017 to 2019 [7–9], and is still part of the trends within Hyperautomation in 2020 Gartner report [10]. Digital twins have also been a popular topic with increasing publications in academic journals [11].

In a larger context, European initiatives such as the European Technology & Innovation Platforms (ETIPs) for Smart Networks for Energy Transition (SNET), argue that digital technologies are enablers to achieve a better system and put digital twin and energy transition at the core of a low-carbon economy [12].

1.2 Motivation

The topics covered in the previous sections highlight the importance of the energy sector digitalization and its connection with digital twins as one of the leading technology trends of digitalization. However, as explained in the Background, the energy sector is composed of seven domains, each with several possible actors. Regarding digital twins, the possible applications are equally broad, making it hard to see what advantages of digital twins are unique for smart grids. Our main motivation is to better understand how digital twins can contribute to specific smart grid domains, mapping what applications are more relevant according to the selected domains. Given the author's knowledge background, distribution and generation were selected for further investigation. We aim to contribute in this research topic by mapping the most common digital twins applications for these two domains, and also evaluating the most common actors for each domain because it provides information on what are the real entities and how this can impact the way the digital twin is implemented for each use case.

1.3 Structure of the paper

This paper is organized in seven sections, starting from the introduction in Sect. 1, digital twin conceptualization in Sect. 2, and related work in Sect. 3 to provide an overview, followed by an explanation of the method applied for this systematic literature review in Sect. 4. The findings are discussed in Sect. 5, organized according to the research questions. Section 7 outlines some possibilities for future work, and Sect. 8 is dedicated to discussion, concluding our analysis.

2 Main aspects of digital twins

To gain an in-depth comprehension of digital twins' conceptualization and applications, this research started with an analysis of previous reviews regardless of the market vertical. The studies were analyzed aiming to map the application domains, architectures and frameworks, tools, and security.

Definition evaluation was not initially included in the objectives, but was quickly identified as a key factor in ensuring that understanding and expectations are in sync for those involved in the study of digital twins. Following this discussion, further study was conducted into the application domains and use cases of digital twins.

A review of the primary tools and techniques employed for modeling and simulation, as well as common architectures and frameworks, was conducted to assess the feasibility of creating digital twins. Furthermore, it was determined if security was being addressed or not.

The literature search was conducted on two applicable bibliographic databases: ScienceDirect and IEEEXplore, using the title query ("digital twin" AND ("review" OR "survey" OR "state of the art")). Only scientific/technical articles were examined, leading to 139 studies that were reduced to 41 after applying format and content criteria during practical screening, where Specific use cases and indirect studies were excluded. These studies were filtered by rigorous systematic review methodologies remaining 21 for further analysis.

2.1 Definition considerations

The term digital twin has been around for approximately 20 years, since Grieves first proposed it in 2002 [13]. However, no common definition has been accepted by both academic and industrial communities. To demonstrate and discuss the lack of consensus and standardization, some authors compiled multiple definitions into tables to evaluate similarities and differences [14–19], but this effort did not change the most accepted definition, which was formalized by NASA in 2012, and is cited in 15 from the 29 papers analyzed [11, 14–27]. According to NASA's definition, a digital twin is "an integrated multi-physics, multi-scale, probabilistic simulation of a vehicle or system that uses the best available physical models, sensor updates, fleet history, etc., to mirror the life of its flying twin. The digital twin is ultra-realistic and may consider one or more important and interdependent vehicle systems" [28].

It is out of the scope of this study to find the common ground between definitions, but some scholars have attempted to do so. As established by the meta-analysis in [29], the authors inferred that the common elements among the numerous definitions are i) virtual representation, ii) bidirectional connection between the real and virtual entities, iii) simulation, and iv) connection across all life cycle stages. Upon analyzing these elements in correlation to NASA's definition, and contrasting them with published use cases, it becomes apparent that not all digital twin applications employ all these elements, thus indicating a misuse of the term. As an example, some studies focus solely on modeling and/or simulating a system of interest without considering the bidirectional communication, while explicitly referring to developing a digital twin instance.

In an effort to address this issue, a classification based on the level of data integration was proposed in [30], with the data flow exchange between the digital and physical objects serving as the principal criterion. This work gave rise to the terms Digital Model, Digital Shadow, and Digital Twin, which have been cited in multiple other researches. Nevertheless, there are other components that are not present in this approach (such as the fidelity of the virtual representation), hindering the differentiation between traditional solutions (i.e., simulation) and digital twins, and, in turn,

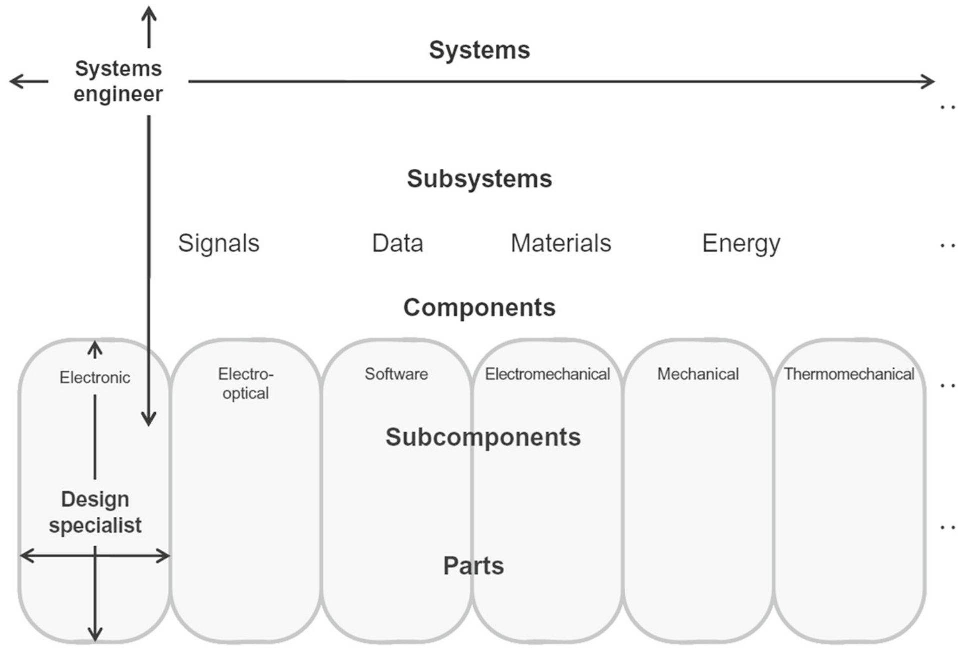

Fig. 2 System design hierarchy and its knowledge domains [31]

prolonging the market time for more complex real-world applications.

It is our opinion that the misconception about the definition of digital twins has its roots in the obscure meanings of the words "ultra-realistic," "mirror," and "system," and its relationship to complex systems organization. When referring to complex engineering systems, if no model is clearly defined at a particular abstraction layer, there is an inherently ambiguity associated with the term "system" and its constituent parts that would be "mirrored."

In Fig. 2, extracted from [31], the author defines a system design hierarchy as composed of: parts, subcomponents, components, subsystems, and systems. Along with this structure, several knowledge domains must be taken into consideration, evidencing how complex a digital twin can be assuming a high-fidelity virtual replica that considers all these levels and knowledge domains. In this way, thinking about a "mirror" does not necessarily relate to "ultra-realistic" in all levels, which, in turn, conveys the idea of modeling a given piece of the hierarchy for all knowledge domains that could go down to atomic levels. Thus, it is understandable why scholars simplify the use cases, misusing the term, and approaching real systems of interest at the component level and only for specific knowledge domains. At the same time, it reinforces the need for a more clear definition that leads this technology to a higher maturity level, instead of calling digital twin many traditional solutions that are in place for years, such as modeling, simulation, and monitoring.

2.2 Application domains

With the advancement of research on digital twins, it has become possible to ascertain patterns and the most recurrent fields of study. Some authors list the papers analyzed in their review according to market verticals [15, 20, 23], while others categorize per lifecycle phase [18, 32]. Additionally, some reviews are already based on a specific market vertical and they list use cases without referring to the lifecycle phase [14, 17, 22, 33, 34].

The outcomes of such studies vary depending on the sector and the phase of the lifecycle that the digital twin addressed. The investigation conducted in [35] (2022), which analyzed 42 papers, revealed that manufacturing and energy were the verticals with the most publications, followed by aerospace and automotive. From a lifecycle perspective, [18] mapped 240 papers published from 2010 to 2019, against each lifecycle phase concluding that the amount of publications is increasing especially for the production and service phases. It is worth noting this reported increase for the services phase, given that [33] analyzed applications in this area with a cutoff date of December 2018, explicitly highlighting a need for digital twins for services, since in several industries the profit margin from services frequently surpasses the margin from product sale. Nonetheless, over the years, [18] shows that there has been a meaningful increase in production/manufacturing, and service phase, approaching the gap indicated by [33].

