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Review article

# Digital twin enabled smart microgrid system for complete automation: An overview

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ABSTRACT

Recent advancements in communication technology (CT) have ignited significant interest in the cutting-edge concept of the digital twin (DT), which holds the potential to revolutionize smart microgrid systems (SMGs). This study delves into the concepts and essential steps involved in constructing a DT-enabled smart microgrid (DT-SMG), emphasizing the necessity for complete automation to enhance device intelligence. Additionally, the paper discusses implementation standards for automation and the need for further modifications to accommodate future applications. The objective is to explore important DT-SMG use cases, and discuss the associated problems and potential solutions within DT-based automation frameworks. Recognizing the criticality of situational awareness, security, and resilience in DT-SMGs, the paper conducts a comparative study, highlighting the pros and cons gleaned from existing literature. These findings offer readers a comprehensive perspective, empowering them to develop and deploy DT technology across a spectrum of power system applications. Finally, the paper looks ahead to the future horizon of DT-SMGs.

## 1. Introduction

Recent advancements in information technology have driven digitalization and automation across industries. The edge computing, cyber-physical systems (CPSs), machine learning (ML), cloud computing and big data analytics (BDA) have played pivotal roles in this transformation of next gen system [1]. These developments enable the real-time gathering, processing, and analysis of data alongside high-fidelity models, creating digital twins of complex systems [2]. These DTs offer exact modelling and better operation for real-time supervision and control, an idea recognized as digital twinning, which is gaining consideration across university and various industries [3].

DT is a concept that has garnered increasing attention across various domains, from manufacturing to power systems. This has sparked significant research enthusiasm in the field of SMG, as they serve as integral components within distribution systems, proficiently coordinating distributed energy generation while also providing management and regulatory capabilities [3]. From a simulation viewpoint, DT represents the next evolution in simulation paradigms [4].

The introduction of DT has a profound impact on how simulation models are utilized throughout the entire lifespan of a system or process [5]. It provides a precise and dynamic representation of a SMG, which proves to be highly advantageous across the entire lifecycle of the SMG, encompassing the planning phase, operational phase, maintenance, and expansion stages. Creating a DT-SMG before the construction of the SMG offers designers a unique opportunity to optimize their designs and thoroughly analyses the potential outcomes of their choices in a cost-effective and low-risk situation [6]. Consequently, by implementing the DT concept, a closed-loop system can be established, connecting the operational and upkeep phases' rear to the initial plan and growth stages

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of the SMG [7].

Addressing the challenges in energy systems, such as inefficient energy distribution networks, transfer costs, and awareness of energy expenses, necessitates the establishment of a universal grid with robust cybersecurity and reliability [8]. Furthermore, the integration of renewables is crucial for achieving clean energy growth. However, current renewable energy sources (RES) suffer from shortcomings like electrical losses, blackout, susceptibility to cyberattacks, and inadequate system protection [9]. Prominent instances of energy supply interruptions, such as the rolling blackouts and the Winter Storm Uri power crisis in Texas, have exposed vulnerabilities in energy markets [10]. The threat of power supply interruptions is further exacerbated by extreme weather events like snowfall, and cyclones, coupled with insufficient infrastructure maintenance, poor optimization, and enduring under investment in power generation and grid structure. To address these challenges, DT technology can play a vital role [11]. In the context of the energy grid, a DT can serve as a digital replica of practical organization, processes, and systems. It enables smart data monitoring, computer modelling, simulate on, and forecasting, and energy management etc., [12]. By utilizing DT technology, users can enhance traditional electric grid planning and decision-making processes [13].

Taking advantage of the promising benefits of DT, numerous companies have begun integrating DT into their SMG solution strategies. Notably, industry giants such as General Electric (GE), Siemens, ABB, and Schneider Electric have emerged as frontrunners in this field. For example, GE has developed a customized DT interface for managing wind farms [14], providing detailed insights into the topography and climatic conditions of these facilities. Similarly, Siemens initiated the development of a digital grid model named ELVIS for the Finland transmission system in 2016 [15]. Additionally, Schneider Electric offers solutions like EcoStruxure microgrid advisor and operation to deliver comprehensive control over SMG system operations [16]. Furthermore, American Electric Power transmission collaborated with Siemens in 2017 to develop a DT-based solution aimed at improving network model coordination and centralizing monitoring information [17]. These solutions reduce the time and manpower required for manual operations. Considering the growing need for DT-enabled SMGs and advancements in this field, the primary contribution of this manuscript is structured as follows.

- This study explores the construction of DT-SMGs, emphasizing the need for complete automation to enhance device intelligence.
- Discussion includes implementation standards for automation and the necessity for modifications to accommodate future applications.
- The paper explores important DT-SMG use cases, addressing associated problems and potential solutions within DT-based automation frameworks.
- A comparative study on situational awareness, security, and resilience in DT-SMGs highlights pros and cons from existing literature.
- The paper looks ahead to the future horizon of DT-SMGs, offering insights into forthcoming advancements.

The paper is structured as follows: Section II: Digital thread: the life line powered by data, Section III: Standards: powering DT of SMG, Section IV: DT-SMG use cases and application, Section V: Future horizons: DT-SMG, Section VI: Conclusion.

## 2. Digital thread: the lifeline powered by data

A digital twin is more than just a final product or technology; it's a dynamic framework supported by data that serves as a business or product enabler. It leads to tangible results, products, outcomes, or new technologies. Essentially, it's a tool to address real-world problems using real-world data [18].

In other words, the seamless synchronization between physical products and their digital counterparts is essential for the effectiveness of DTs [19]. Enabled by dependable and intelligent data from both information and operational sources, the "digital thread" ensures consistency throughout the product lifecycle, serving as the definitive source of information. The basic structure and terms used in DT is illustrated in Fig. 1 [20].

Integrating DTs into the different working environment can feel daunting. One common mistake is expecting them to solve all problems instantly. Instead, recognize that there's no universal solution. Begin with small steps and focus on key objectives to achieve the organizational goals. Therefore, before starting any applications specific to SMG operation, the common objectives are necessarily to follow:

- Decrease CapEx for plant design or distribution upgrades.
- Conduct "what if" safety simulations linked to real assets.
- Rapidly create customized products.
- Shorten product development cycles.
- Enhance asset productivity.
- Minimize unplanned downtime and reduce failure risks.
- Enhance energy efficiency through safe load-shedding.
- Innovate new digital business models or services.
- Transform the customer experience.

### 2.1. Importance of DT for grid automation

DTs are crucial as they encompass utility use cases comprehensively, aid in organizing grid data management, and serve as a bridge to advanced analytics. While they emulate real-world systems such as microgrid, substation and industry etc., their significance extends to drive the innovation and efficiency in system operations. Understanding their potential is essential for navigating today's energy landscape and directing towards advanced system applications as SMG, substation automation and Industry automation [16].

The purpose of a DT in the sector of SMG is to facilitate improved decision-making within a utility's operations by providing advanced simulation and analytics capabilities in a virtualized environment. While expertise and reasoning will increasingly become embedded in the software, DTs currently support human decision-makers by providing contextual insights.

Presently, DT-grid possess the capability to address various decision support requirements that are usually segregated across different domains as described in Fig. 2 [20]. It can adhere to a structured solution hierarchy, encompassing individual physical assets or devices such as circuit breakers or protection relays, broader systems like substations or feeders, the entirety of the grid, and even extend to the grid's edge.

As time progresses, the content within the DT of a device is expected to advance from basic to more intricate representations, although it will always incorporate at minimum a static model of the asset. These DTs can address various decision support needs across different dimensions specific to SMG applications, including:

1) Lifecycle Approach:

- Planning: Forecasting future system requirements and optimizing resource allocation.
- Asset Design: Optimizing the design of assets to enhance performance and efficiency.
- Interdependencies: Modeling the relationships between different lifecycle stages to understand their impacts on overall system performance.
- Operation: Simulating real-time operational scenarios to optimize system performance.
- Maintenance: Predicting maintenance needs and scheduling activities to minimize downtime.

