Digital Twins – Towards a Federated Approach

20 February 2026

Foreword

ENTSO-E, the European Network of Transmission System Operators for Electricity, is the association of the European transmission system operators (TSOs). The **40 member TSOs, representing 36 countries,** are responsible for the secure and coordinated operation of Europe's electricity system, the **largest interconnected electrical grid in the world.**

Before ENTSO-E was established in 2009, there was a long history of cooperation among European transmission operators, dating back to the creation of the electrical synchronous areas and interconnections which were established in the 1950s.

In its present form, ENTSO-E was founded to fulfil the common mission of the European TSO community: to power our society. At its core, European consumers rely upon a secure and efficient electricity system. Our electricity transmission grid, and its secure operation, is the backbone of the power system, thereby supporting the vitality of our society. ENTSO-E was created **to ensure the efficiency and security of the pan-European interconnected power system** across all time frames within the internal energy market and its extension to the interconnected countries.

ENTSO-E is working to secure a carbon-neutral future. The transition is a shared political objective through the continent and necessitates a much more electrified economy where sustainable, efficient and secure electricity becomes even more important. **Our Vision: "a power system for a carbon-neutral Europe"** * shows that this is within our reach, but additional work is necessary to make it a reality.

In its Strategic Roadmap presented in 2024, ENTSO-E has organised its activities around two interlinked pillars, reflecting this dual role:

› "Prepare for the future" to organise a power system for a carbon-neutral Europe; and

› "Manage the present" to ensure a secure and efficient power system for Europe.

ENTSO-E is ready to meet the ambitions of Net Zero, the challenges of today and those of the future for the benefit of consumers, by working together with all stakeholders and policymakers.

* https://vision.entsoe.eu/

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Executive Summary

In the realm of digital innovation, digital twins provide dynamic virtual representations of real systems, enabling more informed and faster decision-making[1]. As transmission system operators (TSOs) accelerate the deployment of digital twins, many implementations have been developed to address specific operational needs.

These tailored solutions ranging from predictive maintenance and dynamic line ratings to 3D building information modelling (BIM) have delivered tangible value and driven meaningful innovation within individual domains. As the expected scale of digital twin deployments grows exponentially, the next step is to ensure that these successful initiatives can interoperate and scale efficiently across organisations and borders. To unlock this next level of value, TSOs should pursue a federated digital twin (FDT) architecture.

A federated approach promotes interoperability through shared semantics, open standards, and strong governance, allowing diverse digital twins to communicate and work together without reliance on a single monolithic platform. This enhances efficiency, decision-making, data liquidity, and synchronisation across networks, while strengthening overall system resilience.

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1   More information on informed asset management can be found in ISO 55000 and CIGRE TB 787 Chapter 1.7.
    A definition of digital twins can be found under **IEC 60050 – International Electrotechnical Vocabulary – Details for IEV number 831-02-04: "digital twin"**.

Digital Twin

A digital twin is a dynamic virtual representation of a real object, system, or process, continuously updated by its real-world counterpart. It is designed to support modern end-to-end processes that demand faster, decentralised decision-making, often with incomplete information. The twin bridges these information gaps by creating comprehensive past, current and future models of (physical) systems, ongoing processes, and historical decisions, enabling organisations to make quicker and more informed choices. "Federated" digital twins refer to loosely coupled twins that interoperate through shared semantics.[2] On the other hand, to realise the added value, digital twins should always be based on use cases that make the benefit explicit and set the scope; otherwise, organisations may lose focus and fail to achieve their goals.

This paper is intended for experts and managers at TSOs and related organisations.[3] It outlines the benefits of the federated digital twin approach and the opportunities it creates for European TSOs and relevant stakeholders. It focuses on strategic, architectural, and governance considerations required to enable interoperable, scalable, and resilient digital twin ecosystems across organisations and borders. This paper is intentionally technology and vendor agnostic. It does not prescribe specific products, tools, or detailed implementation roadmaps, nor does it aim to exhaustively describe individual use cases. Instead, it provides a conceptual and strategic framework to support executive decision making and to guide TSOs, policymakers, and industry stakeholders as digital twin initiatives evolve and scale at national and European level.

Status Quo: The Fragmentation of Digital Twins

Today, TSOs are benefitting from a growing ecosystem of digital twin capabilities embedded in operational technology, enterprise systems, and vendor platforms, including supervisory control and data acquisition (SCADA), enterprise resource planning (ERP), and geographic information system (GIS). This creates significant opportunities for innovation, while also underscoring the importance of architectural choices that support long-term scalability.

As digital twin initiatives multiply, a federated strategy offers a structured way to connect successful projects, avoid unnecessary overlaps, and ensure that insights generated in one domain can be effectively reused across others.

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2 "Shared semantics" means that the systems use the same terms, rules, and meanings. This allows the "coupled twins" to automatically share information with each other because they understand information in the same way.

3 Related organisations: Distribution System Operators (DSOs), energy market operators, regulatory bodies etc.

Solution: Embracing a Federated Digital Twin Architecture

The use of FDTs is a viable solution to ensure long-term efficiency while avoiding unnecessary complexity and costs. This approach combines the simplicity of individual digital twins with a focus on establishing a common framework for communication between different models. However, this requires that projects are not viewed in isolation but rather as part of a larger whole from the outset, necessitating organisational changes, consideration of a common data foundation layer, and cooperation within organisations.

When designing a network of FDTs, integration into data spaces, as outlined in the **ENTSO-E paper on Data Spaces**, should be considered from the start. Both concepts enhance interoperability – Digital Twins provide real-time system representation, while Data Spaces enable secure, sovereign data exchange. This calls for a holistic project approach and organisational collaboration from the outset. Furthermore, federated digital twins should be designed with cyber resilience in mind, aligning with the principles outlined in **ENTSO-E's Position Paper on the European Commission's proposal for a Cyber Resilience Act**, which emphasises the importance of cybersecurity for critical infrastructure and the need for coherence with EU legislation.

Opportunities: Unlocking Value

Achieving a system of FDTs requires ambition, sustained effort, and cross-departmental coordination. Despite initial challenges including high costs and potential delays, FDTs offer substantial long-term benefits, unlocking value by connecting disparate models across timeframes, asset lifecycles, and organisational levels. This interconnected data provides operators with better situational awareness of grid operations, informed decision-making, and enhanced efficiency and resilience.

FDTs facilitate legacy integration, promote collaboration, and support pan-European cooperation, thereby optimising cross-border grid management and empowering energy markets. Additionally, they enable future sector coupling, facilitating deep coordination between power grids and other critical infrastructure sectors. For operators, FDTs deliver operational clarity and resilience; for technology providers, they open innovation pathways; and for consumers, they ultimately enable a more reliable, sustainable, and cost-efficient energy system.

Overall, the FDT is a transformative tool for resilience, efficiency, and value creation. For the C-suite in an organisation, the key message is that the digital twin is not a technology silo but a business-critical integration layer that safeguards investments, accelerates transformation, and unlocks efficiency by embedding intelligence into the very processes that drive the organisation.

At the time of this report, the understanding and development of digital twins is evolving rapidly among system operators, component manufacturers, software providers, and other sectors. To unlock the desired value, system operators should engage in discussion to define their needs and use cases for digital twins. The ENTSO-E and its network of people and organisations can provide significant support in establishing solid foundations that enable TSOs to focus on their role as system integrators for digital twins. This includes specifying requirements, interfaces, standards, and quality criteria for the solutions that the (software) industry should develop.

What are (Federated) Digital Twins?

A digital twin is a dynamic, virtual representation of a (physical) object, system, or process that is continuously updated by its real-world counterpart. It is designed to support modern, end-to-end processes that demand faster, decentralised decision-making, often with incomplete information. By creating a comprehensive model of (physical) systems, ongoing processes, and historical decisions, the twin bridges these information gaps, enabling organisations to make quicker and more informed choices. "Federated" digital twins – the main topic of this paper – refer to loosely coupled twins that interoperate through shared semantics, rather than one monolithic platform.

Figure 1 illustrates the digital twin concept as an end-to-end process that spans the entire lifecycle of a system, from planning and design through construction and operation to decommissioning. A digital twin remains continuously linked to the real-world asset through strong bidirectional interfaces, capturing, integrating, and analysing data to support informed decision-making. While automated digital coupling is a key enabler, manual or indirect methods can also support the digital twin, showing that full digitisation is not strictly required. Depending on the lifecycle phase, the digital twin can exist in different data formats and be embedded in diverse software tools. At its core, the digital twin enables system integration, ensuring that models and real systems consistently interact. It supports data analysis and model-based simulations; for example, in planning and training scenarios or "what-if" analyses.

Thereby, the digital twin serves as a permanent representation within interconnected processes, creating a dynamic feedback loop between virtual representation and real object, with its true value lying in lifecycle coverage, interoperability, and continuous information exchange.

