IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received 9 January 2023, accepted 23 January 2023, date of publication 1 February 2023, date of current version 23 February 2023.

Digital Object Identifier 10.1109/ACCESS.2023.3241588

TOPICAL REVIEW

A Review on Digital Twin Technology in Smart Grid, Transportation System and Smart City: Challenges and Future

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This work was supported by the University of Vaasa, Project by Business Finland, under Grant 27081089141.

ABSTRACT With recent advances in information and communication technology (ICT), the bleeding edge concept of digital twin (DT) has enticed the attention of many researchers to revolutionize the entire modern industries. DT concept refers to a digital representation of a physical entity that is able to reflect its physical behavior by applying platforms and bidirectional interaction of data in real-time. The remarkable deployment of the internet of things in the power grid has led to reliable access to information that improves its performance and equips it with a powerful tool for real-time data management and analysis. This paper aims to trace the continuous investigation and propose practical ideas in originating and developing DT technology, according to various application domains of power systems, and also describes the proposed solutions to deal with the challenges associated with DT. Indeed, with the development of modern cities, different energy layers such as transportation systems, smart grids, and microgrids have emerged facing various issues that challenge the multi-dimensional energy management system. For example, in transportation systems, traffic is a major problem that requires real-time management, planning, and analysis. In power grids, remote data transfer within the grid and also various analyzes needing real data are just some of the current challenges in the field. These problems can be cracked by providing and analyzing a real twin framework in each section. All in all, this paper aims to survey different applications of DT in the development of the various aspects of energy management within a city including transportation systems, power grids, and microgrids. Besides, the security of DT technology based on ML is discussed. It also provides a complete view for the readers to be able to develop and deploy a DT technology for various power system applications.

INDEX TERMS Digital twin, machine learning, microgrid, physical twin, power system, security, transportation system.

I. INTRODUCTION

The power system is moving toward innovative technologies that in turn make the power system structure more complicated. In this way, the new emerging smart technologies carry further capacities such as computing and communication that are not possible to represent in the physical layer. These capacities have raised the sophistication level of power systems and necessitate new approaches to relieve these issues via supplying improved information regarding the physical structure. Digital Twin (DT), first introduced by Grieves in 2002 for productlife cycle management, can be regarded as one of the leading technological tendencies to overcome power system challenges [1]. Therefore, the DT can present promising solutions for power system challenges relevant to the optimal management, operation, control, and security of energy systems. By definition, DT is a digital model of a physical entity that reflects its physical behavior

The associate editor coordinating the review of this manuscript and approving it for publication was Sotirios Goudos.

by applying platforms and two ways interactions of data in real-time. In early of 2012, the first technical paper was released for DT by National Aeronautical Space Administration (NASA) [2]. The primary aim of DT is to provide better or the same information about the physical twin that can be achieved by having a physical entity, indifference to modeling, and simulation of physical system behavior. It is worth noting that significant advances in artificial intelligence, IoT and cyber-physical systems are introduced as novel revolutions in smart power systems. Along with these technologies, the real-time data is continuously collected, processed and then analyzed to provide a digital picture of a physical system and make an accurate concept of current and future system states. Therefore, the dynamic, exact and modern virtual depiction of the desired system is ready for analysis and control in a real-time secure manner. This description represents the concept of DT modeling, which is considered by many industrial sectors, especially the power energy industry. By providing a DT power system as a robust agent, real-time and historical data can be managed in a secure and efficient form, as well as contribute to system operation by supporting maintenance, design and operation management. Being new and complex in idea, the study of DT-based power systems is still in the preliminar stage. DT can be used in the various area of power systems such as fault detection, load prediction, behavior analysis of operators, power system control and analysis, health condition assessment of power tools, and so on [3]. This paper aims to review the continuing research studies and propose applicable ideas in developing and deploying the DT technology, according to various application fields of power systems. In fact, with the growth of cities, in addition to the power system sector, various energy sectors such as transportation systems, smart networks and so on have appeared, which meet various topics that challenge the energy management of cities. Transportation systems are an integral part of the power system and are known as mobile energy resources [4]. The energy management organization or dispatching system in the control center demands information on the main components in real-time for more active management of smart transportation systems' energy infrastructures, especially considering the wide deployment of electric vehicle charging facilities. This information includes parking stations, subways, electric vehicles, traffic assignments, etc. Because energy infrastructure is usually not available in real-time, active operation and management can be provided using the DT architecture for the dispatching system in a sustainable manner. So, DTs can assist to bridge the gap for faster decision-making as a result of comprehensive and optimal management. This architecture in the transportation section has been supported by several researchers. In [5], [6], and [7], the DT approach is used for traffic management, autonomous guide, and instrument failure forecast, respectively.In [8], the application of DT in the smart automotive industry is reviewed. Health and battery managing systems of EVs, smart charging, drive system and converter, and movement management of EVs have been studied. On another side, in the microgrid and smart grid, remote data transmission by a grid as well as various real data-based analyzes are introduced as only some of the related challenges in these fields. Therefore, these problems can be overcome by providing a real twin platform for each section. Generally, examining and studying the process of the DT to help in the analysis, design, control, and development of power systems is a new investigation issue. In this regard, we have investigated a wide range of DT applications in the field under study, and we have decided to summarize these studies as a survey paper. And also suggested ideas are added which help the reader to have a broad view of real-time decision-making.

This paper aims to review the various applications of DT technology in the development of different aspects of energy management within the smart city, including transportation systems, the power grid, and the microgrid. The practical services and suggestions supported by the energy sections DT are broadly studied. In this regard, various applications of DT in the microgrid flowchart are investigated from forecasting, monitoring and management, fault detection, and security points of view. Additionally, network studies based on DT are examined under different analyses such as restoration, reliability, prediction, energy hub, uncertainty, and physical and cyber security. Also, ML technologies are employed to create a secure DT platform. ML technologies can be distributed as a secure auxiliary layer in the DT environment to ensure secure data exchange between the physical and the virtual model. In addition, this paper provides a complete vision for the readers to develop and deploy a DT technology for various energy system applications. Finally, some challenges associated with DT technology and their practical solutions are explained. It is presented that security, standardization, connectivity, data analysis, and data access are some challenges in the DT field that the suggested solutions can help. Fig. 1 illustrates the configuration of this study.

The rest of this paper is organized as follows: in Section II, the paradigm of DT is discussed, and the various applications of DT technology in the development of different aspects of energy management in a city, including transportation systems, microgrid, and power grid are presented in Section III. The assured security of state of art DT technology based on ML is discussed in Section IV. In Section V, the developing and deploying energy system DTs are provided. In Section VI, challenges associated with DT and suggested solutions to overcome them are discussed. Finally, the conclusion of the paper is stated in Section VII.

II. DIGITAL TWIN CONCEPT

In papers are presented numerous definitions of DTs that represent the abilities and awareness of the analysts in various domains. Generally speaking, a digital twin is a concept based on a physical entity that describes complex physical systems that are connected to the available real system through a communication connection. This communication link enables the control, monitoring, and optimization of the

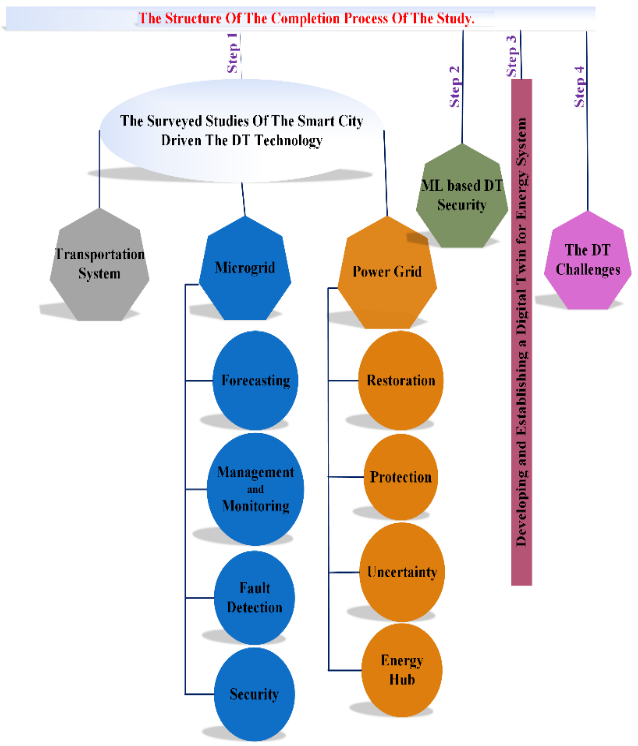

FIGURE 1. The structure of the trend of the study.

physical entity through the continuous exchange of information. This concept was first introduced in the aerospace area and then was developed in other fields with the evolution of advanced technology. In [9], the DT is applied to control and also monitor the product states and production lines in the manufacturing industry. Smart cities use the features of DT for the virtual management of physical productions [10]. Three fundamental notions that describe the DT technology include:

1) DT prototype is the kind or model illustration of the physical twin. In [11], the DT prototype is expressed as the design interpretation that is a particular model of an entity. For instance, the DT prototype of the wind turbine (WT) is a single depiction model for the particular model of a WT.

2) The DT instance is an instance of physical entities according to the DT prototype. The DT instance of WTs presents by the usual DT prototype of the WT model. In fact, it provides a single model-based instance.

