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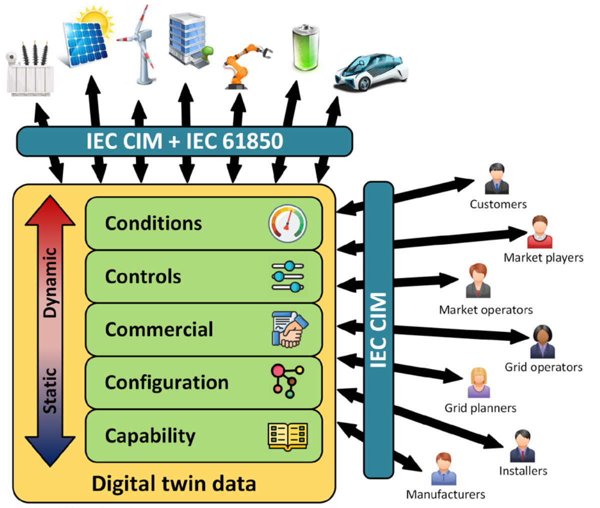
White Paper

Virtualizing power systems: how digital twins will revolutionize the energy sector

Executive summary

A digital twin is a digital representation of a target entity with data connections that enable convergence between the physical and digital states at an appropriate rate of synchronization [1][1]. This white paper focuses on the implications of the electrical power grid within the energy sector as a target entity. Effective use of digital twin technologies can help grid planners and grid operators in a number of important ways:

- Meet net-zero goals
- Handle accelerating load growth
- Support grid resiliency and security
- Support distribution-connected energy resource proliferation
- Overcome infrastructure challenges
- Adapt to climate change



Source: GridOptimize LLC

Models and simulations in the power system are nothing new. What is new is building highly accurate models and sharing those models among departments within electric utilities and between electric utilities in order to support a wide range of planning and operations.

These models come in two basic forms:

Equipment models describe the internal functions of individual devices. They enable analysis and understanding of individual device behaviours, which is vital to the utility's asset management practices.

Grid models describe how equipment is connected into a cohesive system operating as a whole. They enable full-scale grid simulations essential for planning, protecting, and operating today's increasingly complex power system.

As interdependencies grow from a more connected society, alongside traditional users of power system grid models, there will be new consumers of this data. They will include new entities in the electricity sector, such as suppliers of home devices that monitor the value and environmental impacts of electricity usage. In anticipation of new sector coupling, digital twins can help prepare for better collaboration between entities with radically different data needs. For example, the electricity sector will need to work closely with the emerging green hydrogen sector, and with other energy related sectors which will see increased collaboration, such as the electric vehicle network. Building digital twins for such complex systems is not trivial. And building digital twins while the grid is evolving so rapidly is, as the saying goes, "like building the plane while flying".

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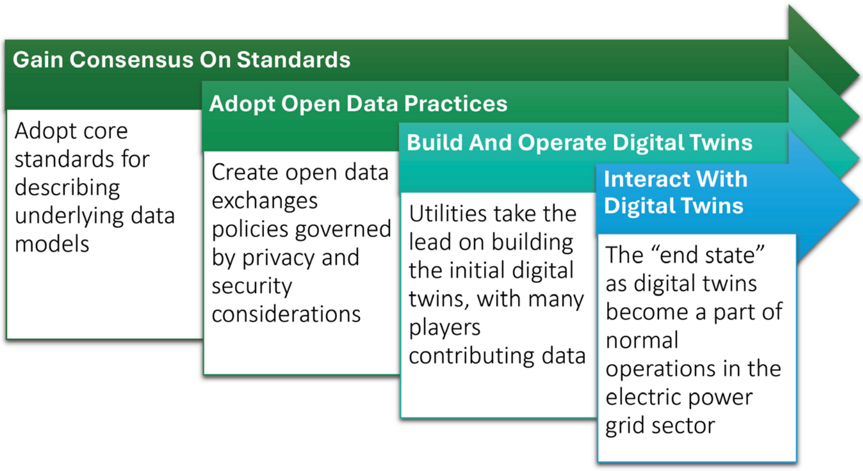
[1] Numbers in square brackets refer to the Bibliography.

One of the key areas of modelling that requires more exploration is the new "grid edge". Utilities and parties connected to the power grid must share more information so that resources like battery storage and electric vehicles can be utilized to achieve the goals of a reliable grid that is economical and supports a green future.

Data from the grid edge married to utility grid models form the core of the digital twin, including data covering all phases of the grid lifecycle. This paper introduces the concept of the five "C" datasets to describe these data: capability data, configuration data, commercial data, controls data, and conditions data. This white paper's recommendations provide tangible actions that government agencies, standards bodies, and digital twin stakeholders can take to unlock the potential of digital twin technologies and their revolutionary impact on the energy sector of the future.



Gain Consensus On Standards

Adopt core standards for describing underlying data models

Adopt Open Data Practices

Create open data exchanges policies governed by privacy and security considerations

Build And Operate Digital Twins

Utilities take the lead on building the initial digital twins, with many players contributing data

Interact With Digital Twins

The "end state" as digital twins become a part of normal operations in the electric power grid sector

Acknowledgments

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List of abbreviations

Technical and scientific terms

AC	alternating current
AGC	automatic generation control
AI	artificial intelligence
AMI	advanced metering infrastructure
AMR	automatic meter reading
AR	augmented reality
BECCS	bioenergy with carbon capture and storage
CGMES	common grid model exchange standard
CIM	common information model
DC	direct current
DER	distributed energy resource
DLMP	distribution locational marginal price
DTI	digital twin instance
DTP	digital twin prototype
EM	electromagnetic
EMS	energy management system
EMT	electromagnetic transient
ESMP	European-style market profile
GEI	global energy interconnection
GHG	greenhouse gas
HIL	hardware-in-the-loop (testing)
IDPP	intelligent digital power plant
IED	intelligent electronic device
IOP	interoperability event
IoT	Internet of Things
IT	information technology
JTC	joint technical committee (ISO/IEC)
LMP	locational marginal price

LTDS	long term development statement
NEMF	numerical electromagnetic field
OPC-UA	open platform communications unified architecture
PLC	powerline carrier
PTP	Precision Time Protocol (IEEE)
RF	radio frequency
RSC	regional security coordinator
SC	subcommittee
SCADA	supervisory control and data acquisition
SDG	United Nations Sustainable Development Goal
SDO	standards developing organization
SGAM	smart grid architecture model
SIL	software-in-the-loop (testing)
TC	technical committee
TSO	transmission system operator
UHV	ultra-high voltage
UML	unified modelling language
V2G	vehicle-to-grid
VR	virtual reality

Organizations, institutions, companies and organizations structures

ANSI	American National Standards Institute
BPA	Bonneville Power Authority
ENTSO-E	European Network of Transmission System Operators for Electricity
ERCOT	Electric Reliability Council of Texas
IEA	International Energy Agency
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IPCC	Intergovernmental Panel on Climate Change

IRENA	International Renewable Energy Agency
ISO	International Organization for Standardization
KEPCO	Korea Electric Power Corporation
KEPRI	Korea Electric Power Research Institute
MSB	IEC Market Strategy Board
NASA	National Aeronautics and Space Administration (US)
Ofgem	Office of Gas and Electricity Markets (UK)
SMB	IEC Standardization Management Board
TMB	ISO Technical Management Board

Glossary

deadband

band of input values in the domain of a transfer function in a control system or signal processing system where the output is zero

feeder

type of electrical line or wire that carries power from a main distribution point, such as a substation, to smaller distribution points or to the end-users

grid edge

area where electricity distribution transitions between the energy utility and the end user

Kirchhoff’s current law

algebraic sum of currents in a network of conductors meeting at a point is zero

Kirchhoff’s voltage law

directed sum of the potential differences (voltages) around any closed loop is zero

Section 1

Introduction

1.1 Mission

The electrical power sector is undergoing the most radical change in its history, which dates back to the deployment of the first power grid nearly 150 years ago. A convergence of factors is stretching power grids to their functional limits, while the electrical power industry strives to decarbonize, promote efficiencies, and prioritize human needs during the transition.

This white paper reassesses digital twin technologies as key tools to address the sweeping challenges of the net-zero transition in the energy sector. It suggests initiating a step change in the role of standards to facilitate the decarbonization, digitalization, and decentralization of the energy sector.

By reassessing the enabling components of highly digital power grids of the future, this white paper demystifies the applicability of digital twin technology for electrical energy sector stakeholders. The text emphasizes the unique benefits of digital twin technologies in integrating renewable energy to deliver maximum benefits for the environment, economy, and for communities today and into the future.

This white paper identifies the key enablers of digital twin technology for the energy sector, dissecting the core components of virtualized power grids through concrete examples. By providing tangible and actionable standards and frameworks, this white paper promotes the capitalization of digital twin technology to revolutionize the energy sector.

Applying digital twins in the power sector has the potential to advance the United Nations Sustainable Development Goals (SDGs). Specifically, power grid digital twins can support:

SDG 7 Affordable and clean energy, by optimizing the placement and operation of renewable energy generation sources

SDG 9 Industry, innovation, and infrastructure, by enabling smart grid technologies, such as self-balancing distribution networks

SDG 11 Sustainable cities and communities, by enhancing urban energy systems, such as improved building load management

SDG 13 Climate action, by improving energy ability to host increasing numbers of distributed and renewable energy sources

1.2 Vision

A revolutionized, decarbonized, digitalized, and decentralized energy sector leveraging digital twin technologies will maximize benefits for the environment, economy, and communities today and in the future.

1.3 Why an energy sector revolution?

Net-zero goals. There is international consensus to reduce greenhouse gas (GHG) emissions as they are associated with global warming and climate change. Net zero is the drive towards balancing human-caused residual GHG emissions with human-led removals [2] resulting in a net-zero increase in GHG in the atmosphere. The Paris Agreement [3] calls for each of the 196 signatory countries to achieve net zero by 2050. As ambitious as that goal is, the looming 45% reduction target for 2030 may be even harder to achieve. According to the International Energy Agency (IEA) [4], global energy usage rebounded in 2021 after the COVID-19 pandemic, leading to the largest ever annual increase in global CO_2 production.

Accelerating load growth. An overall accelerating growth in electricity usage is stemming from many facets of societal transformation, most notably digitalization (converting traditional manual processes into computer-based processes), and electrification (transitioning from fossil-fuel consuming devices like heating systems and vehicles). Energy justice, which aims to ensure the fair and equitable distribution of the benefits and burdens associated with energy production, distribution, and consumption, also promises to generate an increase in electricity needs to achieve fairness and inclusiveness.

Distribution-connected energy resource. Another factor driving change is the large number of customers installing local, small-scale generation devices like solar and wind generation on the distribution system. This disrupts the long-standing design of power grids, which facilitate the flow of energy from large-scale generation on the transmission system to loads on receiving distribution systems. While the deployment of distributed energy resources (DERs) is an overall positive development allowing customers to take part in the net-zero transition, operating power grids in this way requires re-engineering and might necessitate protection scheme reconfigurations and costly grid upgrades.

Infrastructure challenges. By 2030, renewable power will likely surpass 10 terawatts globally, nearly quadrupling the current capacity [5]. This brings to the forefront the limitations of existing transmission capacity, making infrastructure modernization and transmission system expansion a priority. Investment in infrastructure renovation and expansion projects is crucial for facilitating the energy transition and accommodating DERs. The importance of these efforts will be heightened in the coming decades with the increasing prominence of renewable energy sources, whose variability requires robust, flexible grid networks. In other words, infrastructure developments must be aligned with long-term planning and reflect broader strategies, including introduction of local and regional energy markets

Adapting to climate change. In its most recent analysis [6], the Intergovernmental Panel on Climate Change (IPCC) has data to show that major tropical cyclones have increased globally in the last four decades. Severe storm activity has affected power generation, transmission, and particularly distribution systems that extend to the customer's electricity meter. In short, the more severe and the more frequent storm activity, the harder it is to keep the power grid both stable and affordable.

In the electricity sector, resilience refers to a grid's reduced vulnerability to multiple failures, whether due to temporary outages or permanent damages to network and control equipment. Extreme weather and rising temperatures caused by GHG emissions will affect the entire energy sector. With climate change, extreme weather, and increasing power outages, critical electricity infrastructure will need to be both resilient and digitalized to facilitate rapid response and grid optimization.

1.4 Implications of inaction

Accelerating load growth, variability of renewable generation (particularly in distribution systems), limitations of existing transmission system infrastructure, and increasing challenges of extreme weather are together causing a decrease in grid resiliency and complicating efforts to realize the full potential of renewable energy generation in the electricity sector. Developers proposing renewable energy sources are already facing interconnection approval delays and higher costs.

Digital twin technology as a predictive tool to mitigate or eliminate risk is the industry's best strategy for counteracting the increasing loss of power grid resiliency caused by ever-increasing demand, lagging rates of investment in grid infrastructure, and the increasing physical effects of a changing global climate. Digital twins can enable grid designers, grid operators, and grid users to better coordinate the challenges of today and support the increasing pressures and varying requirements of the future. If properly designed with well-organized data ready for use by both traditional grid players and society in general, digital twins will help bring certainty and stability to a future that is currently very uncertain.

