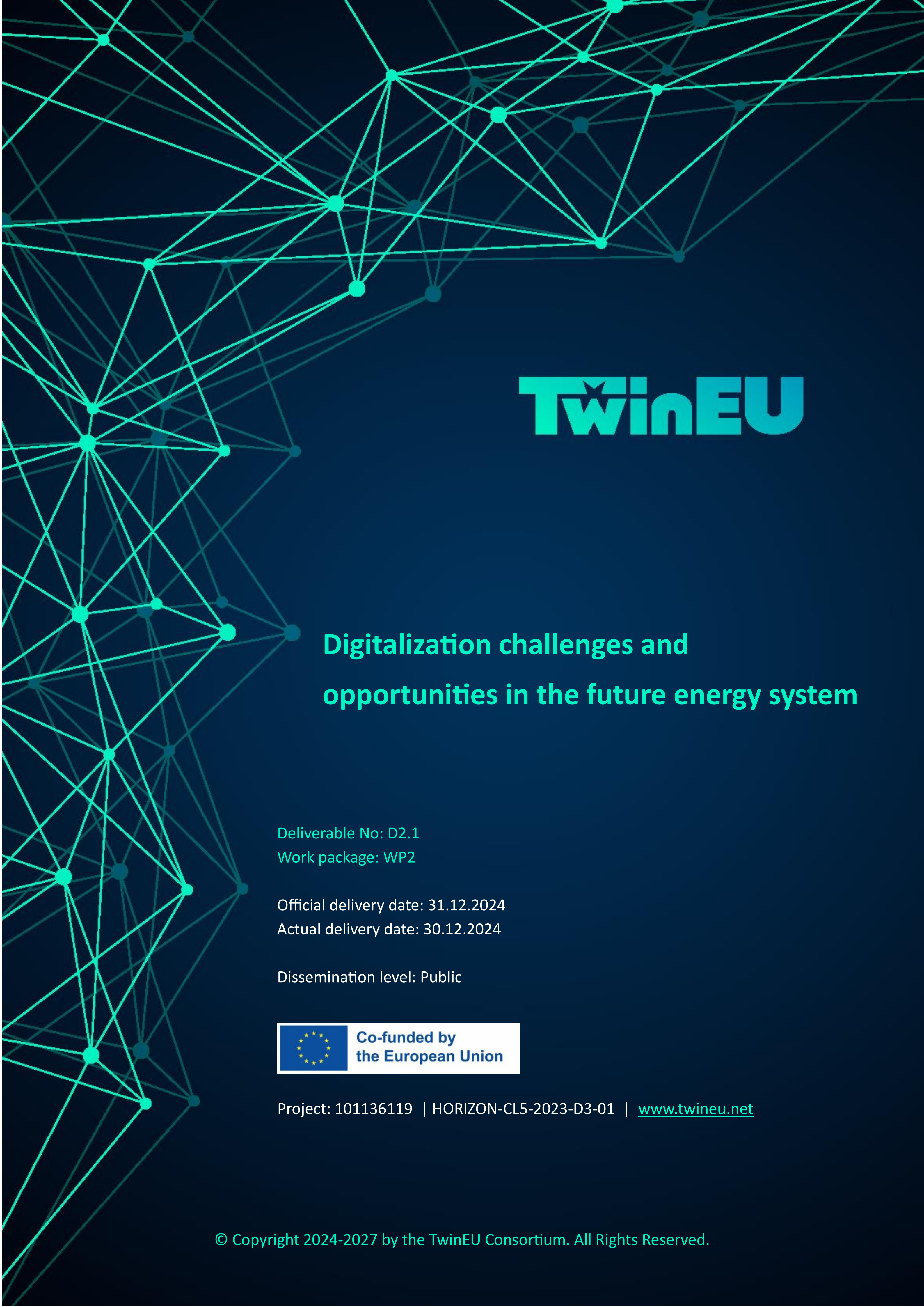

TwinEU

Digitalization challenges and opportunities in the future energy system

Deliverable No: D2.1
Work package: WP2

Official delivery date: 31.12.2024
Actual delivery date: 30.12.2024

Dissemination level: Public

Co-funded by
the European Union

Project: 101136119 | HORIZON-CL5-2023-D3-01 | www.twineu.net

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Version	Date	Authors	Notes
0.1	10.06.2024	Authors	initialize
0.2	04.10.2024	Authors	T2.1 review
0.3	25.11.2024	Authors	T2.2 review
0.4	04.12.2024	Authors	submitted for internal review
0.5	17.12.2024	ENEL, ENG	submitted for external review
1.0	20.12.2024	Ilias Zafeiropoulos	submitted for final review

Responsible Partner	Fraunhofer
Checked by WP leader	Ilias Zafeiropoulos (UBE), 20.12.2024
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List of Abbreviations and Acronyms