2) DT Enabled Simulation:

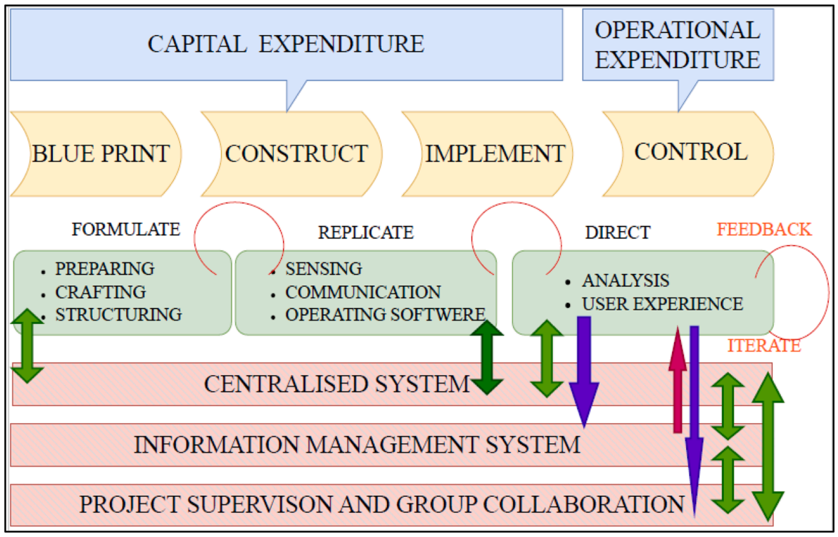


**Fig. 1.** Basic DT platform for modernization.

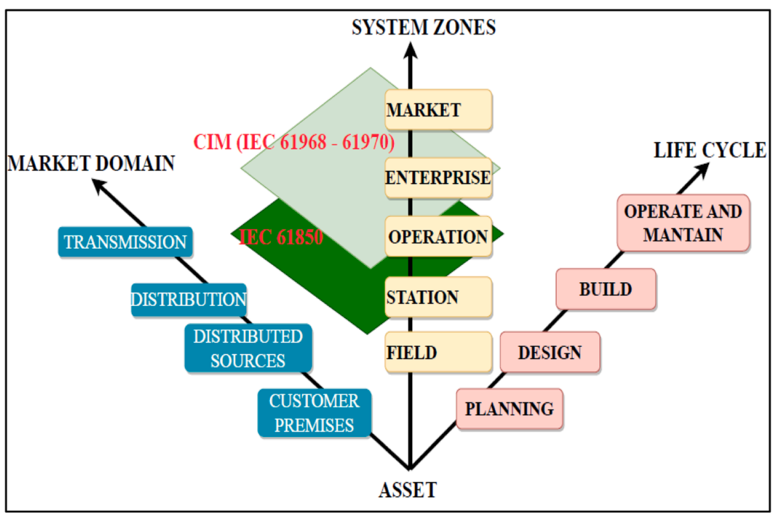


**Fig. 2.** Grid automation through DT.

- Technical Simulations: Assessing technical aspects such as voltage levels, system stability, and component ratings.
- Spatial and Geometrical Constraints: Modeling three-dimensional constraints to optimize system layout and design.
- Dependability: Evaluating factors like availability, reliability, maintainability, and resilience to inform technology choices and maintenance programs.
- Lifecycle Management: Addressing product obsolescence and ensuring the longevity of assets.
- Sustainability: Simulating energy efficiency, CO2 footprint, thermal aspects, and overall energy consumption.
- Financial Analysis: Conducting asset speculation planning, rate of investment analysis, total cost assessment, and exploring delivery models like software-as-a-service (SaaS) [21].
- People-Related Simulations: Support training, operation, maintenance activities, health and safety protocols, and work order management.

Considering current needs and the benefits of DTs, it's evident that integrating DT in SMG applications is crucial for achieving full automation and enhancing device intelligence.

### 2.2. SMG automation

Fig. 3 describes few specific use cases of SMG, including substation and feeder automation, asset performance evaluation, distributed energy management (DEMs), autonomous microgrid operation and coordination, behind the meter control, asset investment planning, augmented and virtual reality, maintenance, planning and design of microgrid, and geographic information system (GIS) [14–16]. Fig. 3 illustrates the above case interrelations within the modern grid landscape. Expanding on the use cases and considering future advancements in grid data management, particular emphasis is placed on DTs. This emphasis stems from several reasons:

- DTs span and offer potential value across all the use cases.
- They facilitate informed and expedited decision-making through robust simulators and analytics within a virtualized, software-defined environment.
- DTs offer a framework for conceptualizing near-term improvements to grid data management.
- They act as a conduit to advanced analytics, promising substantial business advantages.

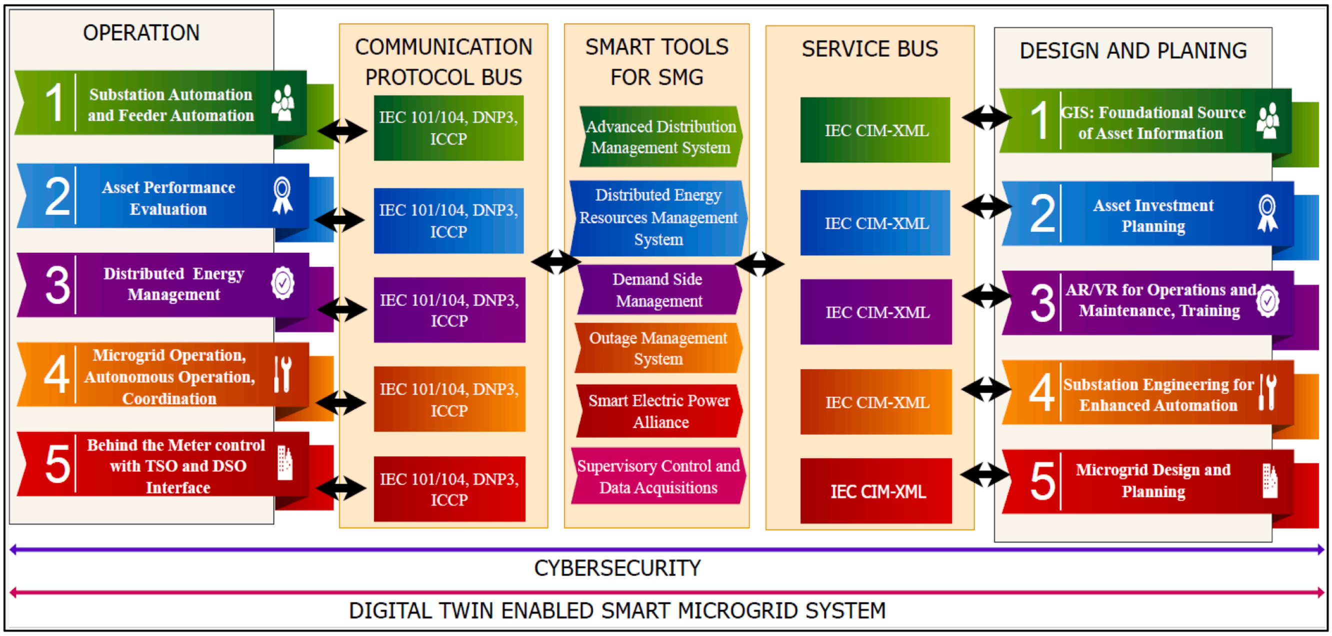


**Fig. 3.** Value driven DT-SMG data management.

- Consequently, the guide concludes with a dedicated section addressing DTs and advanced analytics.

Fig. 4 depicts the relationship between the physical system, comprising processes and components, and its DT, showcasing the exchange of data between the two systems [4]. A data model serves as an example of collected data from both the physical and virtual systems, facilitating transmission between them. By using this technique, the microgrid offers autonomous operation irrespective to the disturbances and non-linearity. The illustrated example gives a comprehensive idea about the DT-SMGS and the future need for grid automation. A digitized SMG will bolster the objectives of key industry value pillars, which can be succinctly summarized as illustrated in Fig. 5.