1.5 What is a digital twin?

In recent years the term "digital twin" has become quite popular in the marketing arena. However, the concept is more than just marketing; it describes a technology that can bring immense benefits if used correctly. The IEC formally defines a digital twin as a "digital representation of a target entity with data connections that enable convergence between the physical and digital states at an appropriate rate of synchronization" [1].

In their groundbreaking research entitled *Digital Twin: Mitigating Unpredictable, Undesirable Emergent Behaviour in Complex Systems*, authors Michael Grieves and John Vickers conceptualized the digital twin and distinguished two fundamental types [7]:

- A **digital twin prototype** (DTP) is used to model the physical system before it is produced so that simulations can be performed to improve the design.
- A **digital twin instance** (DTI) is used to describe an instance of the production version of the physical device throughout the life of that device.

Grieves and Vickers applied the concept of digital twin to NASA projects. Accordingly, here the design of a new rocket engine is used as an example where a DTP of the engine is created and refined during the design process. If seven engines were produced based on the shared DTP, each physical engine would have its own DTI tracking the data associated with its individual lifecycle.

In this context, individual pieces of electrical current-conducting equipment used in the power system can benefit from the digital twin modelling process. From relatively simple devices, such as a line switch, to those as complicated as a hydroelectric or nuclear power plant, the use of DTPs and DTIs can improve design and manufacturing. The more impactful case, however, may be the power grid itself. Power grids are complex, interconnected systems, made up of many components that all work together to keep the voltage and frequency stable for each synchronous system.

Consider a grid operator who must expand a power grid with a new undersea transmission line to connect a planned offshore wind farm. To study different configurations of the new grid, a grid planner uses a digital twin of the existing power system (the grid DTI) with an added model of the proposed wind farm (a small grid DTP including multiple turbine string component DTPs and their relationships), plus several options for the transmission line (again, each option would be a small grid DTP made up of component DTPs and their relationships). The DTI of the existing power system can be combined with the DTP of the farm plus one of the transmission line option DTPs to create an assembled DTP of one alternative for a complete future grid. The various assembled DTPs can be utilized in system studies throughout the project planning and the design and construction process, with a single DTP ultimately emerging as representing the grid design to be energized. Once energization occurs, the assembled DTP becomes the next version of the DTI, adding to the DTI lifecycle history.

During the process of evaluating and culling alternatives, assembled DTPs are used by multiple software tools to perform different types of system simulation studies. Since all the assembled DTPs are expressed in a consistent form (i.e. the same data structure and format) the effort can focus on analyzing simulation results rather than on transforming or manually entering data.

Features that distinguish this approach from historical approaches to managing grid data required to support grid planning, design, construction, and operation include:

- A digital twin of the power system describing the behaviours of each relevant component of the electrical grid.
- A digital twin of the power system documenting how all components are assembled into an interactive network.
- A digital twin of the power system evolving over time with a single history incorporating both planned changes scheduled by the utility and unplanned changes resulting from equipment failures and environmental forces.
- A digital twin of the power system capturing many possible future states with different options for upgrades and expansions and with varying predictions for the many energy producers and consumers.
- A digital twin of the power system managed as a centralized “single source of truth” and thus capable of being uniformly shared with different users.
- A digital twin of the power system that can be leveraged in different tools to simulate different scenarios aligned with the goals of those users.

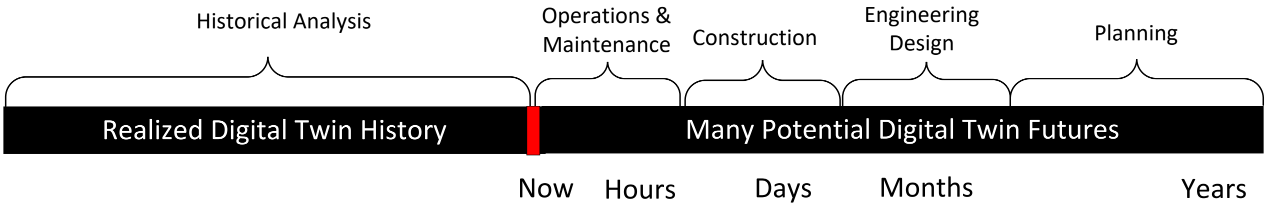


Figure 1-1 | Time-evolving electrical power system digital twin

As shown on the left in Figure 1-1, the power system digital twin (DTI) has a single history evolving over time. A grid operator's planning department has the most future-looking system digital twins (various DTPs), with different planning scenarios associated with different predictions that require different countermeasures to reinforce the grid. Over time, as the future becomes more certain, the engineering design group and the grid operator will be able to create construction plans that address the needs of the grid. This process typically narrows the number of DTPs to one. Those plans are then passed to construction crews who build or reinforce the grid as instructed. Finally, during a process called “energization”, the grid operator energizes the new or upgraded circuits. By that point, it is known which of the multiple future DTPs has been realized, and the associated set of grid changes becomes part of the DTI.

A final note here: each digital twin of a network owned by a single grid operator can interconnect both “horizontally” across transmission grids and “vertically” between transmission and distribution grids. Taking this philosophy to the extreme, all grid operators manage their part of the federated, time-evolving, interconnected electrical power system digital twin.

Section 2

Digital twins today

2.1 The origin story

The most unique feature of digital twins for the electrical power grid is the term “digital twin” itself. Throughout the history of the electric grid, engineers have established digital twins leveraging the technologies of the day to build ever-more-complex models of the power systems. Setting aside the many years when calculations were done by hand on paper, the first major innovation occurred with the advent of computers in the 1950s.

The digital era of power system models was launched in that decade by Glenn Stagg, Homer Brown, Bruce Shipley, Harvey Happ, and other pioneers working to explore computer simulation techniques. By the 1960s, early versions of planning software were utilized to support previous manual calculations, and near the end of the decade two major developments transformed the industry. First, digital supervisory control and data acquisition (SCADA) for automatic generation control (AGC) systems became available to replace analogue controls in transmission control centres. Second, Bill Tinney, and John Walker at Bonneville Power Authority (BPA) in the United States wrote several landmark grid analysis papers [8] outlining computational methods that could solve much larger problems than were feasible by prior methods. Jay Britton, contributing author to this paper, was one of the first to utilize these techniques when he successfully created a three-thousand node tool used for planning power flows.

As every year passed, advances in computer science, in both hardware and software, facilitated development of more sophisticated software tools. Sector trends in the 1960s included several advancements. The first was the inception of the energy management system (EMS) for transmission operations with a detailed simulation capability known as “state estimation”, which took in measurements and fit them to a model of the present state of the grid. Then, leveraging similar methods in an off-line mode, other applications were developed to analyze grid reliability and other concerns. In the long-term planning domain, suites of planning analysis applications came to market and were put into use across the globe allowing grid owners and operators to make better decisions on grid design and development.

Over time, punch cards were replaced with file-based systems, making the editing far more flexible. This led to neighbouring utilities being able to share their files to perform wide-area analyses. In the 1980s, EMSs with state estimation and other simulation applications became the norm; but data quality and data management lagged.

By 1990, most transmission control centres had assigned sufficient personnel to scrub data and get all major simulation applications running in real-time, based on state estimation providing minute-to-minute simulation of the grid. Most EMSs required an engineer dedicated to grid modelling data quality to get a state estimator to “converge”, meaning solving the complex mathematics to create a solution obeying Kirchhoff's laws across the system. Data management tools also improved, although maintaining accurate models of constantly evolving neighbouring systems proved difficult.

In the 1990s, capabilities had progressed so that electricity markets could be introduced based on algorithms like locational marginal pricing, which worked from the state estimation of the grid. With the integration of data quality practices, projections and grid modelling, digital twins became deeply embedded in both grid reliability and grid economics. Where in past decades the grid tended to be overbuilt due to a lack of precise knowledge about how it would perform, now successful operation of the grid was digital-dependent. Computers became cheaper and thus a better option than overbuilding the grid, and common techniques emerged to create power system digital twins in uniform ways.

The 21st century has seen significant transformation in both power systems and their digital twins. For the first time, common models of the grid were being exchanged not only within utilities but also between them in non-proprietary formats. Beginning in 2009, the Electric Reliability Council of Texas (ERCOT), the grid and market operator for that US state, began collecting grid representations from its member transmission utilities using IEC-based standard data exchanges. ERCOT's first model included more than two million individual conducting equipment elements, and during its first decade of operation, it added more than one million new elements, removed half a million old elements, and made hundreds of thousands of parameter changes.

Europe went further, implementing the common grid model exchange standard (CGMES) for all European Union member countries. Like the ERCOT implementation (which collects individual utility models to assemble a grid model for its entire balancing area), each regional security coordinator (RSC) in Europe assembles models from its member transmission system operators (TSOs) in order to facilitate grid congestion forecasting. The roughly 40 TSOs in Europe publish their grid models updated every hour of every day for current conditions including unplanned outages and circuit rating changes. Each RSC then assembles its regional model, performs a power flow analysis, and publishes that model back to the TSOs.

To better understand how grid models can be exchanged, it is important to understand what a grid model is and what it contains. The following sections explain how models of equipment and models of connectivity are used to build grid models.

2.2 Equipment models

The topology of the electrical grid has the key role in any power system digital twin, and it is imperative to understand this foundation before transactional data can be introduced. The representation of the electrical grid must be known in its current state to efficiently operate the grid. This representation is, in fact, the digital twin instance, and is more commonly known in the industry as the "as-built" grid model. A log of grid modifications is kept so that the grid can be traced back in time and incidents can be analyzed to determine causes to inform decisions on grid improvements. Grid planners must also map many potential future states of the grid, or digital twin prototypes, which accommodate anticipated changes to generation sources, consumer loads, and grid equipment owned and operated by each utility.

The electrical grid representation is comprised of individual representations of each piece of equipment installed on the grid. The equipment model tracks the unique characteristics of each type of device, including parameters to track intrinsic values such as line impedance, and operational constraints such as line rating.

Large or complex equipment, like substation transformers and high-voltage transmission lines, have dedicated models, either supplied by the manufacturer or assembled from calculations based on physical characteristics or measured in the field. These models can be thought of as simplified versions of the manufacturing models, retaining only the electrical information needed to perform grid modelling and operations.

Equipment models often incorporate behaviours, including response functions that emulate how the device will operate under changing conditions such as voltage or grid frequency fluctuations. The numerous simple and smaller pieces of equipment, pole-mounted distribution transformers for example, have equipment models that are "shared", meaning typical values are used for all instances.

2.3 Connectivity models

Equipment models are only half the picture. A connectivity model must be created to describe how the equipment is deployed and wired together. A key element of the connectivity model is the terminal. Each piece of equipment in the field has one or more terminals. A breaker or a segment of conductor installed as a distribution line, for example, has a terminal on each end. Other devices, a busbar for instance, might have more than two terminals, while some simple representations of an "edge-of-the-grid" device might be represented with just one.

The terminal connections of each device must be tracked. While much of the equipment can be tracked as a series of connected devices, in many cases the grid is a meshed system. This means the connections are more difficult to track. Indeed, studies utilizing the models need complex algorithms to solve for the flow of power. This complexity comes because the laws of physics require a simultaneous balance across the grid, a balance based on both the intrinsic parameters in the equipment models and the ways in which the devices are wired in the connectivity model.

Electricity transmission systems have relatively few pieces of equipment and hence the model is relatively simple. However, the overall importance of the grid model for transmission is very high. Problems with transmission models can lead to problems operating the grid that can cascade into major outages.

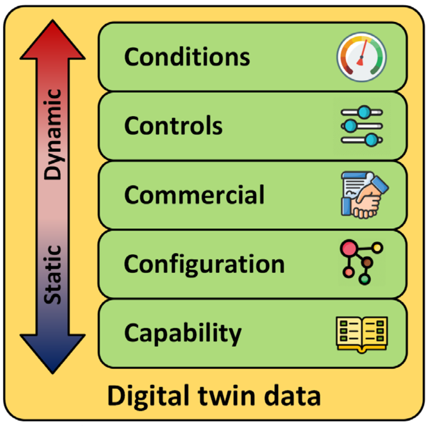
Electricity distribution systems have many more pieces of equipment in their models than transmissions systems do. The amount of equipment to be tracked from a typical utility can number in the millions. Fortunately, the implications of errors in the model generally lead to smaller grid impacts. And since sophisticated studies have not been needed up to now, the challenge of building highly detailed, highly reliable distribution grid models has been largely ignored.

Digital twins offer a revolutionary approach to addressing the complexities and challenges within both electricity transmission and distribution systems. By creating virtual replicas or clones, of physical grid components and their interconnections, digital twins allow for real-time simulation, manipulation, and analysis of the entire grid's behaviour under various scenarios, including sudden storm conditions, emergencies, failures, and planned future modifications. This dynamic modelling capability enables more accurate prediction of system responses: it facilitates the identification of potential issues before they lead to outages, and it assists in planning and testing grid upgrades in a virtual environment – all before actual implementation.

The management process becomes even more challenging when the weather creates storm damage and field crews must make quick fixes to the grid to restore normal operations. Looking to the future, grid planners and engineers will design a set of proposed changes to the grid with new elements using equipment models and a set of proposed changes to the connectivity model. Using both predictive models and live data on storm conditions, digital twins can help grid operators manage damage to grid equipment, guide field crews to make the most effective repairs and to help anticipate the consequences on the immediate grid stability. Ultimately, the adoption of digital twins in power system management promises to produce greater reliability, efficiency, and adaptability in grid operations. In other words, digital twins will be a key tool in the modernization of electrical grids.