Taking the work [18] as a basis and compiling results from other papers, it is possible to summarize common use cases that might be applicable for more than one lifecycle phase:

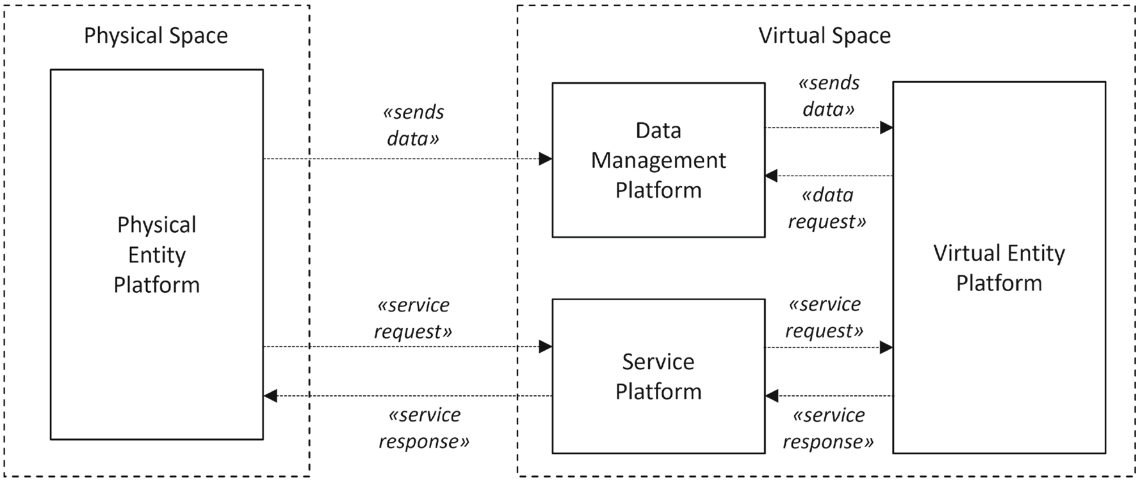

Fig. 3 Example of digital twin architecture extracted from [38]

– Verification; optimization; validation; production control and planning; what-if analysis; predictive maintenance; new business and business models; reduce of capital investment; improvement of flexibility to adapt to specific consumer needs; improve brand loyalty; real-time state monitoring; asset management; traceability; data management; man–machine interaction; costs reduction; improvement of vertical and horizontal integration; health monitoring and analysis; support after sales reconfiguration; fault detection and diagnosis; reduction of operational downtime; improvement of change management of documents and assets; increase of customer interaction and support.

2.3 Architectures and frameworks

We have noticed that some papers apply the terms architecture and framework interchangeably, yet they have distinct meanings. According to TOGAF standard definition [36], a framework "provides the methods and tools for assisting in the acceptance, production, use, and maintenance of an Enterprise Architecture." In our case, we are not dealing with an enterprise architecture, but with one of the possible abstraction levels. In this sense, we can assume the logical abstraction level for a digital twin system, referring to the design, i.e., the structure, data flows, functions, rules, and methods that guide the implementation. The TOGAF architecture framework defines three categories with types of architectural work:

– *Deliverable*: a work defined contractually by stakeholders,
– *Artifact*: a work that describes an aspect of the architecture and may or may not be considered a deliverable,
– *Building blocks*: potentially reusable component that can be combined with other building blocks to deliver architectures and solutions.

Given that TOGAF conceptualization is broader than our architectural scope, we also based this discussion on authors who define architecture and framework from a computer science view. If taken from programming perspective, a framework is related to implementation of an architecture, providing multiple classes that abstract particular concepts, defines how these abstraction layers work together, provides reusable components for application-specific features, and organizes patterns at higher levels [37].

It can be argued that with no consensus on the definition of digital twins, the way the architecture and framework terms are used varies across the studies, although these could be two distinct cases of term misuse. However, there is a basis of agreement that a typical architecture has the presence of a physical and a virtual entity, in addition to the relationship that connects them. An example of an architecture that contains these dimensions is shown in Fig. 3 extracted from [38]. Regarding the framework and assuming a combination of the TOGAF definition and as described by [37] in the previous paragraph, we assume that a digital twin framework approaches the architecture implementation and would be composed by building blocks that are potentially reusable. This premise is aligned with the framework taken as reference in Fig. 4, where we observe multiple building blocks for the physical entity platform, virtual entity platform, data management platform, and services platform. Each of the sub constituents of these building blocks may be reusable in the same project, or even different projects depending on how they adhere to each context.

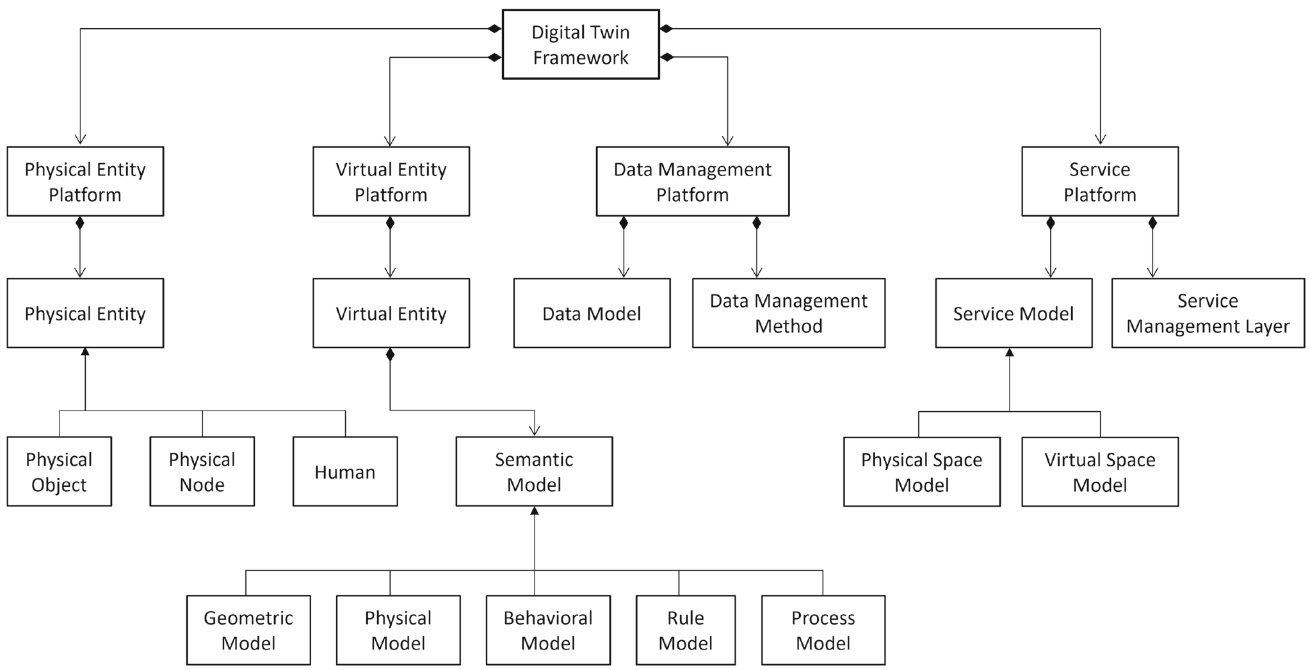

Fig. 4 Example of digital twin framework extracted from [38]

Nonetheless, these terms are not observed in a unified manner across the studies. Actually, attempting to detail digital twin layers, a wide range of terms have been used, including "properties," "characteristics," "enabling technologies," among others. Table 1 from our previous work [39] is an extraction of different authors summarizing how they refer to the layers of further characterization. Upon evaluating the description provided by the authors, it is possible to identify overlapping terms even if they are categorized differently. For example, [19] labels the update frequency as a dimension of the digital twin, while in [15, 20] they label as characteristics and utilize the term "twinning rate" instead. Similarly, some authors seek to detail digital twins by enumerating enabling technologies. In [23], they classified the technologies according to domains (application, middleware, network, and object), but in [17], the enablers were listed without association do domains or building blocks. The aim of this table is not to suggest a new terminology or categorize digital twins features in groups, but to highlight how the lack of consensus on digital twin concept impacts the way it is described and detailed across the studies. Along this table, higher group labels are separated with semicolons, and terms used for these groups are separated with colons, giving an idea of the proposed hierarchy in the studies. This may be a consequence of the researchers' varied backgrounds, but it makes harder for the scientific community to have an intuitive understanding of a digital architecture and framework, and it demonstrates the need for future research on standardizing all terms relevant for digital twin detailing.

2.4 Tools

This section maps tools based on categories that were found during the development of this study. Recalling the architectural functional blocks, similar blocks are applied for the tools, ranging from the integration between the physical and virtual entities, data-related services, modeling, and simulation.

It is important to keep in mind that some solutions, such as cloud services from Microsoft and Amazon, can fit more than one category. This is because some businesses provide a variety of solutions. The identification of all tools and their associated categories, though, is outside the purpose of this study. Additionally, the tool set changes depending on the market vertical, and small fixes could be included in a longer list. Based on the research of [26] and the additional attribution of tools listed in other studies to the suggested categories, Table 2 [39] offers an overview, where the solution suppliers are identified in brackets.

2.5 Security

Security was mentioned as a possible solution provided by digital twins [16, 20, 41], but there is no discussion whether this would be related to the security of the digital twin itself. Although some authors have stated that digital twins require an additional security strategy due to the introduction of new vulnerabilities [18, 22], most reviews have only mentioned it as a challenge [15, 23, 29, 32, 42]. Section 5.5 provides further discussion on this topic for the energy sector papers.