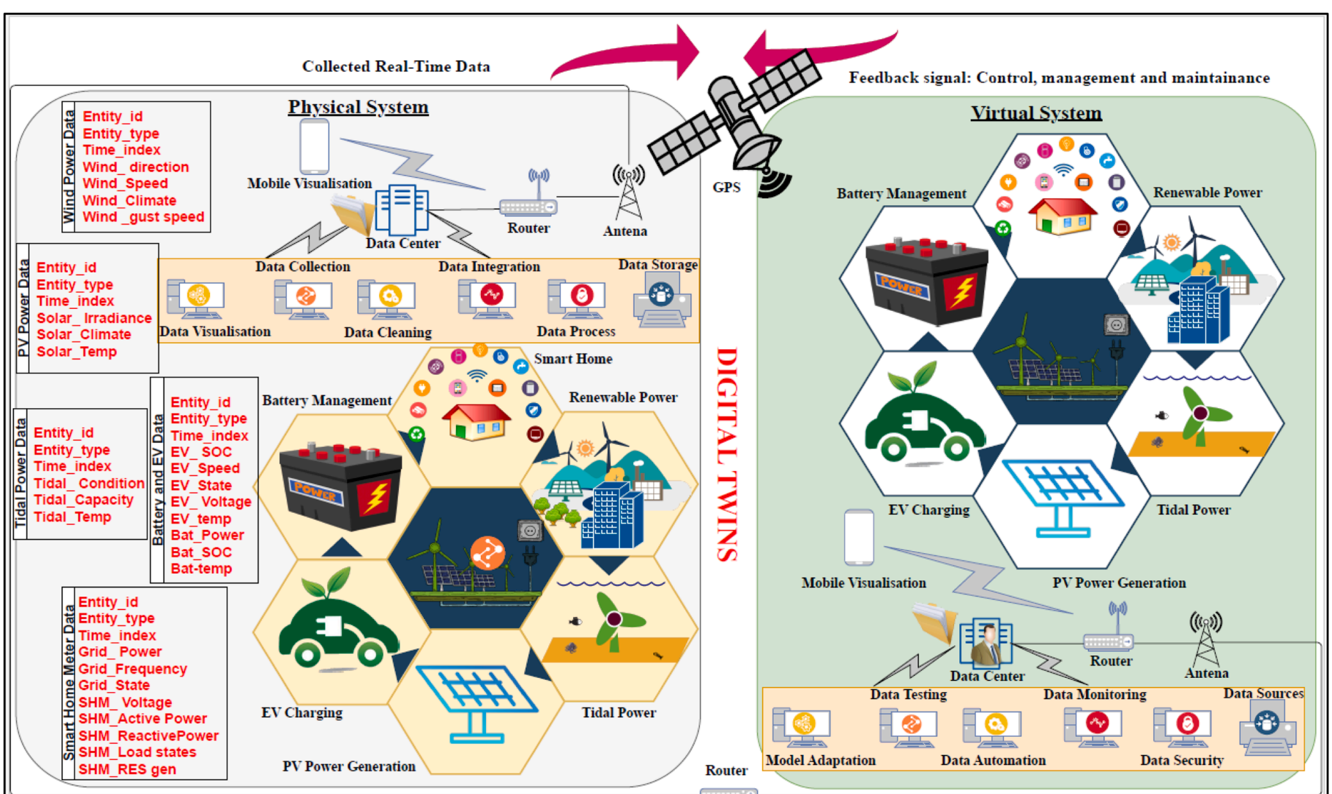


**Fig. 4.** Relationship between Physical and Virtual model of DT-SMG.

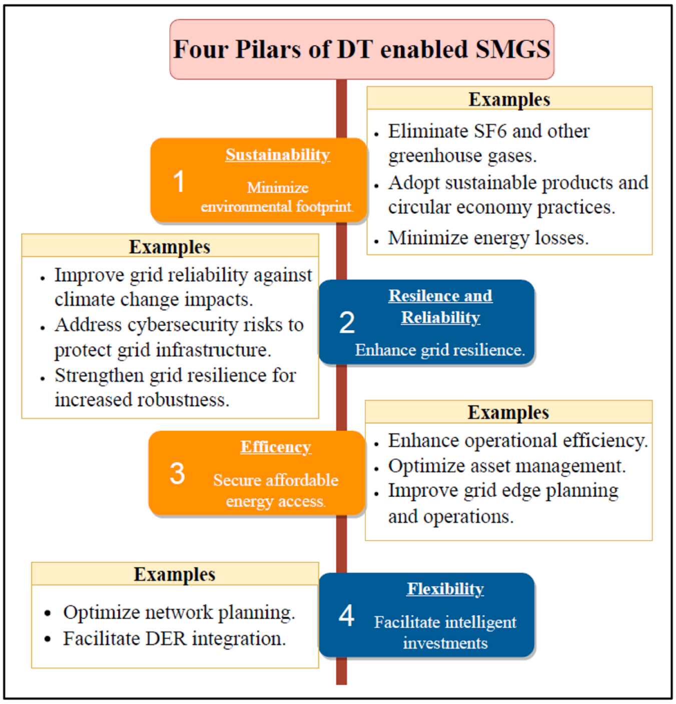


**Fig. 5.** Four pillars of DT-SMG.

## 3. Standards: powering DT of SMG

### 3.1. Existing standards

In many developed nations, specific organizations play a crucial role in shaping country-specific standards. However, international standards organizations strive to promote clarity and consistency in global standards development. Their aim is to establish standards that enhance interoperability and interchangeability on an international scale. The organization associated with standard formation is illustrated in Fig. 6 [22]. The IEC engages with 36 participating countries and ten observer countries to develop and refine standards, particularly through Technical Committee 57 (TC 57) [23]. TC 57 focuses on creating international standards for power systems control equipment and systems, including power management system (PMS), SCADA (Supervisory Control and Data Acquisition), distribution automation, tele protection, and associated information exchange. Working Groups within TC 57 are dedicated to developing standards relevant to SMG distribution utility data management is discussed in Table 1.

The International Electrotechnical Commission (IEC), which produces widely used standards for electric utilities globally.

### 3.2. Need of modification

Fig. 7 illustrates the process whereby emerging use cases may uncover gaps, prompting the development of new standards [24]. Upon identification of a new use case, it is queued and subsequently mapped into the SMG Construction Model (SMGCM) to pinpoint functions and requirements necessitating standards. If gaps are detected, this