2.4 Organizing digital twin data

A digital twin consists of very complex collections of datasets with relationships among the data. Unlike some datasets, such as online sales records or the generation of artificial intelligence (AI) artwork, the data inside a digital twin are constrained by the laws of physics. To better visualize these datasets, one can group them into categories. The formalization adopted in this white paper is shown in Figure 2-1.



Source: GridOptimize LLC

Figure 2-1 | The five “C” datasets

Datasets closer to the bottom of the figure represent static or semi-static information which is essential to understanding equipment and connectivity of the digital twin. As one moves higher in the stack, data become more dynamic, with the highest level representing measurements that may be as granular as sub-cycle resolution. Descriptions of the five “C” datasets are provided in Table 1.

Table 1 | The five “C” datasets

Dataset	**Description**
Capability	Information related to a given manufacturer's make and model of a device related to the limits of its operation, typically known as nameplate, datasheet, or catalogue data; for example, maximum power output
Configuration	Information about the device as it is installed and configured, including the electrical connection and the operational and protection settings; for example, how a transformer is installed in a substation
Commercial	Information about the commercial agreements (contracts) to which the device is subject, including rates, grid services definitions, and aggregation constituencies; for example, an agreement to provide backup power
Controls	Instructions issued to the device, including real and reactive power profiles and grid support service schedules effective immediately or for a future time or times; for example, a battery discharge schedule
Conditions	Measurements collected from sensors embedded or attached to devices including variables such as real, reactive, and apparent power, voltage, and frequency; for example, the terminal voltage at a meter

Section 3

Drivers of radical change

3.1 The new grid edge

Historically, power grid design was relatively straightforward with power flowing in predictable ways from large-scale generation through networks of transmission lines, stepped down to distribution systems, to be finally consumed by electricity customers. Historical interconnections for generation were large-scale facilities, where each type of facility – whether coal, natural gas, or nuclear – came with decades of historical performance information. Now, interconnections are much more complex. New bulk generation often comes primarily from large-scale wind and solar. While the peak output can be understood based on the capabilities of the generation devices, knowing when those peaks happen is dependent on climate and weather patterns.

Loads are, arguably, evolving more quickly than generation. In addition to distributed generation – which is also primarily weather-sensitive – the loads themselves are more complicated. Factors that contribute to this challenge include less regular work schedules; the electrification of more devices, including heating systems and industrial automation; and perhaps, most critically, increasing levels of electric vehicles, which add large and effectively random offsets to the base load. In sum, flows are less predictable, and it is now common to see systems that were designed to flow in one direction reverse with excess generation in places that historically saw only electricity usage.

The effect of load and generation volatility has created a greater need for utilities to understand these new features “behind” the customer’s meter. Thus, for it to be a useful tool, the digital twin, which historically ended at the customer’s meter, now must extend farther. Access to such information is problematic for many reasons. First, there are privacy issues: until there are clear guidelines from governmental bodies, there will be only fragments of intelligence. Second, there are technical challenges: utilities are skilled in the proprietary communication protocols implemented on dedicated networks to monitor their own equipment, but these systems are not well suited to reach into the customer’s equipment. The final challenge is scale. If standards and privacy challenges are resolved, there remains the significant challenge posed for utilities looking to expand their connections from a few hundred to millions of devices on a decentralized power grid.

3.2 Energy storage

Energy storage refers to the capture and containment of energy produced at one time for use later. This concept plays a crucial role in balancing supply and demand in the power grid, enabling the storage of excess energy generated during low demand periods to be released during periods of high demand. Energy storage is critically important as variable renewables sources become a larger fraction of the installed generation capacity [9].

Battery energy storage has become the dominant technology, but it remains expensive to manufacture and install. Roundtrip inefficiencies converting AC power from the grid to DC power in the battery and back leads to significant losses. Developers are now installing systems with direct battery charging from renewable generation to reduce the number of conversions from three (DC generation to AC to DC storage and back to AC for the grid) to a single conversion (DC generation directly to battery and then a single conversion to AC for the grid).

To properly model these elements in a digital twin, utilities must understand how the connections are made and may need to begin to model DC sub-circuits. Perhaps the biggest challenge of storage systems is prediction, as the owners and operators of storage systems have complete control over their operations and may not be required to disclose their plans to the utility. From the utility's perspective, these resources may seem to operate with completely random patterns.

3.3 Electric transport

Electric transport shares many similarities with battery energy storage systems, and because of the potential scale of vehicles that will be available to interact with the grid, electric transport may ultimately be the most important resource on the grid. But the management challenge for electric transport, and hence the grid modelling challenges, are substantially more difficult than for dedicated battery energy storage systems.

Mobility. Of course, the first difference between electric transport and a stationary battery system is the former's mobility. This means the modelling cannot be defined to a specific location and must be treated as a dynamic resource that can appear anywhere on the grid.

Purpose. Equally important, the primary purpose of electric transport is moving people and goods from place to place. Thus, these resources can play an important role in the grid, but only ever a secondary one. Additional capacity from electric transport is what can reasonably be used without risking the owner's ability to use the vehicle without running out of charge, balancing the need for transportation with the value earned by using the vehicle as a grid resource.

Connection. An additional modelling challenge is related to the financial agreements with different entities. When an electric vehicle charges its battery – or provides grid services – it connects to a charging station, and there can be an agreement with the vehicle owner, the charging station owner, or, in the most complex case, with both.

Section 4

Enablers

4.1 Adopt data-centric thinking

For many years, and for the most part up to the present, companies have purchased software solutions to fit their needs, and those solutions have operated on proprietary data stores. This traditional approach is called an application-centric approach: the emphasis is on the features and functions of each application, with the representation of the data only a secondary concern.

As interoperability has become more important, software developers have created interfaces to allow their solutions to exchange data with other solutions, in some cases with a partner solution and in other cases with competing solutions. This is a step in the right direction, but it is not optimal; it encourages point-to-point solutions, with each application needing a unique interface for each dataset.

Instead of this traditional application-centric approach, a better alternative is a data-centric one. By establishing an enterprise-wide data model that each utility manages, software solutions can operate on the central representation of the data. Of course, the more each software company can adopt a standard model, rather than its own proprietary model, the easier it is for utilities to find solutions that can function on that data without translation.

4.2 Improve sensor measurements

A power grid has a vast number of sensors: sensors in power plants, sensors in substations, sensors along transmission and distribution lines, and sensors embedded in customer-owned electric devices. These sensors measure, among other things, voltage, current, temperature, and phase angle.

Each typical thermal power plant has roughly 20 000 sensor points that stream data, generating on the order of two billion measurement values each day. Extrapolating to the entire grid, the number of sensor points is staggering. The number is over three quadrillion (3 × 10^{15}), allocated to the generation, distribution, transmission (including substation equipment), and customer (including electric meter) domains, according to a study by the Korea Electric Power Research Institute (KEPRI) [10]. See Figure 4-1.

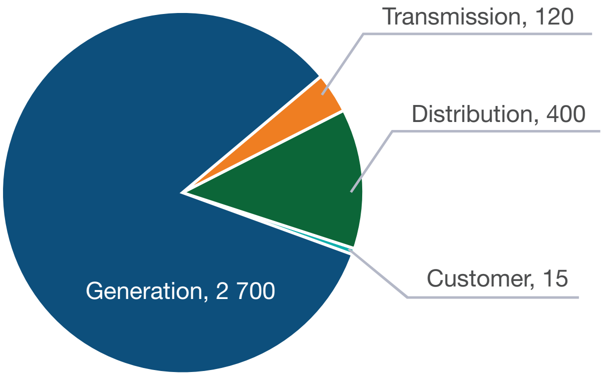


Figure 4-1 | Power grid sensor readings in trillions/year

Many sensor measurement processes can be improved; three of the more important ones are shown in Figure 4-2. All need attention because sensor data is one of the key inputs to power system digital twins.

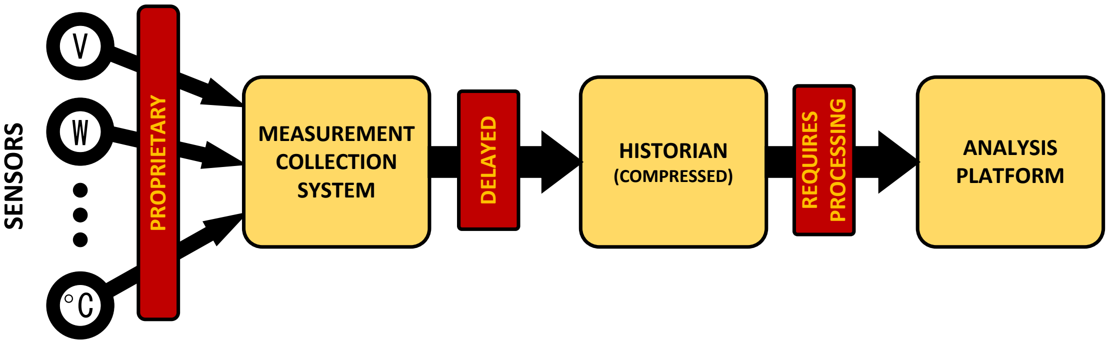


Figure 4-2 | Challenges to sensor data processing

Case study 4-1 – Intelligent digital power plant (IDPP)

Leveraging sensor data from Korea Electric Power Corporation (KEPCO) generation facilities, KEPRI has implemented a pilot system to improve sensor measurements incorporating many of the features identified here. The project has demonstrated several innovative functions including:

- AI-friendly, real-time sensor data management platforms
- SirenX: an early warning system
- AI-based status diagnosis
- IoT-based diagnosis
- Asset performance management

Standard data formats. Even within a single power generation facility, sensors are sourced from different vendors, and the data formats are inconsistent between products, very often using proprietary protocols. In addition to the challenge of different ways of describing similar data sets, many sensors compress readings, for example, by only reporting values outside of a "deadband". Thus understanding measurement data requires knowledge of the data format and the logic employed to store the data.

The IEC 62541 series of standards [11] supports the open platform communications unified architecture (OPC-UA). Wider adoption of this protocol would likely help reduce inconsistently formatted data. OPC-UA may also provide an effective mechanism to publish other power system digital twin datasets, such as equipment details and market information.

Timely access. Another challenge is timeliness. Sensor data collected today is often delayed, and available only later through access to a data historian, a software system optimized to collect, compress, store, and later retrieve large volumes of time-series data. And while useful for analysis of events in the past, the data is often not available to operational systems that might be able to act on the information in near real-time.

Emphasis should be placed on collecting, storing, and exchanging sensor data closer to real-time. Open-source tools readily available in the space could supplant vendor solutions that do not support near real-time data processing.

Analysis-ready datasets. To leverage sensor data effectively today, sophisticated labour-intensive activities are required. Once complete, data can be fed into analysis platforms, including emerging AI processing engines. While not the only issues in this space, time alignment and data interpolation to create complete "snapshots" of the system are prominent ones.

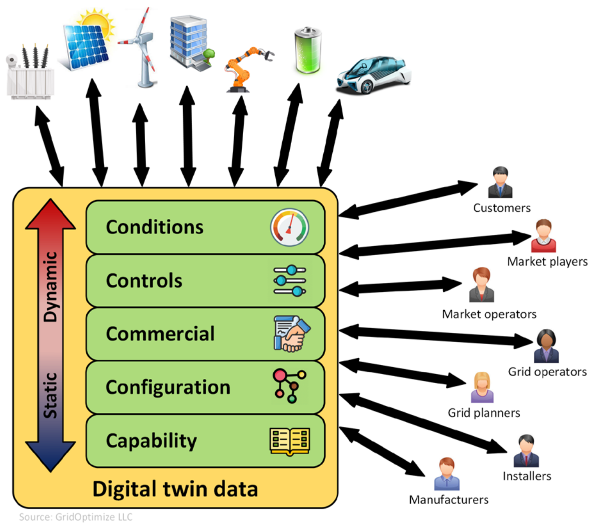
To resolve perhaps the most prevalent issue with sensor data, one should look to IEC 62439. This series of standards focuses on industrial communication networks and, importantly, annexes the IEEE 1588 Precision Time Protocol (PTP). Digital twins can assist in providing a reference model for all the sensor objects, allowing measurement to be tied to established identifiers in the digital twin so that translations to local naming schemes are avoided.

There are many protocols that can be used to communicate controls to devices and to collect measurements from devices. Historically, these communications were implemented using the SCADA protocols; however, SCADA is not well-suited to communicate information outside the utility communications infrastructure. IEC 61850 was developed and deployed to support the need for high-speed, secure communications within substations. This standard has been extended to support communications to the field, including those outside the utility communication infrastructure. It has the potential to become the global standard for field communications.

4.3 Gather data from the grid edge

While today the percentage of sensors at the customer domain is minuscule as a relative percentage (see Figure 4-3), it is likely the area of most growth. There is an explosion of potential sensor data available with customer devices. These devices offer enormous potential benefit if utilities are able to access them and are willing to leverage this data, despite not owning the resource or having full trust in it as a data source.