Table 1 Compilation of terms used to detail digital twins in several studies highlighting the lack of uniformity related to the technology conceptualization and implementation

References	DT details label	Terms used to describe DT features
[15, 20]	Characteristics	Integrated system, clone, counterpart, ties, links, description, construct, information, simulation, test, prediction; virtual mirror, replica, physical entity, physical twin; virtual entity, virtual twin, physical environment, virtual environment, state, realization, metrology, twinning, twinning rate, physical-to-virtual connection/twinning, virtual-to-physical connection/twinning, physical processes, virtual processes)
[20]	Parameters	Form, functionality, health, location, process, time, state, performance, environment
[16]	Components	radio-frequency identification, wireless sensor networks, radio-frequency identification sensor networks, unit level, system level, system of systems level, middleware (service-oriented architecture), communication protocol, communication protocol interface (AutomationML), wireless communication, programming interface through application programming interface, data-driven methods, geometry model, physical model, behavior model, collaborative information model, decision making model, scalability, model interoperability, fidelity, dynamicity, modularity, application interface layer
[23]	Domains, Enabling technologies	Application Domain: model architecture and visualization, software and Application Programming Interfaces, data collection and pre-processing; Middleware Domain: storage technology, data processing; Network Domain: communication technology, wireless communication; Object Domain: hardware platform, sensor technology
[11]	Category, Dimensions	Context: reference object, tangible product life cycle phase, benefits, application domain; Data: data storage, data scope, data quality, data sources, data interpretation; Computing capabilities: trigger types, model look-ahead perspective, computing timing capabilities, update frequency of inputs, update frequency of outputs; Model: digital twin creation approach, modeled characteristics, digital model types, model authenticity, model maintenance, modularity; Integration: digital twin interaction, hierarchy, connection mode, user focus, inter-organizational integration, collaboration; Control: level of cognition, level of autonomy, learning capabilities; human–machine interaction: types of interaction devices, human interaction capabilities
[17]	Enablers	Artificial intelligence, Internet of things, industrial internet of things, virtual reality, augmented reality, hardware, communication technologies, knowledge building, design process, development technologies
[40]	Building blocks, Properties	Physical Entity Platform: physical object (is observed), physical node (observes), human; Virtual Entity Platform: semantic model with geometric model, physical model, behavioral model, rule model, process model; Data Management Platform: data models, data management methods; Service Platform: service models (physical/virtual), service management layers
[19]	Dimension, Level	Update frequency: immediate real-time, event driven, every day, every week; Connectivity modes: automatic, bidirectional, unidirectional; Integration breadth: world (full object interaction), field environment, near field production system, product, machine; Product lifecycle: begin of life, mid of life, end of life; Human-interaction: smart devices, virtual reality, augmented reality, smart hybrid; Digital model richness: geometry, kinematics, control behavior, multi-physical behavior; Simulation capabilities: look-ahead perspective, Ad-Hoc, dynamic, static; Cyber Physical System intelligence: autonomous, partial autonomous, automated, human triggered
[18]	Key technologies	Data-related technologies, high-fidelity modeling technologies, model based simulation technologies
[26]	Supporting tools types	Integration and simulation, digital twin modeling, bridging and twin control, big data processing, big data storage, artificial intelligence–machine learning and application programming interfaces

3 Related work of digital twins in the energy market

While the previous section served as the conceptual basis on digital twins, this section objective is to analyze previous works of energy-related digital twins reviews and highlight the differences between them and our work.

As a starting discussion, it is worth noticing that many studies refer to power systems without detailing the domain. As an example of general application in smart grids, [4] mention use cases in distribution utilities, distributed energy management systems, operation centers, fault diagnosis, batteries systems, and renewable energy generators. Besides these use cases are specific to the energy market, there is no quantitative analysis to provide the most relevant ones. Following a similar broad view of smart grids, in [44] the authors map digital twin applications in power industry into four groups: grid, plant, equipment, and other levels. Some of the mentioned use cases include power grid structure and design, control centers emulation, network security, transformers, turbines, converters, relays, and fault diagnosis, which are alike to the examples given in [4]. Research in [45] also investigated potential uses of the technology, the most common being anomaly detection, smart grid management, dynamic monitoring, and demand forecast. These studies have revealed the significance of the digital twin concept across all aspects of smart grids, suggesting a number of useful applications. However, they did not provide quantitative analysis to identify the most relevant use cases per domain, which is one of the reasons we narrowed our review to two domains, being able to contribute specifically with generation and distribution.

For studies focused on specific domains, it has not been demonstrated the most relevant use case either. In their discussion of Local Energy Communities (LEC) orchestration [43], the authors goal is to develop digital twins that support the balancing reserves of the electricity grid (distribution domain). They contributed with modeling and simulation methods providing relevant references for physics-based models, and data-driven models. Their framework (Fig. 5) highlights prediction, optimization, and control strategies as services provided by the digital twin.

Some scholars have conducted research on enabling standards and technologies for information models suitable for digital twins. Taking into account the wide range of existing solutions, [46] put forward the idea of utilizing the common information model (CIM), a vendor neutral open standard for power systems. They argue that CIM is already used for developing interoperable applications (hardware or software), and, given that interoperability is also a requirement for digital twins, it may provide a framework that enables information sharing. Also approaching standards, in [47] the authors propose the use of communication protocols such as IEC 61850 and IEEE C37.118 because of their flexibility. Moreover, when it comes to the energy sector, some benchmarks are useful for developing study cases on a common research ground. By applying benchmark IEEE 118-Bus System, [48] explored the adaptability of conventional models for developing a power system digital twin (PSDT), what includes enabling technologies that were discussed by [49] such as IoT platforms, and advanced data analytics including artificial intelligence and machine learning.

Such studies reinforce that the perceived benefits are common sense among scholars. However, given that most of them are not domain-specific, there is a gap of knowledge on what can be the final actors of each domain and most common use cases, and that is the significance of our work. We aim at contributing with the energy sector community by doing a quantitative analysis of use cases in generation and distribution domains, specifying the final actors of these two domains, such as detailing services provided by digital twins which for these actors.

4 SLR method

This literature review differs from the one performed for the related work section due to its rigorous and systematic steps. It is based on the methodologies described by [50] and [51] consisting of seven steps: (1) Identify the purpose, (2) Draft Searching Protocol, (3) Apply practical screen, (4) Apply quality screen, (5) Extract Data, (6) Synthesize studies, and (7) Write the review.

Besides the databases, other tools utilized during this research were EndNote 20 for references management (practical and quality screening), NVIVO and Excel to extract data and synthesize information.

4.1 Purpose of the literature review

This literature review sought to identify the current state of knowledge of digital twins in the energy sector. In order to find information for technical aspects of the purpose, the following research questions were elaborated and grouped according to specific categories. Group 1 (NIST domains and use cases) aims to provide information for quantitative analysis of use cases. Groups 2 and 3 (reference architectures, frameworks, and tools) allow a comparison between the conceptual aspects studied in Sect. 2 to evaluate if the architectures and frameworks applied in the energy sector differ from general market. Group 4 (network and binding) focuses on the communication between the real and virtual entities to assess if the studies detail the bidirectional communication, while group 5 is focused on security, which was expected to be present in energy-related studies, given that it is a critical infrastructure sector. Lastly, Group 6 has the

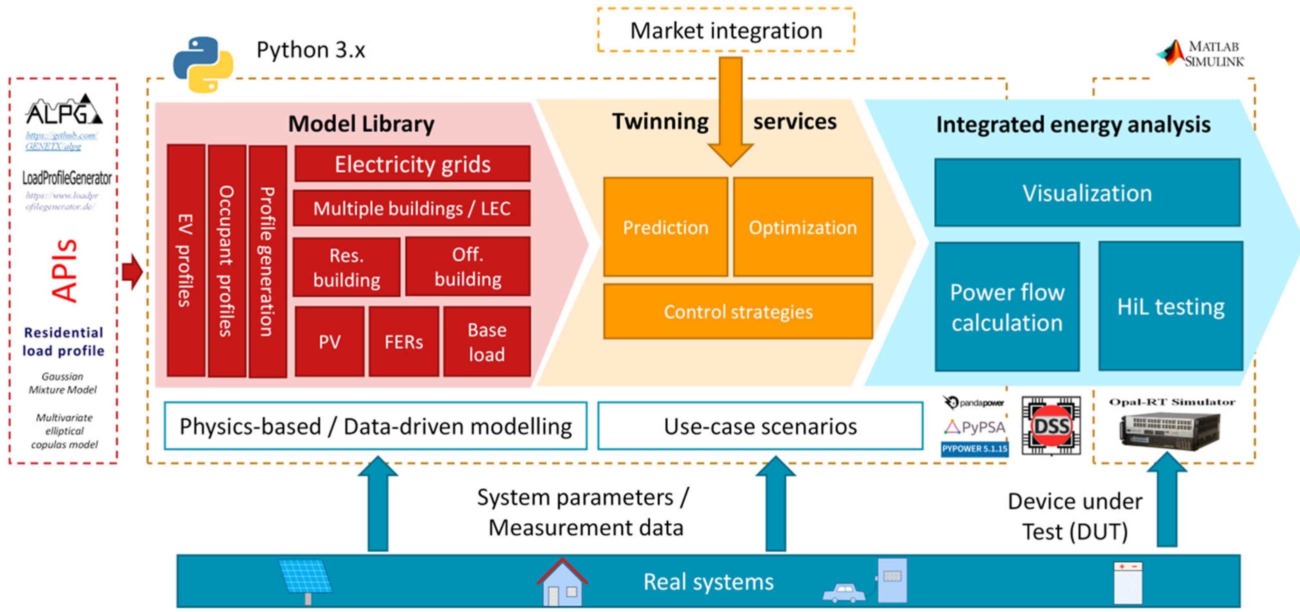

Fig. 5 Digital twin framework for local energy communities digital twins extracted from [43]

Table 2 Compilation of some tools and techniques according to categories

Category	Tool/technique
Bridging/integration	Azure (Microsoft), AWS (Amazon), MindSphere (Siemens), Predix (GE), ThingWorx (PTC), IBM Maximo Asset Health Insights (IBM), RFID, MTConnect, OPC UA, MQTT, ZigBee, XML, IndraMotion MTX (Rexroth), Beacon (Fii-Foxconn), TwinCAT (Beckhoff), SAP (SAP), Codesys (Codesys Group), edge/foggy computing
Data processing	Data fusion algorithms, BigQuery (Google), Spark/Storm/S4/Hive/Mahout/Flink/Pig/Impala (Apache), edge/foggy computing, VoltDB (VoltDB), Azure (Microsoft), AWS (Amazon)
Data storage	MongoDB (MongoDB), MySQL(Oracle/Others), Hadoop/Hbase/Kafka (Apache), Oracle, Azure (Microsoft), AWS (Amazon), BigQuery (Google)
Data analytics	AI algorithms (e.g., feature selection, feature extraction, pattern recognition, stochastic optimization, evolutionary, etc.), ML algorithms (neural networks, fuzzy logic, etc.), TensorFlow (Google), Azure (Microsoft), AWS (Amazon), BigQuery (Google)
Modeling	Meta-information and semantics, ontologies, AutomationML, finite element, finite element alternating method, AnyBody Modeling System (AnyBody Technology), service-oriented architecture (SOA), representational state transfer (REST), Matlab (MathWorks), Matpower (Matpower), InterPSS (InterPSS), OOPS, PowerFactory (DIgSILENT), Modelica (Modelica), Markov chain, ANSYS Twin Builder (ANSYS), NX (Siemens), SolidWorks (Dessault Systèmes), AutoCAD (Autodesk), 3D Max (Autodesk), FreeCAD (Freecadweb), Azure (Microsoft), AWS (Amazon)
Simulation	FEM simulation, Montecarlo simulation, CFD simulation, DDSIM (Damage and Durability Simulator), S2S DFS, Simulink (MathWorks), CAE-based simulation, (CATIA) Dassault Systemes, CIROS Studio (VEROSIM), Simcenter 3D (Siemens), ANSYS Twin Builder (ANSYS), PSS R NETOMAC (Siemens), MWorks (Tongyuan), SUMO (Eclipse), Open Simulation Platform (DNV-GL), Azure (Microsoft), AWS (Amazon)

objective to identify current challenges and directions for future work.