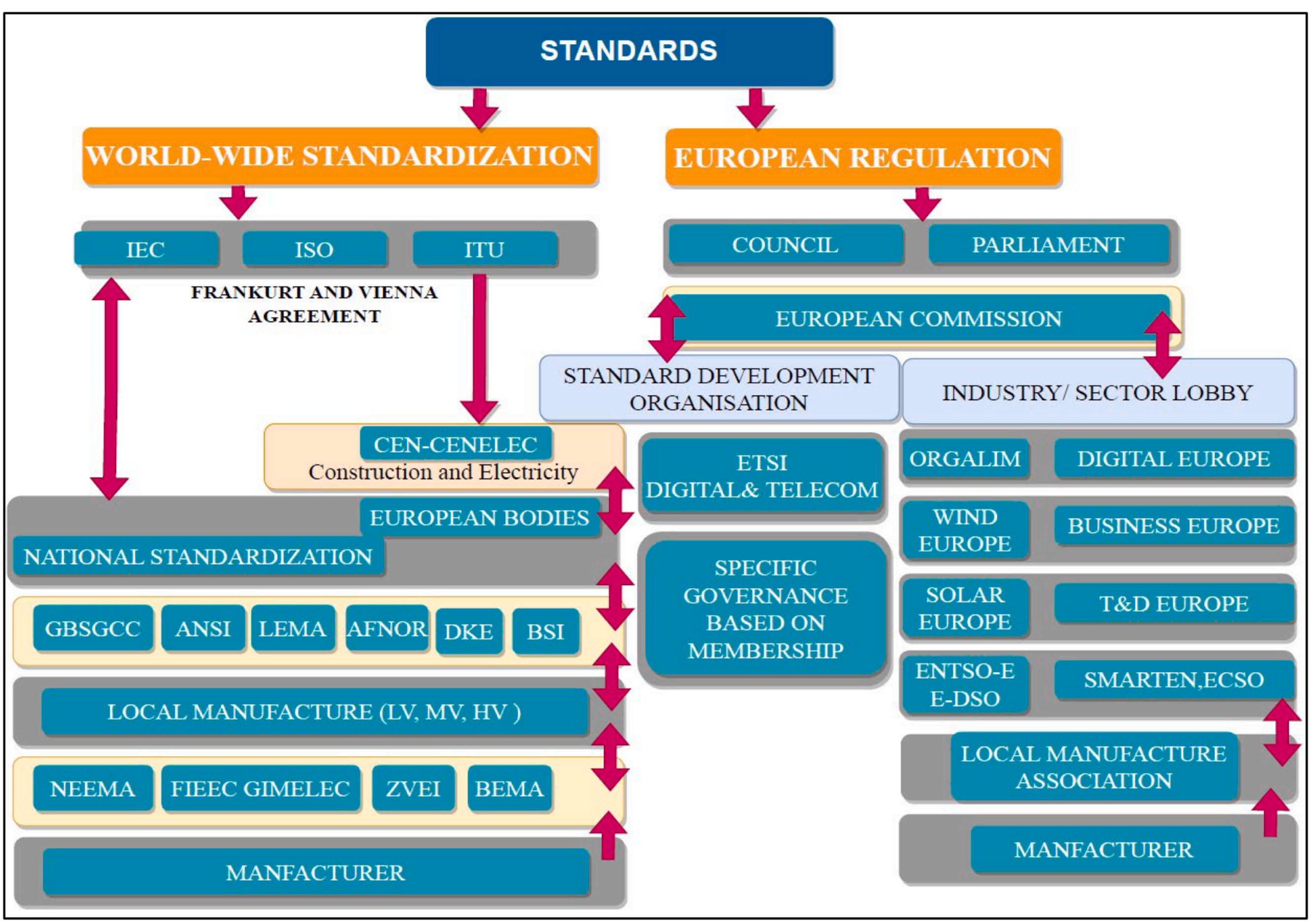


**Fig. 6.** Organization with the grid automation standards.

**Table 1**
TC 57 standards applicable for DT enabled microgrid [23].

| Groups | Accountability | Standards | Explanation |
|---|---|---|---|
| WG-3 | Tele-control Communication | IEC 60,870 | • ***IEC 60,870–5–101:*** Basic protocol defining data frame format and exchange rules between control center and substations.<br>• ***IEC 60,870–5–104:*** Advanced protocol, suitable for modern networks like TCP/IP, with encryption and authentication features for secure internet communication.<br>• ***IEC 60,870–6:*** Covers tele-control application service data units (ASDU) and data transmission formats in tele-control communication.<br>• ***IEC 60,870–7:*** Specifies basic protocols for network access and data transmission across various communication networks, such as serial connections and Ethernet. |
| WG-10 | Intelligent Electronic Devices (IEDs) and associated data model | IEC 61,850 | • Used for Industrial Automation<br>• Exchange real-time data and control commands.<br>• Uses Ethernet-based communication, replacing traditional serial-based communication methods.<br>• Advanced functionalities such as rapid fault detection, self-healing, and improved asset management in power grids. |
| WG-13 | Software Interface for operation and planning | IEC 61,970 | • Exchange of information between power system control and monitoring equipment.<br>• A common framework for communication and data exchange in EMS and supervisory control and SCADA systems.<br>• Plays a crucial role in modernizing power system infrastructures and implementing smart grid technologies. |
| WG-14 | International standard for information exchange in power system operation | IEC 61,968 | • Ensure interoperability and consistency in data exchange<br>• standardizing data exchange between software systems like DMS, OMS, and GIS<br>• Use cases include asset management, network modeling, outage management, and work management. |
| WG-15 | Data Communications and Security | IEC 62,351 | • It focuses on security for power system control operations<br>• Provides guidelines and requirements for securing communication protocols used in power system automation and control.<br>• The standard addresses authentication, integrity, and confidentiality of communication between control centers, substations, and IEDs. |
| WG-16 | Deregulated energy markets | IEC 62,325 | • It focuses on the exchange of information for electricity market transactions.<br>• provides guidelines and specifications for the communication of data related to electricity trading and market operations<br>• Implementation of IEC 62,325 promotes transparency, competition, and efficiency in electricity markets, ultimately benefiting consumers and stakeholders alike. |
| WG-17 | Communications systems for DER | IEC 61,850–7–420 | • Used for power utility automation.<br>• It focuses on modeling logical nodes for control and protection functions in substations.<br>• Streamlines design, configuration, and maintenance of substation automation systems. |

discovery is forwarded to the relevant IEC technical committee for examination and subsequent standards development. Additionally, existing applicable standards undergo verification as part of this process.

SMGCM offers a comprehensive three-dimensional visualization of SMGCM, as depicted in Fig. 8 [24]:

- Domains: These represent various segments of the micro grid, including generation, transmission, distribution, DER, and customer premises. They form a cohesive process and value chain.
- Zones: This hierarchy encompasses process, field, station, operation, enterprise, and market zones, reflecting different levels of power system management. It resembles a potential automation pyramid, where each level plays a specific role in grid operations.
- Interoperability Layers: These layers facilitate interoperability within the smart grid ecosystem. They include component, communication, information, service/function, and business layers, enabling seamless integration and interaction between different system components and stakeholders.

## 4. DT-SMG use cases and applications

### 4.1. Energy management with digital twins (EnerGEM)

1) Challenges [26]:

*Complexity and Variability:* Modern energy systems within microgrids present inherent complexity and variability, challenging conventional energy management approaches (CEMA).

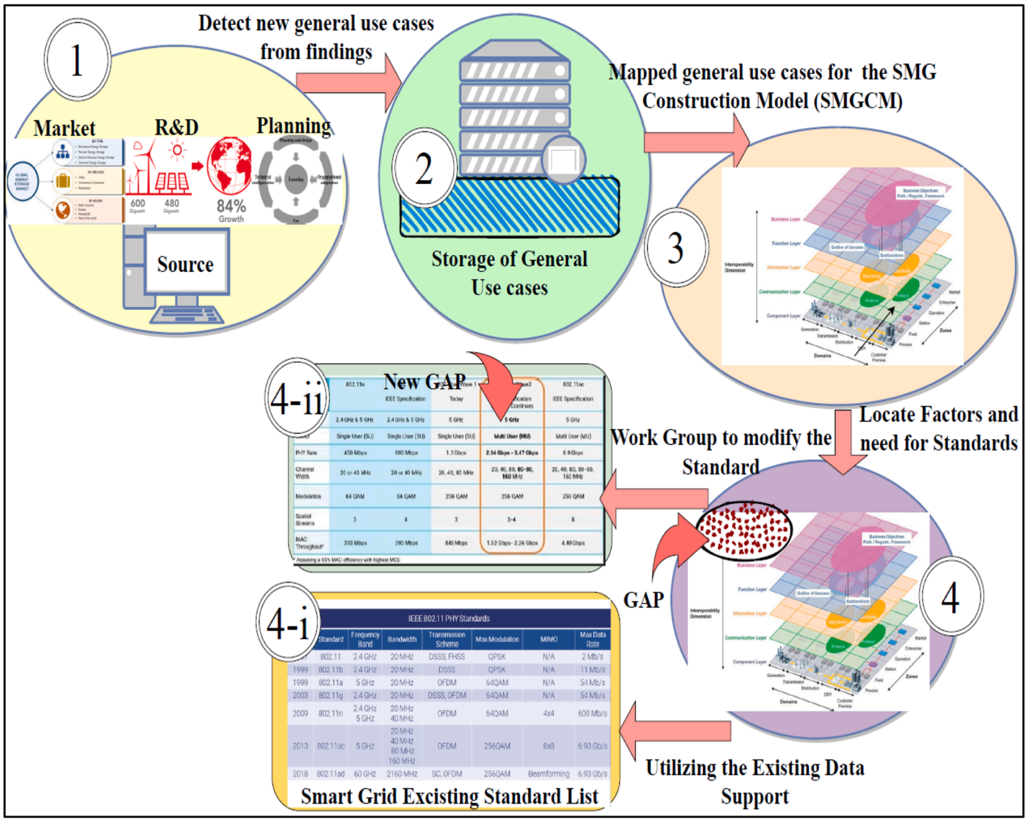


**Fig. 7.** Development of new cases from used cases of SMGCM.

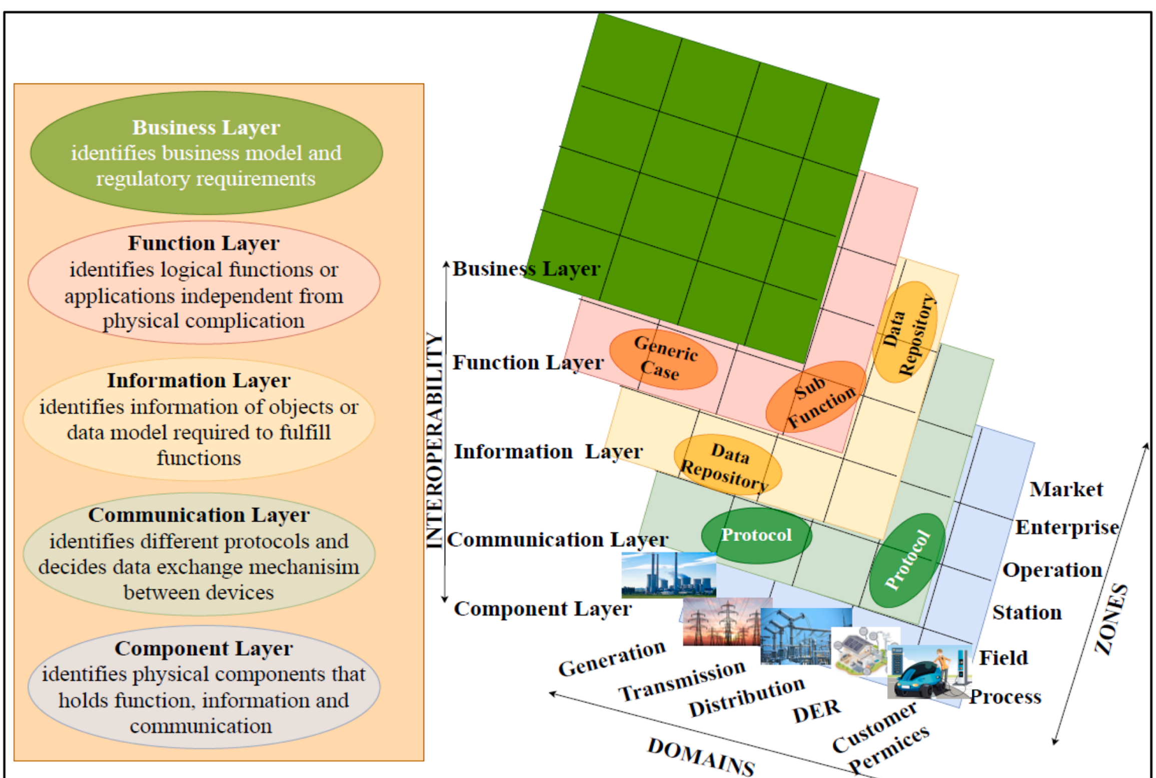


**Fig. 8.** SMGCM modeling.

*Suboptimal Performance:* CEMA may struggle to adapt to the dynamic nature of modern energy systems, resulting in suboptimal performance.