3) A DT aggregate is a group of DT instances and other DT aggregates. DT instances can be formed without other instances, while the DT aggregates cannot. A DT aggregate can present further perception of the model's behavior, which is impossible in the instance class. For example, it is possible to control the wind speed in a particular wind farm, which provides a better understanding of the performance of the whole model. A DT instance of WT makes singly but the DT aggregate is based on a set of instances. It is worth noting that the DT prototypes and DT instances provide on files including Extensible Markup Language (XML) and JavaScript Object Notation (JSON) for expanded data

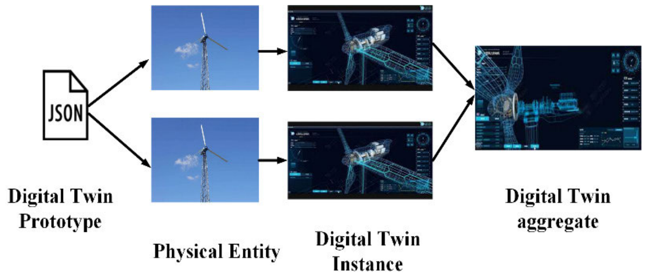

FIGURE 2. Correlation between the DT concepts.

management of the DT. To better comprehend, Fig. 2 gives us an instance of DT.

A DT is a synchronized sample of the digital model or pattern illustrating an existence in the life cycle of the physical system and meeting the requirements of the collection of service cases. To better comprehend and distinguish between the life cycle of the DT and physical twin, virtual and physical environments are distinct in Fig. 3. As mentioned, DT is increasingly used in a diverse spectrum of different industries, such as discrete manufacturing, process manufacturing, energy (power), oil and gas, mining and metals, automotive, life sciences and medical, aerospace, infrastructure and defense. Especially in the field of energy systems, DTs can address some of the highlights that include the following:

- Forecast the energy demand for each consumer through machine learning (ML) approaches in a planning and operation DT.

- Enhance management and distribution of grid using real-time data-based simulation models for distributed energy sources.

- Enhance solar array repair and maintenance by identifying abnormal behavior.

- Anticipated repair and keeping for wind farms to support and assist the service teams.

Indeed, these are just a few challenges that can be supported by DT modeling. In this respect, we have studied and examined different DT applications in the domain under research in the following sections. Also, we propose ideas that help the reader to have a broad view of real-time decision-making. Therefore, in the next section, the investigations carried out in the potential applications field of the DT in the energy field, especially transportation systems and power systems, and the DT security are reviewed. The power system applications that will be studied include the microgrid, electric grid, security, uncertainty, and so on.

III. VARIOUS APPLICATIONS OF DT TECHNOLOGY IN THE ENERGY SYSTEMS

The DT of the smart city is defined as a tool to analyze the dynamics arising from the complicated interdependence between infrastructures (including energy systems), technologies, etc. To develop the smart city DT, it is necessary to deploy the DT of all energy systems within the smart city. Indeed, energy systems are inseparable from the smart city,

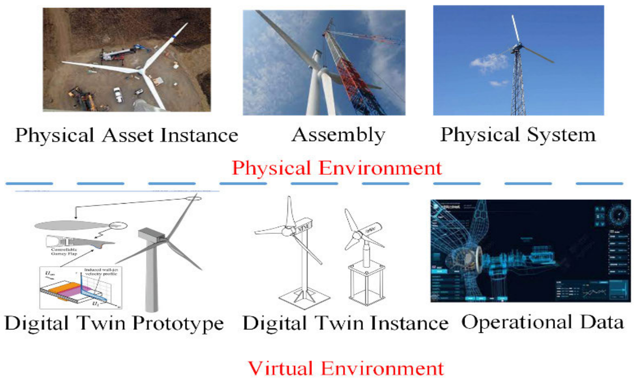

FIGURE 3. Relationship between physical life cycle and Digital Twin.

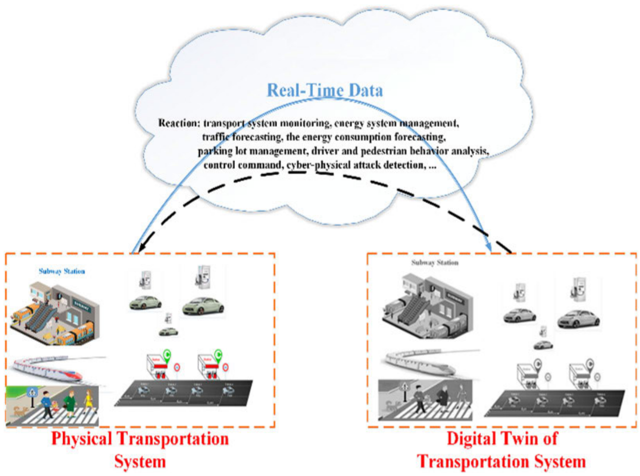

FIGURE 4. An example of a DT concept for transportation system.

which guarantee the quality of cities. Hence, in this section, we study the application the DT in energy systems such as transportation systems, power grids, and microgrids.

A. DIGITAL TWIN APPLICATION IN THE TRANSPORTATION SYSTEMS

The evolution and complexity of smart transportation systems fetched a higher demand for new technological innovations in a sustainable way. Thus, DT technology as an innovation architecture is qualified to scrutinize the lifecycle of various systems such as transportation systems in a digital structure. The infrastructures of transportation systems that can be supported by DT technology include transport system monitoring, energy system management, traffic forecasting, the energy consumption of electric vehicles forecasting, subway regeneration braking energy forecasting, parking lot management, driver behavior analysis, investigation of pedestrian behavior, health system control, cyber-physical attack detection, etc. DT can play a potential role in any of these infrastructures, for example, using DT to monitor the transportation system can reduce maintenance costs.

The advantages of using DT technology include increased reliability and availability through monitoring and simulation to improve performance. In this way, the traffic system DT

TABLE 1. A review of recent investigations on DT approach-based transportation energy systems.

Ref	Application	Motivation
[11]	Traffic forecasting	- Optimal traffic management Save time and money Reduce energy consumption Improve the mental health of drivers Improve performance and operation
[13]	Driver behavior analysis	Improve safety enhance environmental sustainability
[12]	Pedestrian behavior analysis	Improve security
[14]	Cyber-physical attack detection	Improve security
[15]	Transport system monitoring	Real-time monitoring reduce maintenance costs
Proposed	Energy forecasting	Manage and optimize energy consumption Improve operation
Proposed	Parking lot management	Manage and optimize energy consumption Manage parking spaces in real-time Providing EVs security Saving time Reduce parking cost

can lead to accurate traffic forecasting and thus save time and money, reduce energy consumption, improve the psychological health of drivers, and enhance performance. Since DTs structures organize based on data and algorithms, hence complete and accurate traffic forecasting with high-quality models and data in real-time is possible. DT technology is a powerful tool that supports traffic planning in the sustainable formation of urban traffic and its efficient control. Thereby, beyond modeling and planning, the DT can be used in optimal traffic management and record accurate traffic information and extensive EV traffic.

In [11], the DT technology has been used for traffic management and can be employed in the forecast and prediction sphere. DTs can help marketers by predicting the pattern of energy consumption and production of electrical transportation systems as well as lead to better operation and performance, and thus improve management and optimization of energy consumption of these systems. Another application of DT serves as parking lot management, which can control the access of vehicles to the parking, and manage parking spaces in real-time. Other services associated with DT technology in this field include providing complete and accurate information on the number of vehicles in the parking lot, managing and optimizing energy consumption, providing various reports based on period, establishing a secure environment for EVs, improving service to users, saving time, reduce current parking costs.

In [12], the authors suggested the DT technology to analyze and investigate the real drivers' and pedestrians' behavior. In [13] and [14], the DT of drivers and vehicles are assembled in real-time to transfer conferring information to drivers and vehicles in the physical world. This proposed approach has been able to solve the problem of security and environmental sustainability. With the development of the transportation system DT can easily detect cyber and physical attacks in the transportation sphere. Given that transportation systems are evolving and using technologies such as wireless and the IoT, they can be easily targeted by hackers. Transportation systems are dynamically analyzed, so it requires up-to-date technology to detect the attacks in real-time. On the other hand, transportation systems that are closely related to humans are very vulnerable to data security threats. With DT technology, cyber and physical attacks in transportation systems can be smoothly identified. As result, this technology can construct a secure and reliable environment for all agents in the transportation sphere. Pedestrians are an integral part of transportation systems, so their health and safety are of great significance. Therefore, these systems require the implementation of the DT that realistically analyzes pedestrians' behavior. In [15], DT is used to model EVs and monitor their behaviors in order to optimally manage charging programs. Energy consumption parameters and also capacity and frequency of charge are considered for modeling the virtual twin. In the conclusion, Table 1 presents a review of recent investigations on DT approach-based transportation energy systems. Also, Fig. 4. shows a schematic view of a conceptual example of DT for a transportation system.