For executive decision-makers, the digital twin is a strategic capability that bridges business and operations across an asset's lifecycle. It enables a (continuous and bidirectional) connection between the real object and its digital representation. It maintains the interoperability and integration of diverse data formats, tools, and models, serving as a management instrument for lifecycle performance and resilience, and offering transparency, predictive insights, and simulation capabilities.
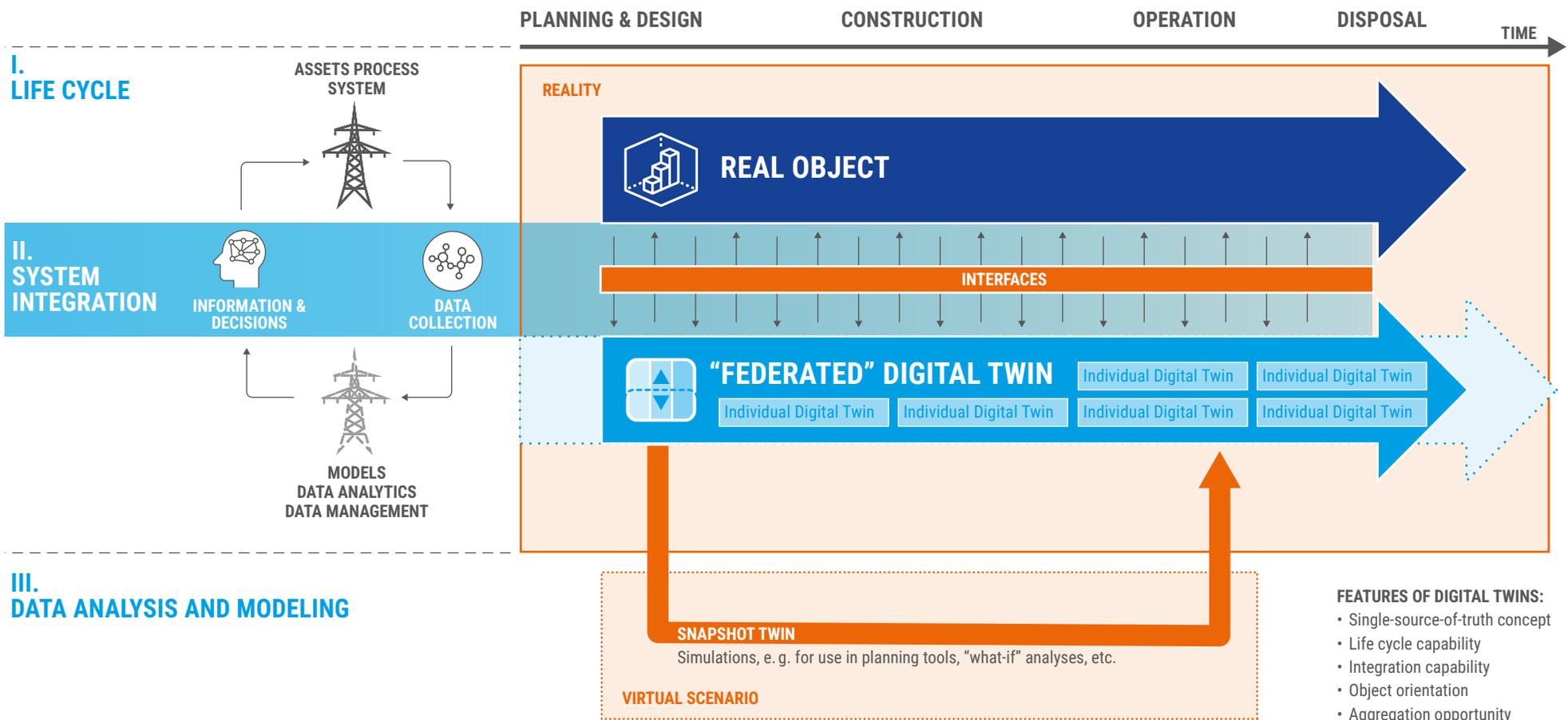
Figure 1: Overview of the digital twin concept. Source: **VDE**

Why (Federated) Digital Twins?

Benefits of Digital Twins and their Importance for TSOs

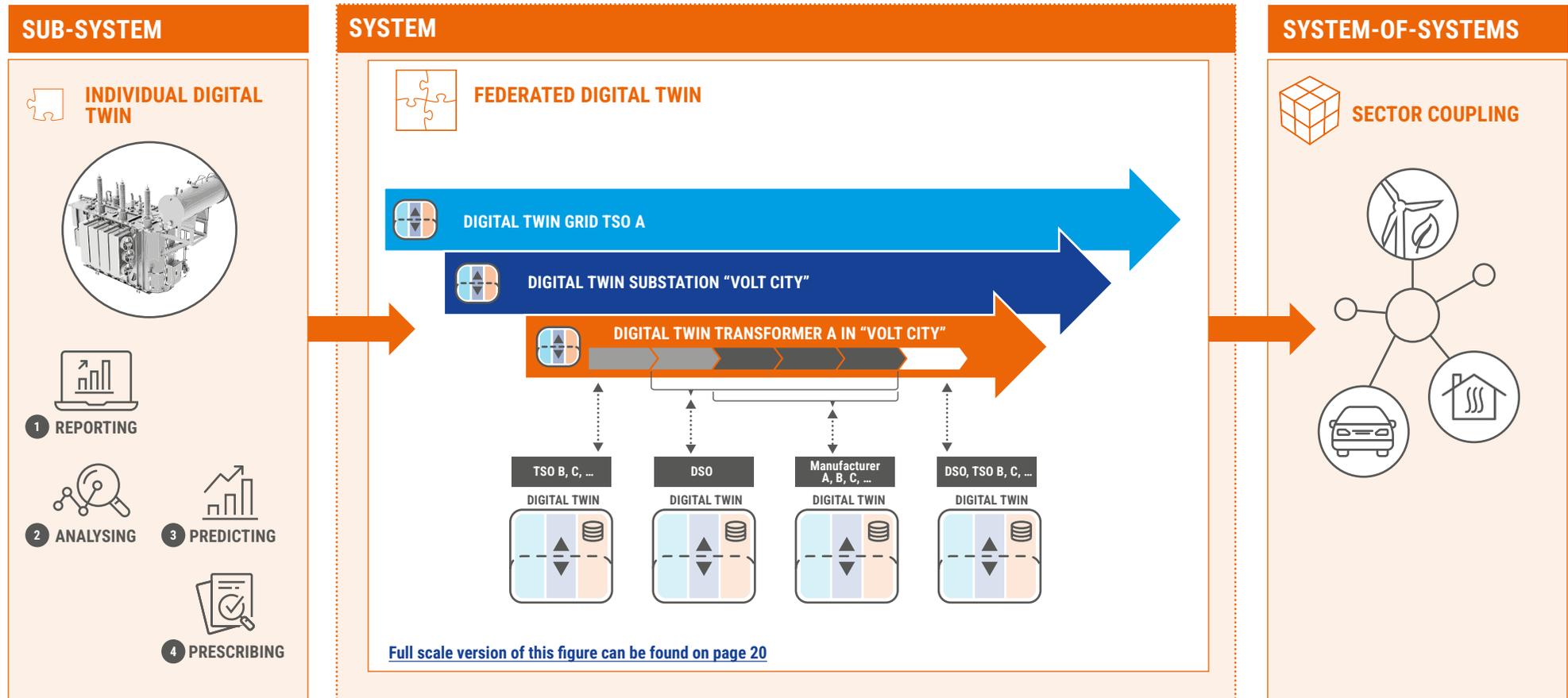Figure 2 depicts the concept of a Federated Digital Twin.

Figure 2: Concept of a Federated Digital Twin for TSOs

TSOs are already utilising digital twins for various use cases across different domains, which have mainly served to optimise processes within individual systems or silos. While these efforts have delivered measurable improvements, their potential is limited. The next breakthrough comes from connecting digital twins across the full end-to-end process chain, eliminating media discontinuities[4], establishing robust interfaces, and enabling true automation across organisational boundaries.

This shift is not only a technical enhancement but is strategically crucial for TSOs. End-to-end digital twins enable holistic process optimisation, offering transparency and resilience in grid planning, construction, operation, and maintenance. They are crucial for the energy transition, as they support scenario simulations for grid expansion and help navigate critical operational decisions under uncertainty.

Moreover, digital twins address the pressing skilled-labour shortage by embedding knowledge into systems, reducing manual effort, and enabling human-machine collaboration through advanced interfaces.

Despite rapid digitalisation, TSOs often operate in fragmented silos, resulting in inefficiencies and a digital paradox of high digital activity but limited systemic impact. Digital twins overcome this paradox by offering an integrated and consistent approach, laying the foundation for future AI applications and more intelligent, automated operational management.

Rather than optional pilot projects, digital twins are now a strategic necessity to unlock efficiencies, accelerate the energy transition, and future-proof the organisation against both technological and workforce challenges. This perspective should guide executive leadership.