Group 1: NIST domains and use cases

- *RQ1:* What is the domain and actor addressed?
- *RQ2:* What is the reported use case?
- *RQ3:* Is the study practical or theoretical?
- *RQ4:* What is the method applied?
- *RQ5:* Who are the stakeholders involved?

Group 2: Reference Architecture

- *RQ1:* What is the architecture adopted?
- *RQ2:* What are the operational requirements of each layer of the framework?

Group 3: Framework and its tools and techniques

- *RQ1:* What are the modeling techniques and tools used?
- *RQ2:* What are the simulation techniques and tools used?
- *RQ3:* What are the data-related (processing, storage and analysis) tools used?

Group 4: Network and binding

- *RQ1:* How is the data flow between the physical and virtual entities (manual, unidirectional or bidirectional?
- *RQ2:* How is the communication implemented in terms of architecture, components and services?

Group 5: Security

- *RQ1:* How is the security of the digital twin itself addressed?
- *RQ2:* How is the security of the communication between the digital twin entity and the physical entity addressed?
- *RQ3:* How is the security of the communication within digital twins addressed?
- *RQ4:* Does the study address any other layer of security? Which one?

Group 6: Challenges and Future Work

- *RQ1:* What are the limitations of this study?
- *RQ2:* What are the challenges?
- *RQ3:* What is recommended as future work?

4.2 Searching protocol

The protocol was designed to allow the searching evaluation and replication by defining the databases and keywords expression. The sources used to identify articles were: IEEE Xplore, ACM Digital Library, ResearchGate, ScienceDirect, Scopus, ProQuest, and Semantic Scholar.

The databases search was conducted with the following query: ((“Document Title” OR “Abstract”: “digital twin*”) AND (“Document Title” OR “Abstract”: “energy” OR “electric*” OR “power” OR “smart grid*”)). This set of keywords intends to perform the initial filter of papers relating digital twin technology with the energy sector, considering different vocabulary that were retrieved from a previous broad analysis. The collection retrieved 3675 papers including duplicates. After eliminating duplicates, 2238 were considered for the practical screening.

4.3 Practical screening

The practical screening phase consists of identifying articles that may contain relevant research to answer the questions stated in the literature review purpose. The inclusion and exclusion criteria adopted in this work are given in Table 3. The papers assessment was conducted by the main author (70%) and a laboratory assistant* at IIK, NTNU (30%). In order to make the selection uniform, after each one had concluded the selection, both assessed 10% of the selected by each other and 5% of excluded. After aligning differences and applying the inclusion/exclusion criteria explained here, the initial 2238 papers were reduced to 275.

4.3.1 Inclusion criteria

1. *Language:* papers written in English.
2. *Content:* the content analyzed through title/abstract must be related to the research questions.
3. *Format:* scientific/scholarly articles published in conferences, workshops and journals.
4. *Date:* no restrictions were made regarding the year of publication because digital twin is an emerging technology.
5. *Market vertical:* papers must be related to digital twins in the energy sector. It is worth commenting though, that when it comes to consumers, papers that approach digital twins focusing on energy consumption efficiency in other fields, were not considered, otherwise the results would be very broad and out of the scope of this study;
6. *Smart grid domain:* papers should be about generation and distribution domains from NIST conceptual model of smart grids

4.3.2 Exclusion criteria

1. *Format:* Letters, editorials, reports, posters, magazines, trade journals, presentations, front and back matter pages such as title pages, abstract pages, index pages, table of contents, and stand-alone images.

Table 3 Inclusion and exclusion criteria

Inclusion criteria	Type
1. Written in English	Language
2. Title eligible	Content
3. Scientific articles published in conferences, workshops and journals	Format
4. Publication year	Date
5. Energy sector	M. Vertical
6. Generation or distribution	Domain
Exclusion criteria	**Type**
1. Letters, editorials, reports, posters, magazines, trade journals, and presentations	Format
2. Secondary studies	Content
3. Articles that do not approach energy sector	M. Vertical
4. Articles of the energy sector, but outside the generation and distribution domains	Domain
5. Articles not found for full text download	Availability

2. *Content:* secondary studies in the form of reviews, surveys, systematic literature reviews, and generic digital twin frameworks.
3. *Market vertical:* articles outside the energy sector that do not meet inclusion criteria five explanations.
4. *Smart grid domain:* papers about transmission, operations, service providers, markets, and customer domains from NIST conceptual model of smart grids are out of the scope.

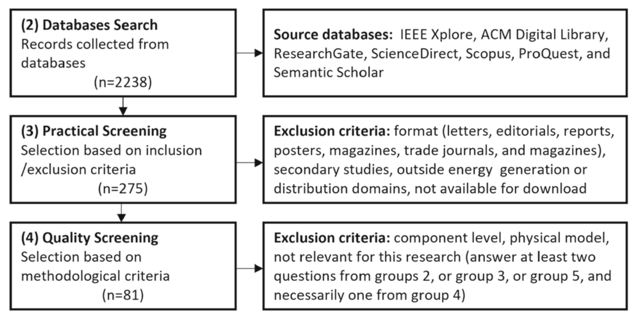

Fig. 6 Summary of papers filtering applied in this SLR

4.4 Quality screening

The 275 studies selected during the practical screening were rated according to a quality assessment defined in a standard form used for each paper. Again, the papers assessment was conducted by the main author (70%) and a laboratory assistant* at NTNU, IIK (30%). The papers that did not meet the criteria were excluded, remaining 81 for the following steps.

4.4.1 Exclusion criteria

1. *Research Questions:* papers that do not answer at least two questions from groups 2, or group 3, or group 5, and necessarily one from group 4. The intention of this combination is to cover at least some aspects related to architecture, framework, security, and, necessarily approach the network, once the bidirectional communication was identified as a key possible differential between a digital twin and traditional solutions.
2. *Component level:* papers in which the use case is at component level are too specific for the aim of this study.
3. *Physical Model:* papers that focus on the physical modeling or structural properties instead of network/data.

4.5 Data extraction

This step consists of systematically extracting data from each paper selected during the quality screening. The extraction form was prepared to store data that contributes to answering the research questions in a consistent and uniform way, and was performed by the coding tool available at NVIVO.

4.6 Synthesis of studies

Given the qualitative nature of most papers on digital twins, the procedure adopted to analyze them and obtain a concept-centric focus was based on synthesis by interpretation and explanation.

4.7 Writing the review

The findings of this literature review are described following standard writing principles aiming to make a theoretical contribution by being critical and using evidence to support the claims.

5 SLR analysis

The following subsections address the topics as organized in the research questions.

5.1 NIST domains and use cases

As explained in the Background section 1.1, the terminology of this paper is based on NIST Smart Grid Interoperability Framework [2].

This work started addressing previous reviews regardless of the market vertical, to map the main scientific findings on digital twins, and then narrowing down to an overview of the energy sector reviews that approached all NIST smart grid domains. This step showed a gap in domain-based studies. Attempting to cover this gap, we focused this paper on two domains: generation and distribution.

After completing the practical screening and start classifying the papers, we noticed that only the NIST domains classification would not be enough because many studies approach more than one domain at the same time; thus, some assumptions were made to enable the categorization and provide an overview on what combination of domains was more present before the quality screening. We categorized the papers into four groups: generation, distribution, multiple domains, and all domains. Nonetheless, for cases where more than one domain is approached, for example, transmission and distribution, the amount of papers were not enough to enable analyzing a trend for this combination. For this reason, the most relevant domain was taken into account for the categorization, with the following considerations:

- Smart grid papers that are generic were considered addressing all NIST domains and labeled in the category “All”;
- Microgrid papers or synonyms as “Local Energy Community” usually embrace generation, distribution, and sometimes transmission. In this work, we labeled them as “Distribution” because this is the main domain approached, similar to power flow papers;
- Papers on electrical power systems or equipment that can be utilized in more than one domain, such as transformers, relays, batteries, high voltage cables, coolers, and so on, were labeled as “Multiple”;
- Power plant papers, regardless of the energy source, were labeled as “Generation”;

Following the same approach, considerations were made to the actors found for the generation and distribution domains:

- *Generation actors*: defined power plant types including wind, solar, nuclear, hydro, and thermal, added to a generic category labeled as power plant;
- *Distribution actors*: substation, microgrid, distributed energy resources (DERs), distribution centers;

For the use cases categorization, the following assumptions were made:

- *Distribution management*: papers related to multiple energy sources to be integrated into the grid considering the uncertainty factor.
- *Fault diagnosis*: papers that approach monitoring, health state, operational reliability, anomalies detection, perception, among others.
- *Generation forecast*: it is applicable for any energy source, but the trend was more noticed for renewable sources, being wind and solar, the most common targets of forecast due to its intermittent power generation nature.
- *Performance optimization*: besides the term performance itself, other approaches of state estimation related to performance were also included in this group.
- *Predictive maintenance*: in addition to explicit prediction-related studies, papers approaching variables estimation, fault prediction, and continuous monitoring were also considered in this category.
- *Reliability forecast*: this category approaches both distribution management and generation forecast, however the focus is on system resilience.
- *Security enforcement*: papers that approach multiple security use cases, such as online network monitoring, security testing, zero trust architectures, and secure embedded solutions.
- *Staff management*: related to human aspects, behavioral, emergence awareness, compliance with regulations, and decision making.

