Alliance for IoT
and Edge Computing
Innovation

Edge driven Digital Twins in distributed energy systems

Role and opportunities for hybrid data driven solutions

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Executive Summary

The paper explores the intersection of Digital Twins and Edge Computing within the context smart grids in the electricity sector in the EU. The goal is to specifically focus on medium and low voltage networks environments. The use cases' primary objectives are to enhance visibility for more advanced grid monitoring and management, with a particular emphasis on integrating the grid edge through digital twins. This integration allows for real-time monitoring, enabling advanced grid management methods and creating opportunities for active consumer participation while increasing grids´ capacity.

Digital Twin technology relevance for electricity sector topics is well defined[1], although use cases are still evolving. This paper focuses on the edge computing driven use cases: including real time production monitoring, production control; performance prediction at different time scales; human robot interaction for assets monitoring; drones-based monitoring, optimisation of asset management and production planning. In services related to the renewable production power plants, applications of Digital Twin include predictive maintenance, fault detection and various diagnostics, state monitoring, equipment performance prediction, and virtual testing.

The ongoing evolution of the Internet of Things (IoT) has led to data generation at the network's edge, particularly in low voltage distribution networks where smart metering requirements and data processing can be efficiently managed on site through edge computing. The paper provides cases where edge computing is a viable solution for handling heterogeneous data with performance requirements such as low latency, crucial for the increasing controllability demands in low-voltage distribution networks.

The integration of Digital Twins at the grid edge is positioned as a key enabler for developing a more efficient energy ecosystem with evolving business models. The devices at the edges of electricity grids serve as physical infrastructure for sector integration, connecting with transport sector (electromobility) and heating & cooling along with dynamic buildings components. Digital Twins driven by edge computing are also expected to provide essential data for infrastructure planning across sectors, fostering the development of cross-sectoral business use cases. The need for data interoperability between different sectors is emphasised as demonstrated in a number of the ongoing research and innovation projects and within the evolving business models.

The paper outlines both challenges and opportunities associated with edge computing and Digital Twins in the distributed energy sector. Challenges include the technical maturity of digital twin technology, lack of plug and play deployment tools, and a shortage of digital skills in the energy sector. Regulatory issues, data privacy, and security concerns[2] are also identified, which requiring innovative policies and regulatory experimentation. On the other hand, opportunities for future growth lie in scalability[3].

The opportunities for future growth in AI and Digital Twins within the distributed energy systems are detailed, emphasising scalability, federated Digital Twins models, linkage to the European Data Space, and the need for determining useful data for collection.

[1] https://www.entsoe.eu/news/2022/12/20/entso-e-and-dso-entity-signed-today-the-declaration-of-intent-for-developing-a-digital-twin-of-the-european-electricity-grid/

[2] https://ecs-org.eu/?publications=ecso-technical-paper-on-cybersecurity-scenarios-and-digital-twins

[3] https://www.entsoe.eu/Technopedia/techsheets/digital-twin

The integration of AI and digital twins presents multiple opportunities in areas such as advanced predictive maintenance for distributed renewable generation, grid integration and management, demand-response optimisation, microgrid development, renewable energy forecasting, energy storage optimisation, decentralised energy trading, energy efficiency improvement, and data driven decision making planning and operations. There are also policy and regulatory impacts expected as part of adaptations of these solutions at various geographical levels to increase energy hybridisation, for example for green hydrogen production and sector coupling at municipal and regional level.

The discussion on AI and edge driven Digital Twins emphasises the importance of data quality and quantity for accurate representations, robust and reliable predictive capabilities, adaptive learning, and improved decision making. The paper suggests that organisations should invest in data collection, storage, and management to support effective implementation, impacting various applications such as energy optimisation, predictive maintenance, and processes optimisation.

Case studies exemplify the practical applications of Digital Twins and AI in energy production, including energy optimisation of microgrids, AI powered wind farm optimisation, AI models enhanced building management, demand-response platforms, AI-enhanced grid management, AI-driven energy forecasting, and AI-based grid automation. These case studies demonstrate the versatility and potential impact[4] of integrating AI and digital twins in various aspects of the energy sector.

We invite interested communities ' representatives to reach out to us, join the discussion on these topics and share the related use case. This is a dynamic document that can accommodate in the future additional use cases and outcomes of the related research projects.

[4] https://www.edsoforsmartgrids.eu/images/E.DSO_White_Paper_digitalised_energy_system_FINAL.pdf

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1. Digital Twins and Edge Computing within energy Smart Grids

The EU set strategic goals in facilitating creation, development and testing of a "Digital Twin of the Electricity Grid that covers dynamic monitoring, (smart) grid planning, secure operation, forecasting and scenario analysis". Main features include modularity, interoperability and capacity to implement Digital Twins at different scales, while integrating decentralised supply and demand sides of the sector. EU research and innovation efforts within the new TwinEU[5] project is focused on creating an overall Digital Twin model interfacing with Energy Data Spaces while "... *enabling new technologies to foster an advanced concept of Digital Twin while determining the conditions for interoperability, data and model exchanges through standard interfaces and open APIs to external actors. Advanced modelling supported by AI tools and able to exploit High Performance Computing infrastructure will deliver an unprecedented capability to observe, test and activate a pan-European digital replica of the European energy infrastructure*".

In the medium and low voltage networks, the key objective is enhancing the network performance visibility to enable advanced grid monitoring and management. The underlying assumption is if grid edge can be integrated through the Digital Twin with standard measurements from end-point meter and other network equipment, it would enable monitoring of the grid status in (or close to) real time. In consequence, more sophisticated methods for grid management could be applied, which would create more opportunities for active consumers, but also could increase the capacity of the grid for absorbing new connections on the demand (electromobility, heat pumps) and supply side. This type of digital twin of a value chain corresponds to product, production and performance digital twins.[6]

Edge computing within energy context

Previously in 2009, the interaction between devices without a human intervention (aka. machine-to-machine communication) experienced a qualitative jump by the development of cloud-based infrastructure services[7]. Devices constantly generating information, in a such called 'Internet of Things' (IoT) fashion, means that the data processing infrastructures need to be updated to cope with a large amount of heterogeneous data. In many cases, data is generated at the 'edge' of the network, and it is also 'consumed' at the edge. Low voltage distribution networks are the perfect example of that paradigm[7], as smart metering requirements are becoming stricter and data processing could be done on site, taking the advantageous distribution network's topology.

Edge computing could be a good solution for managing heterogenous data with some performance requirements such as low latency[8]. Some of the data generated at the distribution network's edge level shows characteristics that are normally associated with big data, for example large volume of generated data due to the increasing resolution, heterogeneity, and variety. Due to the massive electrification at the low-voltage distribution network, controllability requirements are increasing, making it the perfect scenario for edge computing application development.

Reduced latency requirements, enhanced bandwidth, processing-capabilities constrain for cloud infrastructures and the Quality-of-Service (QoS) requirements are becoming the most representative needs that the computing processes at low-voltage distribution networks are facing[9].

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https://cordis.europa.eu/project/id/101136119

[6] https://www.entsoe.eu/Technopedia/techsheets/digital-twin

[7] W. Shi, J. Cao, Q. Zhang, Y. Li, and L. Xu, 'Edge Computing: Vision and Challenges', IEEE Internet Things J, vol. 3, no. 5, pp. 637–646, 2016.

[8] H. Wang et al., 'Data Collecting and Processing Method in Distribution System Using EDFE Computing Technology', in Proc. of the 25th International Conference on Electricity Distribution (CIRED 2019), 2019.

[9] M. Chiang and T. Zhang, 'Fog and IoT: An Overview of Research Opportunities', *IEEE Internet Things J*, vol. 3, no. 6, pp. 854–864, Dec. 2016, doi: 10.1109/JIOT.2016.2584538.

Advanced Distribution Management Systems are not the exception, as the number of smart meters will exponentially increase in the upcoming years.

Low voltage networks context

Power Line Communication (PLC) network suffers from constrained bandwidth, thus limiting the network's controllability, data collection devices should be considered as resource-constrained devices, given that their power consumption and costs should be minimum for being profitable. Therefore, edge computing devices could become an interesting approach for profiting from the already-existing infrastructure while coping with the increasing requirements at the low-voltage distribution network.

One of the key benefits of sector integration is building a more efficient ecosystem that utilises the synergies between different (yet interdependent) sectors. The devices on the edges of electricity grid are oftentimes also a connection points to other sectors, typically transport (electromobility) and heating & cooling and smart buildings. Therefore, they serve as the physical infrastructure of sector integration. Edge-driven digital twins can deliver the data needed for better planning of infrastructures development across sectors (which were previously not available) and will be also the basis for development of cross-sectoral business use cases. This also ultimately points towards the need to focus on data interoperability between different sectors and interoperability of sectoral data spaces.

The evolving concepts and edge driven Digital Twin

Given the complexity of such integration concepts like federated digital twins[10] that collect and analyse the information from various domains and contexts, provide the solution for the problems, and simulate the effects are applicable. This vision necessitates additional components, functions, and functionalities in order to support digital twin federation.

The Distribution Service Organisations' (DSOs') research shows that even moderate changes in consumer behaviour can have significant impact on the potential for adding additional production capacity to the grid. Within context of digital twins, this potential can be explored with greater precision and wider scope. Smart buildings as flexibility providers to the electricity grids, smart building as enabler of edge driven new energy practices and communities and smart network integration (sector coupling) and local energy communities' driven models can be further enhanced through digital twin enabled solutions.[11]

Other evolving concepts, such as AI analytics marketplaces in energy are testing variety of analytics techniques via an AI-based machine leading algorithms and models large variety of presentation modalities, edge-level available storage and computing resources," *facilitating enablement of the development of proactive analytics centred applications, seamless integrated with near real time operational and/or with grid planning systems*". [12]

In conclusion, Digital Twin can become a game changer for energy sector undergoing twin transition within the EU and globally. Edge computing delivering efficient data and Digital Twin observability would allow electricity networks not just to create virtual models, but to run simulations of new policies or new as well retrofitted infrastructure projects, understand their potential impacts before making decisions, consult with regulators and potentially deploy anticipatory investments that are envisioned to unlock scaling up integration of many technologies.