The Issue we address – Status quo and Digital Twin Challenges

The groundwork for the digital twin revolution is already visible across our grids but remains fragmented. While the appendix highlights examples of digital twin use cases making advances in various operational areas, consideration of the challenges associated with integration and cross-departmental collaboration is often limited.

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4   "Media discontinuity" refers to an inefficient way of transferring information as the medium is changed; for example, a CAD drawing is printed on paper and later scanned to become a pdf file.

Risks of Isolated Digital Twin Projects

As stated above, projects on digital twins are already underway across many companies, although most of these initiatives remain role-specific and confined to subsystems or siloed functions. This leads to a proliferation of isolated twins, each optimised for a narrow scope but disconnected from end-to-end business processes. However, given that TSO operations are inherently cross-functional and lifecycle-spanning, these isolated efforts must be integrated into an overarching system of FDTs.

If TSOs continue focusing on isolated digital twin projects without moving towards a federated approach, the following organisational risks will materialise over time:

› **1. Proliferation of silos:** Each department develops its own digital twin, optimised for local needs but incompatible with others, thereby multiplying complexity rather than fostering integration.

› **2. Escalating costs:** Heterogeneous solutions demand higher SLAs, custom interfaces, and duplicated data management, increasing operating costs while economies of scale remain untapped.

› **3. Loss of efficiency:** End-to-end processes cannot be fully automated because handovers between systems remain fragmented. Staff must compensate with manual workarounds, undermining the very promise of digitalisation.

› **4. Governance gaps:** Cross-domain processes lack ownership, data governance remains weak, and accountability for quality or integration can be unclear. Organisational friction grows as technical teams face questions they cannot answer on their own.

› **5. Strategic dead ends:** When isolated twins reach their limits, major reimplementation efforts might be required to enable integration, which not only delays digital transformation but also increases the dependency on vendors and legacy systems.

› **6. Missed resilience capabilities:** Without federation, digital twins operate in isolation, creating silos that limit their potential by preventing sharing data and insights across systems, which is essential for achieving higher maturity levels within the digital grid. This lack of integration hinders the ability to achieve self-configuration, context awareness, and resilience.

This scenario reveals a digital paradox whereby the company strongly invests in digital projects, but system-wide efficiency and resilience do not mature. Consequently, the organisation risks creating an expensive patchwork of digital assets instead of a coherent digital backbone.

The clear conclusion for leadership is that TSOs will only be able to unlock end-to-end efficiency, improve resilience, or prepare for AI-supported operations by moving towards FDTs.

Digital Twin Integration Challenges

The more heterogeneous and individualised these twins are, the greater the effort required for their integration, which poses a particularly critical challenge in time-sensitive processes. This effort is not only due to the technical complexity of aligning diverse systems, but also because existing systems and available asset information are often insufficient to support advanced digital twin functionalities.

TSOs may need to acquire additional data from manufacturers and other external sources to fill these gaps. Therefore, integrating certain assets can be a lengthy process, potentially extending across their entire lifecycle. This makes it crucial to prioritise the assets and business cases where digital twin implementation delivers the greatest value and focus efforts there to drive meaningful progress. Beyond technical hurdles, organisational dynamics play an equally decisive role. Experts who were previously focused on individual systems now find themselves confronted with cross-domain and governance issues.

A foundational challenge lies in **standardisation activities**, such as defining components, processes, and data models. These are typically executed by subject matter experts (e.g., transformer specialists) and ideally span across TSOs, manufacturers, and contractors. Without such harmonisation, integration efforts become fragmented and inefficient.

Once standards are defined, **digitisation activities** follow – implementing tools, setting up interfaces, and training subject matter experts. These tasks are carried out by digitisation experts (IT, OT, etc.) who must translate standardised topics into usable solutions. Their work also involves bridging silos and ensuring seamless data integration, which is often complicated by legacy systems and inconsistent data governance.

Integrating new data or processes will lead to additional costs, while adjusting service level agreements (SLAs) often drives up operating expenses. The introduction of new data streams raises the pressing question of data stewardship in terms of who is accountable for maintaining and ensuring data quality.

Additionally, cross-functional processes often lack clear ownership, quality gates are insufficiently defined, and procurement continues to prioritise short-term benefits over long-term interoperability.

These technical and procedural challenges are compounded by the need for **organisational transformation**. Realising the benefits of digitisation requires a shift in the required workforce capabilities away from a focus on power system experts towards IT skills, which are becoming increasingly necessary. On the other hand, IT experts need to intensively communicate with system experts to co-create solutions that are truly effective. Without mutual trust, built on communication, collaboration, and understanding, resistance can arise, hindering the success of digital twins. Developing alignment and trust is a leadership task, not a technical one.

The joint elaboration of use cases for digital twin solutions and their integration is a good basis for future implementation. Technicians and domain experts cannot and should not be left alone to solve issues regarding governance, ownership, and organisational change. Clear governance and accountability structures are essential to guide this journey, which requires time, commitment, and a shared understanding of long-term goals.

Ultimately, it is essential to also understand the digital twin challenges in terms of organisational development and leadership. Digital twins can only evolve from isolated tools into a federated, company-wide, and eventually cross-sector system-of-systems by addressing trust, governance, and cross-domain ownership at the management level.

The Vision:
Where the Digital Twin Journey is Heading

The long-term vision for digital twins in TSOs is clear: step by step, more processes will be integrated, gradually connecting the entire organisation into a federated and end-to-end network of processes. This is not a radical departure, but a continuation of what utilities have been doing for decades. It will help increase automation and integration, which in turn will improve efficiency, reliability, and scalability.

What is new is that the digital twin allows organisations to think, steer, and optimise processes across traditional departmental boundaries. Finance, asset management, system operations, and cross-sector management no longer remain separate optimisation silos but instead become part of a shared digital ecosystem, which enables holistic decision-making, predictive scenario management, and cross-functional governance at a new maturity level.

The drivers behind this evolution are compelling:

> Workforce scarcity demands increased automation and knowledge embedded in systems.

> Energy system transformation and complexity require flexibility, scenario simulations, and sector integration.

> Cost efficiency in grid operations pushes TSOs to optimise processes across the whole value chain, which requires connecting digital twin components across various business sections and capabilities.

> The EU's ambitious goals on climate change and energy security, as well as strict regulations on how to achieve them.

From this perspective, digital twins are not simply a tool, but a strategic framework for organisational integration and future resilience. They lay the foundation for AI-supported decision-making, smarter human-machine collaboration, and ultimately a more adaptive and efficient energy system.

Maturity Assessment of Digital Twins

Rather than viewing the path towards FDTs in isolation, organisations should evaluate their maturity in digital twin solutions and overall digitalisation, aligning their initiatives with the corresponding stage of the five maturity levels depicted in Figure 3 below:
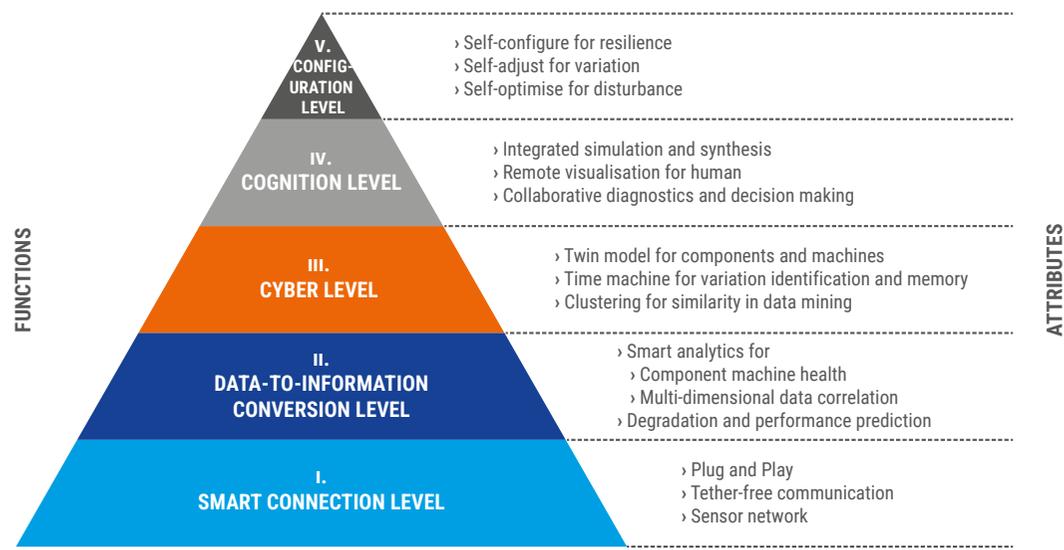

Figure 3: Pyramid of digital twin function levels. Source: **Technopedia**[5]

Organisations can utilise this pyramid to assess the maturity level of their digital twin solutions and identify pathways to achieve greater maturity in developing effective digital twin solutions tailored to the TSO's digitalisation level.