Although one of the practical screening exclusion criteria was to be from the generation/distribution domain, as explained previously, some papers are not specific and a single attribution is not possible. When papers approaching multiple or all domains were attending the criteria (answer at least two questions form groups 2, or 3, or 5, and necessarily one from group 4), they were considered relevant for this research and followed for further analysis.

In Fig. 7, graph (a) shows the amount of papers fitting into each established category before the practical screening and graph (b) shows the same, but after the quality screening, where the previously explained quality criteria had to be full filled, resulting in a higher quantity of papers on the distribution domain.

The digital twin use cases categorization enabled a quantitative analysis similar to the one performed at [52], contribut-

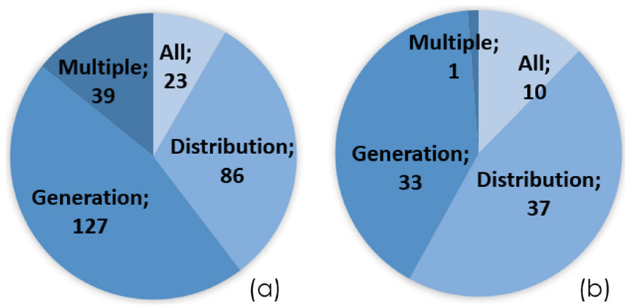

Fig. 7 Statistics on NIST smart domains after the practical screening and after the quality screening

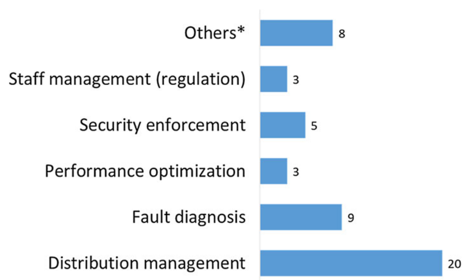

Fig. 8 Use cases statics for the distribution domain

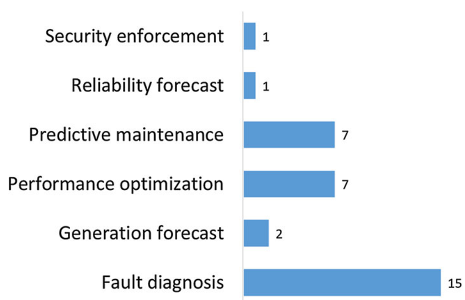

Fig. 9 Use cases statics for the generation domain

ing to identify the most relevant use case for two scenarios. The first scenario in Fig. 8 groups the categories of "distribution," "multiple," and "all" NIST domains, resulting in "distribution management" as the most relevant use case, followed by "fault diagnosis." But in Fig. 9, only use cases from "generation" domain papers were categorized, changing the most relevant use case to "fault diagnosis" followed by "performance optimization" and "predictive maintenance."

5.1.1 Studies design overview and stakeholders

We observed that most selected studies present similar methods for developing their research work, following a path that establishes the background on previous works, conceptualizing a use case relevant for the paper, and performing a practical study case as a proof of concept. Although the quality criteria were developed to collect more technical studies, implementation details are not always explained, limiting the understanding of the tools and techniques that may leverage the application of digital twins.

Regarding stakeholders, only 8 (9,8%) of the studies approached them and their roles. Some just mention them briefly [53, 54] as sources for data gathering and sharing, while when considering larger-scale digital twins, as can be the case for the distribution domain involving several actors, we share the opinion of [20] and [55], who support including both stakeholders and end-user during the designing and implementation of digital twins.

Corroborating this rationale, the papers that broadly approached stakeholders were mainly about the distribution domain, emphasizing how important it is to enable analysis based on different perspectives and priorities that each involved stakeholder may have [56]. Similarly, [57] argue that the digital twin environment must enable these test scenarios from different viewpoints, such as induration and carbon emission. The study [58] was performed by an electrical distribution company in Brazil aiming to develop a power system digital twin prototype to enable services of anomaly detection, predictive maintenance, and automated networking modeling. As part of the solution, they built a third-party platform to share information with stakeholders. An example of stakeholders was discussed in [59], a use case of beyond fifth generation (B5G) enabled smart grid, for which stakeholders range from microgrid owners, resident operators, utility administrators, prosumers, governments, utilities, and regulators.

Regarding the generation domain, where most studies focus on the component level and do not involve many actors, from an internal perspective stakeholders may be from different departments of the same entity [60], such as engineering, maintenance, management, system architects, and process engineers.

5.2 Reference architecture

The findings of reference digital twin architectures from the energy sector review and the generic architectures discussed in the related work Sect. 2.3 are very similar, relying on the common ground of the three basic dimensions: virtual entity, physical entity, and the link between them. There may be discrepancies in the designations given to the dimensions, with some seeing data and services as individual dimensions, while others view them as subsections of the virtual entity. For [61], we can express it as a five-dimension equation with the physical entity, the virtual entity, services, data, and the connection. An extra dimension is also considered by [62], named as the display layer.

To avoid repetitiveness with the previous section on this topic, only the differences will be discussed, and the most relevant one is that some studies associate the term digital twin

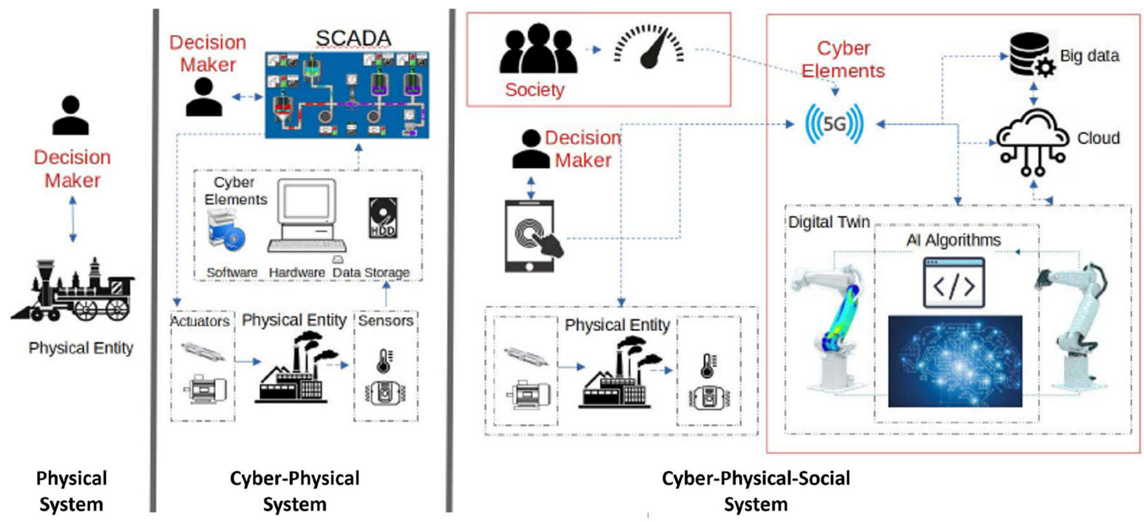

Fig. 10 Digital twin architecture that differentiates from the definition by considering the "digital twin" block mainly as modeling and simulation, including AI algorithms [34]

only with the layer of modeling and simulation, not with the physical entity. Interestingly, NASA's definition does not clearly mention it as well, pointing to an additional finding of our work about the boundaries of the digital twin, and whether the physical entity should or not be one of the architecture blocks. In Figs. 10 and 11, it is possible to see examples of architectures where the block "digital twin" is associated with modeling and simulation, including AI algorithms.

Many studies depict the architecture and start defining the functional blocks within the dimensions still considering as part of the architecture description. In this paper, however, the tools and building blocks detailing is considered as part of the framework, which, as defined in a previous section, is composed of reusable components for application-specific features that enable the implementation of an architecture.

The reason for this decision (building blocks within the framework, not architecture) is based on how the ISA-95 standard and its corresponding Purdue Reference Model are translated to industrial automation architectures. This standard defines a conceptual model for industrial control systems (ICS) with five layers, as recalled in Fig. 12. The levels range from field equipment (sensors and signals) to business related level (Enterprise Resource Management). Based on this standard, most industrial automation architectures present these same five layers, showing the main components of each level without detailing the hardware, software, and services, but showing how the components are connected and labeling their role. As an example, a reference automation architecture was extracted from the PCS7 Siemens catalog [65], where we can see in Fig. 13, the correspondence between the levels of the Purdue Reference Model and this reference automation architecture from PCS7:

– "Field Level" corresponds to Purdue Level 0, showing the sensors and actuators at production process.
– "Control Level" corresponds to Purdue Levels 1 and 2, showing the Programmable Logic Controllers for each system, the switches, computers, gateways, among others.
– "Enterprise Level" for Purdue Levels 3 and 4, where the computers are labeled according to their role in the business planning, logistics, and manufacturing management.

We believe that the data flow model of the Purdue Reference Model, which has been available since the 1990s, is still relevant and enough to detail the main blocks and their corresponding components and roles in each level. It is possible to map this model also to modern IIoT (Industrial Internet of Things) environments, even considering technical features such as time constraints, latency and availability, as explained by AWS [66]. They argue that the use of external resources should be placed on Purdue Level 2 systems or higher, not for Level 0–1 systems. This is possible as the response time in Level 2 is within minutes, compared to seconds in Level 1 and milli/micro seconds in Level 0. Summarizing, we believe that an architecture as exemplified in Fig. 13 is in accordance with the definition considered in this paper, giving room to detail the building blocks, software, and services in the framework description.