Devices can provide information and like traditional electricity meters can be certified to high accuracy and reliability metrics. These metrics are not always cost prohibitive, and many devices on the market today are already compliant with utility requirements. With the wall between utility and



Source: GridOptimize LLC

Figure 4-3 | Digital twin with interactions

customer device removed, the knowledge that can be gained is immense. Data can be harvested from devices dedicated to power production and consumption, such as DC/AC inverters and battery systems, which could, for example, provide local voltage measurement. Sensors that can aid in the management of flexible loads, like smart thermostats and controllable water heaters, could also be more seamlessly integrated.

By combining these data with existing sensor measurements in standard formats, available in near real-time, and ready to be fed into analysis engines, the picture of the power system digital twin comes into focus, as shown in Figure 4-3. Open data practices are essential to success on the grid edge, with options that include both regulations mandating exchange of required data and incentives to customers to open their devices up for access.

4.4 Encourage manufacturer data exchange

When a utility company purchases equipment for the grid from a manufacturer, the utility should also request a simulation model of the apparatus. The simulation model should have sufficient accuracy when integrated in the digital twin of the power system. With different types of simulations often necessary, more than one equipment simulation model might also be required. With appropriate equipment simulation models provided by the manufacturers, the utility company can readily perform simulations using the digital twin as soon as the equipment is purchased.

This practice, unfortunately, is quite different from what is actually being done. Today, experts for different simulation types (including transient stability, frequency, voltage, black start, switching, lightning, inrush current, and protection) must build models for the equipment, sometimes inserting parameters for the equipment by hand into published response models. Building a local simulation model can take weeks.

By focusing on the manufacturers and requesting an official model for each piece of equipment, not only is the inefficiency of the utility minimized, but the reliability of the models should also increase. If standards are developed for publishing these equipment response models, aligned to the requirements of the grid operators, this will lead not only to more effective studies but when used in a real-time digital twin can also improve system reliability.

4.5 Explore multiple representations

A challenge to building a digital twin in the electrical power system is the need for multiple visual representations, specifically a geospatial and an electrical layout. The electrical layout is critical for studies and is stored as a complex connectivity model. Very few geospatial characteristics factor into the connectivity model and are generally confined to the lengths and line spacing characteristics of transmission and distribution lines which enable the calculation of line impedance values. However, from the operations perspective, the geospatial layout is the critical representation: it is essential for guiding crew to the correct locations, estimating renewables output, and coordinating with emergency services.

What makes the issue of multiple representations more challenging is that each electrical grid needs both representations, though different portions of the grid have different requirements for each. The connectivity models for transmission systems and radially operated distribution systems can be derived, for the most part, from their geospatial counterparts. Networked distribution systems typically found in metropolitan areas and especially those found underground are much more difficult to manage because lines that cross using a simple two-dimensional geospatial representation do not necessarily connect electrically.

The most complex electrical models exist within substations. Substations have transformers, capacitor banks, circuit breakers, fuses, busses, and other equipment, all in a relatively small geographic space. So here the connectivity model, if paired with a geospatial representation, is likely to require a three-dimensional model. Fortunately, substations constructed today are often designed using three-dimensional computer-aided design tools, and these representations can become part of the digital twin. Augmented reality (AR) technologies, leveraging these models, allow maintenance crews to perform tasks on the physical equipment overlaid with metadata from the digital twin to improve efficiency and increase safety.

In conclusion, digital twins have the capability to hold and present data in different ways and offer a promising solution to the challenge of managing multiple representations of an electrical power system.

4.6 Leverage graph data stores

Electric utilities are not known for their early adoption of new technologies. A practice of being “one version behind” is common, as it allows other users to find the software developers to eliminate not only performance and logic flaws in software but also security weaknesses that if exposed can present major risks to the power grid. This philosophy also extends to data stores. Most utility systems operate on relational databases. While this technology has served the sector well and has its place, exploring the ideas of graph data stores has much promise for digital twin enablement.

Traditional relational databases store data in data tables. Each table has a key formed from one or more columns in the table, which form a unique data record. For example, a customer account number might be the key to the primary account table. Other tables that need to reference the customer account would use the account number key from the account table as a “foreign” key. These relationships are established by the database designer and allow users with an understanding of the meaning of the relationships to query the database by “joining” tables. This approach works very well for large datasets with limited relationships. However, digital twins of the electrical power system include just the opposite: many small datasets with many relationships.

This is where graph data stores enter the picture. They use nodes to store data elements and allow a node to have many relationships, each with a different meaning between itself and other nodes. This is very different from relational data stores, which have rigid relationships, defined “externally” in the database design. Graph data stores allow for a wide range of relationships to be stored along with the nodes and make it easier to build queries.

4.7 Consider data sovereignty

Data sovereignty is a concept that describes the idea of any particular entity maintaining control over its data and of being able to secure its data in accordance with the regulations under which the entity operates, even when data is being exchanged among different countries with different regulations.

Historically, electric utilities have experienced a greater level of sovereignty over their data than other sectors have had over their data. This is primarily because much electric utility data is considered critical to a country's national security and has been exchanged on dedicated networks owned and operated by the utility or on dedicated networks rented from telecommunications companies. Other sectors rely more heavily on public communications infrastructures.

The electrical power system digital twin, however, represents a departure because it not only requires the information collected through the utility communication infrastructure, it also must leverage data collected through public networks. With these new interfaces, there are therefore data sovereignty issues to consider.

Additionally, should the digital twin data repository be hosted outside the utility IT infrastructures, even more data sovereignty issues arise. The challenge becomes still more critical if the data model for the digital twin is federated, with different entities responsible for different components of the model.

4.8 Bridge other sectors

Historically, electrical power systems around the world could operate relatively independently of other complex systems. Any analysis of a particular power system required a good understanding of the grid itself: what the infrastructure would look like at a particular time with load projections based on climate and weather prediction.

Similarly, other sectors, such as the natural gas pipeline sector, had their own systems for planning and operations – largely independent of the electrical systems. Thus, each industry became oriented toward its data models and its industry-specific constraints, functions, and visualizations. Despite similarities in their foundational data constructs, separate development of the data models by different sectors led to divergent systems that are not easily made interoperable.

As the electrical system becomes the leading energy delivery system for the world, we expect to see more coupling with other sectors, such as natural gas, electric transport, and green hydrogen. Successful coupling in the digital world is highly dependent upon strong interoperability standards for data exchange.

Natural gas network digital twins. Over the past few decades, the interdependencies between gas delivery networks and electrical power grids have become more pronounced. This coupling is based on factors like higher dependence on natural gas as a fuel for electricity production (often displacing coal) and the conversion of end-use systems, such as building heating from gas to electricity, primarily. In the short term, these interdependencies are likely to increase. But as natural gas is replaced with renewable sources of both electricity and heating systems, such overlap is likely to become less important.

Hydrogen network digital twins. Governments and industries around the world are investing in the green hydrogen sector. Hydrogen networks will have a highly coupled two-way dependency with electrical power systems, as the hydrogen networks will use electricity when renewable power generation exceeds demand and produce electricity from the stored hydrogen when demand exceeds generation.

Electric transport network digital twins. Even more complex than the interdependence between the power grid and the hydrogen network is that between the power grid and the emerging electric transport network. Like the two-way hydrogen network, the electric transport network will be able to both consume and provide power. But the choice of when vehicles consume or provide energy will be influenced primarily by their owners' need to charge or drive their vehicles, and not on the abundance or scarcity of electricity. When electric vehicles are grid-enabled, the door will be open for electric transport to provide grid support services, commonly known as vehicle-to-grid (V2G) interactions.

As shown in the bottom portion of Figure 4-4, real commodities, including electricity, natural gas and hydrogen, flow among the real physical systems. Every real flow or at least every flow that is important enough to require modelling will need to be represented in virtual space. Here, data captures information about those commodity flows, such as measurements tracking actual flows in near real-time and predictions about anticipated future flows.

Digital twins for these sectors enable comprehensive modelling of their interactions with the power grid, facilitating optimized operation and planning. For instance, natural gas network digital twins can simulate the impact of gas supply on electricity generation, and hydrogen network digital twins can model the dynamic exchange of energy between hydrogen storage and electricity production. Similarly, electric transport network digital twins allow for the coordination of vehicle charging with grid conditions, enabling bidirectional energy flows and grid support services.

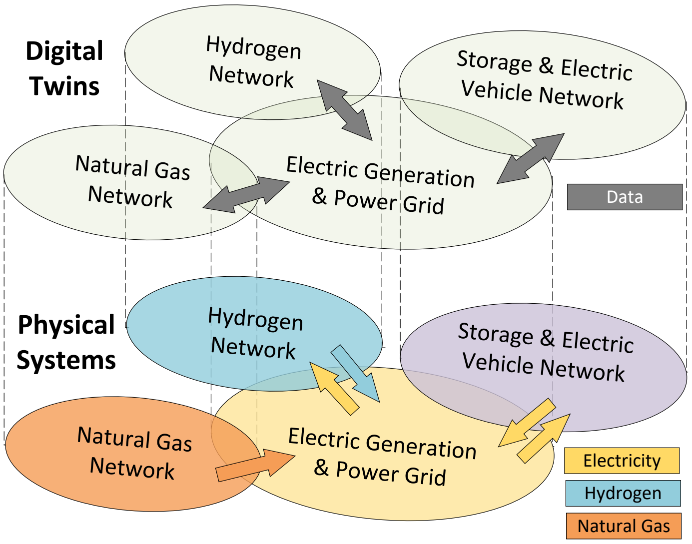


Figure 4-4 | Interdependent physical systems and digital twins

Section 5

Realizing results

5.1 Improve grid planning

The 2016 major power blackout in Australia [12] is an example of how a system can fail, despite every device on the grid operating as designed. Following major storm activity that damaged transmission lines in South Australia, several wind farms tripped offline. The loss of generation in turn triggered a limit violation on a high-capacity import transmission line, islanding South Australia from the rest of the grid, which then experienced a wide-area blackout. Importantly, the generation sources performed as designed, with voltage fluctuations leading to the sources tripping offline as a safety protocol. However, the system likely would have fared better had these generation sources, instead of tripping offline, “ridden through” the issue until the system could recover.

The point here is not to dwell on this failure but to learn from it. More sophisticated digital twins of the grid, which could include models of distributed resources and their operational and off-normal settings, can facilitate more varied study types that can be relied on with greater confidence. The results of such studies can lead to better device settings to help protect both the equipment and the system.

Studies are not only used to identify the root causes of off-normal conditions experienced during infrequent reliability events, like those of the Australian blackout, but are an essential function of every utility’s short-term and long-range planning. Studies are performed before new generation and new loads are approved to interconnect, when major switching activities are scheduled and new circuits are energized, as well as for certain planned maintenance activities. As load and generation, connected to both transmission and distribution networks, change over time, planners must study the grid to see where reinforcements are needed.

As the grid becomes less stable with renewable resources providing a larger portion of the grid’s energy and support services, the need for more sophisticated studies is increasing. Different kinds of studies are performed to analyze a variety of different phenomena across different time domains, as shown in Figure 5-1. These studies include traditional, long-standing, steady-state simulations, transient stability and frequency stability studies that examine sub-second time analysis, and even electromagnetic transient simulation using sub-cycle analyses. There are research initiatives exploring numerical electromagnetic field (NEMF) simulations at even higher resolutions. Generally, the smaller the timescale of the study, (a) the more detail required in modelling the grid representation, (b) the smaller the sections of the grid that are studied at once, and (c) the larger the computing power necessary for calculations.

5.2 Enhance testing and staff training

Conventional approaches to testing protection and automation systems include “open-loop” hardware testing with external test equipment and “closed-loop”, also known as hardware-in-the-loop (HIL), testing with a near real-time digital simulator. The digital twin can provide an alternative because different software-in-the-loop (SIL) stages are possible, starting from open-loop solutions to

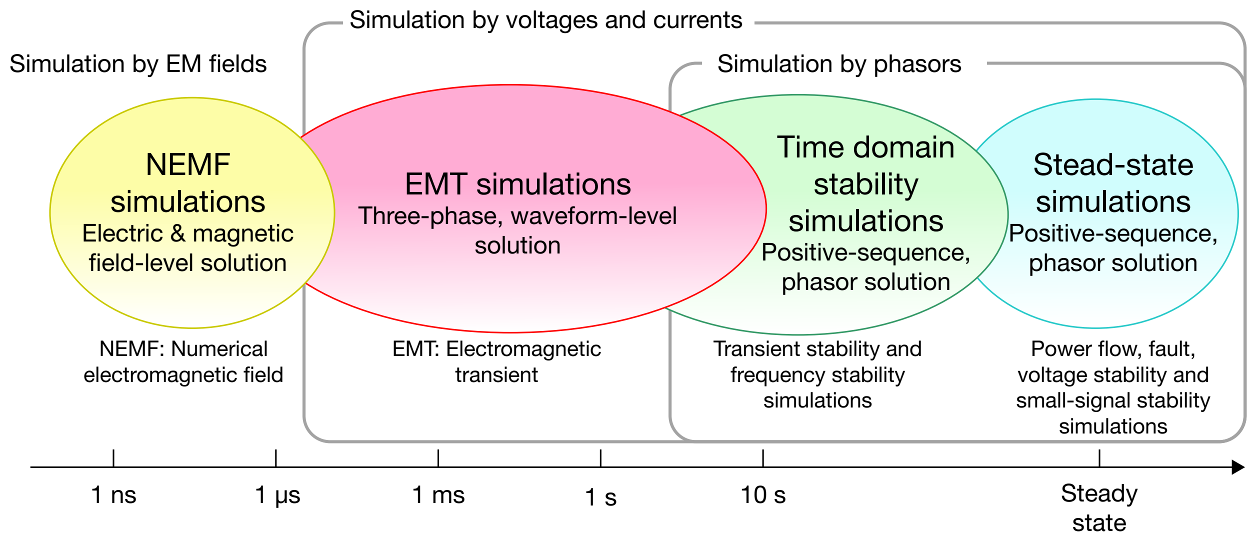


Figure 5-1 | Studies as a function of time domain

fully integrated closed-loop simulations. The test scenarios can be facilitated with a digital twin because testing effort can be focused on the algorithms and the logic of the protection system, rather than on building the grid representations. This can lead to improved processes, including configuration testing, performance testing, and engineer skills development.