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[10] https://www.itu.int/itu-t/workprog/wp_item.aspx?isn=17951
[11] https://smartbuilt4eu.eu/interaction-with-external-environment/
[12] https://www.bd4nrg.eu

2. Challenges and opportunities of Edge Computing and Digital Twins in distributed energy sector

2.1 Challenges, limitations, and barriers

Among technical and scalability challenges the following three challenges can be named:

- Digital Twin technology may be less mature in terms of performance and security
- Lack of tools to facilitate Digital Twin deployment
- Scalability triggers and new business models.

The challenges are being addressed:

- Research and innovation is moving fast. The number of publications has increased exponentially from a few in 2015 to more that one thousand in 2021[13].
- Many standards are under development, in ISO/IEC JTC 1/SC 41 (IoT and digital twins)[14], and also in the smart manufacturing domain[15]. ISO/IEC 30186 (digital twin maturity model) in particular provides hints on how Digital Twin technology can mature: Four maturity aspects are defined (convergence between the twin and the target entity, capability of the twin, integration view, and time management). Five levels are defined for each maturity aspects, from disconnected to unified in terms of on convergence, from mirroring to autonomous in terms of capability, from task specific to enterprise in terms of integration and from unlinked to integrated in terms of time.

It is widely accepted that there is a lack of digital skills in the European energy sector, especially in relation to highly advanced and innovative solutions such as digital twins[16]. Digital twins working with devices on the edge of distribution grids would be deployed by multitude of smaller actors, which might not have the resources and expertise to make use of them. For example, there are over 3000 distribution grid operators in the EU[17], many of them serving significantly less than 100 000 clients. Even the largest DSOs are facing challenges with finding the right qualified personnel, for the smaller ones the challenge is even greater. Moreover, the number of grid operators also implies that there might be potentially 3000 grid digital twins to be created (for each DSO network), which brings the scale of the challenge to another level.

In general, the European regulatory framework for energy data space is divided into multiple regulations, some of the falling on the national level as well. In case of digital twins on the grid edge, the biggest issues to be properly addressed are the data privacy and security requirements and ensuring data accuracy for the grid management. In the first case, the consumer data that will be the key driving force need to be protected and it should be ensured that they are only used with the consent of the consumer.

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[13] https://www.researchgate.net/publication/351827732_Digital_Twin_Origin_to_Future
[14] At the date of the white paper, two standards are published (ISO/IEC 30172 Use case, ISO/IEC 30173
[15] At the date of the white paper, four standards on digital twins for manufacturing are published, ISO 23247-1, 23247-2, 23247-3, 23247-4 and two under way 23247-5, 23247-5
[16] 'Digitalisation of the energy system'. Accessed: Oct. 16, 2023. Available: https://energy.ec.europa.eu/topics/energy-systems-integration/digitalisation-energy-system_en
[17] L. Rullaud and C. Gruber, 'Distribution Grids in Europe - Facts and Figures 2020'. Eurelectric aisbl, Dec. 2020. Accessed: Oct. 16, 2023. Available: https://cdn.eurelectric.org/media/5089/dso-facts-and-figures-11122020-compressed-2020-030-0721-01-e-h-6BF237D8.pdf

Regarding the second point, it should be reiterated that network operators are the ones ultimately responsible for ensuring secure operation of electricity grids. For that, they need to maintain network data accuracy and integrity. Although grid digital twins using data from grid edge devices offer great potential for more flexibility and integration of DER, these need to be integrated with the existing DSO systems for grid management to ensure the continuation of safe electricity supplies.

Other regulatory issues loosely related to deployment of digital twins are the lacking framework for implementation of flexibility markets on DSO level, and the DSO renumeration schemes not supporting investment in innovative activities[18].

The abovementioned challenges could benefit from more regulatory experimentation, both to develop the appropriate policies and to enable the deployment of the digital twins. However, similarly to other actors in the energy sector, regulators face the difficulty of properly implementing regulatory innovation, due to the limited experience and human resources available. This is a very complex process and would enhance the outcomes if there was more leadership and collaboration on the European level to come up with adaptable solutions.

Regulators would benefit from greater insights, related expertise and close collaboration with industry and other stakeholders to implement regulatory innovation efficiently and effectively. New models of collaboration should be explored, regulatory sand boxes were one of the formats suggested for these purposes, but there could be more options, including industrial virtual environments test beds set up.

2.2. General Opportunities for future growth

The future growth in AI and digital twins for distributed energy systems will depend on continued technological advancements, increasing adoption of renewable energy sources, and a greater emphasis on sustainability and overall resilience.

In the rapidly evolving landscape of distributed energy systems, the integration of Artificial Intelligence (AI) and digital twins represents a pivotal shift towards more sustainable and resilient energy networks. This shift is underpinned by a few key drivers: technological advancements, the increasing prevalence of renewable energy sources, and a heightened focus on sustainability and resilience.

Incremental scalability

As the deployment of digital twins will reach a wider scale, it will enable a wider European-level ecosystem of digital twins.

The following sample of benefits for the energy sector can be expected:

Detailed and synchronised digital twins of energy grids

Network operators already use more or less sophisticated models of their grid to track the status and manage the grid operation, deployment of advanced digital twins would enable build a more detailed grid model, connected to network assets in real time. This would enable a more precise information about the real-time behaviour of network assets, with positive impacts on efficiency of network The challenge of grid observability is highest on lower voltage levels, where also most of the new DERs and will be connected in the future. This will require more complex digital models and larger volumes of data exchanged, which can be addressed by using AI enabled services.

[18] 'CEER Status Review Report on Regulatory Frameworks for Innovation in Electricity Transmission Infrastructure', Council of European Energy Regulators (CEER), Brussel, Belgium, Review C20-INF-74–03, Oct. 2020. Accessed: Oct. 16, 2023. Available: https://www.ceer.eu/documents/104400/-/-/8c2aace7-5601-8723-4d45-337073af38d5

Federated digital twins

It is not expected that a single digital twin will be developed for the whole European market, but rather that multiple digital twins will be developed for different purposes and depending on local context. Similarly, it is not advised to rely on a single solution or a provider of digital twin software. Consequently, interoperability standards for digital twins need to be developed and deployed to achieve a federated system of European digital twins that work together efficiently. ISO/IEC JTC1/SC41 is currently proposing the development of a standard that will address behavioural and policy interoperability (ISO/IEC 21823-5).

Security and Privacy in Digital Twins

As digital twins are new paradigms, the security and privacy of digital twins is another challenge to address. ISO/IEC JTC1/SC27 has started the development of a standards on that challenge (ISO/IEC 27568). It leverages the work carried out in a number of EU projects: CONNECT (a digital twin for trust assessment in the connected vehicle), SPADE (drone-based digital twin for agriculture applications).

International Data spaces

Several sectorial data spaces are available for the digital community. Some of them are International Data Space[19], Data Space for Smart and Sustainable Cities and Communities[20], Common European Data Spaces[21]. Leveraging the AIOTI report on the integration of IoT and Edge computing in data spaces[22], ISO/IEC JTC1/SC41 is preparing a proposal for the development of a standard on the integration of digital twins in data spaces[23].

Edge to Digital Twin to Data Spaces in Energy

Digital twins should enable collection of large data and close-to-real-time data, it should be ensured that digital twins are developed in close coordination with activities on the establishment of European data space in energy. A few of the related EU projects can be mentioned: OMEGA-X, TwinEU, int:net.

The digital twins, especially if applied to consumers and other small-scale distributed energy assets, have the potential to produce large amounts of data.

However, it is not fully clear which information exactly will be the most useful for the enhancement of the opportunities named in this document. To avoid unnecessary collection and reduce the amount of investment needed for establishment of digital twins and to reduce the amount of resources needed for their operation and maintenance, it should be further investigated what type of data collection would be the most useful and what use cases are the most relevant.

A common European energy data space is a specific application of data spaces to the energy sector, which is undergoing a profound transition from a centralised, fossil-fuel-based system and the related processes to a decentralised, renewable-based and more efficient and digital tools and technologies enabled system. A common European energy data space is expected to enable access to and use of energy data, facilitate data-driven innovation and optimization, and empower consumers and prosumers in the energy market[24].

[19] https://internationaldataspaces.org/
[20] https://inventory.ds4sscc.eu/
[21] https://dataspaces.info/common-european-data-spaces/
[22] https://aioti.eu/wp-content/uploads/2022/09/AIOTI-Guidance-for-IoT-Integration-in-Data-Spaces-Final.pdf
[23] https://www.iec.ch/dyn/www/f?p=103:38:717302614874355::::FSP_ORG_ID,FSP_APEX_PAGE,FSP_PROJECT_ID:20486,23,118815
[24] https://energy.ec.europa.eu/publications/common-european-energy-data-space_en; https://energydataspaces.eu/

Recently published ETIP-SNET paper on the evolving Data Spaces in energy [25] gives short technical introduction to the topic and states the building blocks. Data Spaces will consist of core building blocks, such as data models, catalogues, metadata, and data exchange mechanisms which are directly related to digital twin models and solutions.

Other sectors

The nine initial Common European data spaces are the following[26]:

- **An Industrial data space**, to support the competitiveness and performance of the EU's industry.
- **A Green Deal data space**, to use the major potential of data in support of the Green Deal priority actions on issues such as climate change, circular economy, pollution, biodiversity, and deforestation.
- **A Mobility data space**, to position Europe at the forefront of the development of an intelligent transport system.
- **A Health data space**, essential for advances in preventing, detecting and treating diseases as well as for informed, evidence-based decisions to improve the healthcare systems.
- **A Financial data space**, to stimulate innovation, market transparency, sustainable finance, as well as access to finance for European businesses and a more integrated market.
- **An Energy data space**, to promote a stronger availability and cross-sector sharing of data, in a customer-centric, secure and trustworthy manner.
- **An Agriculture data space**, to enhance the sustainability performance and competitiveness of the agricultural sector through the processing and analysis of data.
- **Data spaces for Public Administrations**, to improve transparency and accountability of public spending and spending quality, fighting corruption, both at EU and national level.
- **A Skills data space**, to reduce the skills mismatches between the education and training systems and the labour market needs.

Smart sector integration

Digital twins are also a great tool for closer coupling of different sectors in and outside energy industry. Connection of electricity grids with gas, heating and cooling sectors, green hydrogen production and transformation, transport, water and other sectors is expected to enable more efficient coordination, network planning, network operation and more.

Fragmentation of flexibility markets on DSO level, and the DSO renumeration schemes not supporting investment in innovative activities[27].

The above-mentioned issues could be solved by enabling more regulatory experimentation, both to develop the appropriate policies and to enable the deployment of the digital twins.