Acronym	Meaning
AI	Artificial Intelligence
AMI	Advance Metering Infrastructure
API	Application Programming Interface
CGM	Common Grid Model
CGMES	Common Grid Model Exchange Standard
CHP	Combined Heat and Power
CIM	Common Information Model
DC	Direct Current
DEF	Digitally Enabled Flexibility
DER	Distributed Energy Resources
DR	Demand Response
DSO	Distribution System Operator
DSOi	Distribution System Operator Interface
DT	Digital Twin
EC	European Commission
EU	European Union
EV	Electric Vehicle
FDT	Federated Digital Twin
GHG	Greenhouse Gas
HVAC	High Voltage Alternating Current
HVDC	High Voltage Direct Current
ICT	Information and Communications Technology
IEA	Informational Energy Agency
IED	Intelligent Electronic Device
IEEE	Institute of Electrical and Electronics Engineers
IoT	Internet of Things
IT	Information Technology
KB	Knowledge Base
LV	Low Voltage
ML	Machine Learning
MV	Medium Voltage
NIST	National Institute of Standards and Technology

OT	Operational Technology
OWL	Web Ontology Language
PMU	Phasor Measurement Unit
PQ	Power Quality
PV	Photovoltaic
R&D	Research and Development
RDF	Resource Description Framework
RES	Renewable Energy Sources
SAREF	Smart Applications Reference
SCADA	Supervisory Control and Data Acquisition
SGAM	Smart Energy Grid Architecture Model
SIF	Semantic Interoperability Framework
TSO	Transmission System Operator
UC	Use Case
VSC-HVDC	Voltage Source Converter High Voltage Direct Current

Executive Summary

Deliverable D2.1, Digitalization Challenges and Opportunities in the Future Energy System, examines the digital landscape of Europe's energy sector by synthesizing insights from previous EU-funded projects, addressing key gaps, and consolidating stakeholder requirements for the TwinEU project. Drawing on contributions from 86 stakeholders, a review of 31 EU-funded initiatives, and an extensive literature survey, the deliverable aligns with EU policy directives, including the Digitalisation of Energy Action Plan, the Data Act, and the digital twin strategies of ENTSO-E and the EU DSO Entity.

The analysis identifies critical challenges that hinder the adoption of advanced digital tools in the energy sector. Key issues include inadequate interoperability between systems, insufficient data governance and cybersecurity measures, and limited grid observability (particularly at the low-voltage level) which restricts real-time monitoring and advanced forecasting capabilities.

Building on these findings, actionable solutions to address these gaps are outlined. Standardizing data exchange formats and communication protocols is emphasized to enhance collaboration, reduce system fragmentation, and support harmonized interfaces. Strengthening cybersecurity through encryption, real-time threat monitoring, and robust data privacy measures is deemed essential for protecting critical infrastructure and fostering stakeholder trust.

The deliverable also consolidates a comprehensive list of stakeholder requirements for the TwinEU project. A recurring recommendation is to align data sharing practices with EU policies to ensure compliance with privacy and sovereignty obligations, while promoting innovation and investment in digitalisation. Several stakeholders advocate for collaborative or federated digital twin frameworks that can improve planning, operational coordination and cross-border cooperation.

A foundational framework for advancing TwinEU's objectives is provided, by integrating lessons learned from previous projects and analysing stakeholder perspectives. By fostering interoperability, enhancing cybersecurity, and supporting a consistent regulatory environment, the energy sector can accelerate the adoption of digital tools, advancing Europe's goals of resilience, flexibility, and decarbonization.

1 Introduction

Digitalization is reshaping the European Union (EU) energy sector, addressing complex challenges and unlocking transformative opportunities. As the energy system transitions toward decarbonization, digital solutions such as Digital Twins (DTs), Artificial Intelligence (AI), and advanced data analytics are becoming integral in ensuring grid resilience, renewable energy integration, and operational efficiency. Digitalization, particularly through DTs, offers scalable and interoperable solutions that optimize grid operations, foster data-sharing frameworks, and enhance energy market participation.

This deliverable explores these opportunities, with a focus on mapping stakeholder requirements for DTs, analysing their role in the energy system, and developing a Knowledge Base (KB) to support future energy use cases. The findings aim to guide the integration of DTs across the EU energy landscape in a federated way, fostering innovation and addressing key challenges.

1.1 Task 2.1 and Task 2.2

Task 2.1, ***digitalization challenges and opportunities in the system planning, operation, and energy markets***, aims at examining digitalization challenges considering the experiences gained from previous projects such as INTERRFACE, OneNet, BD4NRG as well as CGM programme lessons (CIM/CGMES).

The task focused on consolidating the main outcomes of these projects into a comprehensive knowledge base for DEF, with particular attention to the information and communication layers of the SGAM architecture. The task will identify and analyse the main gaps in data exchanges needed to support the flexibility needs (e.g., data models, communication protocols, tool limitations, missing interfaces and adapters used between system operators). Based on the analysis, proposals will be developed to address these gaps, aiming to enhance system planning and grid operation while improving the flexibility and resilience of the EU energy system.

Additionally, the task will analyse the cyber physical nature of the digitalised pan-European grid, focusing on the convergence of IT and OT practices in the smart grids. The impact of the cyber physical nature on the reliability and resilience of the grid will also be described, identifying key areas for dynamic monitoring and controllability of the physical assets.