5.3 Framework and its tools and techniques

The architecture is a hierarchical system that relies on the coordination of requirements between its layers. As stated by [67], a digital twin depends on requirements that range from computational and communication platforms, both with

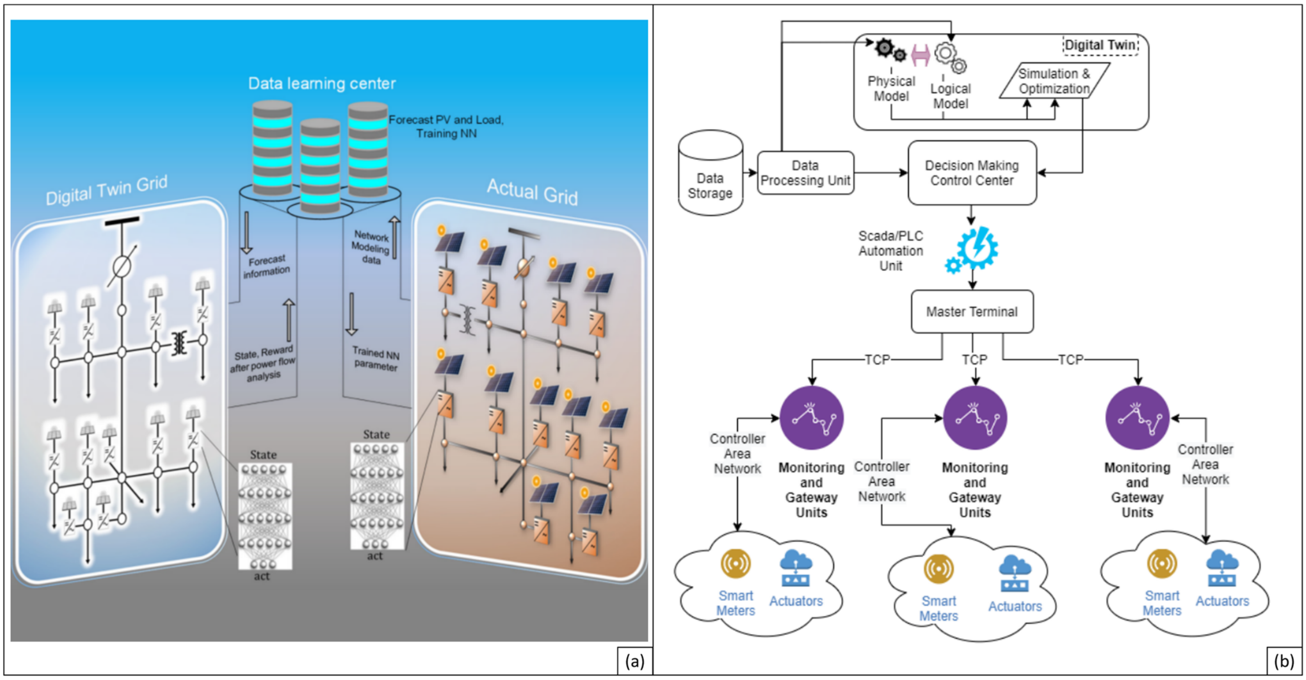

Fig. 11 Digital twin architectures that differentiate from the definition in the following senses: (**a**) the block "digital twin grid" receives forecast information and returns the states, being possible to infer that it is basically a static model/simulation tool for the "actual grid" and other simulations are made outside of this block, in the "data learning center," thus not included in the digital twin [63]. Contrasting with (**b**), different models, simulation and optimization are included in the "digital twin" block [64]

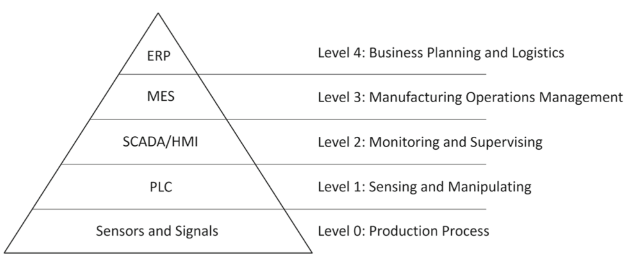

Fig. 12 ANSI/ISA-95 hierarchy pyramid of Purdue Reference Model

hardware and software components. We can then see the digital twin as the set of all its components and their respective configurations within and across the layers, which here are assumed as part of the framework.

Going back to the framework of Fig. 4, we will further explore the four main functional blocks in this section, focusing on similarities and differences found during the relevant analysis for the energy sector.

5.3.1 Physical entity

This section's goal is to provide information for the types of physical entities from the energy sector that have been addressed in the NIST domains selected for this study. Table 4 summarizes the physical entities for the Generation domain and Table 5 for the set labeled as Distribution, Multiple, and All.

Attempting to establish a link between the physical entities for each evaluated domain and the engineering systems hierarchy, it is possible to infer from Table 4 that, for the generation domain, most entities are component or subsystem/system level, usually the main generation unity. For nuclear power the reactor, for solar the photovoltaic conversion unit, for thermal the steam turbine, for wind power the wind turbine, and for hydro the generating unity composed of turbine and generator. These entities are aligned with the most relevant use case identified as fault diagnosis for equipment.

For the distribution domain, the physical entities observed in Table 5 hierarchy are system level, or, as would be called in other literatures, system of systems, once the distribution includes all energy sources. Here, the ability to accurately estimate power demand and generation to balance the grid is the main feature of the digital twin, also aligning with the main use case, which is distribution management. Another interesting finding specific to the energy sector is the use of benchmarks for case studies. Some of the identified benchmarks are:

- IEEE 39-bus [95, 96].
- IEEE 9-bus [96].

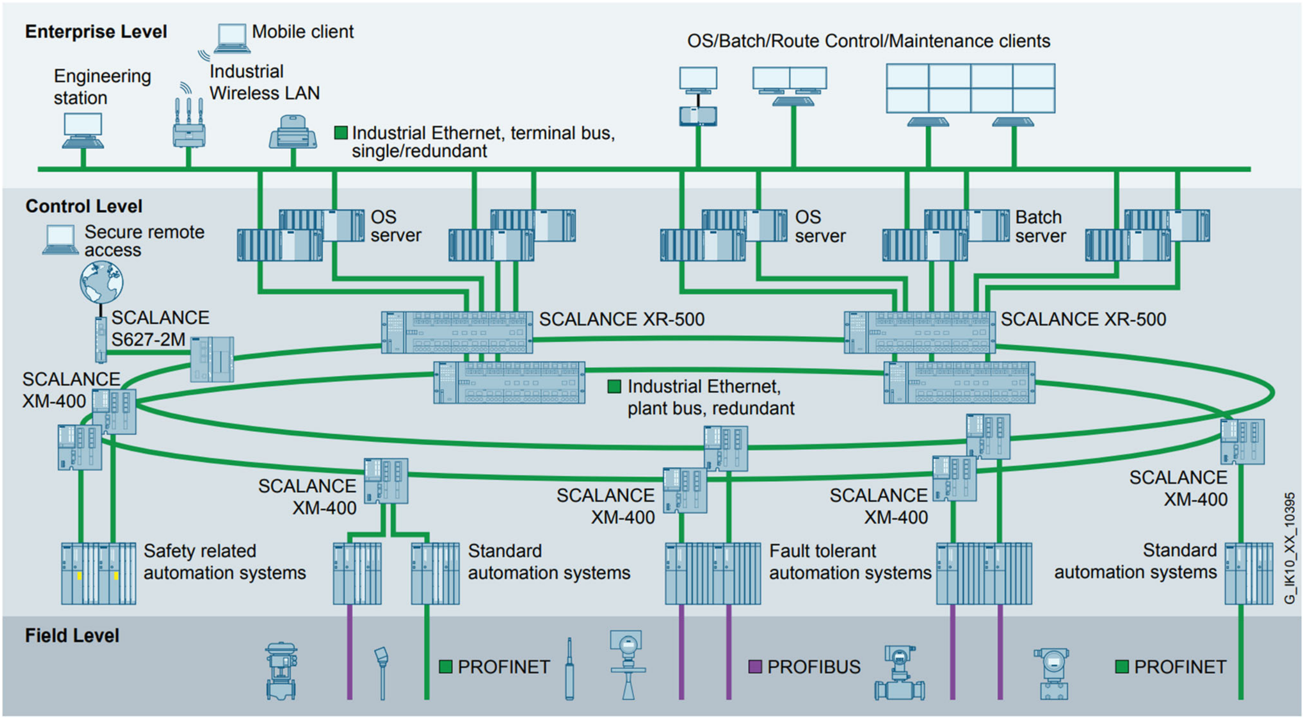

Fig. 13 Automation architecture example extracted from Siemens PCS7 catalog

Table 4 Physical entities modeled in typical actors from generation-related domain

Actor	Physical entities
Hydro	Pressure chamber [68]; generating unity [69]
Nuclear	Reactor core [70]; functional modules of netronic calculations, temperature dynamics, process subsystems, steam generators, pumps, secondary circuits, and auxiliary systems [71]; microreactor [72];
Solar	Photovoltaic energy conversion unit (PVECU) composed of panel, power converter, and electrical sensors [73]; set of PV inverters [63]; single-diode model of a single battery [61]; inverter system and weather data [74]; photovoltaic power station with several panels [75]; photovoltaic solar farm [76]; PV power plant [77]
Thermal	Boiler island, steam turbine island and emission control equipment [78];coal mill and feedwater pump and other key equipment [79]; key equipment from main subsystems (mechanical, lubrication, water cooling, fuel, exhaust, air intake) [80]; gas turbine system [81]; high-temperature thermal energy storage device [82]; steam turbine system [60]; gas turbine system [83]; combustion process, air and flue gas system [84]
Wind	Wind turbine power converter [40]; WT with gearbox failure [85]; turbine's physical system, and weather sensors [86]; direct-drive wind turbine [87]; onshore wind turbines [53]; wind turbine mechanical components [88]; generators, main shafts, gearboxes, yaw systems, pitch systems, hydraulic systems, racks, and wind turbine control systems [89]
Power plant	Large electrical generators [90]; battery energy storage [91]; auxiliary systems, thermodynamic properties, unit models (heat exchanger, pump, compressor, boiler, etc.) [92]; boiler system [57]; four generators connected with the grid (Cigré benchmark) [93]; CEP engine (complex event processing) [94]

– IEEE 33-bus [97].
– Cigré benchmark [93].