However, similarly to other actors in the energy sector, regulators lack the experience and human resources to properly implement regulatory innovation, often leaning on DSOs or other actors to design it. This is a very inefficient process and would require leadership on the European level to come up with replicable solutions.

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[25] https://smart-networks-energy-transition.ec.europa.eu/publications/etip-publications

[26] https://ec.europa.eu/digital-single-market/en/policies/building-european-data-economy

[27] 'CEER Status Review Report on Regulatory Frameworks for Innovation in Electricity Transmission Infrastructure', Council of European Energy Regulators (CEER), Brussel, Belgium, Review C20-INF-74–03, Oct. 2020. Accessed: Oct. 16, 2023. Available: https://www.ceer.eu/documents/104400/-/-/8c2aace7-5601-8723-4d45-337073af38d5

2.3. High impact functionality and services

Breaking down these opportunities, one can find a diverse range of energy sources and technologies, that present significant opportunities for growth in the context of AI and digital twins. These will be described in further detail later in this document, but separated into three topics they include:

Aspect	Description	Benefits
Advanced Predictive Maintenance	AI-powered digital twins support predictive maintenance in distributed energy systems by monitoring assets in real-time, predicting failures, and optimizing maintenance schedules.	Minimizes downtime and extends the lifespan of energy assets.
Grid Integration of Distributed Assets	Digital twins' model Distributed Energy Resources (DERs) like solar panels, wind turbines, and battery storage. AI optimizes the integration of these resources into the grid.	Enhances grid stability, reduces energy wastage, ensures reliable energy supply.
Demand Response Optimisation	AI-driven digital twins model energy consumption patterns, assisting grid operators and consumers in responding to real-time demand needs and enabling demand-response programs.	Reduces energy costs and supports grid reliability.

Table 1: Benefits of edge-driven digital twins in distributed energy systems

Microgrids development and renewable energy forecasting

Growth of microgrids, which are small-scale, self-sustaining energy systems, is accelerating. Digital twins can simulate and optimize microgrid configurations, helping communities and organizations achieve energy independence, resilience, and cost savings.

AI and digital twins demonstrated that can improve the forecasting accuracy of renewable energy sources like wind and solar. Advanced prediction models, considering weather data and historical patterns, ensure better matching supply and demand.

Energy storage optimisation

Distributed energy systems often incorporate energy storage solutions. Digital twins can model the behaviour of energy storage assets, and AI can optimize their operation by analysing real-time data and predicting the most efficient discharge and charge cycles. Moreover, in the current practice, where grid operators use historical data of consumer behaviour for grid operation planning, it is challenging to correctly predict the behaviour of storage assets. This is because storage operation does not have a typical pattern of energy consumption/injection, but it rather reacts on the price developments in the markets.

Digital twins capable of taking the market prices into account would enable far more efficient prediction of storage assets behaviour and would be able to estimate more precisely their impact on grids.

AI-driven digital twins can facilitate peer-to-peer energy trading within decentralized energy systems. Smart contracts and blockchain technology can be integrated with digital twins to enable secure, automated energy transactions among consumers and prosumers.

Aspect	Description
Technology	AI-driven Digital Twins
Application	Facilitating Peer-to-Peer Energy Trading
Reference	GIFT[28] H2020 Project
Integration	Smart Contracts and Blockchain Technology
Function	Enable Secure, Automated Energy Transactions among Consumers and Prosumers

Table 2: Peer-to-Peer Energy Trading

AI and digital twins can identify opportunities for energy efficiency improvements in various sectors. These technologies can analyse energy consumption data, assess equipment performance, and suggest optimizations. Building level, grids and generation assets are some of the examples explored within presented use cases.

Aspect	Description
Technology	AI and Digital Twins
Objective	Identifying Opportunities for Energy Efficiency Improvements
Analysis	Analyse Energy Consumption Data, Assess Equipment Performance
Optimization	Suggesting Optimizations
Application Areas	Buildings, Grids, and Generation Assets

Table 3: Energy Efficiency Improvement

The increasing volume of data from distributed energy systems requires sophisticated analytics. AI can process this data and offer insights for better decision-making, whether in load management, grid planning or for resources allocation.

Aspect	Description
Requirement	Handling Increasing Volume of Data from Distributed Energy Systems
Technology	Advanced AI Analytics
Outcome	Insights for Better Decision Making
Applications	Load Management, Grid Planning, Resource Allocation

Table 4: Data-Driven Decision Making

Data driven decision making

Within the field data-driven decision-making in distributed energy systems, the incorporation of edge-driven digital twins notably enhances capabilities in two pivotal areas: the legal system and environmental impact assessment.

Real-time data generated and analysed by digital twins may provide a foundation for both legal compliance and environmental stewardship. In the legal realm, this technology assist in in navigating a complex regulatory landscape. Thus, having a digital twin supporting legal compliance ensures adherence to energy laws and policies through monitoring and reporting mechanisms.

When assessing environmental impacts, digital twins offer a high level of insight into the ecological footprint of energy systems. By simulating and analysing various operational scenarios, they enable the identification of strategies that minimize adverse environmental effects, thereby informing sustainable practices and policy making in the energy sector.

[28] https://cordis.europa.eu/project/id/824410

Hence, digital twins offer the potential of driving informed, compliant, and environmentally conscious decisions in distributed energy systems.

Regulatory Compliance

In the realm of regulatory compliance within the energy sector, the application of digital twins may serve as a tool for adherence to various regulations. The energy industry is governed by a complex web of standards and regulations. These regulations demand precise monitoring and reporting by the systems to maintain compliance. Digital twins are virtual replicas of physical energy systems, and as such offer a solution by providing real-time data and analytics. The use of digital twins thus ensures that energy providers can promptly identify and rectify compliance issues. Furthermore, considering the dynamic nature of digital twins allows for the simulation of various operational scenarios, facilitating proactive compliance strategies and minimizing the risk of regulatory breaches.

Complementing the digital twins, AI plays a significant role in adapting and supporting the energy industry by processing vast amounts of data, detecting patterns, and predicting potential compliance risks. This capability is particularly valuable given the continuous updates and changes in energy regulations. AI can analyse historical and real-time data to forecast future compliance requirements, guiding energy providers in making informed decisions to stay ahead of regulatory changes. By integrating AI with digital twins, the energy sector can achieve a higher level of regulatory compliance.

Aspect	Description
Sector	Energy
Tool	Digital Twins
Function	Provide Real-Time Data and Analytics for Compliance Monitoring and Reporting
AI Role	Assisting in Adherence to Evolving Energy Standards

Table 5: Regulatory Compliance

As a paradigm, digital twins can be an instrument for regulatory compliance as they can support the following capabilities:

- data usage policies and enforcement to comply with regulations such as GDPR, the Data Act, and the AI Act
- resilience capabilities to address the Cybersecurity Resilience Act and
- assurance and certification capabilities to address trustworthiness.

Distributed energy systems:

The optimization of distributed energy systems through the implementation of edge computing, AI, and digital twins represents a leap towards environmental sustainability. Edge computing enhances the efficiency of these systems by processing data at the periphery of the network, closer to the source of data generation. This minimizes latency and reduces the need for long-distance data transmission, thereby conserving energy. AI algorithms further augment this efficiency by analysing patterns in energy usage, predicting demand, and optimizing resource allocation. Such intelligent system management not only streamlines operations but also significantly reduces energy wastage, contributing to a marked decrease in the carbon footprint of these systems.

Digital twins play a role in this ecosystem by providing a sophisticated layer of real-time monitoring and simulation. Virtual representations of physical systems allow for precise control and adjustment of energy flows, enabling operators to respond swiftly to changing conditions and optimize system performance continually. The result is a more responsive and efficient energy grid, capable of smart scheduling and proactive maintenance.

Together, these technologies foster a more sustainable energy infrastructure, aligning operational efficiency with environmental stewardship. Their combined impact is not just in meeting the immediate energy demands but in doing so in a way that aligns with broader sustainability goals, notably the reduction of greenhouse gas emissions and the promotion of renewable energy sources.

Aspect	Description
System	Distributed Energy Systems Optimized with Edge Computing, AI, and Digital Twins
Impact	Reduction of Carbon Footprint
Methods	Real-Time Monitoring, Smart Scheduling, Energy Efficiency Enhancements
Goal	Contributing to Sustainability Goals

Table 6: Carbon Footprint Reduction

Distributed energy systems with AI-driven digital twins can enhance systems and solutions resilience. In the event of natural disasters, these systems can automatically adjust and allocate energy resources to critical infrastructure, helping communities recover more quickly, while aiming at maintaining critical services.

It is also worth to take into account, resilience and disaster recovery during Low probability high impact use cases.

3. AI and Digital Twins organisational impact

As organizations increasingly rely on sophisticated technologies like digital twins, the need for robust data infrastructure becomes critical. This includes efficient methods for data collection, secure and scalable storage solutions, and advanced data management systems. Such an infrastructure is essential to harness the full potential of digital twins, enabling them to reflect the physical world with high fidelity.

More specifically, energy optimization, predictive maintenance, and process optimization are areas where impact of a wide selection of high-quality data is important.

- Looking into the field of energy optimization, digital twins can provide a detailed and dynamic model of the energy systems. Such knowledge allows for simulation and analysis of energy consumption patterns, which can lead to strategies that enhance energy efficiency and reduce costs.
- Similarly, with enough quality data as basis, digital twins can enhance predictive maintenance with prediction on equipment failures. This not only helps in averting downtime but also optimizes maintenance schedules, ensuring that resources are used judiciously.
- Process optimization also stands to benefit, as digital twins can model production processes to identify bottlenecks and inefficiencies. By analysing data from various stages of the production process, these models can suggest optimizations that enhance productivity and reduce waste.

Organisations across numerous sectors benefit from applying digital twins to their workflow when they are fed with quality and quantity of data. Knowledge is foundational for achieving accurate representations of systems and allows for more informed decisions, optimize operations, and anticipate future challenges.

Thus, investing in sectors such as data collection, storage, and management becomes a strategic decision that will have high impact on revenue and stability. This focus is not just about gathering large volumes of data; it is about ensuring that this data is of high quality - accurate, timely, and relevant.