Task 2.2, ***energy stakeholders' requirements for the digital twin of the pan-European grid***, focuses on identifying and analysing the requirements of key energy stakeholders in order to identify new technological opportunities. This task plays a pivotal role in understanding how various stakeholders interact within the DT landscape, uncovering their primary challenges, and identifying technological opportunities that could address these pain points. By doing so, the task aims to align the DT framework with the operational needs and strategic goals of the energy sector.

A central component of this task is stakeholder engagement, which involves extensive surveys and interviews with 86 entities representing a diverse range of roles, including Transmission System Operators (TSOs), Distribution System Operators (DSOs), market operators, regulatory bodies, and technology providers. These efforts help map the roles and interactions of stakeholders within the DT ecosystem while uncovering the critical barriers they face, such as issues related to data exchange and system integration.

The insights gathered in Task 2.2 guide the identification of technological opportunities and the derivation of actionable requirements that will inform the design of the TwinEU use cases. By understanding stakeholders' aspirations and technological constraints, the project seeks to prioritize innovations that can enhance the implementation and effectiveness of the digital twin. The findings also address emerging challenges, ensuring that the federated DT supports the EU's broader energy objectives of sustainability, reliability, and efficiency.

The objectives of Task 2.2 are structured into four key focus areas. First, **Stakeholder Identification and Mapping** involves categorizing the primary stakeholders and defining their relevance, roles, and interactions in the DT landscape. Second, a **Gap Analysis and Requirements Derivation** identifies stakeholders' key pain points and technological limitations, laying the groundwork for actionable recommendations. Third, **Comprehensive Stakeholder Engagement** ensures that insights are collected inclusively from a wide range of perspectives across Europe. Finally, **Technological Opportunities** are highlighted and prioritized to inform the development of specific TwinEU use cases.

The findings and requirements derived from Task 2.2 are consolidated and prioritized in Chapter 6 of this report. These insights form the foundation for designing an effective and stakeholder-driven DT framework, enabling the pan-European grid to advance towards a digitally integrated, sustainable future.

1.2 Objectives of the Work Reported in this Deliverable

The primary objective of this deliverable is to identify key challenges and opportunities within the digitalization of the EU energy sector. It aims to:

- Consolidate lessons learned from existing projects to enhance system planning, operation, and energy markets.
- Develop a comprehensive Knowledge Base to support future energy system innovations.
- Provide strategic recommendations for addressing interoperability, cybersecurity, and data exchange challenges by understanding stakeholders' needs.

1.3 Outline of the Deliverable

This deliverable is structured into the following chapters:

- Chapter 1introduces the digitalization context, task objectives, and deliverable structure.
- Chapter 2 presents the methodologies for data collection, stakeholder analysis, and ethical considerations.
- Chapter 3 describes the EU's efforts to digitalize the energy sector.
- Chapter 4 consolidates survey results and literature findings to create the Knowledge Base.
- Chapter 5 highlights high-impact factors such as interoperability, system gaps, and cybersecurity challenges.
- Chapter 6 details stakeholders' requirements for digital twins and identifies potential opportunities and limitations.
- Chapter 7 concludes with strategic recommendations and actionable insights.
- Annexes include questionnaires, survey responses, and supplementary material.

2 Methodology

2.1 Task 2.1

2.1.1 Overview of the assessment approach

Task 2.1 "***Digitalisation challenges and opportunities in the system planning, operation, and energy markets***" identified two primary areas where the core challenges and opportunities in digitalization are concentrated: interoperability and cybersecurity. These topics were designated as sub-tasks, with UBITECH Energy assigned as the coordinator for both. To facilitate a comprehensive analysis, these sub-tasks were later merged into one main area.

Under this task, the TwinEU project undertakes comprehensive research to gather knowledge, best practices, and data related to the challenges and opportunities in enabling flexibilities, particularly within the information and communication layers of the SGAM framework [1].

This process includes a two-stream method, as depicted in Figure 1, following (i) a thorough review and storage of relevant scientific literature in an internally shared project repository, and (ii) a detailed analysis of both ongoing and completed research projects. The target is to develop a robust knowledge base (KB) that serves as a TwinEU-project-internal repository for key insights, thereby supporting the project's fine progress and ensuring that it remains aligned with its goals.

The primary aim of this assessment is to explore how flexibility, interoperability, and resilience in energy systems can be enhanced through data integration, standardization, and cyber-physical security, into the SGAM framework.

Simultaneously, the scope of the assessment focuses on identifying key challenges, opportunities, and high-impact factors involved in the digitalization of the EU's energy sector. Defining these boundaries is crucial for outlining the steps to be followed in the project.