B. DIGITAL TWIN APPLICATION IN THE MICROGRID FRAMEWORK

The microgrid is a self-reliant energy system described as a set of distributed energy resources and connected loads. The microgrid is a controllable asset relating to the grid that can function in island mode or grid-connected mode [16]. Microgrids aim to improve the operation of energy systems regarding sustainability, security, efficiency, economics, and energy management. The significant features in the microgrid performance include reliability, security, flexibility, self-sufficiency, and optimality. Although, a great deal of research on the improvement of the microgrid performance has been carried out, investigating and studying the DT process to help in the analysis, design, control, and development of microgrids is an entirely new research topic. In this section, we investigate the DT services in microgrid applications, and recent studies conducted in this field. DTs of microgrids provide different potentials for scheduling, optimization, and planning from management algorithms for distributed power resources. DTs are valuable for the microgrid environment where it is impossible to do a real-time experiment. The microgrids are composed of renewable energy resources, demand and communication network segments. To construct a microgrid DT, we need to create a DT for each segment. First, A DT aggregate consists of DTs of each segment and the DTs aggregate setup are created from all three segments. Thus, creating change in each of the physical sections (physical twins), corresponding changes can be noticed in each section. Fig. 5. shows a schematic view of a conceptual example of DT for the microgrid.Also, different analyzes within fields of energy management, forecasting, security, etc. that need to be done, can be implemented based on the microgrid DT. This means that based on the microgrid DT, real-time

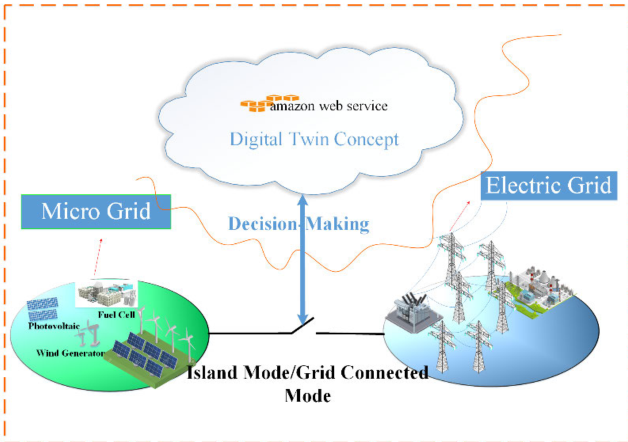

FIGURE 5. An example of a DT concept for the microgrid.

analysis can be provided for each part of the microgrid. In following sections present analyses of microgrids founded on the DT including forecasting, management and monitoring, fault prediction and security. In this regard, a review of recent investigations on the microgrid based on the DT technique is presented in Table 2.

1) FORECASTING

The microgrid DT can be utilized in various microgrid applications. In order to perform various forecast analyses such as load forecasting, system response forecasting, etc., one of the basic requirements is the availability of real-time data, in other words, the reality of the output data is directly related to the reality of the input physical data.It has been proven in the literature that there is a direct correlation between prediction and DT service [17]. Given the specificity of the DT in real-time data presentation, the idea of using the concept of DT in forecast analysis can be practical and efficient. On the other hand, such analyses can be used microgrid digital data output instead of the historical data and achieve a more accurate prediction of energy management or the system response in the future. As the development of microgrid is dependent on expansion and growth of load in the future, on the other hand, accurate load growth prediction can make the microgrid development program more optimal, more efficient. Therefore, it can be inferred that the use of DT can have a significant impact on the long-term planning of microgrid development. It has been proven in the studies that ML algorithms have powerful abilities to solve prediction and diagnosis problems, some of which are mentioned here. In fact, load forecasting depends on several factors that can change the load consumption pattern. Time horizon factor is one of them that includes Short-term forecasting (STLF), Mid-term forecasting (MTLF) and Long-term forecasting (LTLF). A summary of the DL methods used in microgrid for load forecasting is presented in this paper. In order to plan and operate of power system, a DNN for STLF is presented in [18]. In [19], the application of Feed-forward DNN and Recurrent-DNN models using STLF data to compare are studied. Deep belief network (DBN) compound with parametric Copula models for forecasting hourly load is suggested in [20]. In [21] is proposed an approach using DBN made from multiple layers of restricted Boltzmann machine (RBMs) for STLF in the Macedonian for validation of the proposed method. Here, the layer-by-layer unsupervised training method is controlled by fine-tuning the parameters using a supervised back-propagation training method. DRNN–GRU model for STLF and MTLF using consumption data of load building is presented [22]. A residential load forecasting using CNN is suggested in [23]. A stacked denoising auto-encoders (SDAs) model is proposed for electricity load forecasting [24]. The output of SDAs data is used for the training process of the SVR model as input. In [25] two LSTM methods based on hourly and minute ahead for load demand prediction are proposed. In [26], the authors used the DBN method for wind and PV power prediction. In [27] DNN method that includes Long short-term memory (LSTM) and convolutional neural network (CNN) is proposed for deterministic short-term wind power forecasting in northeast China. Due to the high capability of ML algorithms, by integrating these algorithms into the digital environment based on DT, it is possible to support and manage real-time forecasting and analysis issues with high accuracy and efficiency. In other words, by adapting the prediction model with real-time data, an accurate prediction model can be achieved.

2) MANAGEMENT AND MONITORING

Energy management in the microgrid is impossible without having a control program in each system, so the presence of control systems to access data to the central decision system to provide optimal energy management is a requirement of a power system like the microgrid. It is practical if the different measurement systems are installed in the various places of the network for data quantifying. In other words, control systems and energy management systems use measurement data for optimal decision-making. Providing optimal decisions at the energy management level is associated with basic challenges, due to the presence of errors in the data estimate provided by measurement devices. Due to the many efforts made in this area, energy management systemsstill suffer from this problem.In my book, the mentioned challenges in estimating real-time data in energy management can be addressed to some extent by providing real-time data by the microgrid digital department. With this description, the growing use of DT smart equipment for the microgrid can be widely impressive among other technologies. Providing the DT of the microgrid will be possible if the IT system and the operation system are placed in the learning phase, which means that the IT system and the operation system in the microgrid are one of the fundamental requirements in deploying and developing the DT. Therefore, development schedules of the microgrid system should be presented and extended with this perspective (digital perspective). In [28], a framework for energy management handling based on DTs is proposed that smart meters are applied for collecting the entity data. DT- based platform is suggested in [29] for energy demand management. As mentioned, DT technology enables real-time monitoring of renewable energy resources, on account of this technology can resolve the real-time operation and monitoring challenges [30]. In [31], the authors optimized the management of wind farms by presenting wind farm DT, their performance evaluation, and health management. In [32], DT is used to display and process as well as evaluate the performance of energy storage systems in the virtual environment. This technology is applied by aiming to determine the scheduling programs of the operation process. Ontologies and semantic web methods are introduced as common techniques for DT modeling [33]. These methods allow making layered structures for particular architectures of smart grids and different energy systems. Loads profiles of customers, the power generation systems and also substructures of generation can be modeled by ontologies through organized constructions. Also, semantic web technologies provide a certain level of abstraction for energy system simulation and modeling, which can be coordinated and adapted to different energy systems [34]. Edge-based DTs originated to make a virtual simulation surrounding for performance examination to develop the resilience of the microgrids [35].

3) FAULT DETECTION

Given the development of the grid and the operators of network operation and control, the presence of error in the microgrid environment is undeniable. Faults are an integral part of a system and their existence in one part of the system can provoke significant problems in the entire system. Therefore, timely or real-time detection can prevent irreparable damage to these problems. A fault detection system must have timely detection potential to provide a reliable system. A diagnostic system must be able to determine the time and place of the fault as well as the operation of the fault interrupt system in a timely manner. Hence, the need for a fault detection system with access to real-time data is essential. According to the above statements, having real-time analysis can solve these problems. With the original DT of the microgrid, we can have a real analysis of the entire network. As a result, DT makes it possible to detect faults in real time, which in turn leads to the stability, reliability and flexibility of the microgrid. In [36], the development of the DT to guide fault detection is investigated. A fault detection system for distributed energy resources based on the DT concept has been developed in [37]. In this paper various kinds of faults in the PV panels are considered. In [38], a monitoring system based on DT is proposed to predict the faults in a physical power converter within the digital model is entrenched by a controller. In [39], a digital model of a power system is proposed to trace the dynamic faults of voltage and also forecast the dynamic behavior of the post-fault. The concept of DT is utilized for controller design and distributed energy resources in [40]. In [41] and [42], DT technology is developed and deployed to evaluate the controller operation of microgrids. Table 2 gives an overview of current studies on microgrids based on the digital twin approach.

4) CYBER-PHYSICAL INFRASTRUCTURE SECURITY

One of the main challenges in microgrid systems, which is extremely significant, is the growing presence of physical and cyber-attacks in these networks. Attackers can cause widespread disruption at the network level by infiltrating the body of microgrid energy management and critical infrastructure. In these circumstances, detection time and also detection of invasions in the microgrid are significantly important. Therefore, in order to diminish the damage caused by attacks, it is necessary to detect these attacks in the shortest possible time. Hence, on account of these issues, in recent years, many efforts have been made related to attack detection techniques. One of the most common factors in all methods of detecting incursions is lessening the detection time. It means that the detection system must be able to timely detect disturbances caused by attackers in cyber-attacks at the energy management level. In this regard, it is paramount that cyber-attack detection systems have adequate and timely access to real data. With this in mind, given the characteristics of DT in real-time data analysis, it can be promised that cyber-attack detection systems using DT technology can offer better performance by reducing time and increasing efficiency. Integrating the original DT from a cyber-attack detection system into the DT aggregation of the microgrid can solve the challenge of cyber-attacks to an acceptable level. The ANGEL framework is proposed to reduce the effects of cyber-attacks, physical system identification, and treatment [43]. This framework has applied real-time two-way communication between the physical and the digital system to evaluate physical behavior. A DT-based platform for the assessment of real-time security in china is proposed that physical and virtual environments are linked via the SCADA RTU system [44]. In [45], Oak Ridge National Laboratory, DT has been used to support the cyber-attack and physical damages, especially the DT is used for power grid blackouts. In [46], the DT technology is utilized as a solvent to decrease harmonized attacks on a grid of connected power networks. In [47], a DT and Software-defined network is efficiently used to enhance the resilience and stability of the power grid despite cyber-attacks such as packet delay and DOS attacks.