It is discussed above; digital twins may support an organisation in numerous ways. Some examples on premises and data collection usages are presented in the table below:

Aspect	Description
Accurate Representation	Data quality ensures the digital twin accurately represents the physical system. High-quality data about physical assets, configurations, and operating conditions leads to precise digital twins.
Behavioural Modelling	Quality and quantity of data aid in creating behavioural models within the digital twin, capturing the dynamics, interactions, and performance of the real-world system.
Realistic Scenarios	High-quality and abundant data allow digital twins to simulate a wide range of scenarios and operating conditions for comprehensive testing and evaluation.
Robust Predictive Capabilities	AI algorithms in digital twins use data to make predictions and optimize operations. Clean, abundant data enables more accurate forecasts and better action suggestions.
Adaptive Learning	AI algorithms within digital twins improve over time with more data, using historical data to refine predictive models and enhance decision-making.
Improved Training and Modelling	More data enhances the training and modelling of AI algorithms, leading to more accurate, reliable, and generalizable models.

Aspect	Description
Enhanced Predictive Power	Larger datasets contribute to more robust predictions, allowing AI algorithms to identify trends, correlations, and outliers with higher confidence.
Increased Contextual Understanding	High-quality data provides context for AI systems, improving the relevance and appropriateness of AI-generated recommendations.
Reduced Bias	A more comprehensive dataset helps mitigate bias in AI systems, reducing biases from limited or unrepresentative samples.
Scenario Analysis	AI-based suggestions benefit from a wide range of data for scenario analysis, allowing AI systems to consider multiple scenarios and suggest the best course of action.

Table 7: Examples of premises and data collection usages.

Large Scale Management of data may present significant challenge in energy systems. This challenge occurs for two reasons; vast volumes of data are generated by various energy assets and systems, but it may require the integration and synchronization in a meaningful way. This complexity increases further when real-time processing is required for timely insights and responses. When maintaining efficiency and stability of energy systems such accurate knowledge is paramount.

Moreover, ensuring the accuracy of digital twin models is an absolute necessity. The models must accurately reflect their real-world counterparts to be effective. This accuracy depends on both the quality of the data and the sophistication of the algorithms that process this data. Any discrepancies between the model and the actual system can lead to suboptimal decisions and actions, potentially causing inefficiencies or even system failures.

As such, the many various algorithms, models and real-world data poses a challenge in terms of supervision and quality control as it requires the creation of robust and adaptable systems capable of handling this complex interaction. This is especially critical for tasks like energy optimization, demand response, and flexible generation integration, where decisions must be both timely and precise.

Key Area	Description
Energy Production Optimization	Involves using digital twins to enhance the efficiency and effectiveness of energy production. It focuses on optimizing operational parameters of power plants and energy generation assets in real time for improved efficiency, reduced operational costs, and lower environmental impact.
Demand Response Services	Plays a crucial role in balancing energy supply and demand. Digital twins simulate the energy grid and consumer behaviour to forecast demand spikes and adjust supply, preventing grid overloads and enabling the integration of renewable energy sources.
Flexible Generation Integration	Focuses on the integration of various types of energy sources, including renewables, into the grid. Digital twins assist by simulating different generation scenarios, assessing the impact of integrating new sources, and ensuring grid stability despite the variability of some energy sources.

Table 8: Three key areas in the context of digital twin technology in energy systems

The challenges mentioned above requires a multi-faceted approach involving advanced data analytics, machine learning algorithms, and continuous model refinement. When drilling further into the areas, several fields can be addressed.

Aspect	Description
Digital Twin Creation	Optimizing energy production using a digital twin of the energy generation system, involving high-resolution modelling of physical assets and environmental conditions.
Machine Learning for Predictive Analytics	Employing AI and machine learning algorithms to analyse historical energy production data, weather forecasts, and sensor readings for accurate energy production prediction.
Optimization Algorithms	Utilizing digital twin and predictive models for scenario simulation and real-time decision-making, considering constraints like maintenance schedules and grid demand.
Digital Twin of Energy Consumers	Creating a digital twin of energy consumers, incorporating data from smart meters, IoT sensors, and historical energy usage patterns, to manage vast data and ensure accuracy.
Reinforcement Learning and Optimization	Developing reinforcement learning algorithms to optimize energy consumption in real-time by adapting to the behaviour of energy consumers in complex, dynamic environments.
Real-Time Communication and Control	Implementing robust communication infrastructure and real-time control systems for demand response services, using complex event processing and rule-based systems.
Digital Twin of Generation Assets	Modelling flexible generation assets like battery storage, microgrids, using digital twins to accurately represent their non-linear behaviour under various operating conditions.
Machine Learning for Resource Forecasting	Forecasting the availability and capacity of flexible generation resources with AI-driven algorithms, adapting to changing conditions for systems like PMS and BMS.
Optimization of Resource Allocation	Employing complex optimization algorithms for real-time grid management and resource allocation, balancing supply and demand while considering cost constraints and grid stability.

Table 9: Overview of the various aspects and complexities involved in integrating AI and Digital Twins within organizational frameworks, specifically in the context of distributed energy systems

Development and validation of digital twin models and AI algorithms is the core of the system. Additionally, adherence to regulatory compliance and industry standards is expected. Compliance is particularly crucial in areas like environmental assessments and grid operations, where regulatory standards are strict and can lead to significant operational and legal repercussions if not paid attention to.

Stakeholders such as energy producers, grid operators, and consumers must be involved in dialogue to ensure goals are aligned and that the implementation of these technologies is effective and beneficial for all parties involved. This collaboration facilitates the harmonization of technological solutions with practical energy needs and market conditions. Furthermore, the energy sector is dynamic, with evolving needs and emerging technologies, so it is essential to design systems that are scalable and flexible. Systems that can adapt to these changes and integrate new technologies will remain relevant and valuable for a long time.

The approach must also include mechanisms for continuous learning and improvement. This will leverage the adaptive learning capabilities that AI promises. This ensures that models and strategies are refined over time, enhancing their effectiveness and efficiency. Cybersecurity and data privacy must be addressed, and as such necessitate robust security measures to protect sensitive data and maintain system integrity.

Building on the considerations mentioned above, digital Twin and the use of AI in energy production can be demonstrated in various kind of use cases.

Use Case	Description
Digital Twin for Energy Optimization	Integrates data from IoT sensors, weather forecasts, and energy consumption patterns to optimize microgrid energy production, storage, and distribution, reducing energy costs and carbon emissions.
AI-Powered Wind Farm Optimization	Utilizes AI to optimize wind farm performance, including predicting maintenance needs, adjusting blade angles for maximum efficiency, and accelerating environmental assessment lead times while adhering to regulatory requirements.
Demand Response Platform	Involves a digital twin platform integrating data from various energy assets and sensors to predict energy demand patterns and manage energy consumption in response to grid needs, facilitating revenue generation and cost savings for end users.
AI-Enhanced Grid Management	Employs AI and digital twins for managing electricity distribution grids, simulating various scenarios, and optimizing energy distribution in real-time, resulting in reduced power losses and improved grid reliability.
AI-Driven Energy Forecasting	Uses AI to forecast electricity demand and optimize the integration of renewable energy sources, analysing historical data, weather forecasts, and real-time sensor data for better energy production and distribution planning.
AI-Enhanced Grid Automation	Optimizes grid automation using digital twins and AI, creating digital replicas of substations and power equipment for remote monitoring and control, and enhancing grid reliability through predictive maintenance.
AI-Based Battery Storage Integration	Implements AI and digital twins to optimize the integration of battery storage systems into the grid, modelling battery behaviour and managing energy storage and discharge based on real-time demand and price signals.

Table 10: use cases demonstrating digital twin and AI in distributed energy production

Digital Twin for modelling energy supply and demand of edge-to-cloud infrastructure

The wide adoption of digital transformation (DX) is pushing digital services towards cloud-based operation. This is shaping the landscape of cloud computing infrastructure in Europe as an edge-to-cloud continuum. The latter is an ecosystem of autonomous yet connected cloud systems, predominantly diverse in resources and efficiencies, and geo-dispersed [4,7]. Understanding the energy footprint of the continuum is critical to the sustainability of digital transformation efforts. However, developing such understanding bears a range of non-trivial challenges, driven by the variation of energy metrics, coupled with diversity of demand, services and load distribution across different cloud systems. Not to mention the wide mixture of stakeholders involved. At the same time, it is strategically critical for Europe as well as globally to develop this understanding and improve on the status quo. Specially with proliferation of resource-intensive services such as AI [6] and DLT, which may motivate the development of Digital Twin frameworks. So far, modelling the energy footprint of cloud systems has been investigated with extensive research and innovation efforts [8-12], developing mathematical models and optimisation frameworks. However, these efforts have been largely fragmented as they focus on specific problem or at best address 2-3 problems jointly. They consider a limited subset of variables and make a range of assumptions that risk over simplifying or overlooking critical factors in the continuum.

Digital Twinning of the computing continuum can address these shortcomings, as it enables comprehensive modelling frameworks, that can incorporate a large mixture of variables with variant dependency relationships between them and model a variety of 'what if' scenarios. Efforts started emerging to digital twin the continuum, however they are in their infancy and remain similar to modelling efforts conducted so far, with a step further in the complexity. Examples of such efforts have been largely focusing on applying Machine-Learning techniques to solve optimisation problems with examples including [13,14].

Priority metrics for consideration in any Digital Twin include:

- Infrastructure Energy: Power Utilization Efficiency (PUE) of different data centres (a.k.a. nodes) within regions of similar climate, Energy Proportional computing (for consumption per job), energy price offers, green-brown energy supply, CO2 production and flexibility services to continuum providers.
- Digital services: characteristics, resource intensity, restrictions on movability, quality of experience, and induced load on different resources within the continuum and different providers.
- Data: energy systems produce large-scale data with very different features. The volumes and data complexity require resilient management, which often is hard to achieve.
- Skills gap. The energy sector relies on a work force that often is not technical literate, in particular concerning the latest evolutions of IoT-Edge-Cloud.
- The different stakeholders co-existing and interacting in the continuum, including limitations on information sharing across their domains and the interplay of their individual intents. The latter may be aligned in some cases while conflicted in others, posing trade-offs between any combination of metrics in performance, cost and environmental sustainability. Additionally, external factors such as the impact of trust and reliance on hyper scalers presence in Europe and their competition with EU cloud providers should be considered. This is increasingly sitting at odds with the EU data act[29], promoting data sovereignty. Additional metric may well be identified in future research and innovation. Yet, for the next efforts the above need to be modelled and simulated following a modular approach that allow for trackability and dependency analysis.