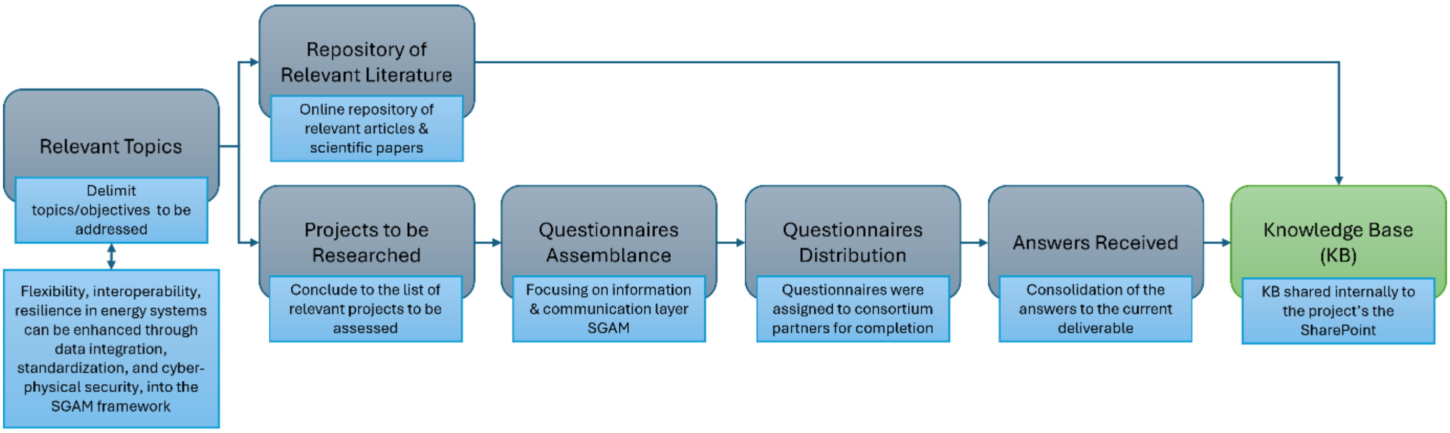

Figure 1: Flow chart to the development of the Knowledge Base (KB)

2.1.2 Information collection method & list of projects

A significant amount of relevant scientific literature has been collected, stored, and internally shared via the TwinEU project's SharePoint. In parallel, a set of focused research questions has been developed to extrapolate valuable insights from relevant EU research projects, ensuring alignment with the previously defined objectives, contributing to the project's broader understanding of digitalization in the energy sector.

For the development of the KB under Task 2.1 – "Digitalization challenges and opportunities in system planning, operation, and energy markets", a qualitative approach has been picked as the primary method for information collection. This includes a survey that has been designed and distributed to Task 2.1 partners, serving as the main tool for gathering insights and data.

The list of the projects to be addressed/researched has been formed based on the description of the task, highly considering the following criteria:

- The selected projects need to have a strong **focus on data interoperability** platforms (e.g., IEGSA, OneNet Connector), standards, and communication layers that enhance flexibility in the energy system. Projects that have developed or implemented new data-sharing frameworks and interfaces are prioritized.
- The selected projects need to identify and **address critical gaps** in data models, communication protocols, and missing interfaces or adapters between system operators (TSOs, DSOs) and customers. These projects focus on overcoming limitations to improve system flexibility and grid efficiency.
- The selection prioritizes projects that **explore cross-sector and cross-border integration** of components, contributing to a more flexible and resilient pan-European energy system.
- The selected projects need to **focus on the cyber-physical** nature of the grid, including IT and OT convergence, cybersecurity, and dynamic monitoring and control of physical assets. Those addressing reliability and resilience in the digitized smart grid are especially important.
- The selected projects need to demonstrate **significant use of the information and communication layers of the SGAM** and lessons learned from standards like CIM/CGMES [2] published by the European Network of Transmission System Operators (ENTSO-E) [3]. Prior successful integration of these elements is essential for leveraging previous experiences.
- The selected projects need to have **demonstrated tangible outcomes and lessons learned** in the areas of interoperability, flexibility, and resilience are chosen. This ensures that they contribute meaningful insights and practical solutions.

Therefore, adhering to the above criteria, the projects' list is assembled, including a total of thirty-one completed and ongoing EU research projects.

The inclusive online survey comprising fifteen core questions was then meticulously designed, developed and shared among the partners. This research instrument referred to as the "T2.1 Research Questionnaire", is presented in Annex A. It aimed to cover a comprehensive range of topics for the researched projects, including project objectives, development of interfaces, data interoperability platforms, standards, protocols, identified gaps, and cyber-resilience topics. The questions produced and included in the questionnaire, extending to the complete spectrum of the requirements identified by the task description, are listed below:

- Question 1 (Q1): What is the **objective of the project** under review?
- Question 2 (Q2): Did the project develop **interfaces** and/or **data interoperability** platforms to enhance **flexibility** and improve the **business processes** (system planning/asset management, system operation, and energy markets)?
    - Question 2i (Q2i): If yes, for what are these interfaces? Can you define them in terms of **information** models, timing requirements and **interaction** sequences?
    - Question 2ii (Q2ii): If yes, provide a **brief description** or picture of each interface's architecture with a reference to the **SGAM model**.