*Higher Costs:* Inadequate handling of complexity and variability can lead to increased operational costs associated with maintenance and system disruptions.

*Risk of Disruptions:* CEMA limitations may heighten the risk of system disruptions, impacting reliability and resilience of energy networks.

*Inefficiency in Resource Utilization:* Without efficient monitoring and optimization capabilities, CEMA may underutilize distributed energy resources, impacting sustainability and cost-effectiveness.

2) Solutions:

In DT-Energy management (DT-EM), the integration of DERs at the distribution level, progressive regulations like FERC 2222 prompt the necessity for coordination between advanced transmission planning and operations, as well as advanced distribution planning and operations [25]. Data monitoring of DERs in real-time presents several solutions and associated values:

*Gathering Behind-the-Meter (BTM) Data:* Enhances DER visibility, identifies hidden load, and improves operational efficiency, grid reliability, and customer satisfaction [27].

*Using Data to Manage System Demand:* Utilizes low-voltage network data to address peak load, low production, and the duck curve effect, supporting TSO grid management, maximizing renewable production, and encouraging more renewable generation.

*Utilizing Dynamic Operating Envelopes:* Utilizes DER forecasts and real-time network conditions to adjust DER limits, enhancing network capacity, maintaining grid reliability, and enabling DER participation in wholesale markets.

*Avoiding Network Congestion:* Enhances DERMS capabilities to schedule DER flexibility, preventing network constraints, improving DER hosting capacity, and facilitating new customer connections.

*Utilizing Data from Flexibility Markets:* Utilizes data from flexibility markets to effectively manage network constraints, enhance network constraint management, and facilitate flexibility markets.

3) Practices:

*International Renewable Energy Agency (IRENA)* [28]:

IRENA underscores the significance of a data exchange platform facilitating equal access to real-time DER information for both Distribution System Operators (DSOs) and Transmission System Operators (TSOs).

*Smart Net Project* [29]*:*

Supported by the Horizon 2020 project, the 3-year SmartNet project aims to enhance coordination between grid operators at national and local levels (TSOs and DSOs) and facilitate information exchange for monitoring and acquiring ancillary services within the distribution segment.

### 4.2. Smart digital twin metering solutions

1) Challenges [30]:

*Integration:* Distribution utilities commencing smart meter installations must integrate metering data with existing legacy systems to fully leverage the benefits of smart metering.

*Data Mining:* Utilities that have completed or are nearing completion of smart meter and Advanced Metering Infrastructure (AMI) deployments must effectively manage metering data for SMG applications.

2) Solutions [31]:

- Smart meters reduce outage durations and related expenses, leading to improved reliability and cost savings.
- Remote meter reading reduces labor costs and vehicle miles driven, enhancing operational efficiency.
- Enhanced customer empowerment through utility bill transparency and accessibility.
- Direct load control programs and consumer incentives reduce peak demand and associated capital expenditures.
- Integration challenges arise when exchanging smart meter data with billing and other software systems, impacting interoperability and system efficiency.

3) Practices [36]:

*Automated Grid Analysis:* Utilize automated processes to analyze data from smart meters, global information system, and customer relationship management systems, enhancing low-voltage microgrid network operations.

*Interoperability Standards:* Establish clear specifications for interoperable systems, promoting seamless integration among head-end, meter data monitoring system, and LV microgrid analytics platforms.

### 4.3. Cyber security

1) Challenges [32]:

*Sophisticated Cybersecurity Threats:* Rising complexity of cyber-attacks, including malware targeting SCADA devices and IT systems, presents significant challenges to critical microgrid security. Fig. 9 illustrates a taxonomy of security and privacy threats associated in microgrid system [31–33].

*Impact on Critical Infrastructure:* Cyber-attacks on power grids can cause widespread disruptions, affecting large populations.

*Ransomware and Financial Impact:* Ransomware attacks, such as the one on power grid, lead to substantial financial losses for organizations, including ransom payments and operational disruptions.

*Supply Chain Vulnerabilities:* The Solar Winds breach underscores the risk posed by supply chain vulnerabilities, as compromised systems can disseminate malicious code to numerous organizations, resulting in widespread data compromise.

2) Solutions:

(i) Sensitive Data Scope:

- Identify the substation-level metrics like capacity, consumption, cost, fuel mixes, and primary energy sources.
- Identification of operational grid resources
- Description of grid structure and connectivity.
- Organization and representation of grid data.

(ii) Protection and Security of Data during System development:

- Encrypted Data Transmission
- Dedicated VPN Usage
- Uniform Data Protection
- Implements secure access controls for machine usage, data manipulation, and storage mechanisms to prevent unauthorized access.

(iii) Data security in Smart Field in Microgrid:

- Smart Industrial Internet of Things Devices: Equipped with built-in security features like cryptographic identity and secure communication, enhancing security without human intervention.
- Cloud Integration: Advanced capabilities allow smart devices to seamlessly integrate with cloud systems, improving efficiency and connectivity.

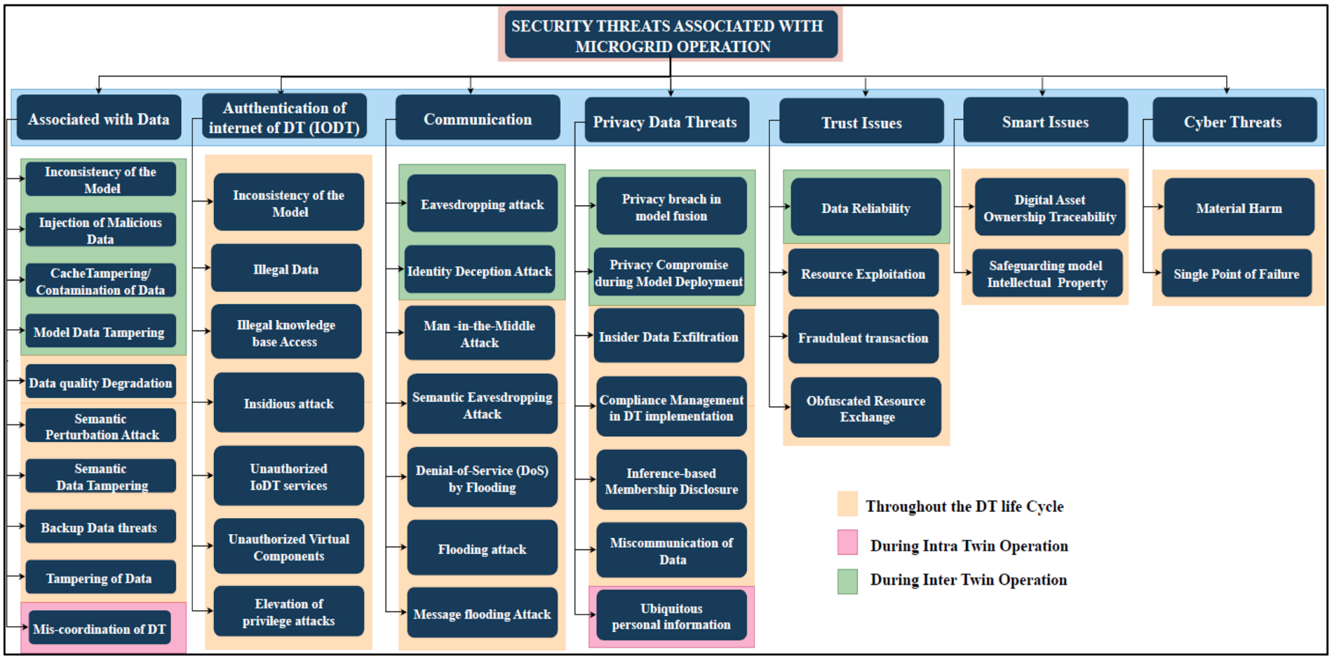


**Fig. 9.** Taxonomy of security threats associated with Microgrid Operation.

- IEC 62,443–4–2 Standard: Globally recognized cybersecurity reference for industrial and distribution domains, offering vital guidelines and best practices [34].