Configuration testing. The digital twin approach has the potential for highly scalable testing, allowing the test of a single device or an entire substation. In particular, the configuration of busbar protection systems is highly complex, with multiple feeders needing to be configured using an array of signals from those feeders mapped into the simulation.

Performance testing. Performance testing includes the verification of the protection system's speed, accuracy, selectivity, and timing across a collection of individual protective devices. These tests are done to approve different devices for use in the field. The digital twin can provide a highly accurate model, especially if the original firmware and protection algorithms can be provided directly by the manufacturer of the protection devices and included in the model.

Engineer skills development. A digital twin can support all interfaces and protocols between different protection devices, making it is easier to learn and scale the protection and automation systems, and in the process supporting the migration to fully digital systems. This virtual environment thus enables cost-effective training of engineers providing a learning environment with a high number of devices.

5.3 Refine prediction algorithms

Building on the insights gained from advanced grid planning and reliability studies, digital twins in the power sector significantly enhance load and generation prediction algorithms. By leveraging comprehensive virtual models that mirror physical power systems, digital twins enable utilities to simulate and analyze complex data streams in real-time. This capability allows for the integration of diverse data inputs, such as historical consumption trends, operational conditions, and real-time environmental factors. The refined accuracy of these simulations empowers better forecasting of both demand and supply variations.

Effective load and generation prediction is crucial for maintaining grid stability, especially as the energy landscape evolves with the increasing incorporation of renewable energy sources and increasing energy storage capacity systems. Digital twins facilitate this by allowing for the dynamic adaptation of energy systems to changing conditions, reducing the risk of over- or under-generation, and ensuring efficient energy distribution. These predictions are vital for routine operations and for anticipating and mitigating potential disruptions, thereby enhancing overall grid resilience.

Moreover, the ability to simulate various operational scenarios through digital twins can aid utilities in developing more robust energy generation strategies. This leads to optimized scheduling and dispatch of resources, ensuring that energy supply meets consumer demand in the most efficient manner possible. Through continuous improvements in predictive accuracy, digital twins drive advancements in energy management and contribute to the broader goals of energy sustainability and reliability.

5.4 Implement flexible demand forecasts

Digital twins in the power sector are revolutionizing the way utilities manage and forecast flexible demand. By creating detailed, real-time simulations of energy networks, digital twins allow for an unprecedented level of analysis and insight into consumer behaviour and system performance. This technology facilitates a deeper understanding of how demand can fluctuate with changes in both external conditions, such as weather patterns, and internal factors, such as consumer usage patterns.

The enhanced forecasting capabilities provided by digital twins enable utilities to predict changes in demand with greater accuracy and granularity. This includes the ability to model how demand might respond to different pricing schemes or to the availability of renewable energy sources, which can vary significantly throughout the day. By accurately predicting these fluctuations, utilities can adjust their generation and distribution strategies in real-time, optimizing energy delivery.

Moreover, digital twins allow for testing of various demand response scenarios in a virtual environment before they are implemented in the real world. This ensures that such strategies are more effective when deployed and helps in customizing energy solutions to meet specific consumer needs without compromising on system stability or efficiency.

5.5 Improve grid reliability

To gain deeper insight into the actual state and operational constraints of the power grid, the digital twin – in this case, the DTI – plays a crucial role in enhancing situational awareness. Unlike traditional control centre systems where the state of the power grid is only vaguely captured by SCADA measurements, the DTI has the potential for much more advanced capabilities. Digital twins are envisioned to continuously fine-tune asset parameters and automatically verify the response to grid events.

Digital twins can also provide near real-time visibility into the power system, including both steady state and dynamic phenomena, enabling not only better situational awareness for the operators but also realistic initialization of model-based simulations, like contingency assessment. This unprecedented observability of the power grid combined with refined load and generation predictions (see Section 5.3) enables the design of near real-time and look-ahead stability-aware applications and, with its decision support capabilities, better equips operators for effective decision making.

With the ongoing trend of reducing power grid inertia and the increased sensitivity of power generation patterns to weather changes, as well as the increased complexity to operate new types of assets, power grid operators must respond more quickly to unexpected disturbances to maintain stable and uninterrupted power supply. The combination of these factors necessitates the automation of actions that have been typically executed manually by operators. Such automation of processes not only reduces the workload of power grid operators but also reduces the likelihood of human error.

Figure 5-2 illustrates how a DTI provides continuous upstream and downstream information flow, enabling near real-time accurate mirroring between the actual power grid and its digital replica in both directions. This significant improvement in conventional power grid operation results in better safeguarding of power grid reliability.

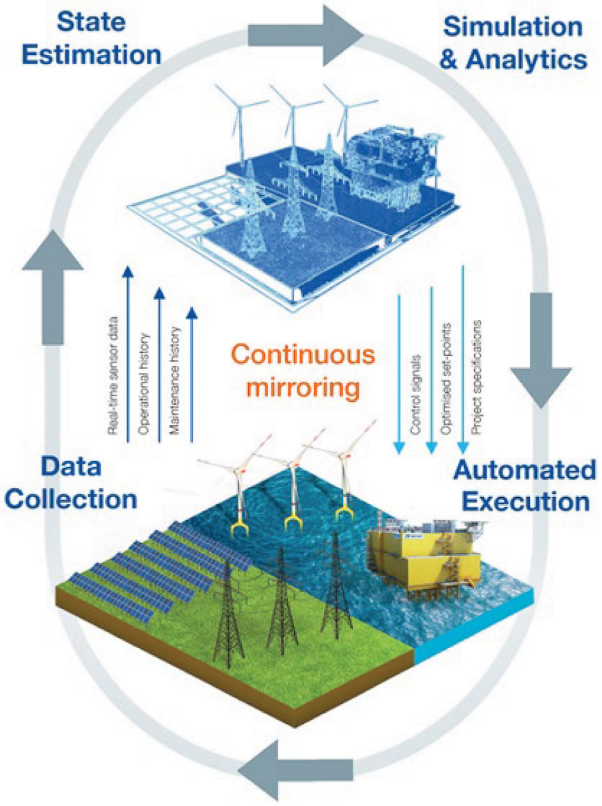


Figure 5-2 | DTI for enhanced grid operation
Source: www.tennet.eu

5.6 Align economic signals

Beginning in the late 1990s, wholesale electricity markets began to operate in North America, most of which employed a technique to align energy prices with true economic signals from the grid. The energy price, called the locational marginal price (LMP), is based on three components.

The "marginal" component is derived from cost of electricity for the last unit of power needed to meet demand, known as the marginal unit. This marginal cost increases as more expensive generation sources are called on to balance the load and generation of the system. There are two "locational" components, one reflecting transmission system constraints, the other transmission system losses. Transmission constraints force more expensive generation that is closer to the loads to be dispatched, raising prices for transmission-constrained load centres. Transmission losses also incentivize generation sources that are closer to the loads because the farther generation is from the loads, the more losses are incurred.

With markets in North America entering their third decade of successful LMP-based market operations, other wholesale markets such as those in Great Britain are considering adopting the technique [13]. Many regulators around the world are also considering how the concept may be applied to retail electricity markets.

While the first component of the LMP, the marginal cost, is based primarily on well-understood operational costs (including fuel costs), the second and third components, congestion and losses, are highly dependent on tools that can calculate the prices based on the grid configuration. This means that a digital twin is essential for accurately calculating LMPs. Active research is underway to develop the equations for emerging distribution locational marginal price (DLMP) calculations, and here too digital twins are essential.

Case study 5-1 – Standard flexibility services

Great Britain has taken significant strides towards more granular distribution services with the introduction of the Flexibility Services. Distribution operators in the region are now procuring standard services, including:

- **Sustain**: a change in generation or load to limited power to below firm capacity
- **Secure**: a change in generation or load based on network conditions close to real-time
- **Dynamic**: the ability to deliver an agreed change in generation following a network abnormality
- **Restore**: following a loss of supply, the ability to either remain off supply, reconnect with lower demand, or reconnect and supply generation

Because these services are procured in advance, distribution operators must study their systems to determine the appropriate levels of each service needed at different locations.

Section 6

Bridging the virtual world

6.1 Preparing for revolution

There have been three major industrial revolutions in our time. The First Industrial Revolution, running from the late 18th century through the early 19th century, marked the change from human and animal powered machines to machines in factories powered by steam and water. The Second Industrial Revolution, often called the Technological Revolution, began in the late 19th century and was characterized by the beginning of electrification, the advent of mass production, and the birth of over-the-wire communication. The Third Industrial Revolution – variously called the Digital Revolution, the Computer Age, or the Energy Revolution – began in the mid-20th century. The shifts in industry caused by these revolutions have included the Bessemer steel-making process, the production line and, relevant to this white paper, the introduction of more flexible electrical power to replace the steam and hydro-powered systems of the past.

During the Third Industrial Revolution, from the mid-20th century through the present day, systems began to rely on computing power to understand the environment (via sensors) and control the environment (via controllers). If the industrial revolutions are viewed as using mechanical and then electrical power to scale beyond human measures, then this third age marks computer power systems that can out-think human brains and source information more accurately and in larger volume than any human could.

The vast number of technological advancements introduced in recent years implies that we may be entering a Fourth Industrial Revolution, which might best be described as the Imagination Age. Only in the future will we really understand the scope of the current transformation, but topics such as the smart phone, the Internet of Things (IoT), augmented reality (AR) and virtual reality (VR), cloud computing, genetic manipulation, nanotechnology, 3D printing, and AI have become defining revolutionary forces reshaping our economic, environmental, and social systems.

In the First and Second Industrial Revolutions, a change in energy source was the driving factor for a societal step change. And so the Imagination Age may also be coupled to the transition to renewable energy sources. A power grid supported by renewable sources to achieve net-zero carbon emissions looks very little like the power grid that was introduced in the Second Industrial Revolution. Every factor listed as part of the Imagination Age will likely play a role in the power grid of the future.

Many components of the Imagination Age have connections to the power systems that are obvious such as IoT to supply vast amounts of measurement and control points and AI to analyze grid conditions to predict potential issues (or resolutions to experienced issues). Other technologies may play larger or smaller roles that only time will reveal. But all this computing power comes at a price.

6.2 Powering the virtual world

Computing power is growing at an accelerated pace. Computing energy usage has nearly doubled since 2015, according to the IEA [14]. This increase is due largely from the introduction of cryptocurrency mining, which now accounts for nearly half a percent of total energy demand, as shown in Figure 6-1. Electricity consumption in data centres has also grown, with energy use split roughly equally between computations and cooling the processors.

The IEA further reports that their base case scenarios suggest that data centre and cryptocurrency processing may nearly double again by 2026, mainly based on AI processing forecasts. The AI component itself should experience an approximate ten-fold explosion in energy usage [15].

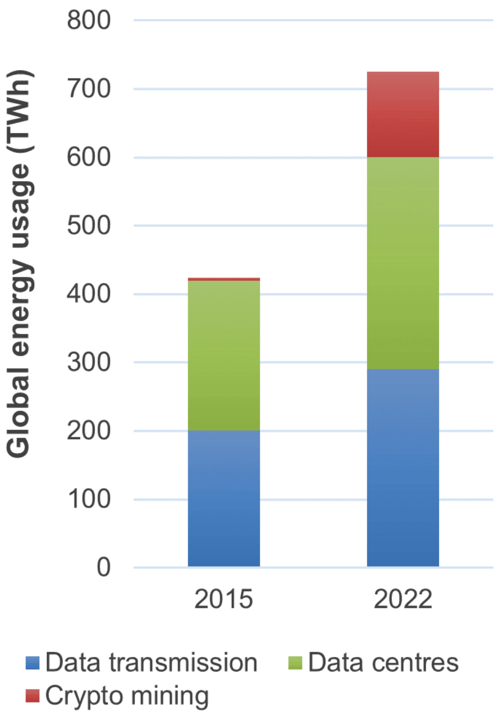


Figure 6-1 | Computing global energy use

More than 90% of the solutions necessary for achieving a successful net-zero outcome by 2050 will involve renewable energy, according to analysis by the International Renewable Energy Agency (IRENA). These solutions include direct supply, electrification, energy efficiency, green hydrogen, and bioenergy combined with carbon capture and storage (BECCS). By 2050, electricity is projected to become the primary energy carrier, with its share of total final energy consumption increasing from 21% in 2018 to more than 50%. This shift is accompanied by changes in sectoral boundaries, particularly the electrification of end-use applications in heating and transportation. The rise in electricity's prominence is primarily attributed to the substitution of renewable electricity for fossil fuels in various end-use applications. Consequently, the annual growth rate of renewable technologies is expected to increase eightfold as this transition takes place [14].