As mentioned above, AI-enabled Digital Twins is an evolving field. Several topics and trends will have to be considered.

Aspect	Description
Edge Computing in Energy Monitoring and Control	Utilizes real-time data processing and analysis at the source for monitoring and controlling energy assets. Edge devices run AI algorithms for predictive maintenance and fault detection.
Digital Twins for Energy Systems	Involves creating digital representations of energy systems like power plants and grids to optimize assets. AI enhances these simulations by enabling predictive analytics and scenario planning.
AI-Driven Predictive Maintenance	Applies AI algorithms to data from edge devices and sensors for predicting maintenance needs of energy infrastructure, minimizing unplanned downtime and reducing operational costs.
Energy Optimization and Resource Allocation	AI assists in optimizing energy consumption, distribution, and resource allocation, predicting electricity demand and adjusting energy production for environmental efficiency.
Supply Chain Resilience and Energy Efficiency	Integrates digital twins with AI for dynamic supply chain management decisions, reducing energy waste and increasing efficiency in production and logistics.
Renewable Energy Forecasting	Forecasts renewable energy production more accurately, improving grid stability by matching energy supply with demand, especially in areas with intermittent renewable sources.
Edge AI for Autonomous Energy Systems	Benefits autonomous energy systems through edge AI for real-time decision-making, optimizing energy generation, storage, and distribution based on local conditions.

[29] https://www.eu-data-act.com/#:~:text=The%20data%20act%20will%20give,objects%2C%20machines%2C%20and%20devices

Aspect	Description
IoT-Edge-Cloud cognitive orchestration	Provides a higher degree of automation and improved processes, facilitating data exchange in federated environments, e.g., cross-sector.
Cybersecurity and Edge Devices	Ensures robust cybersecurity for energy infrastructure with edge devices, using AI to identify and mitigate threats and maintain system integrity.
Regulatory Compliance and Reporting	Facilitates accurate digital twin representations through effective data integration from various sources, ensuring interoperability among different systems and devices.
Human-Machine Collaboration	Augments human decision-making in energy management, focusing on effective human-machine collaboration and improved user experience for knowledge-based decisions.
Ethical and Environmental Considerations	Addresses the environmental impact of energy production and consumption, optimizing energy use and reducing waste from an ethical and environmental perspective.
Scalability and Cost-Effectiveness	Considers the scalability and cost-effectiveness of implementing AI and digital twins, especially for smaller and distributed energy assets, with a focus on seamless integration.

Table 11: Topics and trends within AI and Digital Twins

4. Digital Twins and interfaces with Data Spaces in Energy

When examining digital twins, they are on a basic level virtual representations of physical objects, systems, or processes. They mirror their real-world counterparts in a digital environment. Data Space interact with digital twins through **real-time data synchronisation** through data from assets such as sensors, IoT devices and various other data sources. Such sources allow for continuous update with real-time data and can be used for adjusting the digital twin parameters. This ensures that the digital twin accurately reflects the current state of the physical entity.

This also offers **Enhanced Decision Support** through **Simulation and Predictive Analysis**. Basically, by analysing data from both the digital twin and the data space, AI can provide insights and recommendations to improve real-world operations. For example, in smart manufacturing, AI can suggest process optimizations or maintenance actions based on real-time sensor data and historical performance.

Building upon this, it is to establish **smart environments**, such as smart cities, smart buildings, and smart factories. These environments rely on data spaces to collect data from myriad IoT devices and sensors. The digital twin acts as a centralized platform for aggregating and analysing this data, allowing for efficient management and control. Here it is also worthwhile to take HCI (Human-Machine Interface) into account. The Digital Twin can be combined with other systems to create advanced **human-machine interfaces** (HMIs). These interfaces can for instance provide a 3D visualization with real-time data. It is possible to envision smart energy grids, smart cities or smart vehicles, where a digital twin could display a real-time dashboard to monitor crucial metrics and receive AI-driven suggestions for optimizing energy efficiency.

Data-Driven control further strengthens these areas through AI algorithms can analyse data in real time, and if deviations or anomalies are detected in the digital twin's behaviour compared to the physical counterpart, the system can automatically trigger actions or alerts. A real-life example can from the industrial sector can demonstrate this. If the digital twin of a machine indicates an unusual vibration pattern, the AI system could recommend shutting it down for maintenance to prevent a breakdown. Which brings us back to Lifecycle Management where this integration will be valuable throughout the entire lifecycle of an entity. From design and prototyping to operation and maintenance, they offer a comprehensive view of the entity's history and real-time status. This is beneficial for iterative improvements, predictive maintenance, and resource optimization.

5. Use Cases

5.1 FinSESCo - fintech platform solution for sustainable energy system

FinSESCo is a project where BEIA is working on a fintech platform solution for sustainable energy system interacting and contracting boosting energy saving and renewable energy. The mission of the project is allowing a wave of decarbonisation projects easing the set-up of Energy Performance and Energy Savings Performance Contracting EPCo/ESPCo by end-to-end digitalisation of the energy contracting (and the interacting process for public bodies and larger companies). Using pre-existing data from buildings passes and energy audits, a gamified investment process, providing diversification options in an investor dashboard, smart contracts, a digital encrypted meter- based repayment process and machine learning-based fault detection during operation will be offered by platform modules. A guidance tool allows potential portal developers to steer their projects into the right direction. The competencies and diversity of the partners from 5 EU countries + India include skills for setting up energy related services, also using machine learning and crypto-technology, smart metering, legal tech for energy contracting, and social research for a green energy transition.

5.2 GIFT H2020 – Harbour Energy Flexibility Monitoring Service

The Geographical Islands FlexibiliTy (GIFT) project is a European Horizon 2020 innovation project that aims to decarbonise the energy mix of European islands. The project is developing innovative systems to allow islands to integrate vast amounts of renewable energy sources, such as wind and solar.

GIFT is developing a range of solutions, including:

- A virtual power system that will coordinate and manage the different energy resources on the island, including renewable energy sources, storage systems, and demand response.
- Energy management systems for harbours, factories, homes, and other buildings to help them reduce their energy consumption and use renewable energy more effectively.
- Improved prediction of supply and demand for energy, and Digital Twin for visualisation of data through a Geographic Information System (GIS) platform.
- Innovative storage systems that allow synergy between electrical, heating, and transportation networks.

The project's solutions aim to help islands to integrate more renewable energy into their energy mix, improve their energy efficiency, and become more resilient to energy disruptions.

Harbour Energy Flexibility Monitoring System was integrated with the project's Virtual Power System (VPS), which allows it to coordinate with other energy resources on the island to optimize the overall energy system. The Ferry EMS solution can also be used to provide flexibility services to the grid, such as demand-response and energy storage. Harbour EFMS is software system that helps to optimize the energy consumption and charging of electric ferries. The EMS considers a variety of factors, including the ferry's routing, timetable, battery capacity, and charging infrastructure, to develop a charging plan that minimizes the ferry's impact on the grid and maximizes its use of renewable energy.

The results of the demonstrations have shown that the Ferry EMS solution can significantly reduce the ferry's energy consumption and impact on the grid.

Here are some of the key features of the ferry EMS solution:

- Real-time monitoring of the ferry's energy consumption and battery status.
- Optimization of the ferry's charging plan to minimize the impact on the grid and maximize the use of renewable energy.
- Integration with the GIFT project's VPS to coordinate with other energy resources on the island.
- Ability to provide flexibility services to the grid.

The Ferry EMS solution was developed to make electric ferries more sustainable and efficient and has the potential to reduce the cost of operating electric ferries, improve their environmental performance, and increase their integration with the overall energy system.

In addition to the above, the ferry EMS solution can also help to:

- Improve the reliability of the ferry service by reducing the risk of ferry cancellations due to battery depletion.
- Extend the lifetime of the ferry's batteries by reducing the number of charging cycles.
- Make the ferry service more attractive to passengers by providing a more reliable and sustainable service.

The solution furthers targets balancing charging points with availability, fleets of ships to optimize travel routes with arrival/departure combined with the current prize level in the various energy zones. Additionally, it allows for importing timetables to generate recommendations for demand-response systems, with attention paid to flexibility offers as a part of the European energy flexibility market.

Examples of other use cases included:

- A virtual power plant (VPP) to coordinate the operation of distributed energy resources, such as solar panels, wind turbines, and battery storage systems.
- Energy management systems for harbours, factories, homes, and other facilities to optimize their energy consumption and production.
- Better prediction of supply and demand and visualization of those data through a GIS platform.
- Innovative storage systems allowing synergy between electrical, heating, and transportation networks.

The GIFT project achieved several results, included:

- The development and testing of a VPP prototype.
- The development and deployment of energy management systems for harbours, factories, and homes.
- The development of a GIS platform for visualizing energy supply and demand of data.
- The development of innovative storage systems, such as a hybrid battery system that can be used for both electricity and heat storage.

5.3 RIOT-ES H2020 project. Increased performance in IoT systems

For maximising energy efficiency and increased performance in IoT systems in use cases such as real-life parking occupancy monitoring and management situations, a Machine Learning (ML) Processing service for vehicle detection and counting and a service designed to show some metrics were developed within RIOT-ES EU project[30].

The ML Processing service is responsible for analysing a video stream captured by a CCTV camera using the RTSP protocol. Its main purpose is to detect and count vehicles in real time.

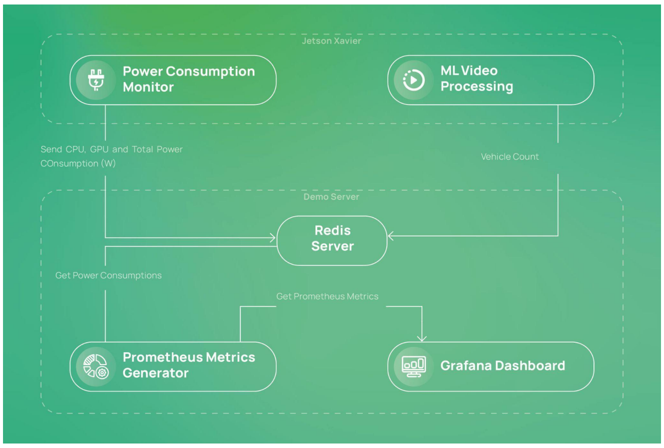


Figure 1 Smart Parking architecture

The RIOT-ES project's achievements in resource-efficient IoT-edge systems have the potential to impact businesses, R&D activities, and the industry. The project offers solutions for reducing energy consumption and enhancing the performance of IoT devices and edge processing systems by optimising energy efficiency while considering performance constraints.