A practical example is TenneT, the Dutch-German TSO, which has advanced step by step along this maturity path. At the smart connection level, it deployed thousands of Internet of Things (IoT) sensors across its substations and offshore platforms to capture real-time asset data.

Moving into data-to-information conversion, TenneT has applied analytics and predictive maintenance models to forecast failures in cables and transformers (**OSIsoft case study**). At the cyber level, it has begun developing digital replicas of grid components and using simulation tools to optimise maintenance and investment strategies (**Cosmo Tech press release**). Today, TenneT is piloting cognition-level functions in the Horizon Europe eFORT project, where real-time digital twins provide decision support and pave the way for configuration-level self-healing grids (**eFORT project**).

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5   Definitions of levels can be found in the glossary

Necessity of Standards and Interoperability for Data Exchange and Collaboration

Regardless of an organisation's maturity level, a key cornerstone for achieving a network of FDTs is that organisations must prioritise openness and interoperability. Individual formats and processes should be the exception rather than the rule, whereby organisations should proactively implement standardisation and normalisation, facilitated by (open) standards that enable seamless communication across various vendors, domains, and lifecycle stages. Standardisation will then be a key enabler for achieving FDTs: establishing cross-unit standards for handling asset and model data creates a single source of truth, allowing future tools to access and leverage consistent information. This not only ensures interoperability of data and tools but also unlocks the full potential of a federated digital twin. Given that a single standard cannot achieve this, a framework of complementary (open) standards is necessary.

Key examples include:

› **IEC 61970 / 61968 and IEC62325 (CIM / CGMES, ESMP):** For power grid data modelling, covering both physical assets and market interactions.

› **IEC 61850:** For real-time data communication within substations and between intelligent electronic devices.

› **ISO / IEC 38505-1:** For data governance to ensure effective, efficient, and trustworthy use across organisations and systems.

› **ISO 8000:** Several norms for data quality and master data management to ensure accurate, consistent, and exchangeable data.

› **ISO 27001:** Fosters improved data governance by embedding security practices into information management, which enhances data quality, mitigates risks, and supports regulatory compliance, such as the GDPR.

› **BIM standards:** For creating detailed 3D models of physical assets during planning, construction, maintenance, and operation phases.

› **Cross-domain standards:** Adopting established industry standards such as **OPC-UA**, **MQTT**, and **SAREF** for integration with broader technological advancements and avoiding vendor or technology lock-in.

› **IEC Smart Grid Map**: Collection of a diverse set of standards applicable to smart electricity grids.

› **Further technical standards** to support practical federated coordination, including latency requirements for cross-TSO interactions (e. g., informed by IEC 61850), data consistency models, and guidance on selecting event-driven vs. polling communication patterns.

As stated above, FDTs rely on interoperability across technical, semantic, and organisational layers. To achieve this, data spaces – as described in ENTSO-E's paper on **Data Spaces in the Energy Sector** – should be considered in their design. Data spaces provide a governed, federated ecosystem for secure and sovereign data sharing, aligning stakeholders through common standards and policies. While digital twins focus on representing and simulating physical assets, data spaces focus on trustworthy data exchange. Together, they are complementary: data spaces supply the infrastructure and governance enabling interoperability, while digital twins enrich data spaces with real-time, model-based insights, fostering cross-domain collaboration and scalable twin federation.

Cyber Resilience, Functional Safety, and System Security in Federated Digital Twins

Cyber resilience is a fundamental prerequisite for the reliable and secure operation of federated digital twins. As these systems will enable cross-organisational data exchange and interoperability across TSOs, DSOs, and other critical-infrastructure stakeholders, their exposure to cyber risks will increase significantly. Accordingly, resilience must be a **design-by-default principle** embedded from the outset, not a later add-on.

Cyber resilience in federated digital twins must build on **proportionate, transparent, and sector-specific requirements** to ensure trust and reliability across all system components. This includes structured risk assessment, formal conformity processes, and alignment with sectoral cybersecurity legislation and frameworks such as the **EU Cyber Resilience Act (CRA)** and the **Network Code on Cybersecurity (NCCS).** In line with ENTSO-E's position on the CRA, resilience measures must reflect the criticality of energy-system functions and support operational continuity rather than impose generic ICT burdens.

Clear **accountability and transparency obligations** for vendors and operators are essential. Manufacturers must disclose which cyber risks their products mitigate and how, and operators must maintain transparent risk governance. These governance requirements ensure that federated digital-twin components can be trusted, verified, and integrated into mission-critical grid operations without introducing unmanaged systemic risk.

However, cyber resilience alone is insufficient. For grid-critical systems, cybersecurity and functional safety must be jointly addressed:

› **Cybersecurity** protects against intentional malicious interference, manipulation, and unauthorised access.

› **Functional safety** ensures that unintended internal faults – such as software defects, configuration errors, or hardware failures – do not lead to unsafe states or system instability.

Security and safety are distinct but interdependent. A system secure against cyber attacks may still destabilise the grid due to software faults, and a system designed for safety may remain vulnerable to targeted compromise. For federated digital twins, this requires **fail-operational capability:** critical functions must continue operating under attack or failure conditions in a controlled state, rather than shutting down.

Maturity Gap: Cybersecurity vs. Functional Safety

In the energy sector, the maturity level between these domains differs significantly. **Cybersecurity has advanced governance, dedicated regulations, and defined Network Codes**, supported by well-established practices and dedicated teams.

By contrast, **functional safety and fail-operational design remain largely implicit.** While many elements exist within system-operation culture and engineering practices, **there are currently no explicit sector-wide standards or harmonised frameworks for functional safety in digital-grid applications.** This gap becomes critical as digital twins, automated decision support, and data-driven control become integral to system operation.

As TSOs and DSOs move towards **more interconnected, interdependent, and automated digital environments,** functional safety becomes a foundational requirement.

Developing this capability requires:

› time to establish suitable standards and industry guidelines

› building organisational skills and engineering competencies

› integrating safety and fail-operational practices in system-development processes

› training operational and engineering staff

› aligning procurement and vendor requirements

At the current stage, **this topic remains insufficiently addressed and represents a hidden systemic risk.** Without proactive action, the sector may face a capability gap precisely when digital-twin-enabled operations become critical for grid stability and system security.

Resilience as a Combined Security-Safety Discipline

True **resilience** – the ability to anticipate, withstand, recover, and adapt – can only be achieved when **security and functional safety are integrated** throughout the lifecycle of federated systems. This extends across organisational boundaries, requiring **coordinated governance, shared risk models, and aligned compliance processes** between TSOs and other operators.

Standardisation and interoperability, while essential to federation, also increase systemic exposure. In today's heterogeneous environment, architectural diversity provides inherent compartmentalisation. As harmonisation progresses, **a single vulnerability or design flaw could propagate across multiple systems.**

Therefore, resilience must be embedded into the **architecture, governance, and standardisation processes** of federated digital twins. Interoperability must be designed in a way that preserves system integrity, ensures energy-system stability, and prevents cascading effects across the European power system.

In sum, resilient federated digital-twin architectures require:

› cybersecurity and functional-safety integration

› fail-operational design principles

› transparent manufacturer and operator accountability

› harmonised regulatory and conformity frameworks

› coordinated cross-TSO governance

› security-aware standardisation processes

› proactive development of safety standards, skills, and processes

This ensures that the benefits of federation – shared insights, improved situational awareness, and coordinated system operation – do not come at the expense of operational stability, safety, and system security.