With the virtual world inherently tied to the physical power grid, it is clear that the simulation models of the past, centralized and locked behind utility firewalls, must evolve. For the Imagination Age to be realized, information must flow from the utility to society at large, and vice-versa.

6.3 Creating a self-balancing power grid

Power grids of the past had essentially zero control over when and where energy was used; balance was provided by the generation side and enough generation was built to cover any possible load profile. This system cannot work in the future for many reasons, but fundamentally because most renewable resources are not controllable in the ways that a fossil-fuel generation system can be.

Small amounts of semi-flexible demand under the moniker of “demand response” appeared in larger quantities around the turn of the century. This can be seen as the first real move towards an electrical system with flexibility not only on the generation side but on the load side as well, with load likely to ultimately have more flexibility than generation.

Power grids with flexible demand necessarily require interactions with the customers – the customers are the ones with the loads, some or many of which may ultimately become flexible loads. Key to the loads being effective in this role is their visibility into grid conditions. Loads must have some idea when and where power will be available. Whether the decision is relatively simple, like does it make sense to heat water in advance of when it is needed because there is excess generation, or the decision is in a complex scenario, like deciding how to charge an electric vehicle (or even when to discharge the vehicle back into the grid), the loads must be able to understand the short-term needs of the customer and the short-term capabilities and limitations of the grid.

The smarter that loads can become in using electricity, the more reliable and less expensive the system becomes. The avoided costs are not trivial. Alternatives include overbuilding the renewable generation portfolio, perhaps several times over, so that all energy scenarios can be met with less flexible loads.

Case study 6-1 – Locational load flexibility

Traditionally, energy consumption has been rigid, tied to the time and place of the demand. Demand response programmes have focused primarily on load shedding (reducing usage) or load shifting (moving usage to a different time). In the face of evolving electricity markets and renewable energy integration, some loads are capable of time-shifting and space-shifting, that is, moving the load to a different location that has cheaper or greener power to consume.

Empirical data and models indicate substantial economic and environmental gains from such practices. For instance, shifting some data centre processing to different geographical locations based on renewable availability and cost can optimize energy use and reduce carbon footprints by 10-20%.

6.4 Accessing digital twins

Building a digital twin is no simple task. The underlying equipment and connectivity models require large sets of data and creation of an evolved data governance process within the utility to manage the data. The management task includes collecting data, validating accuracy, and tracking changes over time. The governance process for the transactional data that sits atop the models can then be streamlined, with little or no human intervention in the collection process.

In the previous section, the topic of how the utility can benefit from digital twins was explored. However, there are many more users outside the utility who could also benefit. How will these users access the data? The process will be gradual, with the utility exposing more data over time. This evolution can be thought of in two major phases.

Online tools. The easiest way to expose information to end-users is through an on-line tool. Many utilities around the world are already providing some of their grid model data to the public. These tools generally allow access to a small amount of the data, for example, displaying a geospatial view of the low-voltage network with available feeder capacity values. Over time, more tools will become available for different users with different needs, expanding beyond today's typical focus of connecting new loads or generation to the distribution grid.

Direct data access. Online tools are helpful, but to truly realize the benefits of digital twins, the underlying data must be exposed. Access is currently limited for many reasons, chief among them security of the power system and data confidentiality established by the data owners. But the data currently locked inside could be used for a wide range of applications, such as providing optimization services for DER owners, giving investment advice on when and where to site local generation, and predicting where to charge electric vehicles at the lowest cost.

Ultimately, much of the data should become accessible to the public to achieve the most societal benefit. This can be achieved, and grid data simultaneously protected, using various data manipulation techniques, several examples of which are listed in Table 2 [16].

Table 2 | Data protection techniques

Technique	Description
Delay	Defer publication for a period of time
Noise	Combining with random data
Anonymization	Replace identifiers with random values
Pseudonymization	Replace identifiers with non-traceable codes
Translation/Rotation	Alter time or spatial orientation
Aggregation	Combine details and reduce granularity
Differential privacy	Obscure individual information while retaining group patterns
Feature extraction	Publish key features as opposed to source details

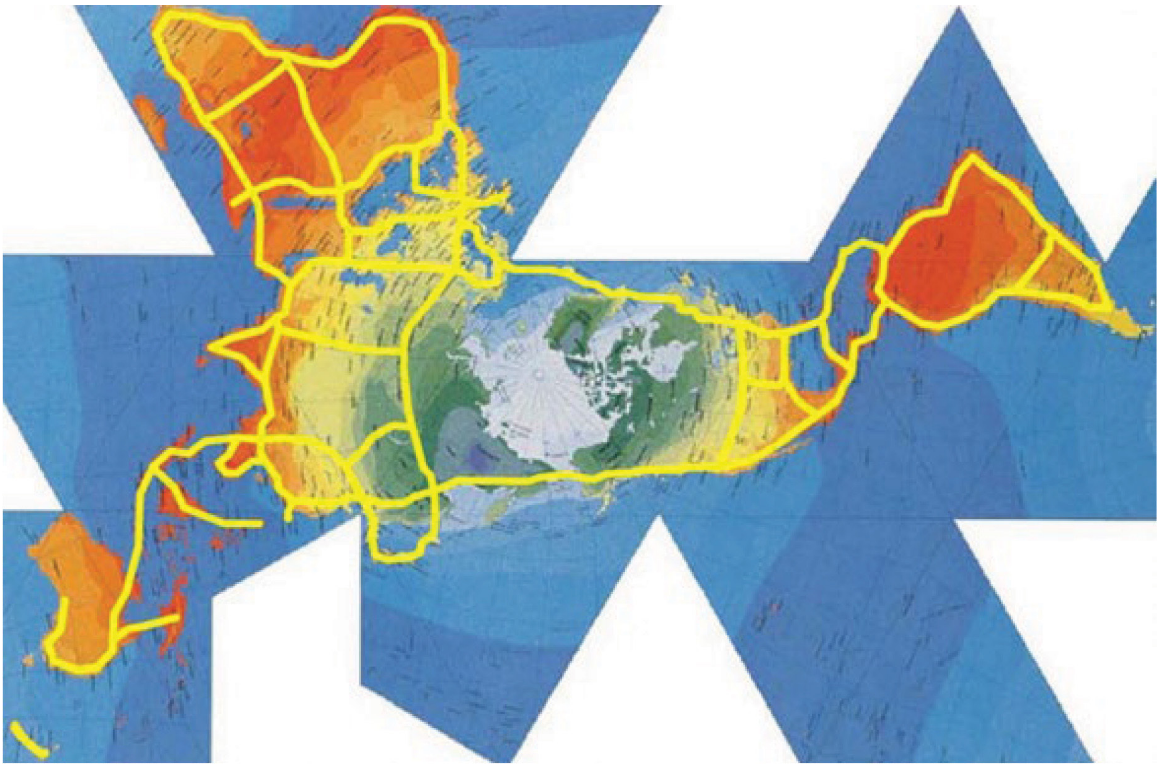


Figure 6-2 | Representation of a hypothetical global power grid. Source: www.terrawatts.com

6.5 Anticipating a global energy interconnection

The core issue with a grid powered by renewable resources is the lack of control over the generation output levels. Flexible demand and storage technologies are solutions; but load can only be shed or time-shifted in limited amounts and during limited times, and storage has its own issues, not least of which are cost and the competition for use in electric transport.

A third option is to increase the capacity and coverage of the transmission grid across the globe, a representation of which is shown in Figure 6-2. This concept has already been realized for information delivery with the Internet covering nearly the entire globe. The telecommunications grid is, however, managed by thousands of different entities in almost two hundred countries.

The concept of a global power grid was explored in the IEC White Paper, *Global energy interconnection*, and outlines the potential benefits:

> *GEI would represent the ultimate stage in the evolution of power grids towards greater levels of interconnectivity: a global energy network of intercontinental and cross-border backbone networks of high and ultra-high voltage (UHV), as well as smart power grids (transmission and distribution networks) in all interconnected countries at various voltage levels. A GEI could connect the power grids of all continents and take advantage of the diversity of different time zones and seasons, thus supporting a balanced coordination of power supply for all interconnected countries.*

Challenges mirror those of any transmission upgrade, including long lead times, major capital investments, land access rights acquisition, cooperation among myriad political entities, and environmental concerns – but at a much larger scale. However, even if the ultimate goal of a single global grid is not achieved, more broadly interconnected “supergrid” transmission systems would deliver positive results. One example would be adding and/or reinforcing interconnections among the current four synchronous areas of North America, into a single supergrid.

The management of supergrids will require more coordination among grid operators than is performed today. Both the long-term planning of the coupled systems and in the near-term operation of such highly coupled systems will need accurate models that digital twins can help deliver.

Section 7

Crucial standards

7.1 Smart energy grid architecture model

The smart energy grid architecture model (SGAM) is a three-dimensional architectural framework that can be used to model interactions among different entities within the smart energy arena [17]. The SGAM is shown in Figure 7-1 [18]. Its two-dimensional model covers the complete set of electric system "domains", from power generation to power consumption at the customer site along the bottom, and information scope "zones" from local process control through substations to enterprise and market along the right. Two core series of standards are shown, the common information model (CIM) and IEC 61850, both of which are managed by IEC Technical Committee 57. The scope of TC 57 ends at the meter, after which other standards, both IEC and non-IEC, are relevant.

7.2 The common information model

The CIM is comprised of an open-source unified modelling language (UML) model and a large collection of data exchange protocol standards

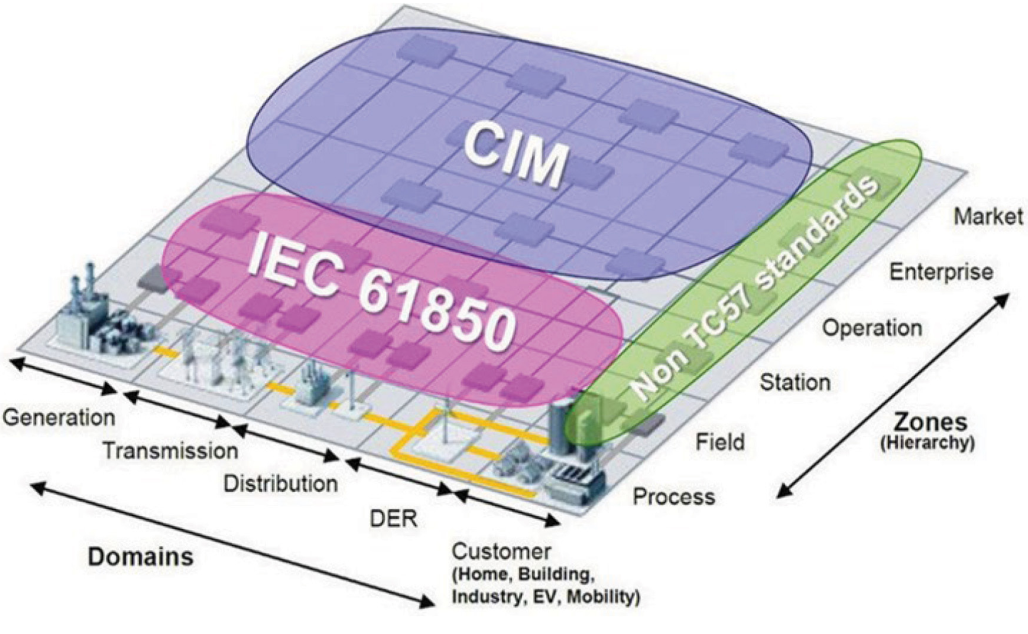


Figure 7-1 | Smart energy grid architecture model managed through the IEC. The exchange protocols are grouped into different domains under TC 57:

- **Grid**: IEC 61970 series
- **Enterprise**: IEC 61968 series
- **Market**: IEC 62325 series
- **Customer**: IEC 62746 series

The standards layer upon one another to provide a comprehensive framework for data exchange profiles for different energy market players. The IEC 61970 series is a mature set of standards focused on the integration of applications and information exchange within the control centre and between the control centre and grid systems. This standard serves as the foundation for the common grid model exchange standard (CGMES) profile standard defined by ENTSO-E. In parallel, IEC 62325-351 and IEC 62325-451 provide a well-established framework for market-related data exchanges in European markets, forming the basis for the European-style market profile (ESMP) exchanges. IEC 62325-452 addresses the need for standards to support data exchanges in North American markets, including the concept of locational pricing. IEC 61968 series complements this landscape by offering a common way to describe utility operations data exchanges, including those related to metering, and asset and outage management.