- Question 3 (Q3): What were the **key findings** regarding the implementation of standards and interfaces to improve **flexibility** and **business** processes (system planning/asset management, system operation, energy markets)?
- Question 4 (Q4): How did the project contribute to the development of **data interoperability** platforms and data-sharing frameworks?
- Question 5 (Q5): Did the project define **communication** and **data exchange** requirements?
- Question 6 (Q6): Which **data models** were used?
- Question 7 (Q7): Which **protocols** and **standards** were applied?
- Question 8 (Q8): What specific **gaps** were identified in terms of data format, information models and communication protocols
- Question 9 (Q9): Can you provide **examples** of tool **limitations** that were identified during the analysis?
- Question 10 (Q10): What were the significant **missing interfaces** and **adapters identified** between system operators, TSOs, DSOs, and customers?
- Question 11 (Q11): How were **data exchange gaps** affecting the support for **flexibility requirements** identified and analysed?
- Question 12 (Q12): What are the proposed **solutions for addressing gaps**?
- Question 13 (Q13): How do these proposals aim **to improve** the **business processes** (system planning/asset management, system operation, energy markets) efficiency while **facilitating the flexibility** and **resilience** of the EU energy system?
- Question 14 (Q14): What **challenges** are anticipated **in implementing these proposals**, and **how can they be overcome**?
- Question 15 (Q15): Are there any **developments** in the project that **address the cyber-physical reliability and resilience** of the electricity grid? [yes/no]
    - Question 15i (Q15i): If yes, what are the cyber and physical **assets/elements** that the project addresses? If yes, what are the potential **risks** identified in the project that are associated with the cyber-physical nature of the grid, and **how are they mitigated**?
    - Question 15ii (Q15ii): If yes, what are the identified **focus areas** in the project **for dynamic monitoring and control** to ensure the reliability and resilience of the grid? If yes, how can the cyber layers of the **pan-European grid** be effectively monitored and protected from potential threats? What are **the propositions of the project**?

The survey was distributed to the relevant partners was conducted considering their Person Months (PMs) in Task 2.1, their expertise, and their relevance/participation to the linked projects. The responses were systematically collected, ensuring high information integrity and completeness.

2.1.3 Organizing the gathered information

The final step regarding the questionnaires' responses management involves several key activities: (i) analysing and organizing the collected data, (ii) conducting the collection, analysis, and reporting of information to generate valuable insights, (iii) populating the KB with this organized data, and (iv) leveraging the KB to extract valuable insights that will inform best practices and support optimal decision-making throughout the remainder of the project.

To efficiently manage the qualitative data collected, a standardized file-naming approach was implemented within the SharePoint platform for each of the completed questionnaires. This approach ensures consistency, making it easier to locate and track the information within the KB.

The scientific literature repository is also stored within the dedicated project's SharePoint area, and it is available for access from the project partners.

2.2 Task 2.2

Task 2.2 "***Energy stakeholders' requirements for the digital twin of the pan-European grid*** " adopts a structured, iterative and multi-layered approach to engage with a wide range of stakeholders in the European digital energy landscape. The steps of the task's progress and methodology are outlined in Figure 2. The methodology described here aligns closely with the overall WP2 timeline. Early-stage tasks (stakeholder mapping, survey question design and initial data collection) fed into the analysis phase and culminated in draft outputs that informed this deliverable, D2.1.