Methical Approach and Process-Driven Design

While a networked approach based on open standards is a significant improvement, this paper advocate for the network to evolve into a system of FDTs to achieve effective scaling. This means that system operators' leaders and technical innovators should not view digital twins as simply additional tools but instead as being fundamentally embedded within the processes and data ontology of the companies and grid systems. The transition towards FDTs is not only a technological journey, but also requires an organisational and methodological transformation, demanding new ways of working, new processes and mindsets across organisations.
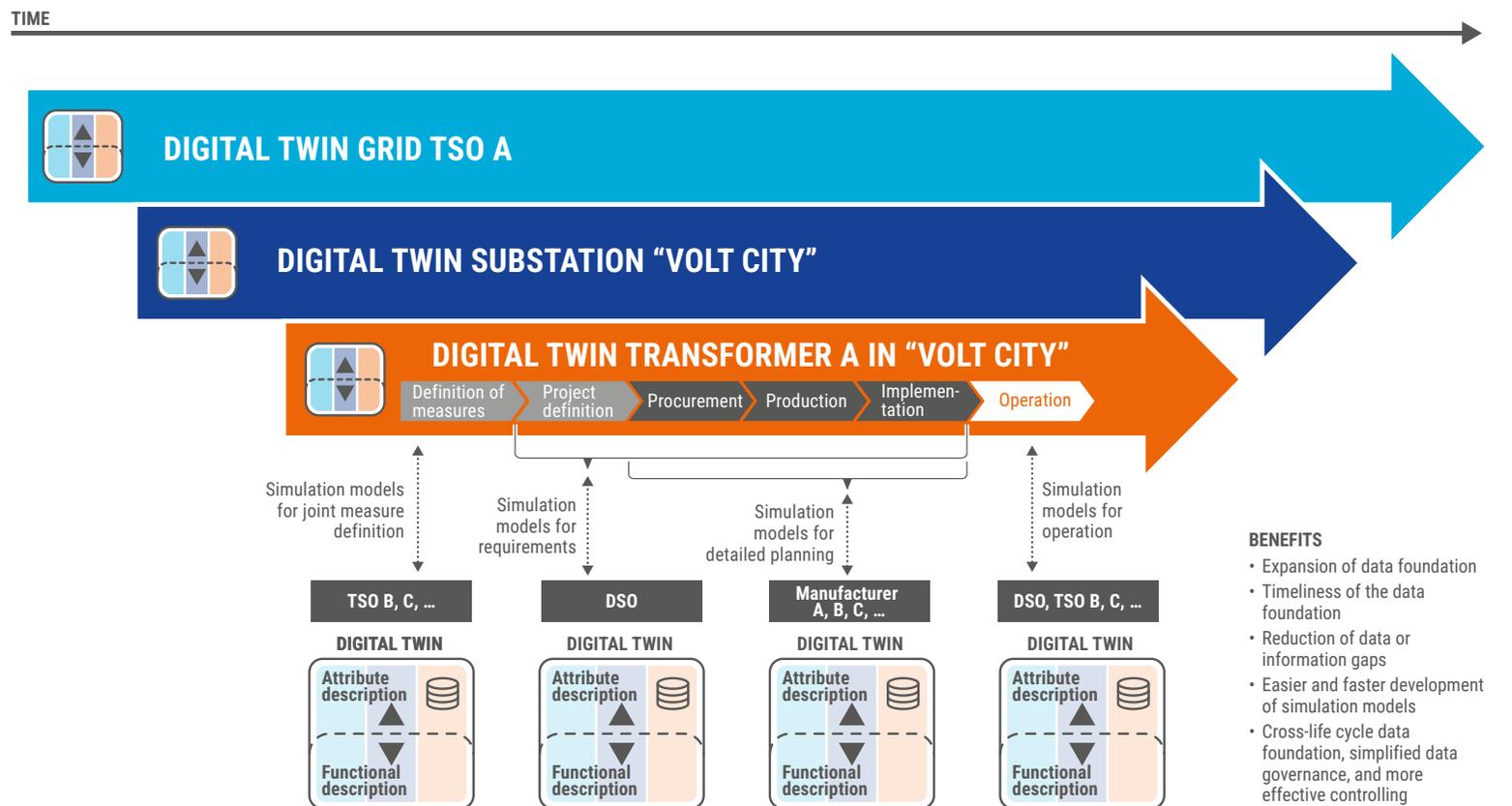

Figure 4: Exemplary integration of multiple digital twins in the context of establishing a new transformer in a substation (**VDE**).

Accordingly, it is necessary to rethink company processes and plan digital twins as part of the **end-to-end process analysis.** Integrating FDTs necessitates a comprehensive framework centred around a methodical approach and process-driven design, incorporating the following priorities. These priorities should serve as guiding principles, recognising that in practice it may not always be feasible to implement all of them simultaneously.

When constraints arise, organisations should assess the priorities carefully and make deliberate choices about which principles to emphasise and which may need to be deferred, while ensuring the overall approach remains aligned with strategic objectives.

> **Follow a structured strategy rather than an unstructured bottom-up approach:** Outlining a clear roadmap with goals, milestones, and timelines, ensuring scalability and sustainability. This helps maintain focus and align resources with organisational objectives.

> **Prefer interoperability over individual solutions:** Prioritising standardisation and normalisation to ensure that interoperability is at the centre of digital twin development.

> **Emphasise process-driven over technology-driven design:** Aligning digital twin development with existing business processes and workflows, enhancing operational efficiency by embedding digital twins into the organisational workflow for real-time insights and informed decision-making.

> **Adopt a methodical approach rather than ad-hoc implementation:** Involving a systematic, step-by-step strategy to implement digital twins, including clear objectives and resource allocation. This minimises risks and optimises outcomes through meticulous planning and execution.

> **Prioritise disciplined engineering over improvised design:** Applying rigorous engineering principles, adhering to industry standards and best practices to ensure digital twins are robust, accurate, and capable of delivering high-fidelity simulations and analyses.

> **Focus on systematic, iterative development rather than one-off deployment:** Involving organised creation and deployment, emphasising iterative testing and continuous improvement. This allows digital twins to evolve in response to changing conditions and requirements.

Leveraging Enterprise Governance and Systems Engineering

To create solutions that align with the aforementioned priorities, organisations need to reassess their existing internal methods and establish frameworks that reflect these guiding principles. Traditional waterfall and agile approaches, while useful in certain contexts, often fall short in delivering sustainable solutions for digital twins.

› Classical methods focus on linear processes and struggle with continuous tech upgrades, resulting in fragmented documentation and poor integration.

› Agile methods offer flexibility but depend on implicit team knowledge, posing challenges for long-term maintainability when projects conclude or team members change.

However, digital twins demand explicit models, traceability, and life-cycle thinking. Given that each twin must be connected not only to its immediate domain but also to the broader organisational and inter-organisational context, this requires structured methods that make dependencies, assumptions, and system boundaries visible. **Enterprise governance** and **systems engineering** become particularly relevant.

Enterprise governance sets strategic direction, helping organisations achieve long-term goals by:

› aligning vision and values with stakeholder expectations;

› implementing consistent policies for decision-making and risk management; and

› ensuring accountability through regular evaluations and reporting.

Systems engineering (SE) offers a methodological backbone, excelling in:

› ensuring traceability from requirements to operation;

› embedding test cases and documentation for manageable upgrades and integration; and

› using explicit models (such as SysML) that remain valid across lifecycle stages;

› providing a holistic, system-of-systems perspective aligned with FDTs.

Example:

Consider a substation scheduled for an upgrade, where several circuit breakers, protection relays, and control systems interact. In an SE approach, the digital twin not only models each asset in isolation, but it captures the entire web of dependencies across the substation. This explicit traceability enables operators to visualise how replacing a single circuit breaker might affect relay settings, grid protection schemes, and even upstream transmission lines. When planning the upgrade, the model highlights potential cascading effects, enabling proactive coordination across teams and ensuring system reliability.

For TSOs, the evident takeaway is that without a methodological shift, digital twin projects risk repeating the same inefficiencies of the past. Enterprise governance and SE are the key enablers that allow digital twins to evolve from isolated tools into a federated, sustainable backbone of the digital grid, making complexity manageable, governance enforceable, and integration scalable.

Outcome: Leap into Federated Digital Twins

TSOs can effectively leap into integrated FDTs by combining networked digital twins leveraged through open standards with a system engineering and end-to-end view, transforming them into vital components that enhance efficiency, drive innovation, and support strategic objectives collaboratively.

This approach enables a comprehensive **lifecycle and system perspective**, whereby a digital twin can and should support the entire lifecycle of an asset, from planning and design to operation and decommissioning, as well as its role at different levels. A digital twin focused on individual stages provides information for the following stages in an integrated way. In parallel, relevant information is also accessible for digital twins at the grid / system level and for operators on other levels. Information is contextual, available, manageable, and actionable, with sufficient quality data enabling data exchange with other FDTs.

An effective FDT solution should emphasise traceability, predictability, governance, quality assurance, and standardised workflows, which form the foundation for an efficient and impactful digital twin ecosystem:

› **Traceability** ensures that every change, interaction, or transaction within the digital twin network is recorded and traceable to its origin. This capability supports compliance, accountability, and the ability to diagnose issues by maintaining a clear lineage of data and decisions.

› **Predictability** leverages advanced analytics and simulation techniques to forecast future states or behaviours. This enhances operational efficiency by anticipating failures, optimising performance, and enabling proactive planning, thereby reducing downtime and supporting informed decision-making.

› **Governance** establishes policies and controls to effectively manage digital twins. It ensures alignment with organisational goals, compliance with industry standards, and ethical use of data. Governance frameworks maintain consistency and integrity across the digital twin network, fostering trust and collaboration.

› **Quality assurance** involves processes to ensure the accuracy and reliability of digital twin models and data. By validating inputs and verifying outputs, organisations can identify discrepancies early, prevent costly mistakes, and enhance the credibility of their digital twin solutions.

› **Standardised workflow** provides a set of consistent procedures for creating and managing digital twins. Standardisation streamlines operations, reduces variability, and facilitates interoperability across systems and vendors, supporting scalability and adaptability.

Together, these aspects create a robust framework that enables organisations to harness the full potential of digital twins, driving innovation, optimising performance, and achieving strategic objectives effectively.

Strategic Imperative and Implementation Approaches

Beyond considering what digital twin solutions should look like, TSOs and collaborating organisations must also think about how to implement them. When introducing digital twins, organisations typically choose between bottom-up, top-down, or what is often referred to as "bombing" approaches (a disruptive introduction by external mandate or vendor, with key competencies often lying outside the TSO).