C. DIGITAL TWIN-BASED POWER GRID APPLICATION INVESTIGATION

Network studies include diverse analyses such as restoration, reliability, prediction, energy hub, uncertainty, and physical and cyber security which each of them provides a separate analysis of network behavior. Developing and deploying the DT-based power grid can improve the network behavior under different conditions. In [48], the authors developed a DT-based platform for online analysis of a large power grid. DT modeling enables the reduction of the response time from minutes to seconds in the entire process. In the following sections, network studies based on DT examine under different analyses, and also as a conclusion, a review of recent studies on the power grid based on the DT technique is presented in Table 3.

1) RESTORATION

Restoring the network to normal operation after a blackout/outage is called power system restoration [49]. The major purpose of restoration is to get the power to the consumers as earlier as potential and without further interruptions. The amount of restoration load and network restoration time are two critical factors that need to be addressed for improvement [50]. It means that if the maximum amount of load is restored in the shortest possible time, the network restoration will be at its best. One of the steps in the restoration process is the start-up of black start units, which are started without the need for a network and provide the power required by nonblack start units. Therefore, choosing and recognizing the relevant black start units and providing the power of which of the units among several nonblack start units is one of the significant issues. On the other hand, demanded power of load and nonblack start units should be supplied from the shortest possible route, so choosing the most optimal route is one of the other problems of load restoration. This event occurs when adequate knowledge of the network is available at the time of restoration and blackout. Having knowledge of the voltage or non-voltage of equipment and generators (amount of power required) at startup, sensitive and insensitive loads, etc can be very effective in achieving the goals mentioned in network restoration. Hence, DT of any network-related equipment can enhance the ease of use of network information.It means that a restoration analysis using DT of the network can be effective in improving the amount of restoration and decreasing the restoration time compared to physical analysis. Consequently, the network DT can provide a real-time solution for getting network return after a blackout without requiring different models and applications by real-time analysis. In [51], the authors integrated the DT and neural network-based decision-making approaches to examine the power grid behavior following vital events.

2) RELIABILITY AND PROTECTION

The probability of proper operation of the system under peripheral conditions within the range required to meet a given goal is called reliability. Power system reliability means the ability of the system to meet the requirements of the consumer and provide sufficient energy supply. Therefore, checking the reliability of power systems has become doubly important. One of the factors that evaluate the reliability index is the energy not supplied (ENS), this index doesn't provide unless an exact environmental parameter model is developed for the reliability analysis [52]. For a more reasonable evaluation of the reliability of the system structures, it is essential to take out state monitoring. Hence, with the

TABLE 2. Various applications of DT in microgrids.

Ref	Application	Motivation
90	Forecast and predict the system response	Maintenance and safe operation Real time control Power scheduling Load routing Optimal planning
91	Monitoring the grid behavior	Help to optimize performance and promotion operator situational cognition Detection of eccentric grid conditions provide automated suggestions for inhibitory efforts to bypass outages
60	Power transformer monitoring	Improve performance
92	Smart home management	Relaxation of home energy management
31	Wind farm monitoring	Coordination
43 44 45	Cyber-physical attack detection Real-time security estimation Cyber security of false data injection and denial of service attacks	Enhance the security and flexibility of the microgrid.
37 38	Fault detection for a PV energy conversion unit Fault detection of the power converter	Improve stability, reliability, and resilience
35	Development planning Prognosis of consumers' manners and renewable energy resource energy supply	Planning and operation development of smart grid
proposed Proposed	Smart island concerning smart EV Coordination of the various energy resources within smart island	Reduce energy consumption Decline energy cost and pollution

availability of the DT models of power system components with updated parameters is practical to carry out real-time monitoring and describe the future and current condition of the physical entity. In [53], the application of the DT model is presented for monitoring wind turbine structure on the reliability analysis. This analysis has been done by applying real and virtual modeling and real-time data monitoring. Be aware that providing the DT technology can cause promising potential in order to face the challenges in the system reliability analysis. In [54], the authors used the DT for optimizing the energy lines and energy sources.

Degradation is an inevitable process in all physical entities that leads to a reduction in system operation and an increase in related costs. Therefore, it is absolutely essential to provide a maintenance plan that supports the aging and degradation processes. In this field, energy systems are no exception. Therefore, the power grid as well as the power systems need a protection scheme for timely maintenance and repair. In this context, a lot of money is lost due to maintenance, especially for equipment that is not available. To increase the reliability of energy systems and extend their life, advanced monitoring systems are needed in different operating conditions. As a result, the concept of DT can be used in this context. Generally speaking, the DT of a protection system can provide analyzes that can be performed during or before the installation of an actual system. In fact, DT modeling can trace the protection system setting. This technique leads to accurate assessment, time-saving and cost-saving, and it is also possible to use this technology more efficiently by observing defects, adjusting and correcting them at each stage of the process. As a matter of fact, in real-time data transactions between real and digital spaces, the difficulties can be investigated and solved without any delay. Since the DT can predict faults and failures in the desired system, hence can plan the maintenance process beforehand. With different simulations, DT can provide the best solution and protection strategies that ease the maintenance of the system. Therefore, using the DT technology can be so valuable in each phase of repair and maintenance. Due to the reaction between physical and digital, it can always be utilized to optimize the system. In addition, With DT technology, distance control and monitoring can be accomplished in situations where quick access is restricted. In other words, the DT of the protection system can provide remote availability to all operators leading to enhanced reliability and diminished cost [55], [56]. In [35], a distance protection relay and the fault location algorithm are trialed and tested using the DT of protection relay in both physical and digital environments. To evaluate the transformer performance of the distribution network, a DT-based distributed network is used for troubleshooting before real-world implementation [57].

3) UNCERTAINTY

Given the existence of unpredictable factors and their random performance, it is very significant to consider uncertainty in many power system problems. In order to solve these problems and control a system, it is necessary to comprehend the system behavior and analyze it. Therefore, real-time monitoring and analysis are vital to control the uncertain behavior of random factors in any system. In power systems, the entry of entities of random nature into the network, such as wind turbines and solar photovoltaics, as well as the unpredictability of the exact amount of consumer consumption and etc. are the major causes of uncertainty in power networks and energy systems. Many techniques have been proposed that model the random behavior of uncertainty parameters [58], but without accurate modeling and real-time analysis of the considered system is not possible. Innovation DT technology can well support the random behavior of physical entity with real-time monitoring and control and online analysis. Given that, with DT technology, the real-time physical behavior of an agent can be observed at any time, so with this technology, the existence of uncertainty can be denied. It means that by examining and analyzing real-time physical entities, their real-time performance can be definitely investigated. In other words, the physical environment requires high fidelity which can be achieved with DT. High faithfulness is a desired feature of DT technology that can support the uncertainty of physical systems.

4) ENERGY HUB

Simultaneous communication and transaction of energy carriers with each other in the network are included in a concept

TABLE 3. Various applications of DT in the power grid.

Ref	Application	Motivation
56 35	Protection	Increase remote availability of all operator Enhance reliability Remote control and monitoring Decrease the maintenance of the system Predict faults and failures
proposed	Restoration	Locate the most optimal route Choose and recognizing the black start units Obtain the shortest possible time of restoration
54	Reliability	Fault location Fault diagnose time Operated time of reliability analysis
proposed	Uncertainty	High fidelity environment
proposed	Energy hub	High-quality data integration and exchange

called an energy hub [59]. Using the energy hub set, which is basically a converter for converting different types of energy in different parts of an urban system, practically other sectors such as gas and urban water will also participate in energy consumption management [60]. A great deal of effort has been dedicated to the integration and energy consumption management of the hub system [61]. In accomplishing this, there is a demand for approaches and systems that control and monitor energy consumption and provide energy efficiency by analyzing behavioral modifications. In this regard, it is critical that platforms and control systems have adequate and timely access to real data. Given the characteristics of DT in real-time data control, monitoring, and analysis, it can be promised that hub energy systems using DT technology-driven hub systems can present more reasonable performance. Therefore, integrating the initial DT from energy carriers such as water, electrical and gas into the DT aggregation of the energy hub can solve the challenge of energy management, integration and exchange to an acceptable level. An example of a DT concept for the energy hub is represented in Fig. 6.