5.3.2 Virtual entity modeling

The intention of this section is to enrich the assessment summarized in Table 2. In the reference framework of Fig. 4, there is a functional block for modeling the virtual entity, but not for simulation. However, we can assume that the simulation is implicitly included in the service platform. An important aspect to highlight about the virtual entity is that modeling and simulation, despite being different functionalities when represented in a reference architecture/framework, are very often developed and implemented by the same tools, and that is the reason why the new tools and techniques identified during the systematic literature review are grouped together:

- Modeling and Simulation tools and techniques: TermoflowTM [78], semiautomatic modeling from formal specification [73], OpenFAST (for wind turbine) [40], DSL (Domain-Specific Language) [69], gradient boosting regressor and random forest [80], modeling based on state machine [98], METHONTOLOGY approach [82], convolution neural network [99], Scikit-learn toolbox and EnergyPlus [56], Cigré benchmark [93], OpenDSS [100], KNIME analytics platform [68], AnyLogic [101], IEEE 39-bus benchmark [95];

Additionally, the engineering hierarchy and the requirement for updates during all lifecycle phases interfere with how the actual entity is modeled and why modeling and simulating are increasingly intertwined, which might be one of the essential differences between a digital twin and conventional solutions. Modeling and simulation have been in the market for a lengthy period, but before, the simulations were just static models over time. But the need of the market for predictions to foresee scenarios and improve decision making has created a space for dynamic models. This way, the previous physical, mathematical, or logical models are becoming hybrid and increasingly include data-driven algorithms that can be regularly updated. Existing component level models based on equations are still applied. However, when it comes to system level and its intrinsic high complexity to link all knowledge domains among its components, hybrid models gain strength. In this paper, it was noticed that the dynamic models usually rely on AI and ML for their implementation.

5.3.3 Data management

The examination of the related work showed a greater focus on data management than the systematic literature reviews that typically center around single use cases. From Table 2, where the tools were categorized, three groups were about data, comprising processing, storage, and analysis. The framework taken as a reference from Fig. 4 shows two subfunctional blocks within the Data Management Platform, which are Data Model and Data Management Method. Other categories found in a nonstructured way throughout the analyzed papers were related to data acquisition, pre-processing, storage, and processing.

5.3.4 Services

Services make up another relevant block, also identified as one of the architecture's layers and framework's functional block.

Services can be performed online or offline, depending on the real-time need for the outcome. Some examples of online services are visualization, monitoring, alarming, state estimation, protection, and control. Offline services may include analysis and assessment, system planning, model validation, and disturbance analysis.

- Energy sector common services: the services coincide with what was called previously as use cases. Here, some are repeated to highlight energy-related services such as load balancing [56, 63, 64], demand forecasting [56, 59, 118, 126], power flow analysis [55, 55, 63, 97, 101, 103, 113, 116, 119, 129], three-phase short-circuit diagnosis [129], among others that may be more generic to different market verticals, such as fault diagnosis, state estimation, operational planning, and so on.

5.3.5 AI and ML as enabling technologies

A search for terms related to AI and ML on all papers provided results in 76 studies out of 81, which corresponds to 93,8%. 16 of these (19,7%) approach the topic directly as a key part of the study.

According to [122], a digital twin is a dynamic virtual model and, for this reason, they propose a solution that is updated periodically by inputting new data to a neural network model used for security assessment purposes. An important aspect of their work is that there is a bidirectional communication between the virtual and the real entities and one parameter of the solution is the time resolution. In this case, a sub-second delay. Google Tensor Flow was used for the offline training, what was also observed in other studies [56, 59, 68, 80, 91, 96, 117].

Similar to [122] system level approach, but with a different objective, [56] proposed a management tool for multi-vector energy systems which evaluates demands, supplies, and storage from different sources, using machine learning to predict the energy demand when there is a pattern, and artificial neural networks in cases where no patterns are found. This was demonstrated by an example of a government building, showing that it is feasible to optimize energy consumption by calculating the cost for different scenarios and selecting the option that best suits the user-defined parameters.

Generic and more theoretical approaches, such as those proposed by [82] and [114] highlight the trend for utilizing neural networks and machine learning for the simulation functionality of digital twins. While [82] proposed a gray box, defining as partially theoretical with data to complete the model, and modeled in MATLAB, [114] designed a pure theoretical modeling engine based on several algebraic equations. Both proposed the comparison between the simulated results and the real entity measurements, so that the system is continuously updated to be as realistic as possible.

When dealing with forecasting situations, many scholars study a broad range of AI/ML techniques applied to different actors of the power generation domain. A solution

Table 5 Physical entities modeled in typical actors from distribution-related domain

Actor	Physical entities
DERs	5 DERs response power [102]; prosumers facility [103]; Battery Energy Storage Systems (BESS) [104]; DER and ESS (Energy Storage Systems) resources [101]; PV inverters [100]
Electrical Power Systems	Distribution transformers [105]; 2 level inverters [106]; Gas-insulated Switchgear (GIS) [107]; converter station [99]; communication network [108]
Energy Management System (EMS)	Power line communication [109]; heating system electrification in part of the social housing stock and interventions in the transport sector through increased EV charger installation [56]
Microgrid	IEEE 39-bus benchmark [95]; generic generators from several sources [110]; energy units (solar, wind or conventional generator) [111]; distribution controllers [112]
Power Flow	Carbon neutrality-focused systems [113]; control room EMS (Energy Management System) [114]; general power system components of single or multiple loads and their sensors [115]; multi-energy flow including electricity, heat, gas, and hydrogen [116]; control center system [55]; IEEE 9-bus and IEEE 39-bus benchmark power systems [96]
Pricing	Transformers, wind turbines, solar panels, CHP systems, TESs, boilers and Evs [117]
Smart Grid	Smart meter devices, controller units, storage units, and analytics applications for network management and monitoring [64]; distribution transformer, smart meters [118]; transmission line, transformer, controllers, circuit breakers [119]; medium voltage feeder, transformer, measuring devices [120]; energy providers [121]; dispatching control center SCADA [122]; energy providers and stakeholders [59];generic power equipment [123]; DERs and DSOs [124]; synthetic NEM (S-NEM2300) composed of power stations, substations, wind farms, and transmission lines [54]; end-users platform of consumption monitoring [52]; control center system [67]
Substation	Substation module, equipment supervision module, and personnel positioning module [125]; medium and low voltage distribution network [126]; converter system [127]; regional multi-energy system integrating hydroelectric, wind power, photovoltaic, combined cooling, heating and power, energy storage, and electric vehicle charging facilities [128]; substation components [129]; MV/LV transformers, and grid cables [58]; primary equipment and sensors of the substation [98]; transfer switches, PMUs, power transformers, energy meters and sensors [130]; IEDs, RTUs, control room [131]; IEEE 33 node distribution power system with photovoltaic arrays, wind generators, and circuit breakers [97]; terminal equipment of distribution network [62]; PV loads, transformers, cables [132]

with Microsoft Azure platform based on deep learning was developed by [53], using temporal convolution and k-nearest approaches to predict the generated power given the wind speed estimation for a wind turbine. Following a similar context, [61] developed a digital twin to support decision making for power grid dispatching of wind power farms, using data mining and artificial intelligence technology to achieve output forecast of new energy field groups. In the case of hydro source, [68] predicted the pressure of the oscillating water column using machine learning.

Other applications may include anomalies detection of different natures. [76], for example, studied solar farms and proposed a digital twin based approach to detect anomalies of the physical system. The technique used for the time series simulation was deep learning, more specifically autoencoders.

5.4 Network and binding

The aim of the research questions focusing on network is to better understand the bidirectional communication that is described in most definitions. Given that one of the quality screening inclusion criteria was that the paper should necessarily mention the communication, all studies analyzed approach the networking to some degree. The need to state the communication as bidirectional may be to differentiate from other traditional unidirectional solutions that are manually or automatically connected from the physical entity to the virtual one. From [64] “a bidirectional communication platform for real-time continuous data management with high availability is essential,” but the authors gave no details explaining what exactly is shared, what are the operational requirements, and how this channel affects the solution. In [107], the authors affirm that the process is bidirectional and that the real-time communication allows the synchronization between the virtual and real entities.

According to computer science terminology, this interconnection that couples data sources and synchronizes them is called binding, a term that is not common in the literature (used only in 4 out of 81 papers), but the term “synchronization” and stemmed words is present in many studies, 41 out of 81. This data sharing for synchronization relies on the goal of updating the digital twin throughout the lifecycle of the real system, allowing the services to be more reliable, thus improving decision making.

Attempting to comprehend the necessary features of this communication, some of the use cases were assessed to identify the nature of the data exchange. For [56], the model states, set-points and forecasts are updated. Similarly, in [78] the operating performance of a thermal power plant is extracted and shared with the virtual platform, and in [111], the live states are updated when a change happens. An example refers to solar power plants transmitting irradiance, voltage, frequency, and settings back to the real system at every simulation cycle [100].