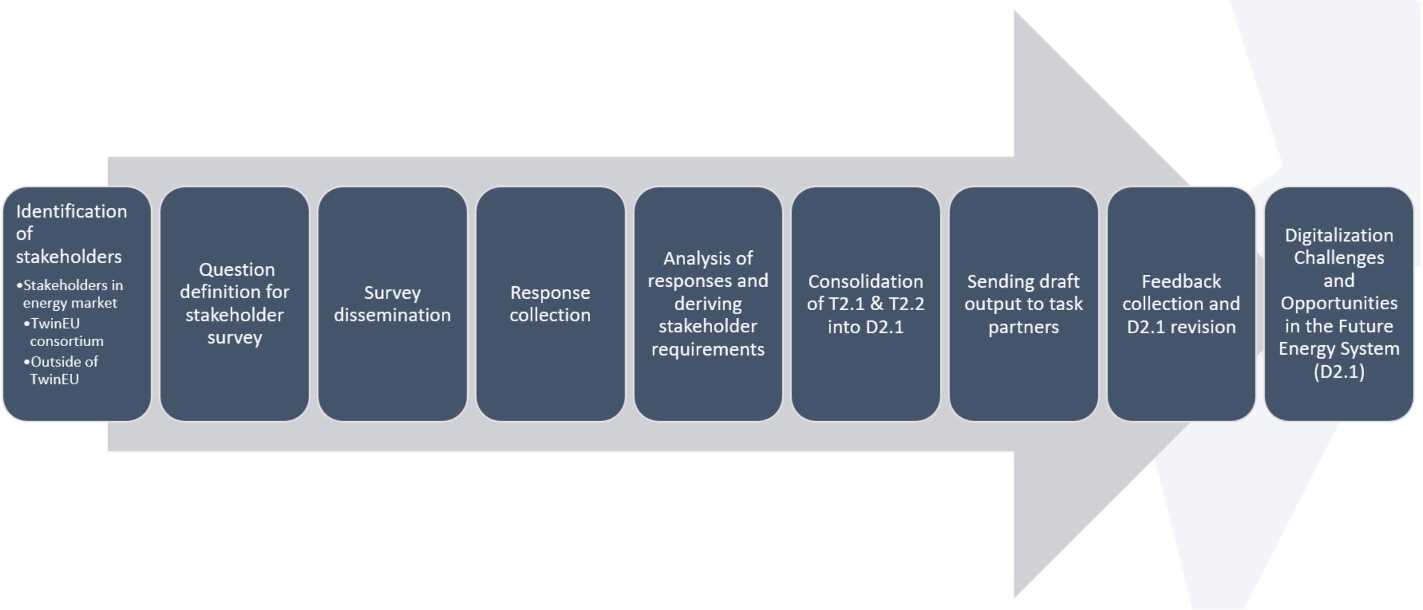

Figure 2 Methodology of Task 2.2

Stakeholder identification and categorisation:

The first step was to establish a robust stakeholder landscape, to capture a broad segment of the energy sector. Key actors, such as TSOs, DSOs, regulators, and technology providers were identified. This mapping extended beyond the TwinEU consortium to include external stakeholders with a prominent role in the DT environment. By categorising the stakeholders according to their domain (e.g. market actors, regulators, ICT providers), we ensured a balanced representation of interests and influence. This approach aligns with Task 2.2's objective to understand the varying stakeholder requirements for a pan-European digital twin of the electricity network.

Survey design, dissemination and initial data collection:

A structured questionnaire (see Annex C)was developed to capture stakeholders' current practices, technology needs, interoperability requirements, data governance considerations, and willingness to integrate DT solutions. Reflecting the iterative process outlined in Figure 2 and timeline in Figure 3, the surveys were disseminated through multiple channels, including direct email outreach, professional social media (LinkedIn), TwinEU 2nd General Assembly, and sectoral conferences such as ENLIT. This multi-channel dissemination strategy, aligned with the planned activities, enabled broad participation within the specified timeframe.

Activity	1	2	3	4	5	6	7	8	9	10	11	12
Agreement on stakeholders				░								
Agreement on interview questions				░								
Distributing questions					░							
Gathering results & defining requirements					░	░	░	░	█			
Sending T2.2 output partners									▨	█		
Feedback period for T2.2 output report									▨	█		
Consolidation T2.1 & T2.2 output into D2.1									▨	█		
Sending first D2.1 draft										▨	█	
Sending second D2.1draft											▨	█
Submitting D2.1												░

Figure 3 Activity timeline of Task 2.2

Data Analysis and Requirements Consolidation

Survey responses were systematically analysed to identify key trends, stakeholder priorities and technology gaps relevant to DT implementation. Insights were extracted and synthesised into a prioritised set of requirements. These requirements, detailed in Chapter 0, serve as actionable guidelines for the design of the TwinEU use cases. This consolidation process is in line with the methodology chart, where initial findings from Tasks 2.1 and 2.2 inform the development of Deliverable D2.1.

Face-to-face interviews to enrich and validate findings:

Face-to-face interviews with selected energy stakeholders are planned for subsequent activities and will be reported in D2.2. Conducting the interviews after publication of D2.1 will ensure that the stakeholders have access to preliminary TwinEU findings and can give more focused and valuable input.

3 Digitalizing the EU Energy Sector

3.1 EU Action Plan for Digitalizing the Energy Sector

In order to end the massive dependence on imported fossil fuels, tackle the climate crisis, and ensure affordable access to energy for all, the EU has set ambitious targets for decarbonization through the European Green Deal [4] and REPowerEU [5] plans. Massive investments are foreseen in solar PVs, heat pumps and electric vehicles by 2030. To achieve a reduction in greenhouse gas emissions by 55% a high share of 42.5% renewables is required in the energy mix [6]. Digitalization of the energy sector is a key enabler for this clean transition; thus, the EU has published an EU Action Plan for digitalising the energy system as a substantial part of the investments foreseen for the European energy system. Through the EU Action for digitalising the energy system plan [7], several strategic targets, listed below, have been identified along with specific steps towards their achievement.