IV. ML BASED DIGTAL TWIN SECURITY

One of the requirements for using DT in different applications is to create a secure platform for data exchange between the physical twin and DT in the energy systems. In DT, the speed of analyzing real-time data is significant because it faces a high volume of data. Therefore, security methods should be used that establish security in the shortest possible time. In order not to interfere with the presentation of real-time data and real-time analysis, it is necessary to use the capability of ML-based security approaches. Due to the literature, a security approach based on ML (machine learning) has the ability to create a secure platform for detecting cyber attacks in the shortest time. In [69], the CNN algorithm is proposed to detect replay attacks. In [70], a conditional deep belief network based on a distributed deep learning (DL) algorithm has been suggested for the detection of thief electric in the smart city. The high detecting accuracy has demonstrated the effectiveness of the proposed method. A stacked deep polynomial network for intrusion detection is applied in [64] that can classify datasets into normal and attack data. DBNs are studied

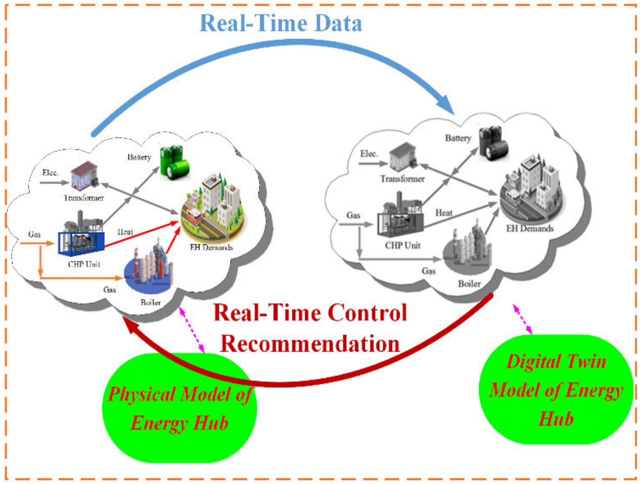

FIGURE 6. An example of a DT concept for an energy hub.

in [66] and [67] for the same task. In [67], hybrid models combined DBN, MLP and RBM are applied for Denial of service attack (DOS attacks) detection for electric vehicles in the smart city. The SAE approach to detect the manipulated data in the SG is suggested in [68]. Similarly, for prediction and detection of the power system security weak spots, stacked auto encoder (SAE) is suggested [69] that output results have been proven the model has a simple implementation with low training time. A hybrid model combined CNN and LSTM algorithms are proposed in [70], where the model was used for electricity theft detection. CNN is used for the smart grid data extraction and classification. A combination of CNN, LSTM and SAE structures is presented in [71] for a similar purpose. Attacks are recognized as a serious threat to the supervisory control and data acquisition (SCADA) system. In order to address this issue, the CDBN algorithm is suggested in order to identify the False Data Injection Attacks (FDIAs) in the smart grid [72]. To secure the SG, wide and deep CNN model is suggested that it used for electricity theft detection [73]. In [74], two different types of attacks based on FDIA have been detected by using the MLP method. In [75], the authors suggested a semi-supervised learning approach based on adversarial AE for detecting FDIAs distribution systems. In [76], a deep-learning-based CNN algorithm is proposed for network intrusion detection for the SCADA system. In [77], a novel Cyber security method based on the Generative adversarial network (GAN) structure is presented. The attacker to the power grid follows two aims. The first objective is to be hidden from the system defender, and the second aims to earn profit through its FDI into the system. The results show the proposed model detects FDI very well and with high precision.

These articles are only part of the studies done in the ML-based security field. According to many kinds of research and their results in this domain, ML and other subclasses such as DL can be a suitable and more efficient platform for establishing security in the DT environment. Hence, due to a large amount of data in DT, the application provided in

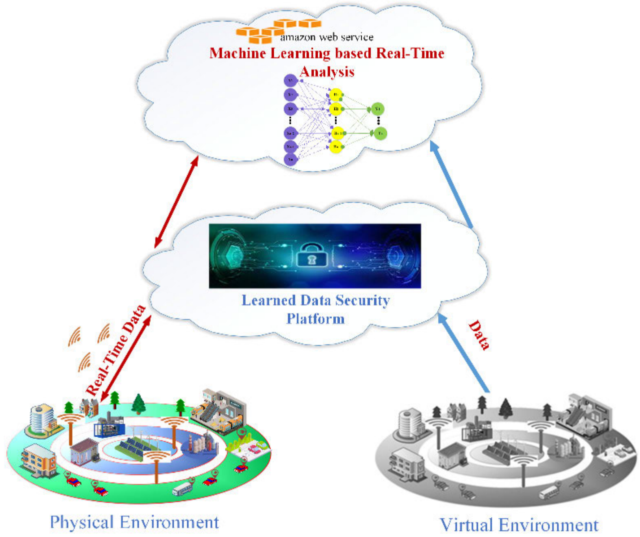

FIGURE 7. ML-based DT security improvement conceptual model.

the previous sections alone cannot provide network security. Therefore, to provide a secure platform in the DT environment, the demand for additional layers (as ML) in addition to the DT layer is essential. The suggested conceptual model to improve the ML-based DT security is represented in Fig. 7. On this subject, in [78], a CNN-based DL in a power system is proposed to create a secure environment as the Automatic Network Guardian for ELectrical systems (ANGEL) Digital Twin.

V. DEVELOPING AND ESTABLISHING A DIGITAL TWIN FOR ENERGY SYSTEM

To establish a DT-driven model, three parts should be considered including physical space, virtual space, and data interaction between both spaces. Determining the nodes of a particular system and modeling them is crucial to designing a DT. The integrated model of these nodes is integrated with a series of data including historical data, sensor source data, etc. to create an accurate model under various states [79]. By evaluating the DT model states in the specified time period can be solved and analyzed the model. With this perspective, a comprehensive understanding of the state of the system allows for analysis and decision make. Since, the modes of most models change continuously over a period of time, the model must be simulated dynamically. Designing a DT includes different phases such as modeling physical systems, connecting real-time data and evaluating and adapting the model. The basis of the design of a DT is modeling that can reflect the actual behavior of physical beings. A virtual model can be built using the historical data acquired from different states of the system and integrating them with information based on system dynamics. In this regard, the physics-based model, data-driven model, and a combination of them are utilized. The physics-based model is established in accordance with the mathematical and physical models, and when there is insufficient information regarding the parameters, the example is specified according to the data obtained from the current state of the system. The state of art technologies like AI techniques are widely utilized for parameter designation [80], [81]. In [82], an artificial neural network (ANN) is employed to adjust the inverter model parameters. Data-based models are used when the mathematical formulation of elements is impossible and this model can consider a large amount of historical data which is a basic issue for a physics-based model. Yet, the need for large volumes of data in different states is essential for training the machine learning approaches. Also, the data-driven model is continuously improved with real-time data to increase the accuracy of the model and be consistent with the actual model. Accordingly, different models with various purposes could be deployed and developed. It is noteworthy that transferring the data and models in a secure and accurate form is a fundamental capability of the DT.

The model of DT is dependent on real-time data for coupling between physical and digital models. This data is collected via IoT devices, smart meters and other measuring devices. As known, controlling large amounts of data obtained from several sources is a difficult issue. Cutting-edge data analysis approaches are needed for preprocessing the primary data after collection. Data is also shared through secure and reliable connection systems which are selected based on the desired prerequisites and targets. These prerequisites include quantitative and qualitative necessities. The wired, wireless and hybrid communication systems can be used for this aim. It is essential to pre-process and unify the primary data to ready the collected data for specific purposes like management, control, monitoring and etc. In this regard, the advanced technology of big data analyticsbased cloud can be used to process the initial huge data to obtain the desired information. Therefore, big data analyticsis a key element in DT modeling. In the DT technique, due to the massive storage abilities and computational power of the cloud, big data analytics can be applied for different applications such as data mining and organization, dimension lessening, filtering, processing and etc. Many approaches based on big data have been suggested for various intents in the smart grid and smart city [83], [84]. Also, big data analysis is employed to integrate continuous and discrete information flows of the microgrid. In addition to cloud computing, fog and edge computing can be implemented for the transition delay of data and integration of various services. In [85], a case study of artificial intelligent approaches to edge computing is studied. DT is a real model of a physical entity, therefore keeping the consistency and accuracy of the intended model is of vital significance. But, it is a challenging issue due to ongoing shifts over a period of time in the operating states and the environment of physical systems. In addition, the continuous updating of the model is another related challenge, due to real-time data being continuously gathered via control and monitoring applications and then processed through the data analysis techniques, updating of the model is done during the lifetime of the system. As mentioned, evaluating and adapting the model is one of the steps of establishing the DT. In this regard, adjusting the parameters and optimizing the physical directions can be useful. Besides, different stimulus procedures can be tracked for model adaption. The functional changes in the observed data within a specified period of time can be used for updating the desired model. Advanced ML algorithms such as deep learning and reinforcement learning are effective strategies that can be used for these purposes. In [86], a survey of ML techniques is studied.

Generally speaking, a real-time DT model can be deployed and developed by using Simulink, Simscape, MATLAB and Raspberry pi hardware [87]. The desired model is deployed on the Raspberry pi hardware that is considered a real model. The Raspberry pi hardware transmits a state of the system and input/outputs to the cloud amazon service so that a twin model can be created simultaneously in the cloud and can accurately detect and analyze a system. In fact, the desired hardware with Wi-Fi power can easily communicate to the cloud to share the physical states of entities that are implemented in the hardware environment, to the cloud. A DT model and error detection algorithm are established in the amazon cloud service. So, as the physical model of an entity is implemented in the Raspberry Pi, the DT model of the same entity is also implemented on amazon cloud with the same inputs so that it can conduct a real-time, accurate, and efficient diagnosis of the system.

VI. WHAT ARE THE DIGITAL TWIN CHALLENGES IN THE FIELD OF POWER SYSTEMS AND HOW CAN THEY BE TACKLED?

This section draws principally the challenges coupled with DT and is discussed in four separate parts.