These standards do not extend into the realm of controllable resources deployed on the distribution grid, particularly those located “behind” a customer’s electricity meter. Proposed standard IEC 62746-4 is expected to play a pivotal role in bridging this gap by introducing a set of message profiles tailored to convey grid instructions, grid conditions, pricing signals, and resource capabilities within the emerging DER space. This specific standard aims to provide a straightforward set of data exchanges suitable for various simple DERs, such as stand-alone battery systems and collections of demand-response resources. The overarching goal is to establish a standardized communication framework that enhances interoperability and streamlines interactions in the dynamic landscape of DERs.

A critically important characteristic of the collection of CIM data exchange standards is their use of a common underlying information model, which provides a framework for organizing electric utility data and defining data exchanges for both vendor products and utility implementations. The design and execution of data sharing solutions can thus be rooted in CIM, benefiting greatly from the abundance of established standards, tools, artifacts, and practices. This ensures a shared understanding of data across various software tools and multiple exchanges.

The foundational premise here is that for new technologies and integrated data innovations, such as AI systems and, importantly for this white paper, digital twin technologies, to deliver value, they must be based on standardized data. The CIM is increasingly being recognized as the solution to this challenge.

Encouragingly, the core modelling on which the specifications of IEC CIM standards are based, particularly in electric grid modelling, is stable. A well-structured IEC process allows local and regional implementation of CIM-based data exchanges to contribute improvement suggestions into the ongoing dialogue driving the evolution of the standards. It is recognized that adaptations may be necessary for applications that are more dynamic, such as the management of power usage in a smart home. This acknowledgment showcases a nuanced approach to standardization that accommodates both stability and adaptability in response to evolving requirements.

Case study 7-1 – Great Britain’s CIM based Long Term Development Statement [19]

The Long Term Development Statement (LTDS) is a regulatory requirement for distribution utilities in Great Britain to make grid models publicly available, primarily to assist parties interested in utilizing the electricity distribution network. This typically takes the form of siting a new load or a new generation source and leverages the interconnection application process.

The regulator in Great Britain, Ofgem, recently announced that the new “form” of the LTDS will leverage CIM data structures. This cutting-edge improvement will give developers in this region the ability to load the LTDS data into any CIM-compliant study platform and analyze the system impacts of developments they are considering. It is anticipated that this improvement will significantly streamline the connection process by enabling developers to propose better-sited projects, thereby reducing the evaluation burden faced by distribution utility staff.

7.3 IEC 61850

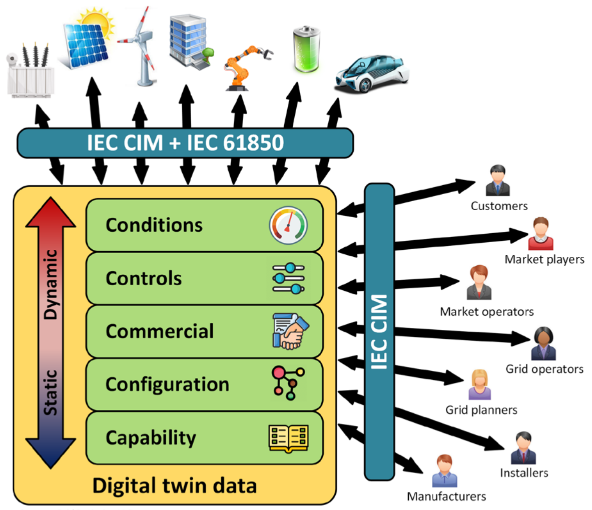
IEC 61850 stands as a pivotal international standard, defining communication protocols for intelligent electronic devices (IEDs) within electrical substations. Historically focused on communicating to equipment in the substation, the IEC 61850 series of standards has grown substantially in recent years with dedicated extensions for hydro generation controls and interactions with DERs. The scope of IEC 61850 includes the following.

Engineering. Manipulate and configure models and exchanges among tools, including IEDs and substation configuration tools.

Data modelling. Represent the primary devices like circuit breakers and transformers and secondary devices such as protection relays and control units.

Communications. Support data being used “on the wire” for monitoring and control objectives, in the form of either client/server architectures (historically between the substation gateway and protection relays/IEDs) or multicast with peer-to-peer communications among multiple station devices.

Emphasizing interoperability and interchangeability, IEC 61850 addresses the practical challenges of integrating diverse technologies within the energy sector by establishing a fit-for-purpose, universally accepted framework for market players to interact with the power grid in a deeply digital way. Since the CIM is designed for data exchanges between systems, adding IEC 61850 capabilities allows for CIM messages to be delivered to devices, completing Figure 7-2.



Source: GridOptimize LLC

Figure 7-2 | Digital twin leveraging communication standards

7.4 Enabling device data exchange

The expanding universe of devices to which utilities need to send controls data and from which utilities need to receive conditions data is enabled by three basic patterns: one that leverages traditional utilities communications infrastructure, and two that leverage public communications infrastructure. The distinction between these last two is the presence or absence of an intermediary in the communications chain. The three patterns are shown in Figure 7-3.

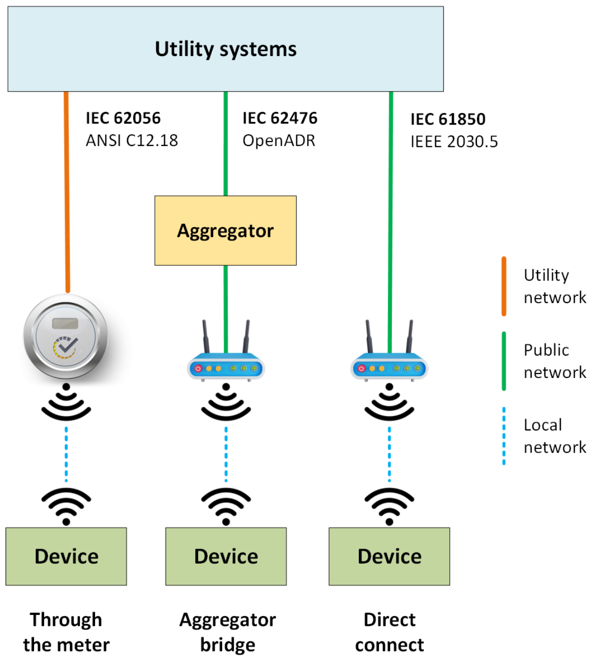


Figure 7-3 | Edge-device communication options

Through the meter. With the introduction of automatic meter reading (AMR) and then advanced metering infrastructure (AMI), electric utilities were able to receive and eventually send basic controls to individual customer sites. These communications leverage the IEC 62056 series of standards (ANSI C12.18 in North America) implemented on a wide range of technologies, such as radio frequency (RF), powerline carrier (PLC), and cellular networks, and they provide a natural pathway for utilities to communicate with devices other than the utility meter. The challenge is getting from the meter to those devices, a problem that is often surmounted with ubiquitous wireless solutions, including Wi-Fi, Bluetooth, Z-Wave, and Zigbee protocols. There are disadvantages, however: the closed network is not easily opened to the customer, and the technology requires management that not every utility is willing to embrace.

Aggregator bridge. As demand response programmes became more popular in recent decades, another communication channel was implemented at scale. As opposed to the through-the-meter approach, which was highly rooted in standards, this new aggregator-specific approach was initially unique to each technology, often with different protocols for each vendor even in the same technology space. Over time, multiple manufacturers voluntarily adopted the OpenADR communication protocol, allowing utilities to manage devices from different manufacturers in the same platform. This trend continues today with DERs. International standards have lagged behind industry, with the forthcoming IEC 62746-4 standard potentially filling this gap. Aggregator-based approaches have a disadvantage opposite of the meter-based path: utilities have only limited visibility of information brokered by the aggregator. That said, many utilities prefer an aggregated view of these resources, and this perspective naturally supports this approach.

Direct connect. As DERs, and in particular DERs with smart DC/AC inverters, become embedded in the management of voltage and frequency on the grid during normal operations and play larger roles in the protection schemes during off-normal situations, neither the meter-based path nor the aggregator-based paths are optimal solutions. Rather, a standard protocol that the utility, the customer, and potentially other parties, like aggregators, could leverage is emerging as a solution. The standard, which eventually will be used to support this option, is not established globally, and, consequently, utilities are considering a variety of options, including IEC 61850-7-420, IEEE 2030.5, Sunspec Modbus, and DNP3.

From a modelling perspective, the CIM and IEC 61850 have some overlap. Both represent power system domain assets for the eventual goal of finding an efficient way to represent, integrate, and utilize electrical devices and complex systems. Harmonization efforts are well underway, which will allow for the CIM to have a “path” to devices via IEC 61850.

7.5 ISO/IEC JTC 1/SC 41

ISO/IEC JTC 1/SC 41 represents a joint effort between IEC and ISO to provide international standardization for IoT and digital twin technologies. IoT integrates a multitude of technologies, ranging from network to cloud computing and AI, that are inherently network-intensive and data-driven.

The joint technical committee emphasizes the significance of processing this data through advanced analytics to unlock value and contribute to the realization of a “smarter” world. As of November 2020, the committee's scope expanded to encompass standardization in the field of digital twin, along with its related technologies.

Most notably, the committee has developed an international consensus position on the definition of “digital twin” across IEC and ISO. For ISO/IEC JTC 1/SC 1, a digital twin is defined as [1]:

> *A digital representation of a target entity with data connections that facilitate convergence between the physical and digital states at a synchronized rate. It possesses capabilities such as connection, integration, analysis, simulation, visualization, optimization, and collaboration.*

This definition broadly mirrors wider industry sentiment. Gartner and Deloitte [20] describe a digital twin as an evolving digital profile of the historical and current behaviour of a physical object or process. Implementation involves an encapsulated software object or model reflecting a unique physical entity, relying on real-time, real-world data measurements across various dimensions.

The committee is actively developing a range of essential foundational standards for digital twin technologies that have horizontal application across the foundational, interoperability and applications domains shown in Figure 7-4. Strategic approaches to digital twin standardization adopted by this committee include a focus on foundational standards such as vocabularies, reference architectures, interoperability, and trustworthiness.

One key cross-sectoral standard for digital twin technology is ISO/IEC 30173. This standard establishes terminology for digital twins and explores types of digital twins, digital twin system contexts, digital twin lifecycle processes, functional views of digital twins, and digital twin stakeholders.

The committee advocates systematically collecting use cases across all application domains to document standardization requirements. It also proposes an “incubator” to initiate applications for various domains and address potential gaps.

If you have a use case of digital twin applications, the committee is currently inviting submissions.

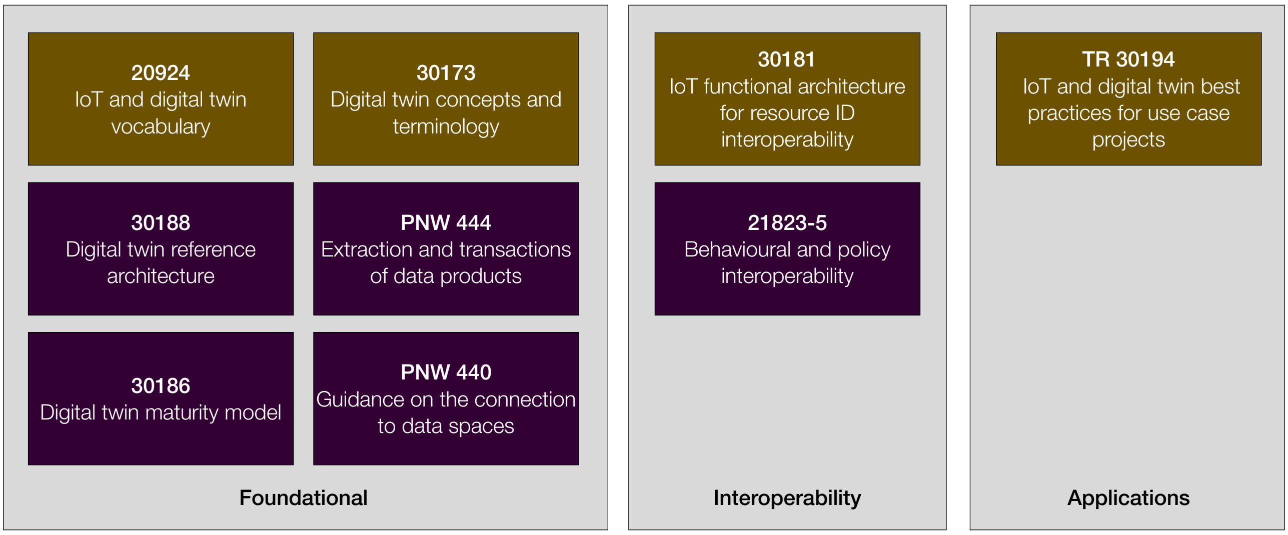


Figure 7-4 | ISO/IEC JTC 1/SC 41 scope related to digital twins

Section 8

Recommendations

To realize the vision of a revolutionized, decarbonized, digitalized, and decentralized energy sector that leverages digital twin technologies, it is essential that government agencies, standards bodies and digital twin stakeholders work collaboratively to gain consensus on standards and open data practices.

As shown in Figure 8-1, each stakeholder group has unique responsibilities in enabling digital twin technologies in the energy sector. The recommendations that this white paper makes are addressed to distinct stakeholder groups, specifically:

Government agencies. Government agencies include national and regional bodies that set policy, such as ministries, regulators, and commissions.

Standards bodies. Standards bodies include global standards developing organizations (SDOs), like the IEC, as well as national committees.