The findings, particularly in the Smart Cities use cases, can revolutionise urban management, including traffic control, waste management, energy usage, and public safety.

The demonstrated functionalities, such as vehicle detection, and counting, can drive industry adoption of energy-efficient IoT systems.

5.4 BD4NRG H2020 project. Digital Twin for edge driven smart buildings and buildings clusters

Monitoring building performance can be a multifaceted approach integrating indoor environmental quality and comfort, energy efficiency of systems and interfaces with EV charging, electricity generation and storage components. Moreover, public sector buildings can play a flagship role within municipalities to lead the way of smart building management, Digital Twin technologies adaptation as well as interfaces with the grid for provision of flexibility of demand service.

The quality of indoor environments has a profound impact on human well-being. As we spend around 90% of our time indoors, we should pay more attention to indoor environmental conditions.

[30] https://riot-es.org

On the other hand, indoor environments are closely linked to outdoor environments, as buildings account for about 40% of the global energy consumption and 1/3 of global greenhouse emissions. Improving the energy efficiency and sustainability of buildings, while advancing digitalisation and smart grid adaptation can not only reduce the environmental impact but also enhance the indoor environmental quality, as well as the economic and social benefits for the occupants and the society, while leading by example at the municipal level.

Enercoutim has developed and continuously improving a digital platform for energy efficiency and indoor environment improvement for buildings of different purposes. The demonstration platform, "Municipal Cluster", is located in Martimlongo, Municipality of Alcoutim, in the Algarve, Southern region of Portugal. The research and pilot demonstration facilities include a community swimming pool, a sports centre, an elderly house, a school and a residential house, as well as the Solar Lab, a special laboratory facility equipped with PV panels, a battery, an EV charger and smart appliances.

The solution focuses on creating a human-centric (Industry 5.0) system that uses algorithms to process data securely and efficiently, while ensuring computation effectiveness, flexibility, open standards, security by design, and scalability. The solution aims to leverage edge computing for Digital Twin creation based on industry 4.0 approaches of data management.

The Digital Twin solution can benefit all the building occupants, reduce carbon footprint and have positive spillover effect while interfacing electricity generation site. The solution intends to:

- Integrate all building occupants in the improvement of the indoor environment, by providing them with feedback and recommendations on how to optimise well-being level, and performance. Raise awareness about the importance of monitored indicators among many other factors.
- Energy efficiency, by minimizing the energy consumption and waste of the building, as well as the greenhouse gas emissions, compliance as to electricity consumption per sqm of public facility.
- Building Operations and maintenance and needs for retrofitting improvements while providing continuous monitoring of performance.
- The solution collects and analyses indoor environmental quality and energy consumption data from connected buildings and updates AI-powered digital twins of buildings clusters which can be scaled up beyond into regional approach. The solution also provides analytics and visualisation tools that help building managers, municipalities, and users make informed decisions for improving energy efficiency and indoor environment quality, while understanding climate change parameters in the area. The solution offers the modelling facilities for: Energy consumption and demand prospects; Energy efficiency; HVAC performance; Carbon footprint; Indoor environment quality; Predictive maintenance.

The Digital Twin[31] target is to advance services creation, achieve the best possible level of indoor environment quality with the lowest possible electricity consumption while integrating edge computing driven analytics to make operations and maintenance decision, while getting facilities ready for smart grids integration.

[31] https://www.bd4nrg.eu

5.5 BD4NRG H2020 project. Distributed edge enabled RES generation

Fast-growing green energy demand, increasing quality of EV mobility, seasonal energy demand spikes and energy poverty challenges require new modern tools for efficient and effective management in distributed renewable generation facilities. To address the challenges and opportunities of the energy transition, such as the increasing share of RES, the decentralization of energy production, the integration of energy markets, the empowerment of energy consumers, and the reduction of greenhouse gas emissions Enercoutim developed an innovative solution, that leverages the power of artificial intelligence, digital twins, and smart analytics to optimise the management and performance of distributed renewable energy sources.

The data gathering the solution collecting and processing real-time data from IoT devices of RES, such as various photovoltaic panels, batteries, and other green energy sources as well as local weather data. Then using machine learning and optimization algorithms, enabling the system to find the most cost-effective and sustainable way for facilities management and maintenance, based on predicted energy consumption, demands and environmental conditions.

The core of the solution is AI-powered digital twins for assets, which are virtual representations of the physical assets and their behaviour. The digital twins enable the system to monitor, analyse, and simulate the RES in a realistic and dynamic way, as well as to test and implement different scenarios and strategies for improving their efficiency and reliability.

The solution also allows the augmentation of digital twins to aggregate PV panels, batteries and other smart energy assets into complex augmented digital twins to manage and predict the behaviour of generation site, buildings cluster or whole municipality.

The solution provides a number of smart analytics and smart reporting tools that offer recommendations on how to optimize the RES operation and performance, as well as how to reduce the energy costs and environmental impact, to help different stakeholders, such as RES owners, operators, managers, consumers, and municipalities, to make informed decisions for improving their energy and maintenance strategies, supporting the development of energy communities.

The solution is flexible, secure and reliable by design, and able to adapt to different types of RES, locations, and contexts. It also provides a wide range of integration tools for further integrations and collaborations. Among these integration tools, a special focus is on Energy Data Space integration.

5.6 Eddie H2020 dataspace project. Digital Twin for real-time residential flexibility market participation

Prosumers – whether residential, community, city, or industrial scale – are playing new central focal role to enable cross sectorial integration using their energy and flexibility data to actively contribute to a variety of flexibility markets. Moreover, the use of flexible DER located in residential environments allows to mitigate critical peak prices through wholesale markets as well as reduce TSO and DSO Grid congestions. In this context new digital platforms are leveraging IoT, edge computing as well as federated cognitive cloud architectures with edge digital twin processing to optimally orchestrate DER through energy data spaces.

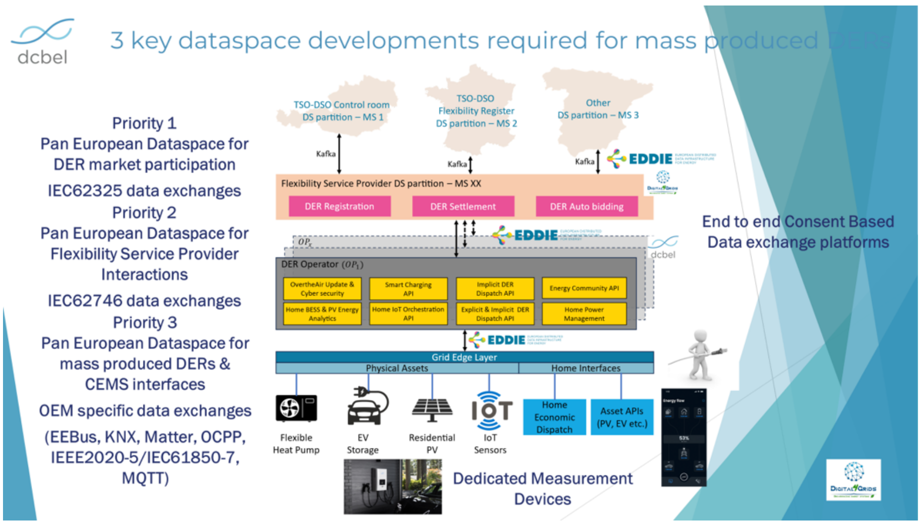
This is pursued at the lowest voltage levels of the energy value chain, which includes home appliances and behind-the-meter DER and managed by resources operators integrating with Flexibility Service Providers (FSP) Virtual Power Plant platforms that optimise the associated DER flexibility through their flexibility portfolio.

This approach requires rethinking the way data is processed from far edge dedicated measurement devices, attached to DER, and exchanged throughout different federated actors running layers of Digital twin optimisation through the electricity value chain. The Eddie project is investigating new dataspace frameworks to allow real-time data exchange and streaming across service providers operating different types of Digital Twin while taking advantage of a variety of domain specific data exchange standards through consistent data space dictionaries.

The Eddie use case covers the implicit participation of Residential DER flexibility into Balancing and Congestion Redispatch markets as considered through the target model of the new European Flexibility code and the Digitalisation of the Energy Action Plan. It covers key process of DER registration, near real-time baseline nomination, bidding as well as activation and imbalance settlements.

Future carbon neutral houses will soon require to incorporate new Digital Twins to support net-zero analytics and electricity cost benchmark calculations as defined through the directive "Energy Performance of Buildings" and, hence, provide near real-time as well as monthly indications to home owners about their 24-7 home carbon efficiency as well as their available flexible capacity to respond to grid congestions and emergency events. The associated Digital Twin will continuously optimise home energy costs and carbon footprint while maximising local PV self-consumption and minimising electricity costs (considering real-time energy and flexibility prices).

While new flexible DERs are integrated through home environments from different equipment vendors - such as heat pump, EV bidirectional chargers as well as home batteries - these devices require to integrate with new local edge optimisation digital twins through standardised dataspace interaction which is prototyped by Digital4Grids through the Eddie project. New integration approaches are considered to automate and facilitate the associated integration of bidirectional EV chargers, home stationary batteries and solar PV inverters (directly with DC technology, resulting in improved efficiency).



Local home energy management solutions are becoming essential digital twin building blocks to share residential DER data through multi-sided data exchange platforms, which are operated using distributed cloud infrastructures and integrating advanced real-time digital twin optimisation as a service. Reference DER data dictionaries are prototyped leveraging IEC CIM standards to enable plug-and-play registration of DER into TSO-DSO flexibility market as well as new real-time data stream across relevant actors of the energy flexibility value chain: from DER operator to energy community managers up to Flexibility Service providers and grid operators (TSOs and DSOs), hence automating associated residential DER transactions.

5.7 Predictricity – artificial intelligence for demand response market participation

Predictricity[32] is a project led by Aalto University, where various artificial intelligence solutions were investigated and developed together with several partner companies in Finland to support their participation in the demand response electricity market. The project includes the creation market simulator, i.e., ancillary market digital twin, based on various data sources such as the open data from the Nordic energy market (Nord Pool), Fingrid (Finnish electricity grid operator), and also weather data. This market simulator is used to train and develop artificial intelligence models that forecast the price in the ancillary market. An agent-based solution is developed that foresees the market trend and carry out market bids in the market simulator, where various scenarios are simulated that demonstrates how the solutions optimize the participation of DERs or energy assets owned by various stakeholders in the relevant ancillary markets, which include e.g., the frequency containment reserve and frequency restoration reserve.