A. DATA ANALYSIS AND DATA ACCESS

The IT infrastructure currently in use is incapable of supporting data analysis in a DT environment. Generally speaking, DT requires advanced substructures that facilitate data analysis and the effective performance of the DT. In other words, DT cannot succeed without an interconnected and powerful IT infrastructure.

For this purpose, a high-performance GPU can be used. For example, Amazon, Microsoft, and Google can provide users with significant services in the cloud. But the use of cloud services in data analysis still brings relevant security challenges.

Edge computing can be a potential approach to prevent and reduce data transmission delay and increase bandwidth. In fact, edge computing enables fast and accurate data exchange and analysis. In other words, edge computing plays an important role in preprocessing, storage, analysis, etc.

B. CONNECTIVITY WITHIN THE DT FRAMEWORK

The IoT technology enables connectivity within the DT framework, but due to the development of this technology (emergence of 5G), there are still connectivity-related challenges (such as software errors and power outages) during real-time monitoring. For instance, the existence of missing data can significantly affect the performance of algorithms. Therefore, it is necessary to use a method to ensure that the lost data is found and a complete connection.

C. SECURITY

Security and privacy are among the challenges associated with advanced technologies. In the context of DT, there is a risk of cyber-attacks due to the huge volume of data and information exchange. DT is required to follow updates on privacy and security laws. Therefore, creating a secure platform has become a requirement and results in a highly reliable digital platform. Due to the cycle, secure and decentralized structure of the blockchain technology, this technology can deal with this problem and assist DT to ensure security. In fact, with the blockchain technology, it is possible to ensure a secure environment among agents.

D. STANDARDIZATION

Another challenge associated with DTs is standardization, which can decelerate the development of this technology. In fact, a standard form should be used to define, save and execute the DT model, which allows interoperability and integration among the DTs. For example, in the hub energy system, the existence of various infrastructures, such as electricity, water, gas, etc., require a synergy platform for interoperability between systems. This challenge can be tackled with Semantic Web technology or using the DT definition language.

VII. CONCLUSION

This article aims to provide a comprehensive overview based on the DT applications in the transportation systems and power systems fields. The necessity of using the DT technology for energy systems origins from the increasing complexity of electrical equipment and systems, which demands their timely analysis and assessment. In fact, transportation systems DT can bring remarks such as saving time and money, increasing drivers' mental health, and improving performance through real-time analysis and monitoring of transportation systems, pedestrian behavior, and traffic. Also, using the microgrid DT can have a significant impact on the long-term planning of microgrid development In terms of forecasting, integrating DT technology and forecasting methods can improve the efficiency and accuracy of forecasting In other words, by matching the prediction model with real-time data, an accurate prediction model can be achieved. From the energy management and monitoring view, DT enables systems and operators to make an optimal and more efficient decision. Furthermore, it can ease performance evaluation and improve health management. The microgrid DT can improve stability, reliability, and resilience by monitoring and detecting faults in time. Provided the attributes of DT in real-time data analysis, it can be proven that cyber-attack detection systems adopting DT technology can present a better performance by lessening time and advancing efficiency. The power grid DT can provide a real-time solution for returning the grid after contingencies occur in the restoration process. Protection systems DT can enable remote access for all agents, which leads to increased reliability and reduced costs. By DT modeling of energy systems, a high-fidelity and reliable environment can achieve that supports the uncertainty of physical systems. As mentioned, energy hub systems require access to high-quality data for the integration and exchange of energy between energy carriers, which can promise by creating potential synergy between DTs of energy carriers. In the case of cyber security, creating a secure platform based on machine learning as a security layer, will lead to an increased trust for data exchange and information feedback between virtual and physical space. The rapidly evolving and globalized DT technology is posing new challenges to the overall electrical engineering research community. In line with this perspective, we explored some of these challenges and opportunities in the current research, deciding to cover the rest of them in the future research.

REFERENCES

[1] M. Shahzad, M. T. Shafiq, D. Douglas, and M. Kassem, "Digital twins in built environments: An investigation of the characteristics, applications, and challenges," *Buildings*, vol. 12, no. 2, p. 120, Jan. 2022.

[2] J. Granacher, T.-V. Nguyen, R. Castro-Amoedo, and F. Maréchal, "Overcoming decision paralysis—A digital twin for decision making in energy system design," *Appl. Energy*, vol. 306, Jan. 2022, Art. no. 117954.

[3] A. Fuller, Z. Fan, C. Day, and C. Barlow, "Digital twin: Enabling technologies, challenges and open research," *IEEE Access*, vol. 8, pp. 108952–108971, 2020.

[4] M. Jafari, A. Kavousi-Fard, T. Niknam, and O. Avatefipour, "Stochastic synergies of urban transportation system and smart grid in smart cities considering V2G and V2S concepts," *Energy*, vol. 215, Jan. 2021, Art. no. 119054.

[5] S. A. P. Kumar, R. Madhumathi, P. R. Chelliah, L. Tao, and S. Wang, "A novel digital twin-centric approach for driver intention prediction and traffic congestion avoidance," *J. Reliable Intell. Environments*, vol. 4, no. 4, pp. 199–209, Dec. 2018.

[6] M. Ibrahim, A. Rassõlkin, T. Vaimann, and A. Kallaste, "Overview on digital twin for autonomous electrical vehicles propulsion drive system," *Sustainability*, vol. 14, no. 2, p. 601, Jan. 2022.

[7] M. You, Q. Wang, H. Sun, I. Castro, and J. Jiang, "Digital twins based day-ahead integrated energy system scheduling under load and renewable energy uncertainties," *Appl. Energy*, vol. 305, Jan. 2022, Art. no. 117899.

[8] S. Haag and R. Anderl, "Digital twin–proof of concept," *Manuf. Lett.*, vol. 15, pp. 64–66, Jan. 2018.

[9] R. Laubenbacher, A. Niarakis, T. Helikar, G. An, B. Shapiro, R. S. Malik-Sheriff, T. J. Sego, A. Knapp, P. Macklin, and J. A. Glazier, "Building digital twins of the human immune system: Toward a roadmap," *NPJ Digit. Med.*, vol. 5, no. 1, pp. 1–5, May 2022.

[10] G. Bhatti, H. Mohan, and R. Raja Singh, "Towards the future of smart electric vehicles: Digital twin technology," *Renew. Sustain. Energy Rev.*, vol. 141, May 2021, Art. no. 110801.

[11] B. Ketzler, V. Naserentin, F. Latino, C. Zangelidis, L. Thuvander, and A. Logg, "Digital twins for cities: A state of the art review," *Built Environ.*, vol. 46, no. 4, pp. 547–573, Dec. 2020.

[12] M. Yan, W. Gan, Y. Zhou, J. Wen, and W. Yao, "Projection method for blockchain-enabled non-iterative decentralized management in integrated natural gas-electric systems and its application in digital twin modelling," *Appl. Energy*, vol. 311, Apr. 2022, Art. no. 118645.

[13] Y. Liu, Z. Wang, K. Han, Z. Shou, P. Tiwari, and J. H. L. Hansen, "Sensor fusion of camera and cloud digital twin information for intelligent vehicles," in *Proc. IEEE Intell. Vehicles Symp. (IV)*, Oct. 2020, pp. 182–187.

[14] V. Damjanovic-Behrendt, "A digital twin-based privacy enhancement mechanism for the automotive industry," in *Proc. Int. Conf. Intell. Syst. (IS)*, Sep. 2018, pp. 272–279.

[15] T. Maurer. (2017). *What is a Digital Twin?* [Online]. Available: https://community.plm.automation.siemens.com/t5/Digital-Twin-Knowledge-Base/What-is-a-digital-twin/ta-p/432960

[16] D. T. Ton and M. A. Smith, "The US department of energy's microgrid initiative," *Electr. J.*, vol. 25, no. 8, pp. 84–94, Oct. 2012.

[17] Z. Guo, K. Zhou, X. Zhang, and S. Yang, "A deep learning model for short-term power load and probability density forecasting," *Energy*, vol. 160, pp. 1186–1200, Oct. 2018.

[18] G. M. U. Din and A. K. Marnerides, "Short term power load forecasting using deep neural networks," in *Proc. Int. Conf. Comput., Netw. Commun. (ICNC)*, Jan. 2017, pp. 594–598.

[19] Y. He, J. Deng, and H. Li, "Short-term power load forecasting with deep belief network and copula models," in *Proc. 9th Int. Conf. Intell. Human-Machine Syst. Cybern. (IHMSC)*, Aug. 2017, pp. 191–194.

[20] A. Dedinec, S. Filiposka, A. Dedinec, and L. Kocarev, "Deep belief network based electricity load forecasting: An analysis of Macedonian case," *Energy*, vol. 115, pp. 1688–1700, Nov. 2016.

[21] L. Wen, K. Zhou, and S. Yang, "Load demand forecasting of residential buildings using a deep learning model," *Electr. Power Syst. Res.*, vol. 179, Feb. 2020, Art. no. 106073.

[22] A. Estebsari and R. Rajabi, "Single residential load forecasting using deep learning and image encoding techniques," *Electronics*, vol. 9, no. 1, p. 68, Jan. 2020.