Stakeholders. Stakeholders is the largest category and includes all the entities that might operate digital twins, such as electric utilities, or contribute data to digital twins, such as independent power producers, or utilize data, including end consumers and researchers and academics. It is important to note that this large category is anticipated to grow over time as more parties become interested in the electric power system.

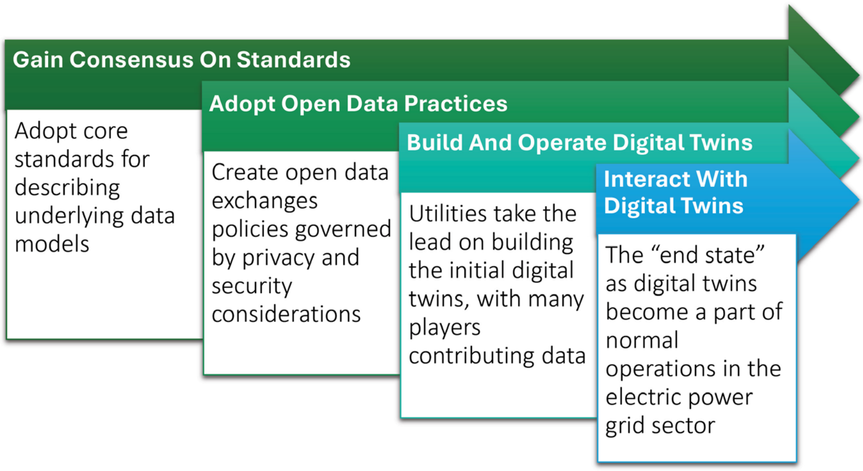


Figure 8-1 | Recommendations overview

8.1 Gain consensus on standards

One of the themes of this white paper is that for digital twins to become useful tools, many different entities must provide and, critically, also manage their comprising datasets. This requires adoption of core standards for describing foundational information models, like the physical grid equipment and connectivity models, to ensure that the transactional data that sits "on top" is well-organized and meaningful.

	Gain consensus on standards Recommendations
Government agencies	▪ Work with utilities to define digital twin requirements ▪ Work with national committees to identify high priority standards to enable power system digital twins and requirements identified by utilities ▪ Mandate, where appropriate, the use of the CIM for machine-to-machine information exchanges and IEC 61850 to push data to and pull data from grid-edge devices and work with manufacturers to adopt and implement standards ▪ Help stakeholders advance standards to cover requirements and work proactively with national committees to facilitate agile standards development processes
Standards bodies	▪ IEC Members to adopt the CIM and IEC 61850 as national standards to provide the foundational pillars for a digitalized energy sector ▪ Provide mechanisms for interested parties to learn about the importance of digital twin standards in the energy sector to drive their greater use in industry digital twin pilots and prototypes ▪ IEC Standardization Management Board (SMB) to carry out a review of existing digital twin "horizontal" standards and their applicability to the energy sector ▪ IEC SMB and ISO Technical Management Board (TMB) to request relevant application technical committee to develop use cases to support the ongoing work within ISO/IEC JTC 1/SC 41 ▪ Publicize the critical need for participation and recruit stakeholders from across the data value chain, i.e. data users alongside data producers; and establish liaison mechanisms with external technical groups heavily involved in energy data ▪ Provide governance for utilizing energy data standards, either in the form of advisory groups, external engagement activities, or partnerships with relevant government departments and regulators to mitigate risks of duplication in key energy data standards enabling digital twins ▪ When overlapping domains appear, coordinate with relevant SDOs to resolve different perspectives, as has been achieved with existing IEC/ISO collaborations
Stakeholders	▪ Get involved with national committees to support the standards development process by feeding insights on requirements and use cases ▪ Provide financial support and resource commitment for employees to participate in relevant standards development activities ▪ For university stakeholders, teach and sponsor research on digital twins and the foundational data management concepts that underpin them

8.2 Adopt open data practices

Open data for power system digital twins is basically a bilateral activity: utilities will need users' data to build and manage accurate digital twins; and digital twin users will need access to as much of the data in the digital twin as is feasible. These exchanges must be governed by firm policies that respect valid privacy and security concerns.

Adopt open data practices Recommendations	
Government agencies	▪ Improve awareness of regulatory frameworks, especially around privacy and security constraints, so that standards can support them ▪ Fund initiatives to support the development of common data spaces: platforms that enable data curation, management, and integration across domains
Standards bodies	▪ Engage with stakeholders to distil necessary requirements for open data practices and translate these requirements into the standards portfolio; these could be done through technical committee consultation or external industry workshops
Stakeholders	▪ Get involved as soon as possible to ensure standards support individual data requirements ▪ Supply use cases and issues applying existing standards and communicate these needs to national committees to enable existing standards to be revised or new standards developed to meet the requirements of the energy sector ▪ Include grid reliability and security in the open data practices through participation from grid operators in the requirements setting activities

8.3 Build and operate digital twins

Building on the previous recommendations, which set the stage for success, these recommendations focus on the implementation of digital twins. Utilities will need to take the lead in building the initial models behind digital twins. But there are many players who must contribute to this process to ensure digital twins deliver real value.

Build and operate digital twins Recommendations	
Government agencies	▪ Fund digital twin initiatives that leverage consensus-based standards and open data practices ▪ Reduce regulatory hurdles and support simplification of the standards landscape by removing duplicative/conflicting standards ▪ Fund pilots for power system digital twins; embedding high priority standards and open data practices as necessary pre-requisites
Standards bodies	▪ Develop digital twin toolkits outlining key enabling standards and their applicability to better connect data producers and data users with the technical content ▪ Provide education to digital twin developers and potential users on standards development and the useability of available standards. National committees should consider drawing from their technical expert pool in the development of these educational assets ▪ Actively support digital twin interoperability by hosting interoperability events (IOPs) and providing test data and software tools
Stakeholders	▪ Digital twin implementers should gather stakeholder input when developing implementation roadmaps and learn about the standards, making intentional choices to apply those standards ▪ Share experiences, both positive and negative, with government bodies and national committees ▪ Participate actively in national committees' engagement efforts, whether through the technical committees or external workshops

8.4 Interact with digital twins

Finally, digital twins must be leveraged. These recommendations focus on the “end state” as digital twins become a part of normal operations in the electric power grid sector.

The world’s energy system’s rapid transition towards a more flexible, less centralized and renewables dominated model is a welcome pathway toward decarbonization. However, without the full utilization of digital twin technologies, we face significant challenges balancing these goals with those of high security and reasonable cost to consumers.

The magnitude, complexity, and urgency of contemporary energy sector challenges – both technical and socio-economic – necessitate a step change in the energy sectors’ lagging adoption of digital twin technologies. Energy sector stakeholders must share more information with one another but also with standards makers to develop the essential information base to cost-effectively implement renewable technology and sustainable practices with confidence in their efficiency, reliability and security.

Comprehensive, well-informed, and standards-based digital twins are crucial for maximizing renewables-based digital technologies, products, and services, facilitating whole-system integration, and enabling energy sector stakeholders to make informed decisions that will revolutionize the energy sector. This approach is imperative for achieving a future that is decarbonized, decentralized, and deeply digital.

Interact with digital twins Recommendations	
Government agencies	▪ Educate the stakeholders on the potential benefits to be gained from using digital twins through use cases and narratives ▪ Monitor digital twins’ implementation processes and publicize successes
Standards bodies	▪ Educate the stakeholders on the role of standards to support digital twins ▪ National committees, engaging with government agencies, should publish implementation guides and offer training opportunities
Stakeholders	▪ Leverage digital twins to optimize real-world operations ▪ Utilize best practices from other sectors to aid its development in the energy sector ▪ Leverage the power system digital twins with digital twins from other segments

Bibliography

[1] ISO/IEC 30173:2023, *Digital twin – Concepts and terminology*. Available for purchase: https://webstore.iec.ch/publication/68081 [Accessed: 29 August 2024]

[2] Intergovernmental Panel on Climate Change, Sixth Assessment Report (IPCC AR6), Working Group III, Annex 1, 2022 [Online]. Available: https://www.ipcc.ch/assessment-report/ar6/ [Accessed: 29 August 2024] (Definition of net-zero greenhouse gas emissions, modified)

[3] United Nations Climate Action, For a livable climate: Net-zero commitments must be backed by credible action [Online]. Available: https://www.un.org/en/climatechange/net-zero-coalition#:~:text=Through%20this%20UN%2Dbacked%20campaign,Off%20Air [Accessed: 29 August 2024]

[4] International Energy Agency (IEA), An updated roadmap to Net Zero Emissions by 2050 [Online]. Available: https://www.iea.org/reports/world-energy-outlook-2022/an-updated-roadmap-to-net-zero-emissions-by-2050 [Accessed: 29 August 2024]

[5] International Renewable Energy Agency (IRENA), World Energy Transitions Outlook, 2021 [Online]. Available: https://www.irena.org/publications/2021/Jun/World-Energy-Transitions-Outlook/digitalreport [Accessed: 29 August 2024]

[6] Intergovernmental Panel on Climate Change (IPCC), Sixth Assessment Report (IPCC AR6), Working Group I, Climate Change 2021: The Physical Science Basis [Online]. Available: https://www.ipcc.ch/report/sixth-assessment-report-working-group-i/ [Accessed: 29 August 2024]

[7] GRIEVES, M., VICKERS, J., Digital Twin: Mitigating Unpredictable, Undesirable Emergent Behavior in Complex Systems. In: Kahlen, J., Flumerfelt, S., Alves, A. (eds) *Transdisciplinary Perspectives on Complex Systems*. Springer, Cham., 2017 [Online]. Available for purchase: https://link.springer.com/chapter/10.1007/978-3-319-38756-7_4 [Accessed: 29 August 2024]

[8] TINNEY, W. F., WALKER, J.W., Direct Solutions of Sparse Network Equations by Optimally Ordered Triangular Factorization. *Proceedings of the IEEE*, Vol. 55, No. 11, 1967, pp. 1801-1809 [Online]. Available: https://www.engineering.iastate.edu/~JDM/ee553/Tinney1.pdf [Accessed: 29 August 2024]

[9] KOOHI-FAYEGH, S., ROSEN, M.A., A review of energy storage types, applications and recent developments. *Journal of Energy Storage*, Volume 27, 2020, 101047, ISSN 2352-152X [Online]. Available: https://www.sciencedirect.com/science/article/abs/pii/S2352152X19306012?via%3Dihub [Accessed: 29 August 2024]

[10] Overview of IDDP Platform Research and Its Future Plan, KEPRI, 2024 [Online]. Available: https://www.kepri.re.kr:20808/idpp/Overview%20of%20IDPP%20Platform(www.kepri.re.kr).pdf

[11] IEC TR 62541-1:2020, *OPC Unified Architecture – Part 1: Overview and concepts*. Available for purchase: https://webstore.iec.ch/publication/61109 [Accessed: 29 August 2024]

[12] The Blackout Report, Biggest Blackouts in History: South Australia 2016, September 28, 2021 [Online]. Available: https://www.theblackoutreport.co.uk/2021/09/28/south-australia-blackout-2016/ [Accessed: 29 August 2024]

[13] Office of Gas and Electricity Markets (Ofgem) Great Britain, Assessment of Locational Wholesale Pricing for GB, 2023 [Online]. Available: https://www.ofgem.gov.uk/sites/default/files/2023-10/Ofgem%20Report%20-%20Assessment%20of%20Locational%20Pricing%20in%20GB%20%28final%29.pdf [Accessed: 29 August 2024]

[14] International Energy agency (IEA), Tracking data centres and data transmission networks, July 2023 [Online]. Available: https://www.iea.org/energy-system/buildings/data-centres-and-data-transmission-networks#tracking [Accessed: 29 August 2024]

[15] Data Center Frontier, IEA Study Sees AI, Cryptocurrency Doubling Data Center Energy Consumption by 2026, 2024 [Online]. Available: https://www.datacenterfrontier.com/energy/article/33038469/iea-study-sees-ai-cryptocurrency-doubling-data-center-energy-consumption-by-2026 [Accessed: 29 August 2024]

[16] National Grid ESO (Great Britain), Virtual Energy System [Online]. Available: https://www.nationalgrideso.com/future-energy/virtual-energy-system [Accessed: 29 August 2024]

[17] IEC SyC Smart Energy, IEC SRD 63200: SGAM basics [Online]. Available: https://syc-se.iec.ch/deliveries/sgam-basics/ [Accessed: 29 August 2024]

[18] IEC SyC Smart Energy, CEN-CENELEC-ETSI Smart Grid Coordination Group – Smart Grid Reference Architecture, 2012 [Online]. Available: https://syc-se.iec.ch/wp-content/uploads/2019/10/Reference_Architecture_final.pdf [Accessed: 29 August 2024]

[19] Office of Gas and Electricity Markets (Ofgem) Great Britain, Response to Formal Consultation on the Form of Long Term Development Statement, 2024 [Online]. Available: https://www.ofgem.gov.uk/sites/default/files/2024-04/LTDS%20Direction%20Letter%20300424.pdf [Accessed: 29 August 2024]

[20] Gartner Information Technology Glossary: Digital Twin [Online]. Available: https://www.gartner.com/en/information-technology/glossary/digital-twin [Accessed: 29 August 2024]

Notes

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