- **An EU framework for sharing data**: Seamless, interoperable and secure data transfers are key elements of the digitalised energy system. The establishment of a common European energy data space [8] will ensure a coordinated framework for exchanging and valorising the energy data by all different actors in the energy sector.
- **Strategic EU coordination for grid investments**: The Commission is implementing targeted measures to efficiently coordinate significant grid investments for the digital era. The re-establishment of ‘Smart Energy Expert Group’ including the ‘Data for Energy’ (D4E) working group will support the Commission in developing and rolling out a common European data space for energy. D4E will develop a portfolio of European high level use cases for data exchanges, will mobilize the full rollout of smart meters across Europe, will promote the interoperability and procedures for access to metering and consumption data for demand response and customer switching (as provided by the Electricity directive, Article 24) and will support the code of conduct for energy-smart appliances. The EU Research and Innovation, and Digitalization programmes (Digital Europe, Horizon Europe) will facilitate the deployment and demonstration of the European data space for energy.
- **New services, skills and empowerment for energy consumers**: A legal framework that empowers consumers and protects their privacy and security is put forward under the proposed Data Act [9]. The Commission is also running the initiative of Fitness Check of EU consumer law on digital fairness [10], ensuring the consumers’ rights based on the Electricity Directive. Targeted actions by the energy communities will be taking place to support the knowledge sharing on digital tools that enable the local consumption and peer-to-peer exchanges of daily produced electricity. In order to ensure that skilled workers and trained professionals will be able to deploy new data-driven services and innovative technology solutions, the European Commission will establish a large-scale partnership on the digitalization of the energy value chain as part of the EU’s Pact for Skills **Error! Reference source not found.**.
- **Cybersecurity enhancement**: The Commission is taking targeted measures to increase the cyber resilience of the electricity system addressing cybersecurity risks and ensuring an accessible and competitive market for new services and products. The NIS 2 Directive [12] offers the possibility of carrying out coordinated risk assessments of critical supply chains. The Network Code for Cybersecurity [13] includes rules on common minimum requirements, planning, monitoring, and reporting crisis management. The Commission has highlighted energy as a priority sector of critical infrastructure and provided guidelines [14] for the secure exchange of information, and enhanced capacity to anticipate, prepare for, respond to, and

quickly recover from any disruptions. The Cyber Resilience Act [15] sets harmonized cybersecurity rules to implement on digital products and market surveillance, addressing devices embedded in the energy supply cycle.

- **Promote greater efficiency and circularity in the energy consumption of the Information & Communication Technology (ICT) sector**: The global electricity consumption of the ICT sector is estimated to rise up to 13% of the global electricity consumption, thus the sustainability of the growing energy needs of the ICT sector is an important part of the clean and digital energy transition. The Eco-design for Sustainable Products Regulation (ESPR) [16] will establish new rules that ensure 'circularity' of products entering the EU market, as well as minimum sustainability requirements on public procurement of products and an energy labelling scheme for the computers. The EU code of Conduct for the sustainability of telecommunications networks, the environmental labelling scheme for data centres [17] and the updated requirements on the operating conditions of servers and data storage products are under development. Additionally, an energy label for servers and data storage products are included in the revision of the eco-design rules for servers and data-storage products [18]. Finally, the Commission is planning to cooperate internationally with standardization bodies to develop an energy-efficiency label for blockchains.
- **Design an effective governance for an EU-wide coordinated approach on digitalization**: The EU is supporting the energy and digital transition synergies based on the EU's main frameworks for Member State planning and EU funding tools, i.e., deliver the REPowerEU objectives through the Recovery and Resilience Plans (RRPs). It is also promoting synergies among the National Energy and Climate Plans (NECPs) and the National Digital Decade strategic roadmaps, valorising the requirements analysis performed by the Smart Energy Expert Group on a Member State level. Furthermore, a wide portfolio of cooperation instruments and funding mechanisms is planned, enhancing structural and joint planning by public authorities in cooperation with the private sector, as well as continuous support for R&I, among EU entities and internationally, with partnerships and cooperation agreements. Finally, the action points indicated under the legal framework (point 3) that is designed to empower consumers and enhance privacy, further adds to the pan-EU coordinated approach for digitalization.

3.2 Digitally Enabled Flexibility

As the shares of variable renewables such as solar PV and wind increase, power systems need to become more flexible to accommodate the changes in clean energy output. In this clean transition era, the electricity grids are called upon to both operate in new ways and leverage the benefits of distributed resources. The key element of these future grids will be flexibility, the ability of the grid to maintain the balance between generation and load under situations of uncertainty. The main sources of flexibility are controllable generation (i.e. gas turbines, biomass, concentrated solar power (CSP) generation etc.), storage (i.e. batteries, hydro pump storage, flywheel, thermal batteries etc.) and consumers' demand response, through their voluntary management of their generation and consumption patterns.

Digitally enabled flexibility (DEF) is based on ICT technology that optimally manages the distributed energy resources (DER) and the grid assets in order to respond to fluctuations in demand and supply. The widespread adoption of smart ICT technologies for the grid is very much dependent on interoperability i.e. the ability of smart grid actors, components, and applications to work together by exchanging data and information.

The next-generation electricity grid is expected to integrate interoperable technologies, particularly in the energy, transport, information and communication fields with the aim to increase reliability, affordability, and sustainability of the energy ecosystems. Such technologies include electric mobility solutions, demand response techniques, AI, distributed ledger technologies, blockchains, storage devices, distributed energy generators,

DEFs can have positive impact on several aspects of the energy system:

(i) <u>Stability and power quality</u>: The expansion of solar and wind energy adoption amplifies grid stability concerns due to localized voltage fluctuations. Digitally enabled flexibility can skilfully manage voltage fluctuations and power quality issues tied to renewable sources. Additionally, digital measures for flexibility management can minimize energy losses and enhance overall grid efficiency.