[23] C. Tong, J. Li, C. Lang, F. Kong, J. Niu, and J. J. P. C. Rodrigues, "An efficient deep model for day-ahead electricity load forecasting with stacked denoising auto-encoders," *J. Parallel Distrib. Comput.*, vol. 117, pp. 267–273, Jul. 2018.

[24] D. L. Marino, K. Amarasinghe, and M. Manic, "Building energy load forecasting using deep neural networks," in *Proc. 42nd Annu. Conf. IEEE Ind. Electron. Soc. (IECON)*, Oct. 2016, pp. 7046–7051.

[25] M. Khodayar, J. Wang, and M. Manthouri, "Interval deep generative neural network for wind speed forecasting," *IEEE Trans. Smart Grid*, vol. 10, no. 4, pp. 3974–3989, Jul. 2019.

[26] W. Wu, K. Chen, Y. Qiao, and Z. Lu, "Probabilistic short-term wind power forecasting based on deep neural networks," in *Proc. Int. Conf. Probabilistic Methods Appl. Power Syst. (PMAPS)*, Oct. 2016, pp. 1–8.

[27] A. Francisco, N. Mohammadi, and J. E. Taylor, "Smart city digital twin–enabled energy management: Toward real-time urban building energy benchmarking," *J. Manage. Eng.*, vol. 36, no. 2, pp. 1–11, Mar. 2020.

[28] R. S. Srinivasan, B. Manohar, and R. R. A. Issa, "Urban building energy CPS (UBE-CPS): Real-time demand response using digital twin," in *Cyber-Physical Systems in the Built Environment*, C. Anumba and N. Roofigari-Esfahan, Eds. Cham, Switzerland: Springer, 2020.

[29] A. Ebrahimi, "Challenges of developing a digital twin model of renewable energy generators," in *Proc. IEEE 28th Int. Symp. Ind. Electron. (ISIE)*, Jun. 2019, pp. 1059–1066.

[30] K. Sivalingam, M. Sepulveda, M. Spring, and P. Davies, "A review and methodology development for remaining useful life prediction of offshore fixed and floating wind turbine power converter with digital twin technology perspective," in *Proc. 2nd Int. Conf. Green Energy Appl. (ICGEA)*, Singapore, Mar. 2018, pp. 197–204.

[31] M. Lamagna, D. Groppi, V. V. Nezhad, and G. Piras, "A comprehensive review on digital twins for smart energy management system," *Int. J. Energy Prod. Manage.*, vol. 6, no. 4, pp. 323–334, 2021.

[32] G. Steindl and W. Kastner, "Semantic microservice framework for digital twins," *Appl. Sci.*, vol. 11, no. 12, p. 5633, Jun. 2021.

[33] M. Glatt, C. Sinnwell, L. Yi, S. Donohoe, B. Ravani, and J. C. Aurich, "Modeling and implementation of a digital twin of material flows based on physics simulation," *J. Manuf. Syst.*, vol. 58, pp. 231–245, Jan. 2021.

[34] Y. Xu, Y. Sun, X. Liu, and Y. Zheng, "A digital-twin-assisted fault diagnosis using deep transfer learning," *IEEE Access*, vol. 7, pp. 19990–19999, 2019.

[35] H.-A. Park, G. Byeon, W. Son, H.-C. Jo, J. Kim, and S. Kim, "Digital twin for operation of microgrid: Optimal scheduling in virtual space of digital twin," *Energies*, vol. 13, no. 20, p. 5504, Oct. 2020.

[36] P. Jain, J. Poon, J. P. Singh, C. Spanos, S. R. Sanders, and S. K. Panda, "A digital twin approach for fault diagnosis in distributed photovoltaic systems," *IEEE Trans. Power Electron.*, vol. 35, no. 1, pp. 940–956, Jan. 2020.

[37] N. Tzanis, N. Andriopoulos, A. Magklaras, E. Mylonas, M. Birbas, and A. Birbas, "A hybrid cyber physical digital twin approach for smart grid fault prediction," in *Proc. IEEE Conf. Ind. Cyberphysical Syst. (ICPS)*, Jun. 2020, pp. 393–397.

[38] P. Palensky, M. Cvetkovic, D. Gusain, and A. Joseph, ''Digital twins and their use in future power systems,'' *Digit. Twin*, vol. 1, p. 4, Aug. 2022.

[39] A. Joseph, M. Cvetkovic, and P. Palensky, ''Prediction of short-term voltage instability using a digital faster than real-time replica,'' in *Proc. 44th Annu. Conf. IEEE Ind. Electron. Soc. (IECON)*, Oct. 2018, pp. 3582–3587.

[40] E. F. Fongang, ''Towards resilient plug-and-play microgrids,'' Ph.D. dissertation, Dept. Elect. Eng. Comput. Sci., Massachusetts Inst. Technol., Cambridge, MA, USA, 2019.

[41] J. K. Nowocin, ''Microgrid risk reduction for design and validation testing using controller hardware in the loop,'' Ph.D. dissertation, Dept. Elect. Eng. Comput. Sci., Massachusetts Inst. Technol., Cambridge, MA, USA, 2017.

[42] B. Goia, T. Cioara, and I. Anghel, ''Virtual power plant optimization in smart grids: A narrative review,'' *Future Internet*, vol. 14, no. 5, p. 128, Apr. 2022.

[43] W. Danilczyk, Y. Sun, and H. He, ''ANGEL: An intelligent digital twin framework for microgrid security,'' in *Proc. North Amer. Power Symp. (NAPS)*, Oct. 2019, pp. 1–6.

[44] M. Zhou, J. Yan, and X. Zhou, ''Real-time online analysis of power grid,'' *CSEE J. Power Energy Syst.*, vol. 6, no. 1, pp. 236–238, 2020.

[45] J. Huang, L. Zhao, F. Wei, and B. Cao, ''The application of digital twin on power industry,'' *IOP Conf. Earth Environ. Sci.*, vol. 647, no. 1, Jan. 2021, Art. no. 012015.

[46] R. A. Kerekes, ''Seeing double: Digital twin for a secure, resilient grid,'' Oak Ridge Nat. Lab., Oak Ridge, TN, USA, Tech. Rep., Accessed: Dec. 29, 2021. [Online]. Available: https://www.ornl.gov/blog/seeing-double-digital-twin-secure-resilient-grid

[47] Z. Yin, N. Cheng, T. Luan, and P. Wang, ''Physical layer security in cybertwin-enabled integrated satellite-terrestrial vehicle networks,'' *IEEE Trans. Veh. Technol.*, vol. 71, no. 5, pp. 4561–4572, May 2022.

[48] M. Zhou, J. Yan, and D. Feng, ''Digital twin framework and its application to power grid online analysis,'' *CSEE J. Power Energy Syst.*, vol. 5, no. 3, pp. 391–398, 2019.

[49] V. Biagini, M. Subasic, A. Oudalov, and J. Kreusel, ''The autonomous grid: Automation, intelligence and the future of power systems,'' *Energy Res. Social Sci.*, vol. 65, Jul. 2020, Art. no. 101460.

[50] M. M. Adibi and L. H. Fink, ''Power system restoration planning,'' *IEEE Trans. Power Syst.*, vol. 9, no. 1, pp. 22–28, Feb. 1994.

[51] Y. Jiang and T. H. Ortmeyer, ''Propagation-based network partitioning strategies for parallel power system restoration with variable renewable generation resources,'' *IEEE Access*, vol. 9, pp. 144965–144975, 2021.

[52] S. L. Podvalny and E. M. Vasiljev, ''Digital twin for smart electricity distribution networks,'' *IOP Conf. Mater. Sci. Eng.*, vol. 1035, Sep. 2021, Art. no. 012047.

[53] M. Wang, C. Wang, A. Hnydiuk-Stefan, S. Feng, I. Atilla, and Z. Li, ''Recent progress on reliability analysis of offshore wind turbine support structures considering digital twin solutions,'' *Ocean Eng.*, vol. 232, Jul. 2021, Art. no. 109168.

[54] A. W. Momber, T. Möller, D. Langenkämper, T. W. Nattkemper, and D. Brün, ''A digital twin concept for the prescriptive maintenance of protective coating systems on wind turbine structures,'' *Wind Eng.*, vol. 46, no. 3, pp. 949–971, Jun. 2022.

[55] A. M. Lund, K. Mochel, J.-W. Lin, R. Onetto, J. Srinivasan, P. Gregg, J. E. Bergman, J. R. K. D. Hartling, A. Ahmed, and S. Chotai, ''Digital twin interface for operating wind farms,'' U.S. Patent 9 995 278, Jun. 12, 2018.

[56] S. K. Andryushkevich, S. P. Kovalyov, and E. Nefedov, ''Composition and application of power system digital twins based on ontological modeling,'' in *Proc. IEEE 17th Int. Conf. Ind. Informat. (INDIN)*, Helsinki, Finland, Jul. 2019, pp. 1536–1542.

[57] A. Bonetti, C. Harispuru, M. Pitzer, M. Pustejovsky, N. Wetterstrand, and S. Kachelries, ''Digital twin technology for virtual testing of power system relay protection,'' in *Proc. 3rd Global Power, Energy Commun. Conf. (GPECOM)*, Oct. 2021, pp. 154–160.

[58] A. Raqeeb, A. Bonetti, A. Carlsson, C. Harispuru, M. Pustejovsky, and N. Wetterstrand, ''Functional digital twins of relay protection and relay test equipment enabling benefits in training and remote support,'' in *Proc. 16th Int. Conf. Develop. Power Syst. Protection (DPSP)*, 2022, pp. 129–134.