[32] https://predictricityweb.rahtiapp.fi/en/index.html

6. Conclusions and recommendations

Massive electrification, as the best solution towards decarbonisation, introduces several changes on the low-voltage distribution networks due to the massive penetration of DERs and flexible loads. Legacy centralised Advanced Distribution Management Systems (ADMS) platforms will face new challenges, given the massive data generated by newly introduced metering end-devices and the increased network capability requirements.

This paper described a set of use-cases that are likely to be driven by the edge, through growth of business cases, expanding deployment, and service offerings. For such use-cases, the integration of AI in a Digital Twin, deployed and operationally driven by the edge, introduces novel challenges to be tackled by short-to-long term research and innovation efforts. This paper outlined some of the key challenges, including the dependency of AI on data and the energy profile of Digital Twin edge services. The former illustrates heterogenous data supply to AI services, in terms of volumes, quality and rate to name a few metrics. Added to that, data confidentiality is a strong consideration in the energy sector, coupled with privacy as usage patterns can reveal personal habits.

All the above is driving federated AI services where there is less requirement for data sharing across authoritative or ownership boundaries. Orthogonally, Energy considerations have been given for operating digital services at the edge, including Digital Twin. The paper outlined the trade-offs that need to be addressed, particularly between the resource intensive components of Digital Twin services, the high energy cost at the edge and the supply of green energy. Being able to address these trade-offs to realise energy-efficient services and their operation at the edge is a critical objective to maintain sustainable digital twinning ecosystems in various sectors, most importantly in energy.

New solutions and models are required to meet these challenges. Digital Twin-centred technologies are being implemented to address smart sector integration challenges, provide greater observability and serve as policy tool, while developing in sync with EU Data Spaces in Energy. In parallel, the deployment of energy infrastructure and service at the network edge is proliferating. However, their operation, requirements and impact are not fully grasped yet. Hence, there is a growing need to develop Digital Twin solutions, fit for the edge in terms of deployment and modelling considerations, as examples and blueprints for future implementation.

To grasp the expected benefits of Digital Twins-enabled use case, a larger implementation of this edge driven solution in a real-world environment has to be tested, demonstrating the advantages that edge-computing may have for DSOs in the upcoming massive electrification paradigm.

Energy Marketplaces[33] and novel approaches to AI toolboxes and faster scaling up for AI algorithms development are some of the evolving tools to facilitate wider deployment as demonstrated in BD4NRG project and use cases developed within the project by large scale pilots.

[33] https://aioti.eu/wp-content/uploads/2021/03/Open-Energy-Marketplaces-Evolution-Published.pdf

Integration and synchronised development of Digital Twins, EU Energy Data Spaces and cross leverage of AI models and tools at the edge of system components are the evolving challenges and opportunities for twin transition, resilience and decarbonisation. To promote faster implementation of Digital Twins, which are still in the early phase of adoption, the policy makers could encourage further innovation and research projects that would advance the maturity of the technology, deliver important learnings about the role of digital twins in the system, and contribute to collaborative creation of practices and standards across the EU.

It could be beneficial to provide a **sufficient level of regulatory flexibility**, in the form of regulatory sandboxes and other instruments, that would facilitate testing digital twins in practice.

Building the **institutional capacity** for adopting digital twins is also an opportunity. Besides the industry and grid operators, regulators and policy makers could work on enhancing their capabilities in understanding and supporting the digitalisation of the energy sector, including advanced digital technologies. Among the grid operators, there is also a potential to bridge the gap between early adopters, and other, oftentimes much smaller, grid operators that do not have the expertise in digitalisation.

Adopting digital twins in a truly **pan-European coordinated way** also offers a possibility for further work on standardisation and the creation of European energy data space. Although there are well-advanced data standards adopted across the industry, these could be further enhanced to cover the new use cases connected to grid edge and digital twins.

Based on the analysis of this paper, we propose the following recommendations for the policy makers, regulators, industry, grid operators and other stakeholders who are interested in adopting Digital Twins in the energy sector:

- **Further support for research and innovation projects** that would advance the maturity of the technology, deliver important learnings on the role of digital twins in the system, and contribute to collaborative practices and standards across the EU.

- **Provide a sufficient level of regulatory flexibility**, in the form of regulatory sandboxes and other instruments, that would facilitate testing digital twins in practice and evaluating their impacts and benefits withing short and medium term.

- **Enhance stakeholders' capabilities** in understanding and supporting the advanced digitalisation of the energy sector, by investing in training, education, and knowledge exchange.

- **Further enhance the data standards** adopted across the industry, to cover the new use cases connected to grid edge and Digital Twins, and to ensure interoperability, security, and privacy of the data.

As a final note, this report provides insight on the integration of AI in distributed energy systems using digital twins. This can be used in future architecture work and standards focusing on the integration of AI with digital twins serving as building block of evolving European Data Spaces in Energy.

Definitions

Artificial Intelligence: Artificial Intelligence (AI) is an interdisciplinary field that combines theory and practice. It is about assisting human activities, mainly via software and, in some cases, even replacing them. AI involves the use of information systems, data within management systems and dedicated algorithms. AI performance is based on the combination of the availability of a large amount of data, large computing capacity, and machine learning algorithms. As electricity networks are generating a growing amount of data, due to the deployment of smart meters and increased measurement and communication capabilities, their impacts on grids need to be considered. (E.DSO Technology radar)

Cybersecurity and Resilience in the energy system: Cybersecurity is an essential requirement for the reliability of the increasingly digitalised energy system. It plays a key role for the energy system to remain secure and robust against cyber incidents and major attacks, covering the whole value chain of the energy system, from production and transmission to distribution and the consumer, including all the digital interfaces along this path. (European Commission – Digitalisation of Energy Action Plan)

Data privacy: Metering data and further data on flexibility provision is often tied to an individual person as electricity consumer. Thus, it is personal data and as such governed by the EU data protection regulations, such as the General Data Protection Regulation (GDPR). This adds additional requirements and complexity to system architectures necessary to implement the GDPR regulations and manage consent from individuals. (EnTEC report on Common European Energy Data Space)

Distributed energy resources (DER): is local power generation through small scale windmills, solar and other units which are connected to a larger power grid at the distribution level.

Digital twins: are virtual replicas used for understanding, monitoring, diagnosing and forecasting installations, processes and, ultimately, an entire system such as the European electricity or energy system. Digital twins are emerging as future tools for improving performance through outage anticipation and increasing resilience through remote automatic control and near real-time decision-making support. Their aim is both to enable operations to be represented as closely as possible to reality, and to digitally capitalise on descriptive data about assets throughout the lifecycle of structures. Digital twins include four core technologies: the Internet of Things, simulations (using 3D modelling where appropriate), artificial intelligence, and cloud. (E.DSO Technology radar)

Discovery in immersive mode also enables businesses to showcase their activities to a non-expert audience. In the longer term, the technical advances expected will greatly extend the capacity for remote robot control and virtual collaborative work. (E.DSO Technology radar)

DSO: Distribution System Operator (DSO) is an entity (or even a model) for deciding how electricity is delivered to and also supported by residents and businesses (prosumers) considering the recent developments in the relationship between consumers/prosumers and grid operators.

Edge computing: refers to a distributed computing architecture that is characterized by decentralized processing power. In concrete terms, edge computing allows data to be processed directly by the device that produces it or by a local computer. In this case, it is no longer necessary to transmit the data to a remote data centre to analyse it. Edge computing enables data to be processed in real-time and in large quantities as close as possible to its source, with reduced bandwidth usage, lower latency and the necessary security layer for sensitive data. This technology is mainly found in the field of IoT, where it competes with cloud computing. (E.DSO Technology radar)

Edge devices: are entities connected to the Internet and interact with other devices and provide services for a better user experience locally and they can be anything from sensors, cameras, microphones, robots, and even things like refrigerators and cars with varied computing, storage and communication capabilities.

Energy Consumption of the ICT sector: Although it brings overall net benefits to our economy including by enabling emissions reductions, the ICT sector accounts for approximately 7% of global electricity consumption and it is forecasted that this share will rise to 13% by 2030. This electricity use at worldwide level is currently comparable to the cumulated electricity consumption of the entire population taken together in Germany, France, Italy, Spain and Poland, and thus requires comprehensive planning given the demand it puts on our electricity grid. Ensuring that the growing energy needs of the ICT sector are met in synergy with the climate neutrality objective is therefore an essential part of the twin green and digital transition. It is important to address: (i) the energy and resources consumption over the full ICT value chain; and (ii) key emerging additional sources of ICT-related energy consumption. (European Commission – Digitalisation of Energy Action Plan)

Energy trading: is a process involving commercial decision-making and market execution using transparent data exchange on the trade floor, or operations, to barter energy with price transparency, market monitoring, controlled access, and regulatory compliance.

Enhanced load forecasting: Conventional load forecasting techniques have been widely used over the past 30 years. These forecasts have tied load demand to the economic activity of the country and temperature variations while assuming inelasticity of the load to price sensitivities. Enhanced load forecasting goes beyond the traditional linear regression method of forecasting load, which is based on economic activity and temperature forecast, considering the load inelastic to price sensitivities. It leverages the advancements in machine learning to predict the variability of the load at the customer level, this variability continuously increasing with the penetration of distributed energy resources, storage and electric vehicles. With the deployment of advanced metering infrastructures and variable tariffs offered on a retail level, new bot-tom-up methods are being tested that leverage the power of big data and predictive analytics to better understand customer decision-making mechanisms as well as its sensitivity to variable price signals for improved prediction of load demand. (ENTSO-E Technopedia)

European Energy data space: The energy data space will reinforce the availability and cross-sector sharing of data, in a customer-centric, secure and trustworthy manner. This will facilitate innovative solutions and support the decarbonisation of the energy system. The energy data space will help the further integration of renewables, increase the energy system efficiency, and ensure a smooth and competitive transition towards the electrification of sectors such as heating and transport. (Commission Staff Working Document Accompanying the Digitalisation of the Energy System Action Plan)

Generative AI: Generative AI refers to Artificial Intelligence and Machine Learning algorithms that use existing content to generate new content. Generative AI can generate text, sound, images, etc. Based on models stored in a database, it can produce its own similar model. For example, today's artificial intelligence systems can be trained to recognize a distribution network component in images, whereas Generative AI systems can be trained to generate an image of a distribution network component. Large Language Models will make it possible to create texts in automatic ways (responses to customer requests, support for communications, reports, etc.). Generative AI may be used for operation and employee support, network development studies, asset management, network control, etc. The use of generative AI will require specialized resources and adapted validation processes (bias/accuracy monitoring, privacy and security management) before establishing confidence in processes critical to grid operators and other stakeholders. (E.DSO Technology radar)

Local Energy Trading: Market platforms for local energy trading, including peer-to-peer trading, are currently being developed and tested. The platforms are limited to a single region or community, typically defined by grid limitations. They enable increased local production and consumption and relieve transmission and distribution grids, particularly during peak time, thereby limiting congestions. (ENTSO-E Technopedia)

Predictive maintenance: is a proactive maintenance technique that uses real-time asset data collected through condition-monitoring devices/sensors during normal operation, historical performance data, and advanced analytics to forecast when asset failure may occur.