3) Practices [35]:

*Resilience and Reliability:* Better cybersecurity reduces cyber-attack impact, enhancing power system reliability.

*Corporate Sustainability:* Transparent breach management and compliance maintain brand image and customer trust, supporting financial sustainability.

*Cost Efficiency:* Investing in cybersecurity minimizes attack costs, improving overall financial performance.

### 4.4. Augmented and virtual reality (AR and VR)

1) Challenges [37]:

*Equipment Complexity:* Electric power equipment in microgrid is inherently dangerous and consists of many devices from different manufacturers, varying in appearance and capability.

*Need for Specific Operational Practices:* Maintenance and troubleshooting of this equipment can be complex, requiring adherence to specific operational and safety practices.

*Challenges with Unfamiliar Equipment:* Field technicians often face challenges when dealing with unfamiliar equipment, especially when the correct manuals are not available in the field.

*Collaboration in Extreme Events:* During extreme events, such as mutual assistance programs, technicians from different utilities may need to work together, further highlighting the need for standardized procedures and knowledge transfer.

*Rapid Training Requirements:* The evolving technical environment of utilities, with increased automation and digital technology, requires rapid training of new workers to manage more complex systems and procedures.

2) Solutions: (Mixed Reality) [38]

*AR Technology for O&M:* AR technology enhances the competence and flexibility of operations and maintenance personnel by providing real-time data, digital user manuals, procedures, and diagrams, reducing downtime and human errors.

*VR Training Exercises:* VR exercises accelerate training by offering highly realistic simulations via PCs or tablets, disconnected from the real-time network, allowing personnel to learn quickly in diverse scenarios.

*Remote Assistance with AR and Expert Solutions:* AR solutions are complemented with remote expert assistance, enabling personnel to receive online advice from experts, enhancing problem-solving capabilities during maintenance tasks.

3) Practices:

*Enhanced Safety:* AR technology improves safety by verifying equipment identity, providing detailed information, and guiding technicians through procedures, reducing errors and unsafe practices. 3D geo-positioning ensures worker safety.

*Improved Cost Efficiency:* AR systems allow operators to preview tasks, identify tools, and improve efficiency. Access to accurate information on smart devices reduces operation costs by saving time, minimizing errors, and eliminating return trips to dispatch center.

*Enhanced Flexibility and Sustainability:* AR adoption streamlines maintenance and restoration, allowing distribution operators to maintain DERs online efficiently.

### 4.5. Substation automation

1) Challenges:

Utilities face challenges in managing the influx of data generated by digitization.

2) Solutions:

- Establishing a unified and standardized IT framework is crucial for effective data management in microgrid based power system.
- The framework should enable easy data exchange and interoperability.

- Leveraging standards like the IEC 61,850 suite can enhance data management capabilities [23].
- Integration of industrial operational technology systems with legacy systems is necessary.
- Data originating from diverse sources such as sensors, IEDs, SCADA, and work management systems must be incorporated.

3) Practices:

Schneider Electric focuses on two data management aspects for existing substations in substation automation [16].

- Firstly, the company aim to gather design and architecture data by digitizing existing design, specification, configuration, and construction data.
- Secondly, they seek to gather real-time operating data by retrofitting enhanced data collection methods, such as installing sensors.

### 4.6. DT enabled microgrid application

A Comparative Table 2 has been created, contrasting the benefits and limitations of the previously executed cases, providing a succinct overview of DT-SMG applications. This offers a clear and concise understanding of the current state-of-the-art and future advancements necessary for DT-SMG automation.

## 5. Critical assessment of DT-SMG

### 5.1. Implementation challenges and solutions in SMG

***Limitations:***

- **Data Protection and Jurisdiction Issues:** In the context of smart microgrids, multiple Digital Twins and their integration into emulated systems can raise concerns about data protection and residency, particularly in cross-border data exchanges. The transfer of data across jurisdictions may be subject to data protection laws, which can become complex, especially when personal data is involved. The need for a lawful basis and a Data Protection Impact Assessment (DPIA) to ensure compliance is critical in such situations [54,55].
- **Synchronized Data State:** The synchronization of data between physical and digital twins is fundamental for ensuring accuracy and reliability in smart microgrid applications. Divergence in data states could lead to performance degradation or errors in decision-making, undermining system effectiveness [56].
- **Data Governance and Access Control:** A clear governance structure for data, from its creation to withdrawal and final deposition, is essential to ensure security and quality. Without proper access control, data might become vulnerable to unauthorized access, altering the decisions made by the microgrid system. Additionally, clear ownership, data consent, and compliance policies need to be developed [57,58].
- **Proprietary Data Protection:** In smart microgrid applications, where advanced analytics are employed, proprietary data—such as energy consumption patterns, forecasting models, and demand response data—may be exposed. Securing such information and classifying it appropriately before incorporating it into algorithms is necessary to mitigate potential risks [59].

***Proposed Solutions:***

- **Data Encryption and End-to-End Security:** To address data security challenges, implementing encryption protocols such as AES and Homomorphic Encryption can ensure the secure transmission and storage of data in smart microgrids. For instance, using

**Table 2**
Microgrid Digital Twin Solution: DT application to microgrid and Distribution system.

| No. | Application | Pros | Cons |
|---|---|---|---|
| [32] | Monitoring utility parameter | • PMUs and DT concepts enhance the observability.<br>• Digital mirror architecture offers the ability to simulate and visualize various system states. | • DT centric control offer complexity in design and integration.<br>• Data security and privacy concerns. |
| [31] | Real-time monitoring of distribution systems | • Accuracy and comprehensive analysis.<br>• DT and leveraging measurements from the LV side, this approach avoids expensive instrumentation on the MV side. | • Data management and computation of resources.<br>• Developing an accurate mathematical model of distribution transformers to serve as DTs. |
| [8] | Smart home energy management | • Smart home as a polystructure system offers interaction between both energy and information flows.<br>• Seamless integration of energy resources | • Analyzing energy-information processes in a polystructure system<br>• Integrating data from various components and sources within the smart home |
| [39] | Managing the distribution system control | • Seamless integration of renewable energy.<br>• Enhanced monitoring and optimization capabilities.<br>• Automation of model generation ensures accuracy. | • Complexity in implementation and scalability.<br>• Dependence on data quality and availability.<br>• Validation of algorithms is crucial. |
| [40] | Virtual power plant (VPP) | • Addresses stability and reliability in power grid.<br>• VPPs offer a solution for integrating DERs.<br>• DTs can enhance VPPs by providing real-time simulation, state of health monitoring, and predictive maintenance. | • DTs in power system applications, may require significant computational resources.<br>• DT model creation for diverse resources can be complex and may require standardized protocols. |
| [41] | Distributed DT in Power system | • Addressing complexity in power system through DT.<br>• Facilitating monitoring, controlling, and testing operations.<br>• Distributed DTs enhances system adaptability and accuracy. | • Distributed DTs may require computational resources.<br>• Monitoring systems can be challenging. |
| [42] | Power system dispatching | • This offers real-time, and flexible decision support.<br>• DT virtual model provides real-time on-line physical model and power flow calculation services.<br>• DT enables faster speed and improved decision-making. | • This may require investments in infrastructure design.<br>• Accuracy and reliability of the DT virtual model is crucial.<br>• This may pose challenges in terms of interoperability and compatibility. |
| [43] | Demand driven energy management | • Demand-driven energy management (DDEM) technique optimizes the operation of modular parallel input parallel output DC/DC auxiliary power supply (APS). | • Implementation of DDEM technique may require sophisticated control algorithms.<br>• Integration DT-DDEM into existing power systems may require |

(*continued on next page*)