While each of these approaches can be valid in the early stages, the crucial success factor is identifying the suitable moment to transition to a holistic, top-management-driven strategy, enabling a sustainable FDT to emerge that unlocks the full potential without disrupting the organisation.

Approach	Advantages	Disadvantages	Path to federated digital twin
Bottom-up	› Strong ownership by technical experts › Fast prototyping and innovation › Solves immediate local problems	› Creates silos and heterogeneity › Limited scalability › Costly integration later	› Scale successful pilots into company-wide programmes › Establish governance and C-level sponsorship
Top-down	› Strategic alignment from the start › Clear governance and end-to-end view › Resources allocated by management	› Risk of over-engineering › Slower early results › Weak buy-in if not inclusive	› Maintain strong feedback loops with technical teams to ensure practicality › Embed incremental rollout
Disruptive (external mandate)	› Rapid mobilisation › Strong external push (regulation; vendor) › Forces organisational attention	› Low ownership, high resistance › Potential mismatch with › processes › Risk of organisational shock effects	› Rebuild trust and ownership › Reframe external solutions into a coordinated and management-led integration strategy

Table 1: Various approaches to federated Digital Twin

Strategic Imperative

In practice, all three approaches can play a role depending on the organisational context and maturity. However, the turning point always comes when bottom-up or mandated solutions reach their limits. At this stage, only a top-management-driven approach can align governance, allocate resources, and resolve organisational questions (e. g., data stewardship, SLA responsibilities, cost allocation).

Without this transition, organisations risk remaining stuck in fragmented solutions that create more complexity than value. Strong management steering can enable digital twins to evolve into a sustainable federated framework that drives automation, unlocks cross-functional synergies, and supports long-term resilience.

What's Next?
Steps towards Federated Digital Twins

This chapter provides a practical guide for advancing federated digital twins within TSOs.
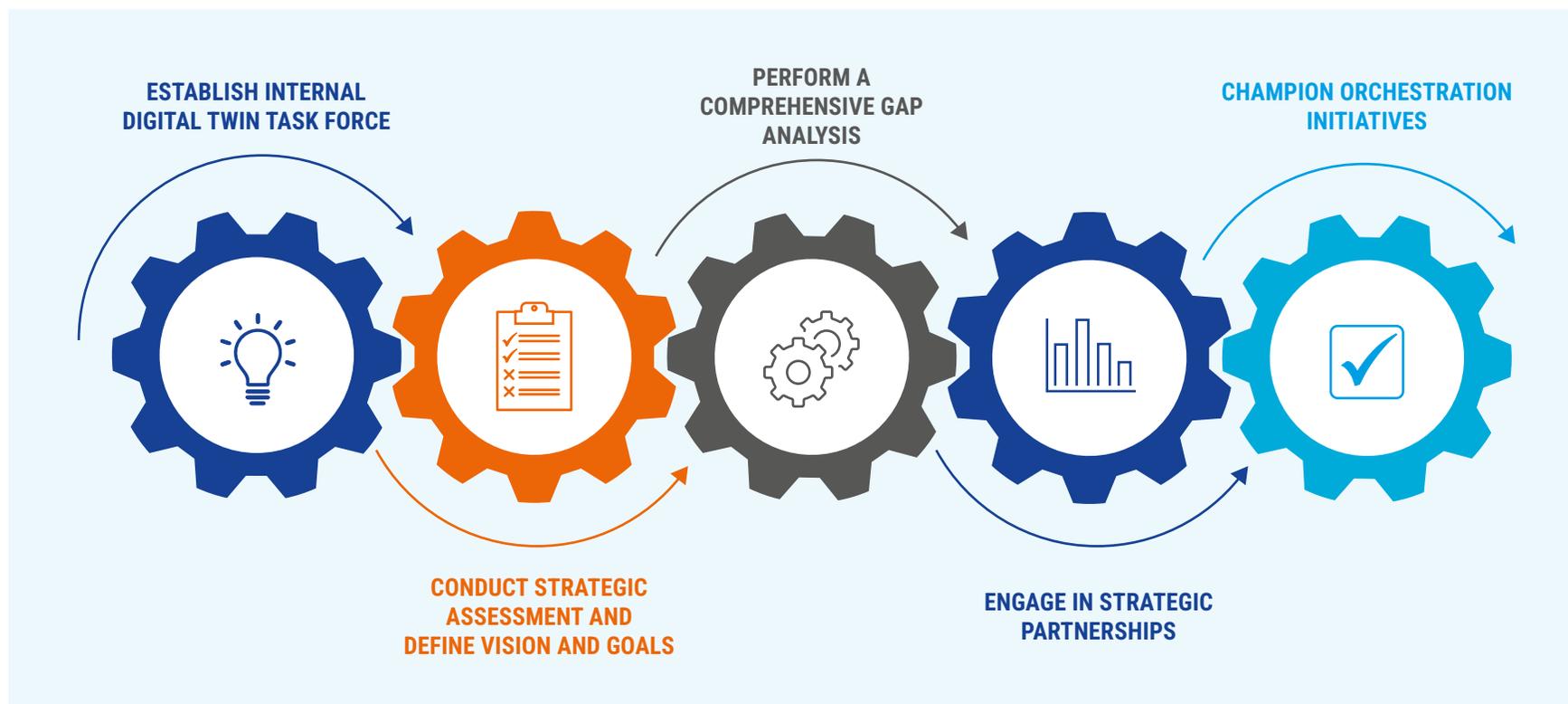

Figure 5: Steps towards Federated Digital Twins

1. Establish an Internal Digital Twin Task Force

Action: Designate an FDT lead and establish a dedicated cross-functional digital twin leadership group involving all relevant departments. Define clear roles, responsibilities, and decision-making protocols (e.g., **RACI Matrix**).

Impact: Creates accountability and a structured foundation for cross-department collaboration, reflecting the critical first step to break organisational silos and achieve meaningful cooperation and data. The digital twin leadership group can ensure that all digital twin efforts serve the unified vision and approach the goals, enforcing policies and influencing decisions.

2. Conduct Strategic Assessment and Define Vision and Goals

Action: Set strategic goals for digital twin implementation. Analyse core business processes to identify where digital twin capabilities will generate the highest value. Define long-term objectives and transformation priorities. Begin internal communication early to ensure stakeholders are aware of the vision, goals, expected improvements, and the roadmap for realisation, including the broader organisational transformation.

Impact: Aligns the organisation around a shared vision and identifies where digital twin technology can deliver real-world impact. Lays the groundwork for effective resource allocation and long-term planning.

3. Perform a Comprehensive Gap Analysis and Define Use Cases

Action: Map current digital twin projects, data assets, and system models. Evaluate data quality, system integration, process readiness, and cybersecurity maturity. Identify pain points and priority gaps. Define concrete Digital Twin use cases that provide a clear value to the organisation.

Impact: Provides a clear picture of current capabilities in comparison to future needs. Supports a focused, realistic roadmap that builds on existing assets while addressing critical weaknesses with concrete goals. Well-defined use cases highlight tangible business value and help prioritise high-impact initiatives.

4. Engage in Strategic Partnerships

Action: Collaborate with the European Commission, ENTSO-E, TSOs, DSOs, vendors, academia, and industry bodies to align on open standards, data interoperability, and shared architectures. Facilitate structured dialogue among system operators to define digital twin needs and use cases. Leverage ENTSO-E's network to establish common requirements, interfaces, and quality criteria, enabling TSOs to act as system integrators. Use initiatives like TwinEU, European Commission Roadmap on Digitalisation and AI, and the DESAP Digital Twin Roadmap to guide collaboration. Leverage the strategic importance of power grids for climate, defence, and digitalisation goals to gather support for initiatives.

Impact: Accelerates progress through knowledge exchange and standardisation. Promotes alignment across the European power system, avoiding duplication of effort and increasing efficiency by ensuring that digital twin solutions are interoperable, scalable, and tailored to real system operator needs.

5. Champion Orchestration Initiatives

Action: Launch use-case based pilot projects and initiatives that are explicitly anchored in concrete, high-impact use cases to leverage the partnerships and close the gaps identified. Define clear indicators of performance and targets to be achieved. The digital twin leadership group should follow the results closely by measuring success with key performance indicators (KPIs) closely related to the defined goal and adjusting actions in response to deviations. Examples for orchestration initiatives include encouraging vendor-agnostic solutions to reorganise processes for a digital twin architecture, integrating existing digital twins into a federated architecture, and jointly developing a digital twin with partners.

Impact: Financial and technical results delivery, validation of technical choices, thus increasing credibility. This creates internal momentum and fosters adoption at multiple levels, with initial success stories serving as templates for full-scale implementation and to secure stakeholder buy-in.