Smart Grid: A smart grid is a digital electricity network that includes two-way electricity distribution allowing coherent operation of electricity grid with prosumers, consumers and real-time demand response for a more reliable, efficient, and sustainable electricity distribution.

Smart meters: Smart meters are electronic devices that not only measure bidirectional energy flow but also provide two-way communication between consumers and their utility, helping utilities know about blackouts, demands and availability of energy to maintain more reliable energy services.

Virtual & Augmented reality: Virtual Reality (VR) refers to simulation technology, popularised by the gaming sector, which immerses a person in a digitally created artificial world, either realistic or imaginary. Other implementations such as Augmented Reality (AR) and Mixed Reality have also emerged. The current barriers, particularly in terms of reproducing the physical interaction (touch, force feedback, etc.) between the individual and the digital environment in which they are evolving, and the cost, are set to be overcome in the coming years. VR tools enable the remote provision of assistance by experts to field technicians during the operation of their tasks.

Virtual Power Plants: The aggregation of distributed renewable energy generation and batteries enables their participation in balancing, wholesale or flexibility markets. Furthermore, aggregation services provide prosumers and small generators with the necessary technology and control, and the aggregator acts as a responsible party in the power and flexibility markets. This means that small-scale flexibility resources which could other-wise not have participated can offer their flexibility to TSOs and DSOs. Projects cover ICT tools, definition of products to be offered and business models for the aggregation of small-scale renewables. (ENTSO-E Technopedia)

References

[1] European Commission, ‘Commission Staff Working Document - Country Fiches for Electricity Smart Metering (SWD/2014/0188)’

[2] F. Pilo, G. Pisano, and G. G. Soma, ‘Advanced DMS to manage active distribution networks’, *2009 IEEE Bucharest PowerTech: Innovative Ideas Toward the Electrical Grid of the Future*.

[3]A. P. Sakis Meliopoulos e*t. al.* ‘Advanced distribution management system’, *IEEE Trans Smart Grid*, vol. 4, no. 4, pp. 2109–2117.

[4] Q. Gemine, D. Ernst, and B. Cornélusse, ‘Active network management for electrical distribution systems: problem formulation, benchmark, and approximate solution’, *Optimization and Engineering*, vol. 18, no. 3, pp. 587–629, 2017.

[5] N. D. Popović, D. S. Popović, and I. Seskar, ‘A novel cloud-based advanced distribution management system solution’, *IEEE Transactions on Industrial Informatics*, vol. 14, no. 8, pp. 3469–3476, Aug. 2018, doi: 10.1109/TII.2017.2780060.

[6] N. Jacobs *et al.*, ‘Analysis of System and Interoperability Impact from Securing Communications for Distributed Energy Resources’, *2019 IEEE Power and Energy Conference at Illinois, PECI 2019*, Apr. 2019.

[7] W. Shi, J. Cao, Q. Zhang, Y. Li, and L. Xu, ‘Edge Computing: Vision and Challenges’, *IEEE Internet Things J*, vol. 3, no. 5, pp. 637–646, 2016.

[8] J. Fan and S. Borlase, ‘The evolution of distribution’, *IEEE Power and Energy Magazine*, vol. 7, no. 2, pp. 63–68, Mar. 2009, doi: 10.1109/MPE.2008.931392.

[9] IEEE, ‘2030.11-2021 - IEEE Guide for Distributed Energy Resources Management Systems (DERMS) Functional Specification’.

[10] A. Koirala, L. Suárez-Ramón, B. Mohamed, and P. Arboleya, ‘Non-synthetic European low voltage test system’, *International Journal of Electrical Power and Energy Systems*, vol. 118, Jun. 2020, doi: 10.1016/j.ijepes.2019.105712.

[11] L. Lampe, A. M. Tonello, and T. G. Swart, *Power Line Communications: Principles, Standards and Applications from Multimedia to Smart Grid*, Second Edition. 2016.

[12] H. Wang *et al.*, ‘Data Collecting and Processing Method in Distribution System Using EDFE Computing Technology’, in *Proc. of the 25th International Conference on Electricity Distribution (CIRED 2019)*, 2019.

[13] M. Chiang and T. Zhang, ‘Fog and IoT: An Overview of Research Opportunities’, *IEEE Internet Things J*, vol. 3, no. 6, pp. 854–864, Dec. 2016, doi: 10.1109/JIOT.2016.2584538.

[14] A. Blanquet, B. Espírito, S. H. Barbosa, E. Distribuição -Portugal, P. Santos, and B. Fischer, ‘Edge Digital Substation: A Disruptive Automation Field Project’, 2019.

[1] Al-Qaseemi SA, Almulhim HA, Almulhim MF, Chaudhry SR. “IoT Architecture Challenges and Issues: Lack of Standardization. In Future Technologies Conference (FTC), 2016, pp. 731-738.

[2] Botta A, De Donato W, Persico V, Pescape A. ”Integration of Cloud Computing and Internet of Things: A Survey”, Future Generation Computer Systems, 2016, vol. 56, pp. 684-700.

[3] Shafi M, Molisch AF, Smith PJ, Haustein T, Zhu P, De Silva P, Tufvesson F, Benjebbour A, Wunder G. "5G: A tutorial overview of standards, trials, challenges, deployment, and practice." IEEE Journal on Selected Areas in Communications, 2017, vol. 35, no. 6, pp. 1201-1221.

[4] Cloud-Edge working group, European Alliance for Industrial data, edge and cloud. “EUROPEAN INDUSTRIAL TECHNOLOGY ROADMAP FOR THE NEXT-GENERATION CLOUD-EDGE", 2023

[5] The European Commission. "Energy-efficient Cloud Computing Technologies and Policies for an Eco-friendly Cloud Market", study report, 2020

[6] eit community, funded by the European Union. "EMERGING AI AND DATA DRIVEN BUSINESS MODELS IN EUROPE", A report of the Cross-KIC Activity "Innovation Impact Artificial Intelligence"

[7] RICE, IDC, Technopolis Group, Fraunhofer ISST. "Edge Computing Taxonomy and Characterisation", Edge Observatory for Digital Decade. Edge Computing Nodes: Characterisation, Deployment Monitoring and Trajectories. STUDY 2022/012, the European Commission Framework Contract SMART 2019/0024, Lot 1, July, 2023.

[8] H. Xu and B. Li, "Joint request mapping and response routing for geo-distributed cloud services," 2013 Proceedings IEEE INFOCOM, Turin, Italy, 2013, pp. 854-862, doi: 10.1109/INFCOM.2013.6566873.

[9] C. T. Do, N. H. Tran, Chuan Pham, M. G. R. Alam, Jae Hyeok Son and C. S. Hong, "A proximal algorithm for joint resource allocation and minimizing carbon footprint in geo-distributed fog computing," 2015 International Conference on Information Networking (ICOIN), Cambodia, 2015, pp. 324-329, doi: 10.1109/ICOIN.2015.7057905.

[10] K. Poularakis, J. Llorca, A. M. Tulino, I. Taylor and L. Tassiulas, "Service Placement and Request Routing in MEC Networks With Storage, Computation, and Communication Constraints," in IEEE/ACM Transactions on Networking, vol. 28, no. 3, pp. 1047-1060, June 2020, doi: 10.1109/TNET.2020.2980175.

[11] M. AL-Naday, N. Thomos, J. Hu, B. Volckaert, F. de Turck and M. J. Reed, "Service-Based, Multi-Provider, Fog Ecosystem With Joint Optimization of Request Mapping and Response Routing," in IEEE Transactions on Services Computing, vol. 16, no. 3, pp. 2203-2214, 1 May-June 2023, doi: 10.1109/TSC.2022.3211739.

[12] M. AL-Naday, T. Goethals and B. Volckaert, "Intent-based Decentralized Orchestration for Green Energy-aware Provisioning of Fog-native Workflows," 2022 18th International Conference on Network and Service Management (CNSM), Thessaloniki, Greece, 2022, pp. 184-190, doi: 10.23919/CNSM55787.2022.9964993.

[13] Z. Zhou et al., "Secure and Latency-Aware Digital Twin Assisted Resource Scheduling for 5G Edge Computing-Empowered Distribution Grids," in IEEE Transactions on Industrial Informatics, vol. 18, no. 7, pp. 4933-4943, July 2022, doi: 10.1109/TII.2021.3137349.

[14] W. Zhang, S. Toor, M. Al-Naday, "Federated Machine Learning for Resource Allocation in Multi-domain Fog Ecosystems," in IEEE International Conference on Cloud Networking (Cloudnet) 2023, New York Area, USA.

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AIOTI is the multi-stakeholder platform for stimulating IoT and Edge Computing Innovation in Europe, bringing together small and large companies, academia, policy makers and end-users and representatives of society in an end-to-end approach. We work with partners in a global context. We strive to leverage, share and promote best practices in the IoT and Edge Computing ecosystems, be a one-stop point of information on all relevant aspects of IoT Innovation to its members while proactively addressing key issues and roadblocks for economic growth, acceptance and adoption of IoT and Edge Computing Innovation in society. AIOTI's contribution goes beyond technology and addresses horizontal elements across application domains, such as matchmaking and stimulating cooperation in IoT and Edge Computing ecosystems, creating joint research roadmaps, driving convergence of standards and interoperability and defining policies.