**Table 2** (*continued*)

| No. | Application | Pros | Cons |
|---|---|---|---|
| | | • Demonstration of DDEM implementation on APS modules shows tangible energy savings. | modifications and compatibility considerations. |
| [44] | Cyber security of the radial distribution network | • Novel real-time attack localization strategy utilizing a DT as a cyber-physical reference model.<br>• Compute Residual Rate of Change, for differentiating False Data Injection attacks. | • This strategy may require significant computational resources and integration efforts.<br>• Ensuring accuracy and reliability of DT-based reference model and computed metrics is critical for effective attack localization. |
| [45] | Machine learning in DER application | • Introduction of Hybrid Machine Learning Model (HMLM) for building modelling and energy storage calculations.<br>• Use of synthetic output data from experimentally calibrated Energy Plus models for smart homes, reducing the need for extensive experimental data collection. | • HMLM into DER platforms may require compatibility and interoperability considerations.<br>• Adoption of CTA 2045 and Energy Star metrics for characterizing HVAC systems may require coordination and consensus among stakeholders. |
| [46] | ANGEL-DT framework for microgrid | • ANGEL DT framework for improving the security and resiliency of microgrids.<br>• Enabling real-time data visualization and assessment of system health and behavior. | • This may require modifications and compatibility considerations.<br>• Continuous validation and refinement of the ANGEL framework are necessary to address evolving threats and maintain system security. |
| [47] | Health monitoring of inverter | • Noninvasive nature of the method ensures minimal disruption to the operation of the converters.<br>• Incorporation of a physics-informed model with uncertain parameters enhances the accuracy of the digital twin. | • Neural network-based digital twin may require significant computational resources, particularly for real-time model updating.<br>• Adoption of this method may require training and upskilling of personnel to effectively utilize and manage the digital twin. |
| [48] | Regional Distribution Network | • Addresses adverse effects of distributed energy sources on distribution networks.<br>• Optimizes control strategy for load variance and stability enhancement. | • Requires sophisticated modeling and computational resources.<br>• Expertise in optimization and energy storage system design may be required. |
| [49] | Distribution Network Planning | • Utilizes DT, advanced computing, and other technologies for effective distribution network planning.<br>• Considers electric power flow, dynamic load changes, and distributed power generation to ensure future grid adaptability. | • Implementation may require significant investment in technology and expertise.<br>• Integration of digital twinning and advanced computing into planning processes may pose challenges. |
| [50] | Distribution Network | • Focuses on real-time data fusion of physical and virtual spaces in DT for distribution networks, enhancing accuracy and effectiveness.<br>• Uses ontology technology of power digital twin virtual and real data, providing a foundation for fusion architecture. | • Coordination among stakeholders may be needed to align fusion objectives and priorities.<br>• Continuous monitoring and updating of the system are necessary to adapt to changing data dynamics and ensure optimal performance. |
| [51] | Renewable Energy Integration | • Uses cost-effective digital twin real-time hybrid simulation platform for engineering education in renewable energy fields.<br>• Platform enables real-time information retrieval of renewable energy systems via Ethernet-based communication. | • Ensuring compatibility and interoperability with existing educational curricula is crucial for effective integration.<br>• Continuous updates and enhancements may be necessary |
| [52] | Distributed Energy Resources with OpenFMB | • Introduces methodology to add grid code functionality to legacy DERs using open field message bus (OpenFMB) framework.<br>• Enables grid support functions through Distributed Intelligence (DI), fostering decentralized grid architecture. | • Implementation may require significant resources and expertise.<br>• Integration challenges may arise with legacy DERs and OpenFMB framework. |
| [53] | Active Distribution Network Planning | • Acknowledges the significant transformation of distribution networks into flexible active distribution networks.<br>• Provide auxiliary decision support platform to improve economic operation and renewable energy consumption. | • Integration challenges may arise related to compatibility and scalability.<br>• Adoption of the platform may require training of personnel. |

Homomorphic Encryption in combination with Secure Multi-Party Computation (SMPC) can provide privacy-preserving data synchronization across microgrid systems, ensuring data integrity and confidentiality [60,61]. Furthermore, blockchain integration can enhance transparency and immutability in smart microgrid data transactions [62].

- **Cloud and Edge Computing for Data Processing:** The hybrid approach of combining cloud and edge computing can optimize data processing in smart microgrids. Cloud computing can scale resources dynamically, reducing operational costs, while edge computing ensures low-latency processing of critical data close to the source, such as energy consumption or grid status updates. This approach not only reduces costs but also enhances security by minimizing potential data transmission risks [63,64].
- **Automated Data Integrity Checks and Synchronization:** Implementing automated checks for data integrity and synchronization between the physical and digital components of smart microgrids can minimize the risk of data discrepancies. These checks ensure that any changes in physical assets are promptly reflected in the digital

model, using predictive algorithms to forecast system changes and improve operational efficiency [65].

### 5.2. Interoperability and standardization in SMG

***Limitations:***

- **Lack of Standardization:** One of the key challenges in smart microgrid implementation is the lack of standardization in communication protocols and data models. Smart microgrids often utilize multiple legacy systems with incompatible data formats and interfaces, making it difficult for different components to interoperate seamlessly. This lack of uniformity hinders integration efforts, increases costs, and reduces the scalability of solutions [66–68].
- **Data Integration:** Integration between various smart microgrid systems (e.g., energy generation, storage, demand response) and other enterprise systems is challenging. This problem is exacerbated by disparate legacy technologies and the inability to efficiently exchange data across platforms, which limits the optimization potential of microgrid operations [69].

***Proposed Solutions:***

- **Open Architectures:** To address interoperability, adopting open architectures with common data models like the Industry Foundation Class (IFC) can facilitate data exchange across different platforms. Open architectures improve system accessibility and flexibility, enabling easy integration of new components into the microgrid ecosystem, as well as collaboration across various domains [70,71].
- **API Integration and Middleware:** Middleware solutions, such as YANG-powered middleware for smart microgrids, can integrate legacy systems with modern digital solutions. This reduces integration complexity and enables real-time data sharing between systems that were not initially designed to communicate with each other, ensuring seamless interoperability [72,73].
- **Standardized Communication Protocols:** Standardizing communication protocols like MQTT, OPC UA, and RESTful APIs can ensure smooth data flow between diverse systems in a smart microgrid. These protocols are lightweight and facilitate secure data exchanges, promoting seamless system integration and real-time decision-making in microgrid environments [74].

### 5.3. Cost and complexity in smart microgrids

***Limitations:***

- **High Initial Investment:** The upfront costs for deploying a smart microgrid are significant, as they require investments in sensors, IoT devices, and integration of complex systems. Smaller organizations or those with limited resources might find it difficult to justify the initial expenditure, especially when the return on investment (ROI) is not immediately clear. Early adopters also face the challenge of unifying various data types and technologies across different platforms, which can increase costs [75,76]
- **Complexity in System Integration:** Integrating various technologies, such as renewable energy sources, energy storage systems, and IoT-connected devices, into a cohesive smart microgrid platform can be complex. Additionally, maintaining cybersecurity across such a vast, distributed system adds to the technical and operational challenges [77,78].

***Proposed Solutions:***

- **Modular Deployment and Scalability:** A modular approach to deploying smart microgrids allows organizations to start with smaller, manageable implementations and scale gradually as the benefits become apparent. This approach minimizes initial costs and reduces the risk associated with full-scale implementation. Microservices architectures also improve the scalability and maintenance of smart microgrid systems, allowing businesses to integrate new technologies seamlessly [79,80].
- **Open-Source Tools and Shared Resources:** Open-source frameworks, such as OpenMETA and OpenPLC, provide a cost-effective solution for creating and managing smart microgrid systems. These platforms offer essential tools without the financial burden of proprietary software, making advanced technologies like IoT and machine learning more accessible to smaller businesses and enabling collaborative development efforts [81,82].
- **Cost-Benefit Analysis and Phased Investments:** Performing a comprehensive cost-benefit analysis before implementing a smart microgrid can help prioritize investments and identify areas where the highest returns can be achieved. Phased investments allow businesses to spread costs over time, reducing financial strain and enabling more efficient capital allocation [83,84].

## 6. Real time case studies for SMG application

### 6.1. Siemens mindsphere for SMGs (SMS-SMG) [85]

SMS-SMG influences DT knowledge to improve SG processes by integrating the physical grid machineries with a digital IoT platform. This permits real-time data monitoring, data analytics, and decision-making.

**Practical Findings:**

- **Deployment:** MindSphere develops IoT sensors to monitor grid performance, offering perceptions for predictive maintenance. Looking at the operational data, it enhances the power transfer and allows green energy sources integration.
- **Achievements:** This offers 25 % reduction in downtime via predictive fault detection, optimizes green energy integration, and offers cost-effective solutions.
- **Obstacles Mitigated**: The variations in renewable energy power generation and grid failures are alleviated through automated monitoring and analytics.

### 6.2. Singapore's energy market authority (EMA) [86]

Singapore's EMA gears DTs to develop urban power management systems, addressing problems associated to green power generation and urban power demand variations.

**Practical Findings:0**

- **Deployment:** DTs model grid behaviour, considering solar and wind energy dynamics, and engagement of machine learning approaches for demand and supply prediction, and energy transfer.
- **Achievements:** Decreased the operational costs by 15 %, reduced fossil fuel dependency by 20 %, and enhanced the outage management through proactive disturbance modeling.
- **Obstacles Mitigated:** Balancing demand and supply chain in practical applications by ensuring grid reliability amid growing green power contributions.

### 6.3. GE renewable energy for wind farms [87]

GE services DTs to enhance wind farm operations by offering real-time analytics on turbine performance, predictive maintenance, and energy output improvement.