Expected Outcomes and Opportunities

Achieving the Vision

Achieving a system of FDTs will require ambition, sustained effort, and close coordination across departments and partners. While initial implementations might succeed, new use cases will emerge that are perhaps not be feasible without reimplementation, leading to high costs and potential delays in grid digitisation. This process presents a dilemma, as inconsistent approaches among network operators could create a benchmark gap, with some doing it "right" and others "wrong."

Moreover, the journey requires overcoming cultural barriers and embracing change management. The transition towards FDTs demands resources, discipline, and a willingness to adapt to evolving operational and regulatory demands. Addressing these challenges is crucial to ensuring a cohesive and effective transformation.

However, the risks of delaying are greater, as postponing action will allow technical debt to accumulate, leave valuable data underused, and limit the organisation's ability to adapt to evolving operational and regulatory demands.

Opening the Doors for the Future

The FDT is more than simply a new tool. It is a new paradigm for managing power systems by creating a rich, validated, and interconnected ecosystem, enabling real integrated end-to-end processes that can be leveraged for transformative applications, including innovative AI applications.

The rise of AI and machine learning: With high-quality data from federated twins, AI models can train on larger datasets and enhance applications such as predictive maintenance and automated grid optimisation beyond their current capabilities.

Beyond human-machine interfaces to decision support and context awareness: Moving beyond traditional human-machine interfaces (HMIs) – which often overwhelm users with raw data – the FDT embeds itself within company processes and ontologies to contextualise data. This enables users to easily access relevant information, improving the performance of AI applications and facilitating more efficient decision-making.

Human-in-the-loop systems: The role of users transitions from micromanaging to strategic decision-making. While the system autonomously manages routine events, it ensures transparency by presenting users with relevant, contextualised information for complex situations and key decisions, empowering them to make informed choices swiftly and safely.

Efficiency: FDTs offer a scalable and adaptable digital infrastructure that enhances network management and optimisation. While initially higher costs might be incurred, these systems enable more effective and efficient processes, ultimately improving the network utilisation. Literature suggests that applications such as dynamic line rating can enhance network performance by reducing curtailment of renewables and optimising system operations on an 80% or 100% green system **(Source)**. Despite a potential substantial immediate financial impact, the long-term benefits include improved network management and operational efficiency.

Legacy integration: FDTs facilitate the integration of legacy systems by offering interoperable interfaces and protocols. This ensures smooth transitions and minimises disruptions, allowing existing infrastructures to seamlessly adapt to new digital frameworks.

Ownership and collaboration: Collaborative frameworks address ownership concerns by defining clear roles and responsibilities, promoting equitable access and benefits for all stakeholders involved, fostering transparency, trust, and cooperation within the energy ecosystem.

A crucial opportunity for significantly enhancing resilience in modern energy grids lies in the use of FDTs. This network of digital replicas of grid components enable decentralised, real-time coordination and system-wide visibility, allowing for faster fault detection, predictive maintenance, and coordinated responses to disturbances. Each grid component maintains its own digital replica while securely sharing essential data across the network, which can self-adjust based on real-time data, adapting to changing conditions to maintain stability and prevent cascading failures.

Once implemented, an FDT provides a unified, real-time view of assets and operations, significantly strengthening the grid's ability to anticipate, prevent, and respond to disruptions. This resilience is not only technical but organisational, creating faster decision-making, more efficient resource allocation, and improved coordination during both routine operations and emergencies.

Beyond enhancing day-to-day resilience, digital twins shape future capabilities through advanced simulations and predictive modelling, enabling teams to train in realistic virtual environments and prepare for scenarios before they occur in the real world. This will improve situational awareness, refine operational strategies, and reduce the risks of costly errors. Over time, the digital twin will become a central tool for both immediate response and long-term planning, delivering lasting value across the organisation.

In an increasingly dynamic and decentralised energy landscape, this proactive capability is essential for integrating renewables, managing volatility, and safeguarding grid stability. By supporting distributed, real-time coordination, digital twins enhance resilience and improve situational awareness during both normal operations and critical events.

Pan-European and Cross-Sector Cooperation

Europe's power system is becoming increasingly integrated and interdependent across markets, networks, and regulations. As electrification accelerates and the energy transition deepens, fragmented digital infrastructures are no longer viable. A pan-European FDT ecosystem provides a unified digital platform that facilitates this cooperation and makes it manageable. This pan-European network will be an important stage, building upon initiatives such as INSIEME.

Enhanced cross-border grid management: Creating a digital space where TSOs and DSOs across Europe can securely exchange validated models and data dynamically enables more accurate simulations of continental power flows, optimising cross-border redispatch, increasing the efficiency of interconnectors, and ensuring a new level of shared grid stability across Europe.

A unified and empowered energy market: Digital grids can enhance (European) energy markets. Through lightweight, secure platforms, customers can offer flexibility from their EVs, heat pumps, and batteries, participating in local and national energy markets and directly contributing to a more resilient and democratic energy system. Digital grids make this immense load of information manageable, supporting system operators to ensure stable operation in the grid of the future.

Support for future sector coupling: The federation enables the future integration of electricity twins with digital twins from other critical infrastructure sectors. This allows deep coordination between the power grid, public infrastructure (street, water, and gas planning), power-to-X applications, and meteorological services for hyper-accurate renewable forecasting.

Conclusion

Adopting a federated approach to digital twins provides the energy industry with a pragmatic and future-ready framework. By avoiding lock-in to centralised systems, companies can retain control over their data while benefiting from secure collaboration and shared insights. This model promotes interoperability across diverse assets and markets, enabling businesses to innovate more quickly, optimise their operations, and unlock new value streams.

Crucially, it creates the foundation for scaling digital twin solutions across entire portfolios and supply chains without compromising security or competitiveness. For industry players, this approach is not only about technological alignment but also about building the necessary trust and flexibility to thrive in an increasingly digital and decarbonised energy landscape.

Although the journey is complex and demands sustained collaboration, the motivation is clear: a flexible, secure, and truly European digital infrastructure that supports an affordable, resilient, and sustainable energy future. With dedication and collaboration, the long-term benefits of this transformation are within reach.

Appendix

List of acronyms/abbreviations

Abbreviation	Meaning
ENTSO-E	European Network of Transmission System Operators for Electricity
ESMP	European Style Market Profile
TSOs	Transmission System Operators
DSOs	Distribution System Operators
SE	Systems engineering
FDT	Federated Digital Twin
BIM	Building Information Modelling
SCADA	Supervisory Control and Data Acquisition
ERP	Enterprise Resource Planning
GIS	Geographic Information System
SLAs	Service Level Agreements
DESAP	Digitalisation of Energy System Action Plan

Abbreviation	Meaning
KPIs	Key Performance Indicators
HMIs	Human-Machine Interfaces
OPC-UA	Open Platform Communications Unified Architecture
MQTT	Message Queuing Telemetry Transport
SAREF	Smart Applications REFerence ontology
GDPR	General Data Protection Regulation
CIM	Common Information Model
CGMES	Common Grid Model Exchange Specification
SysML	Systems Modeling Language
INSIEME	Integrated Network for data Space and Interoperable Energy Management in Europe
IoT	Internet of Things

Table 2: Abbreviations

Glossary

Smart connection level

Plug-and-play devices, wireless communication, and sensor networks build the foundation by connecting assets and generating raw data.

Data-to-information conversion level

Analytics transform raw sensor data into information, enabling insights into asset health, performance degradation, and predictive maintenance.

Cyber level

Digital twins emerge at this stage, providing models of assets and subsystems, enabling memory, variation analysis, and clustering for system-wide data mining.

Cognition level

Integrated simulations and "what-if" analyses enable operators to make informed decisions together with their digital twins. At this point, the control centre transforms, as human operators increasingly collaborate with systems, making the human-machine interface a central element that requires special attention.

Configuration level

The highest maturity level, where systems become context-aware and self-aware, capable of self-configuration, self-adjustment, and self-optimisation for resilience. Digital twins are the key enablers for bringing this awareness into the system, ensuring robustness against disturbances and adaptability to change.

Selected Use cases

Examples of Existing Digital Twin Applications

——— 3D / BIM Modelling

A digital twin for the use case "3D design and BIM modelling" offers a dynamic, data-rich representation of physical assets such as electrical substations. While 3D design defines spatial structure and BIM manages multidisciplinary data, the digital twin integrates real-time sensor input, operational parameters, and historical records. This enables advanced use cases, such as simulating power flows and switching options directly in the 3D model, as well as training and planning.