[59] S. Kuber, M. Sharma, A. Bonetti, C. Harispuru, and A. Soroush, ''Virtual testing of protection systems using digital twin technology,'' in *Proc. 75th Annu. Conf. for Protective Relay Engineers (CPRE)*, Mar. 2022, pp. 1–8.

[60] P. Moutis and O. Alizadeh-Mousavi, ''Digital twin of distribution power transformer for real-time monitoring of medium voltage from low voltage measurements,'' *IEEE Trans. Power Del.*, vol. 36, no. 4, pp. 1952–1963, Aug. 2021.

[61] A. Kavousi, T. Niknam, and M. FotuhiFiruzabad, ''Stochastic reconfiguration and optimal coordination of V2G plug-in electric vehicles considering correlated wind power generation,'' *IEEE Trans. Sustain. Energy*, vol. 6, no. 3, pp. 822–832, Jul. 2015.

[62] M. Sheikh, J. Aghaei, H. Chabok, M. Roustaei, T. Niknam, A. Kavousi-Fard, M. Shafie-Khah, and J. P. S. Catalao, ''Synergies between transportation systems, energy hub and the grid in smart cities,'' *IEEE Trans. Intell. Transp. Syst.*, vol. 23, no. 7, pp. 7371–7385, Jul. 2021.

[63] B. Kazemi, A. Kavousi-Fard, M. Dabbaghjamanesh, and M. Karimi, ''IoT-enabled operation of multi energy hubs considering electric vehicles and demand response,'' *IEEE Trans. Intell. Transp. Syst.*, vol. 24, no. 2, pp. 2668–2676, Feb. 2022.

[64] K. Esapour, F. Moazzen, M. Karimi, M. Dabbaghjamanesh, and A. Kavousi-Fard, ''A novel energy management framework incorporating multi-carrier energy hub for smart city,'' *IET Gener., Transmiss. Distribution*, vol. 17, no. 3, pp. 655–666, Feb. 2023.

[65] A. A. Elsaeidy, N. Jagannath, A. G. Sanchis, A. Jamalipour, and K. S. Munasinghe, ''Replay attack detection in smart cities using deep learning,'' *IEEE Access*, vol. 8, pp. 13783–137825, 2020.

[66] A. A. Diro and N. Chilamkurti, ''Distributed attack detection scheme using deep learning approach for Internet of Things,'' *Future Gener. Comput. Syst.*, vol. 82, pp. 761–768, May 2018.

[67] Y. Otoum, D. Liu, and A. Nayak, ''DL-IDS: A deep learning–based intrusion detection framework for securing IoT,'' *Trans. Emerg. Telecommun. Technol.*, vol. 33, no. 3, p. 3803, Nov. 2019.

[68] G. Thamilarasu and S. Chawla, ''Towards deep-learning-driven intrusion detection for the Internet of Things,'' *Sensors*, vol. 19, no. 9, p. 1977, 2019.

[69] B. A. Tama and K.-H. Rhee, ''Attack classification analysis of IoT network via deep learning approach,'' *Res. Briefs Inf. Commun. Technol. Evol.*, vol. 3, pp. 1–9, Nov. 2017.

[70] M. Aloqaily, S. Otoum, I. A. Ridhawi, and Y. Jararweh, ''An intrusion detection system for connected vehicles in smart cities,'' *Ad Hoc Netw.*, vol. 90, Jul. 2019, Art. no. 101842.

[71] H. Wang, J. Ruan, G. Wang, B. Zhou, Y. Liu, X. Fu, and J. Peng, ''Deep learning-based interval state estimation of AC smart grids against sparse cyber attacks,'' *IEEE Trans. Ind. Informat.*, vol. 14, no. 11, pp. 4766–4778, Nov. 2018.

[72] T.-E. Huang, Q. Guo, H. Sun, C.-W. Tan, and T. Hu, ''A deep spatial–temporal data-driven approach considering microclimates for power system security assessment,'' *Appl. Energy*, vol. 237, pp. 36–48, Mar. 2019.

[73] M. N. Hasan, R. N. Toma, A.-A. Nahid, M. M. M. Islam, and J.-M. Kim, ''Electricity theft detection in smart grid systems: A CNN-LSTM based approach,'' *Energies*, vol. 12, no. 17, p. 3310, 2019.

[74] R. R. Bhat, R. D. Trevizan, R. Sengupta, X. Li, and A. Bretas, ''Identifying nontechnical power loss via spatial and temporal deep learning,'' in *Proc. 15th IEEE Int. Conf. Mach. Learn. Appl. (ICMLA)*, Dec. 2016, pp. 272–279.

[75] Y. He, G. J. Mendis, and J. Wei, ''Real-time detection of false data injection attacks in smart grid: A deep learning-based intelligent mechanism,'' *IEEE Trans. Smart Grid*, vol. 8, no. 5, pp. 2505–2516, Sep. 2017.

[76] Z. Zheng, Y. Yang, X. Niu, H. N. Dai, and Y. Zhou, ''Wide and deep convolutional neural networks for electricity-theft detection to secure smart grids,'' *IEEE Trans. Ind. Informat.*, vol. 14, no. 4, pp. 1605–1615, Apr. 2018.

[77] A. Sayghe, J. Zhao, and C. Konstantinou, ''Evasion attacks with adversarial deep learning against power system state estimation,'' in *Proc. IEEE Power Energy Soc. Gen. Meeting (PESGM)*, Aug. 2020, pp. 1–5.

[78] Y. Zhang, J. Wang, and B. Chen, ''Detecting false data injection attacks in smart grids: A semi-supervised deep learning approach,'' *IEEE Trans. Smart Grid*, vol. 12, no. 1, pp. 623–634, Jul. 2020.

[79] H. Yang, L. Cheng, and M. C. Chuah, ''Deep-learning-based network intrusion detection for SCADA systems,'' in *Proc. IEEE Conf. Commun. Netw. Secur. (CNS)*, Jun. 2019, pp. 1–7.

[80] S. Ahmadian, H. Malki, and Z. Han, ''Cyber attacks on smart energy grids using generative adverserial networks,'' in *Proc. IEEE Global Conf. Signal Inf. Process. (GlobalSIP)*, Nov. 2018, pp. 942–946.

[81] W. Danilczyk, Y. L. Sun, and H. He, ''Smart grid anomaly detection using a deep learning digital twin,'' in *Proc. 52nd North Amer. Power Symp. (NAPS)*, Apr. 2021, pp. 1–6.

[82] N. Khaled, B. Pattel, and A. Siddiqui, *Digital Twin Development and Deployment on the Cloud: Developing Cloud-Friendly Dynamic Models Using Simulink®/SimscapeŮ and Amazon AWS*. New York, NY, USA: Academic, 2020.

[83] X. Song, H. Cai, J. Kircheis, T. Jiang, S. Schlegel, and D. Westermann, ''Application of digital twin assistant-system in state estimation for inverter dominated grid,'' in *Proc. 55th Int. Universities Power Eng. Conf. (UPEC)*, Sep. 2020, pp. 1–6.

[84] X. Song, T. Jiang, S. Schlegel, and D. Westermann, ''Parameter tuning for dynamic digital twins in inverter-dominated distribution grid,'' *IET Renew. Power Gener.*, vol. 14, no. 5, pp. 811–821, Apr. 2020.

[85] S. S. Reka and T. Dragicevic, ''Future effectual role of energy delivery: A comprehensive review of Internet of Things and smart grid,'' *Renew. Sustain. Energy Rev.*, vol. 91, pp. 90–108, Aug. 2018.

[86] Y. Zhang, T. Huang, and E. F. Bompard, ''Big data analytics in smart grids: A review,'' *Energy Informat.*, vol. 1, no. 1, pp. 1–24, Dec. 2018.

[87] G. Carvalho, B. Cabral, V. Pereira, and J. Bernardino, ''Computation offloading in edge computing environments using artificial intelligence techniques,'' *Eng. Appl. Artif. Intell.*, vol. 95, Oct. 2020, Art. no. 103840.

[88] S. M. Miraftabzadeh, M. Longo, F. Foiadelli, M. Pasetti, and R. Igual, ''Advances in the application of machine learning techniques for power system analytics: A survey,'' *Energies*, vol. 14, no. 16, p. 4776, Aug. 2021.

[89] N. Khaled, ''Streamlined process for cloud based diagnostics using Amazon web services,'' SAE Tech. Paper 2021-01-0159, 2021, doi: 10.4271/2021-01-0159.

[90] T. Kong, T. Hu, T. Zhou, and Y. Ye, ''Data construction method for the applications of workshop digital twin system,'' *J. Manuf. Syst.*, vol. 58, pp. 323–328, Jan. 2021.

[91] C. Brosinsky, D. Westermann, and R. Krebs, ''Recent and prospective developments in power system control centers: Adapting the digital twin technology for application in power system control centers,'' in *Proc. IEEE Int. Energy Conf. (ENERGYCON)*, Jun. 2018, pp. 1–6.

[92] V. N. Shvedenko and A. E. Mozokhin, ''Methodological foundations for the formation of information space and digital twin objects in smart Homes,'' *Autom. Documentation Math. Linguistics*, vol. 53, no. 6, pp. 303–308, Nov. 2019.

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