**Practical Findings:**

- **Deployment:** The developed DTs analyse the data from wind turbines, senses the parameters like wind speed and blade pitch for

enhancing the power generation. Predictive maintenance decreases the unforeseen downtimes.
- **Achievements:** This offers 20 % reduction in turbine downtime and enhanced energy efficiency with cost-effective maintenance solutions.
- **Obstacles Mitigated:** Handling the environmental disturbances in large-scale wind plants by considering the reduced operational costs and energy yield.

### 6.4. South Australia's Tesla battery project [88]

The world's largest lithium-ion battery, Tesla's Megapack in South Australia, utilizes DTs for optimizing the energy storage and offering grid stabilization.

**Practical Findings:**

- **Deployment:** Simulates battery performance under variable demand conditions, optimizing energy storage and dispatch strategies.
- **Achievements:** Enhanced grid stability during peak demand, faster emergency response, and improved renewable energy integration.
- **Obstacles Mitigated:** Efficiently handling intermittent renewable generation and energy storage for large-scale systems.

### 6.5. Shanghai electric's solar microgrid DT [89]

Shanghai Electric optimizes solar microgrid efficiency by integrating DTs to model energy generation and manage battery performance.

**Practical Findings:**

- **Deployment:** DTs simulate solar panel performance under varying conditions and optimize battery usage to ensure consistent energy delivery.
- **Achievements:** Boosted solar panel efficiency by 10 % and prolonged battery life through charge-discharge optimization.
- **Obstacles Mitigated:** Ensuring effective solar energy storage and minimizing energy wastage.

### 6.6. Hitachi ABB power grids in Japan [90]

Hitachi ABB employs DTs for balancing renewable energy sources and diesel generators in remote island microgrids.

**Practical Findings:**

- **Deployment:** DTs simulate supply-demand dynamics, optimizing renewable-diesel integration for fuel efficiency and cost reduction.
- **Achievements:** Reduced diesel usage by 30 %, improved reliability in isolated grids, and significant cost savings.
- **Obstacles Mitigated:** Stabilizing remote microgrids while minimizing environmental impact.

### 6.7. Orsted's offshore wind farms in Denmark [91]

Orsted uses DTs for offshore wind farm operations to predict weather impacts and schedule proactive maintenance, ensuring uninterrupted energy generation.

**Practical Findings:**

- **Deployment:** Real-time weather data guides turbine adjustments and maintenance schedules.
- **Achievements:** Increased turbine uptime by 15 %, reduced emergency repair costs, and extended operational lifespan.
- **Obstacles Mitigated:** Operating in harsh offshore environments while maintaining energy efficiency.

### 6.8. Statoil energy systems in Norway [92]

Statoil integrates DTs into hybrid renewable systems to optimize energy outputs from wind and solar power.

**Practical Findings:**

- **Deployment:** DTs guide resource allocation by simulating energy outputs under varying conditions.
- **Achievements:** Achieved an 18 % improvement in energy efficiency, better grid stability, and reduced carbon emissions.
- **Obstacles Mitigated:** Balancing hybrid systems to maintain consistent energy supply.

### 6.9. EDF energy's smart grid in the UK [93]

EDF leverages DTs to enhance urban microgrids by optimizing renewable energy integration and resource distribution.

**Practical Findings:**

- **Deployment:** DTs predict demand fluctuations and optimize renewable contributions based on real-time data.
- **Achievements:** Increased energy utilization during peak hours and reduced dependency on fossil fuels.
- **Obstacles Mitigated:** Adapting to high energy demands in urban settings while maintaining flexibility.

### 6.10. India's national smart grid mission (NSGM) [94]

India's NSGM integrates digital twin (DT) technology in urban microgrid pilot projects to improve energy distribution and enhance grid efficiency.

**Practical Findings:**

- **Deployment:** DTs simulate energy distribution scenarios, focusing on optimizing peak load management and renewable energy integration. The models evaluate grid behaviours to identify transmission bottlenecks and recommend solutions for improved energy flow.
- **Achievements:** Achieved reduced transmission losses through real-time monitoring and dynamic system adjustments. Secondly, Enhanced utilization of renewable energy sources, contributing to India's clean energy goals.
- **Obstacles mitigated:** NSGM addresses the complexities of managing grid operations in densely populated urban areas, ensuring energy reliability and sustainability amidst growing demand.

## 7. Future horizons: DT-SMG

*Limited availability of capital:* DT can be used for comprehensive simulations of cost-cutting measures, modeling different distribution capacities to assess their impact on microgrid performance and cost-effectiveness. By simulating CapEx strategies, designers can make informed decisions about resource allocation and investment priorities.

*Regulatory uncertainty:* Leverage the visualization capabilities of the DT can be used to simulate different regulatory scenarios. By incorporating regulatory parameters into the simulation, stakeholders can better understand the potential impacts of different regulatory paths on the microgrid's operations, revenue streams, and compliance requirements.

*Microgrid as a public utility:* DT can be used to analyze the implications of serving multiple customers within a microgrid framework. By visualizing and evaluating the impact of various customer configurations and demand profiles, designers can address the complexities associated with designating a microgrid as a public utility and ensure its efficient and equitable operation.

*Uncertain utility support:* DT can be used to conduct cost-benefit analyses of microgrid implementation within load pockets. By simulating the potential costs and benefits of integrating a microgrid into the utility infrastructure, stakeholders can assess whether the reduction in CapEx outweighs the potential loss of customer revenue and make informed decisions about utility support for microgrid projects.

*Perceived high technical risk:* DT can be used to model "what-if" scenarios and assess the technical feasibility and risks associated with different components and configurations.

Through simulating the impacts of commercially available compared to custom-made equipment and examining their effectiveness across different scenarios, stakeholders can minimize technical uncertainties and enhance the design and functioning of the microgrid.

*Perceived high financial risk:* DT can be implemented to conduct comprehensive financial analyses of community microgrid projects. By integrating real-time data and simulating various revenue scenarios, stakeholders can assess the financial risks and rewards associated with multi customer microgrid and make informed decisions about investment strategies, revenue streams, and risk management approaches.

## 8. Conclusion

The exploration of DT-SMG systems reveals a transformative potential to redefine modern power systems. This study underscores the importance of automation in enhancing device intelligence and adaptability, enabling SMGs to meet the demands of a dynamic energy landscape. By elucidating the foundational principles and providing practical insights into constructing DT-SMG frameworks, this work establishes a solid foundation for further advancements in the field.

Building on these foundations, future research should focus on integrating advanced analytics such as artificial intelligence and machine learning into DT-SMG systems. These technologies can unlock predictive maintenance capabilities, enhance energy forecasting, and enable autonomous decision-making, further optimizing system performance. Additionally, addressing the scalability and interoperability of DT-SMGs across diverse energy systems and regulatory environments is crucial to their widespread adoption.

Another critical area for advancement lies in designing robust cybersecurity frameworks to safeguard data transmission and storage within DT-SMG systems. As these systems handle sensitive and real-time information, ensuring their security is paramount. Furthermore, real-time optimization techniques for energy distribution and load balancing should be explored to maximize efficiency and system reliability. Economic viability analyses will also be essential to assess the cost-effectiveness and long-term benefits of deploying DT-SMGs on a large scale.

The practical impacts of DT-SMG systems on the energy industry are profound. These systems promise enhanced operational efficiency, reduced resource wastage, and significant cost savings. By integrating real-time monitoring and predictive capabilities, they improve grid reliability and mitigate disruptions. Moreover, the seamless integration of renewable energy sources within DT-SMG frameworks supports global decarbonization goals, making them instrumental in the transition toward sustainable energy practices. Their adaptability allows for customized solutions across various applications, from urban grids to remote off-grid systems, highlighting their industrial versatility.

The shift towards DT-enabled SMGs represents a paradigm shift with immense potential to address contemporary energy challenges. By fostering innovation through interdisciplinary research and collaboration, these systems can usher in a new era of resilient, intelligent, and sustainable energy solutions. The journey to harnessing the full capabilities of DT technology is a step toward shaping a brighter and more sustainable future for generations to come.

## CRediT authorship contribution statement

**Buddhadeva Sahoo:** Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Subhasis Panda:** Writing – review & editing, Writing – original draft, Validation, Supervision, Software, Project administration, Formal analysis, Data curation, Conceptualization. **Pravat Kumar Rout:** Writing – review & editing, Visualization, Supervision, Project administration, Methodology, Formal analysis. **Mohit Bajaj:** Writing – review & editing, Visualization, Validation, Supervision, Project administration, Investigation. **Vojtech Blazek:** Writing – review & editing, Visualization, Validation, Supervision, Project administration, Methodology, Investigation, Funding acquisition.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Data availability

Data will be made available on request.

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