Some 3D / BIM models are incorporating CIM / CGMES information to provide more operational context and advanced capabilities. DESAP – a joint initiative of ENTSO-E and the EU DSO Entity, driven by the European Commission – has mapped challenges and opportunities for digital twins across the electricity system. Its **joint report** highlights Fingrid's ELVIS system (Finland, TSO), which integrates 3D asset models with operational data for planning and lifecycle management, and Enel (Italy, DSO), which has implemented 3D distribution network models linked with operational platforms.
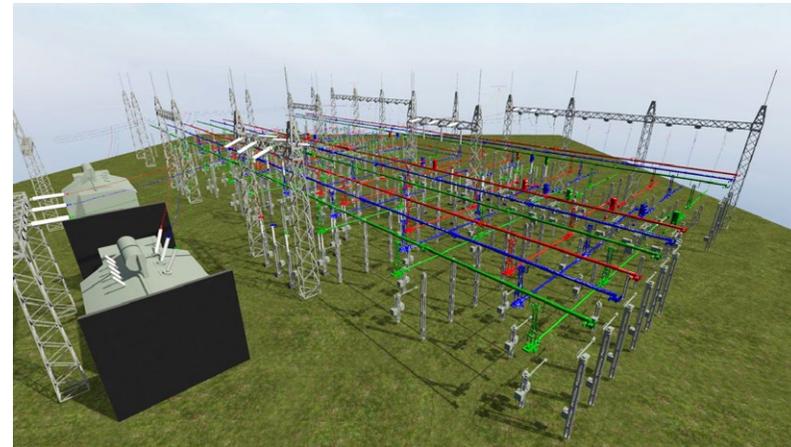

Figure 6: 3D/BIM Modeling (source: APG)

Dynamic Asset Rating

Digital twins are utilised in dynamic line rating (DLR) to create a virtual, real-time model of overhead transmission lines, which calculates their maximum current-carrying capacity (ampacity) based on actual and forecasted environmental conditions. The digital twin continuously updates ampacity across the entire line by integrating weather data (such as wind speed, temperature, and solar radiation), line design, and geographical information.

This data-driven approach enhances accuracy, reduces the need for physical sensors, and enables operators to optimise grid performance, plan ahead, and improve system reliability. According to the DESAP report, Swissgrid (Switzerland, TSO) has implemented advanced DLR with integrated weather and sensor data, Energinet (Denmark, TSO) applies model-based DLR approaches, and MAVIR (Hungary, TSO) is piloting AI-driven DLR without physical sensors.
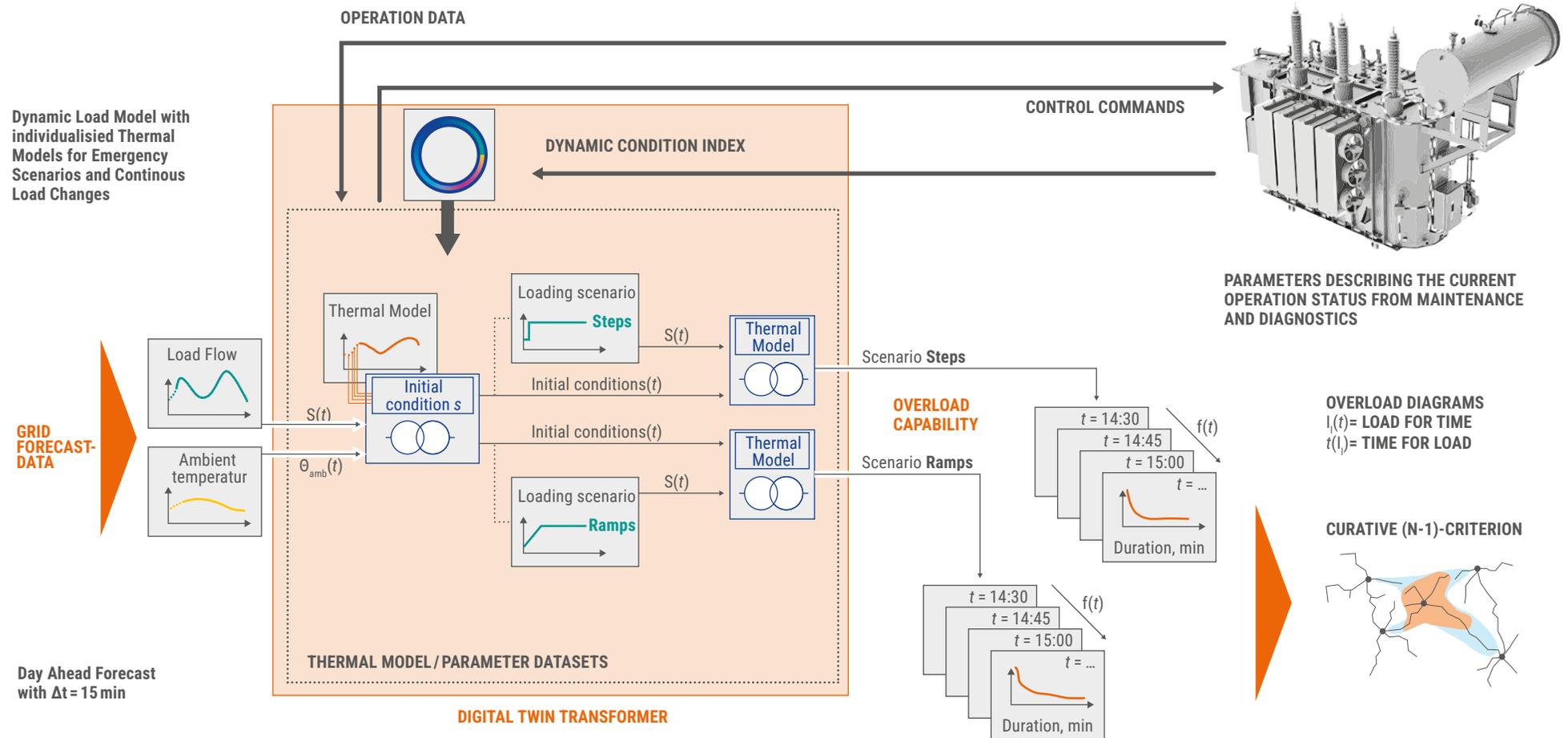

Figure 7: Dynamic Asset Rating (**VDE**)

Network Planning

Digital twins replicate electricity networks in a virtual environment, combining real-time data, historical records, and predictive simulations. They help grid operators monitor performance, test future scenarios such as distributed energy resources (DER) and electric vehicle (EV) growth, and compare upgrade strategies before implementation, enabling proactive, cost-efficient, and resilient grid planning.

The DESAP report highlights Fingrid's ELVIS and Enel's 3D grid modelling platform as advanced examples, while Swissgrid (Switzerland) and Statnett (Norway) are also featured for their use of network-level twins in system planning and resilience studies.

Predictive Maintenance

Digital twins of electric equipment such as transformers or switchgears combine real-time monitoring, historical data, and simulation to detect early signs of faults, including overheating or insulation degradation. Digital twin models can help simulate fault progression, enabling timely, condition-based maintenance that reduces downtime, optimises schedules, and extends asset life.

The DESAP report highlights Swissgrid's use of risk-based asset management supported by digital twins, while E-REDES (Portugal, DSO) utilises its low-voltage digital twin, incorporating AI, smart meter data, and image processing to predict faults and optimise maintenance planning.

CIM / CGMES for Federated Grid Modeling

A notable example of a federated data and model exchange architecture in the energy domain is the use of CIM / CGMES by European TSOs. Each TSO maintains its own system model and operational data while securely exchanging standardised grid models to build a Common Grid Model (CGM) for coordinated planning and real-time security analysis. This structure preserves data sovereignty while enabling cross-border situational awareness, interoperability, and collaborative simulation, illustrating a mature and scalable federated approach in critical infrastructure.

At the same time, it also demonstrates the practical challenges associated with advanced federated syste m modeling, particularly the complexity of harmonising data, tools, and governance across many independent stakeholders. Further information can be found in ENTSO-E's documentation on CGMES (Common Grid Model Exchange Standard) and the Common Grid Model processes.

Legacy Systems Evolution

─── GIS Systems

GIS systems are increasingly incorporating data from other systems such as SCADA and ERP to extend beyond simple documentation and provide simulation functionalities. These functionalities include power flow analysis, topology analysis, and short circuit calculations, enabling grid operators to more efficiently plan new connections or grid reinforcements.

─── ERP Systems

ERP software is evolving and integrating advanced functionalities for simulation and monitoring, becoming digital twins for business processes or even entire organisations, enabling the optimisation of business and investment decisions.

─── SCADA Systems

SCADA systems are evolving beyond supervision and control to include simulation and modelling capabilities for what-if scenarios. By integrating data and providing multiple advanced functionalities, SCADA systems are evolving into digital twins for real-time operations.

Contributors

Anna Gorczyca-Goraj	PSE S.A. / Convener RDIC WG5
John MacAllan	50 Hertz Transmission GmbH / TF Leader Digital Twins
Andreas Strasser	APG
Daniel Alfa	50 Hertz Transmission GmbH
Siddhesh Gandhi	ENTSO-E
Edel Wallin	Svenska Kraftnät
Konstantīns Serafimovs	AST
Rishabh Bhandia	TenneT TSO B.V.
Kjell-Petter Myhren	Statnett SF
Hanno Stagge	TenneT TSO GmbH
Mateusz Hordejuk	PSE S.A.
Piotr Szabelak	PSE S.A.

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