For the physical implementation of the communication channel, a wide range of technologies can be applied, as shown previously in Table 2. The technologies explored here are complimentary and may guide to more energy-related implementations:

- *FPGA (Field Programmable Gate Array)*: in [73] they justify the use of an Artix-7 FPGA due to higher speed and resources performance for the digital twin estimator of a PV cell. We found other applications in [106], where an FPGA was utilized to emulate the physical hardware firmware, and to program the behavioral model of wind turbines in [87].
- *Raspberry Pi*: similarly to FPGA, some studies applied Raspberry Pi to implement the RTUs (Remote Terminal Unity) between the physical and virtual entities [111, 112, 132];
- *SCADA*: Interestingly, 31 studies mention some sort of connection with records from the Supervisory Control and Data Acquisition (SCADA) system. SCADA systems can provide multivariate time series data that allows the modeling of the system, and continuous parameters update [119]. According to [80], any industrial sector can adapt SCADA supervisors to establish data exchange between the physical and virtual entities.
- *Industrial Fieldbus*: getting data from the field usually requires compatibility features where communication protocols play an important role. Examples given by [107] include Modbus, Industrial Ethernet, optical fiber networks, among others for the collection, and MQTT, HTTPS, RPC for transmission. Adding to the collection protocols, besides Modbus, [100] communicates with DERs using also DNP3 and proprietary protocols, [81] established a communication interface with Profibus to integrate a gas turbine DCS with a PC based digital twin platform. In the context of the distribution domain, other common protocols are IEC 61850 [54, 55, 95, 107, 114, 130].

5.5 Security

From the research questions in the group entitled Security, it is possible to see that the initial goal was to understand this topic in different layers of the digital twin, starting from the security of the digital twin itself, then of the communication intra and inter systems, and any other layer and/or application that could be approaching security. During the papers analysis of the systematic literature review, the finding from the first review discussed in Sect. 2.5 was reinforced, that security is not a main topic in the use cases and, even when it is mentioned, it is not possible to answer the four questions. Naturally, if the query for the papers collection focused on security, many other studies would have appeared for evaluation, but the energy restriction on our query limits the results to provide a feasible reading work and restrict the market vertical. For this reason, the findings about security were grouped regardless of the research questions to provide an overview of how it is being approached and what are the gaps, being the first identified gap the lack of focus on security.

Using the words from [64], although "a digital twin can both provide and undermine security based on its deployment," from the 81 papers under analysis, only three approach security directly [64, 95, 106], while others discuss briefly or just mention. From an application perspective, when security is the main topic, it is deployed as a security layer not focusing on the security of the digital twin itself, as can be seen in the following studies description.

Approaching smart grid security with digital twins, [64] argue that this sector lacks of security standardization and propose a digital twin structure with a framework consisting of a virtual entity, cyber-threat intelligence database for grid-specific attacks, simulation of attacks, and data analysis to perform vulnerability and risk assessment. All these layers would be continuously updated, including the latest attack vectors, to provide better security evaluation.

In a smaller scale, [95] focused on microgrids in a project entitled ANGEL (Automatic Network Guardian for ELectrical systems) where the digital twin framework sophistication is stated as level III, with physics-based simulation, physical system, and adaptive GUI, but not machine learning, which would characterize it as level IV. For their proof of concept, the IEEE 39-bus benchmark was modeled in MATLAB/Simulink and tested with a three-phase fault in the physical system that is alarmed in the digital twin when a divergence is noticed. Based on this result, the authors defend that the solution could also be applied for security cases such as false data injection, denial-of-service, topology attack, and vulnerabilities in general.

A more specific application still focused on grid devices was developed by [106] with embedded security in the control and hardware layers. The aim was to emulate and verify hardware patchings in the digital twin before applying them to the real devices. An FPGA was utilized together with LabVIEW to allow the interface during the Hot-Patching operation, adding a protection layer before the real implementation.

6 Discussion and contributions

This section will address the contributions provided by this work by discussing them according to the groups of the research questions (use cases, architectures, frameworks and tools, network and binding, and security). By first approaching the digital twin conceptualization regardless of the market, we could compare it with energy-related studies showing how it is progressing in this critical infrastructure sector.

Domain-specific use cases: one of the gaps identified in the related studies and also from our review studies selection was the lack of smart grid domain-specific use cases. Even though the application domains are common sense, few studies address it in a quantitative way. For this reason, we categorized the use cases for the generation and distribution domains for all the 81 papers and quantified the amount resulting in the most relevant ones. The criteria used to categorize the actors was explained in the "SLR Analysis," 5.1, being easily reproducible in case other researches want to perform this statistics. By doing the statistical analysis, we were able to indicate that the progress of digital twins in the energy sector regarding distribution and generation domains are, respectively, fault diagnosis, and distribution management. Moreover, we further investigated what were the physical entities of each actor, providing a comprehensive list in Tables 5 and 4.

Architectures, Frameworks, and Tools: from the comparison with the broad conceptualization, we identified a difference between the most accepted definition and how the energy-related studies establish the digital twin boundaries represented in architectures: while NASA's definition includes the real entity, services, data management, and virtual entity, most analyzed studies label as digital twin only the virtual entity, which is translated most of the times as the modeling and simulation block. Therefore, it shows the need for consensus regarding the digital twin boundaries when representing it in an architecture or a framework.

We noticed that the issue presented in the related studies about the interchangeable use of the terms "architecture" and "framework" repeated itself in our data set. Thus, we contributed with a new perspective based on the well-established Purdue model applied to reference automation architectures showing how it relates major suppliers, e.g., Siemens, highlighting how a framework is expected to differ from an architecture by detailing tools and reusable blocks.

Turning now to the tools, it was performed a comprehensive compilation divided into categories: bridging, data processing, data storage, data analytics, modeling, and simulation. Naturally there are overlaps of tools that are applicable to more than one category, but the idea is to provide an overview and serve as consulting material for the choice of market solutions. It is also worth noticing that the set of tools might change according to the use or the researchers approach. For example, a use case of wind turbines can make use of OpenFAST, or utilize MATLAB or Labview for the modeling and simulation. One of the limitations of this discussion is that the papers evaluated lacked details of implementation, decreasing the understanding of the technical challenges for tools selection and utilization. Interestingly, AI and ML are mentioned by 90% of the papers, which may be related to the dynamic nature of modeling in digital twins when compared to traditional static models.

Network and Binding: the evaluation of the questions related to the network and bidirectional communication, resulted in showing that the term "synchronization" is applied than "binding," appearing in approximately 50% of the studies. This was an unexpected finding given that the bidirectional communication is part of the digital twin definition and yet not well explored. Even when mentioning synchronization it is not often discussed in terms of shared values, latency issues, security issues, and so on. Thus, our contribution was limited, but it was possible to identify some variables specific to the energy sector such as states, setpoints, weather forecasts, performance indicators, voltage, frequency, current, among others.

Security: no significant information was found about the security of the digital twin itself or its application as a security layer, showing a gap in this field for energy-related studies. Even being aware of our research limitation due to the marked filter that could exclude papers only about the cybersecurity of digital twins, taking into consideration that smart grids are critical infrastructures that might require security measures by law, it was expected to find more information on how it is being addressed.

7 Challenges and future work

Before stating challenges and future work, it is important to highlight some of the limitations that may influence how the research questions were answered. For our systematic literature review, we considered only studies from the energy sector that followed a combination of the research questions. This decision may have limited or even excluded papers that detail digital twins in regard to the technical topics covered (architecture, framework, stakeholders, network, and security). During the analysis, we noticed that many layers of the digital twin still lack more consistency in definitions, tools, and applications to allow more real-world applications. This starts with the lack of consensus for the term definition itself, which may lead to a misuse of terminology and impacting how other layers are defined and implemented. Moving to the implementation, the gaps found about the lack of focus on detailed architecture and framework, security, stakeholders, and network integration would be a natural progression of this work. The next step of this research will focus on proposing an architecture and framework that takes into consideration the specific needs of the energy sector.

8 Conclusion

On the question of the digital twin definition, this study reinforced that there is a misconception. We discussed some reasons like the utilization of broad terms such as "ultra-realistic," "mirror," and "system" and proposed using the concept of systems engineering design hierarchy to better translate what is the real entity and what knowledge domains will be addressed in the virtual entity.

When evaluating use cases according to smart grid domains as defined by NIST, the collaboration comes from finding the most relevant use case for the two domains chosen as scope, being distribution management for the distribution domain studies, and fault diagnosis for the generation domain. Still, for the generation domain, another finding that stands out from the results is that few studies address hydro power plants. Given the energy transition and considering that this energy source is renewable and composes a great percentage of power generation, it was expected to be the main focus in more papers. According to the World Economic Forum [133], countries such as China, Brazil, Canada, USA, Russia, and Norway are among the ones who produce most hydroelectric power.

Taking into consideration the recent cyber-attack cases in critical infrastructures, one unanticipated result was that no focus is given to the security of the digital twin itself. Few papers address security, and when they do, the digital twin role is an additional security layer, without further discussions on the vulnerabilities that it may add to the system.

There are additional aspects that could possibly be advantageous in discovering any deficiencies for digital twin execution, pertaining to both technical and human elements. The bidirectional communication was stated to be present in all selected papers, but requires deeper exploration of what is shared and how the outcomes of the digital twin go back to the real system. From the studies, the data exchange from the real entity to the virtual one is clear, and usually used to create and update the models that are further used for the simulations. In turn, the simulations result provide information that guide better decision making, regardless of the use case. However, the human–machine interface that displays the results is not necessarily the same as in the real system, so the communication could be unidirectional only. None of the studies stated an autonomous feedback that impacted the system automatically. Moreover, given that the use cases allow better decision making, it was expected that also the stakeholders would be more present in the discussions, but who are the stakeholders, what are their roles, and how each of them have access to the information is commonly discussed.

The present results show interesting findings not only for the energy sector, where use cases and gaps were identified, but also for gaps related to the architecture, framework, network, and human aspects involving decision making.

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