(ii) <u>Smooth grid Integration of Distributed Energy Resources</u>: Integrating DER like solar panels, batteries, heat pumps and EV chargers will be transforming the future electricity grids and requires sophisticated management due to their decentralized and variable nature. The big data generated can be treated by digital flexibility software modules for optimal decision-making. This enhances grid stability and empowers DER as integral components of a resilient distribution network, ensuring reliable energy services.

(iii) <u>Congestion Management</u>: Digitalized flexibility mechanisms can alleviate the grid congestion by intelligently redistributing power flows and optimizing energy distribution, significantly enhancing grid efficiency. Furthermore, these flexible capacities can extend the lifespan of grid components through capacity management and defer the need for immediate investments in infrastructure. This dual benefit not only facilitates faster connections for new customers and reduces waiting times, but also contributes to a more cost-effective and sustainable grid planning and development. An example is represented by the efforts that TSOs make to implement the Regional Operational Security Coordination (ROSC). This consists of a congestion management process aimed at optimising remedial actions based on the System Operation Guidelines (Art. 75 and 76) [19] legal framework.

(iv) <u>Grid Resilience</u>: Local flexibility resources serve as valuable backups during disturbances, ensuring stable power quality and grid stability, especially in isolated areas. These resources are enhancing the overall grid resilience by minimizing critical grid situations and reducing the likelihood of shutdowns. Flexibility measures ensure grid resilience against equipment failures, extreme weather, and cyberattacks, rapidly adapting to maintain stability and dependable energy delivery.

(v) <u>Energy Transition</u>: Digitalized flexibility measures can support the electrification of sectors like transportation and industry with clean energy from RES, enabling System Operators to overcome the significant challenges of sector integration.

(vi) <u>Demand response and consumer engagement</u> flexibility at the DSO level enable the implementation of demand response programs. These programs allow DSOs to adjust electricity consumption patterns in response to supply-demand imbalances or grid constraints. By incentivizing consumers to shift their usage during peak hours, DSOs can improve grid reliability and reduce the need for expensive infrastructure upgrades.

(vii) <u>Enhance the coordination among TSO-DSO and consumers</u>: Digitally enabled flexibility can facilitate the operation of flexibility markets and ensure the seamless cooperation of System Operators and consumers, fine-tuning grid operations on local and regional scales. By establishing interoperability, TSO markets efficiently handle broad regional coordination and frequency compensation, while local flexibility markets address specific and immediate grid needs at the DSO level.

4 Consolidation of Survey Responses and Literature Research for Knowledge Base Formation

The completed questionnaires, presented in Annex B, were collected, carefully reviewed, and systematically filtered to ensure clarity and relevance. The gathered data was then analysed from multiple perspectives, with the goal of identifying and extracting the most meaningful and relevant insights for the TwinEU project. During this final stage of the process, the information was consolidated to form a solid overview, aligning with the original objectives set out for the research. This comprehensive assessment and synthesis of the collected data represent the peak of the desktop research efforts, providing a robust foundation for creating the project's KB.

4.1 Common Objectives and Focus Areas in Surveyed Projects

The initial approach for assessing and categorizing the outcomes involves identifying the core objectives of the projects and aligning them with shared focus areas. These focus areas emphasise the key criteria used in compiling the list of researched projects and provide a horizontal framework for grouping the projects and their results, ensuring that key themes and shared goals are clearly recognized and systematically addressed. This approach facilitates a more structured analysis, allowing for an inclusive understanding of how the various projects intersect and contribute to the broader objectives of TwinEU. Therefore, the focus areas comprise:

- **Providing enhanced flexibility and market participation through integrated platforms:** Summarizing the researched projects, under Task 2.1, which primarily focuses on enabling flexibility in energy systems, integrating DERs into markets, and fostering enhanced cooperation between stakeholders:
    - BeFLEXIBLE: Focuses on increasing flexibility and cooperation between TSOs, DSOs, and stakeholders.
    - XFLEX: Integrates decentralized flexibility assets into a unified platform for both local and wholesale markets.
    - CoordiNet: Demonstrates cost-efficient models for ancillary services and grid flexibility.
    - OneNet: Develops an open architecture for cross-country energy markets with a focus on flexibility.
    - Platone: Enhances flexibility through local market platforms and grid services.
    - EUniversal: Promotes flexibility solutions to integrate distributed resources across the energy system.
    - FEVER: Provides solutions for flexibility services in energy markets.
    - FlexCHESS: Focuses on the flexibility of energy storage systems for market participation.
- **Data sharing platforms and interoperability:**
  These projects primarily aim to develop platforms and standards for seamless data exchange and interoperability between different energy systems:
    - DATA CELLAR: Creates a federated energy data space to support energy communities.
    - SYNERGY: Implements a big data architecture to facilitate data sharing and analytics for grid stability.
    - BD4OPEM: Develops an open innovation marketplace with data harmonization for grid operations.

    - BD4NRG: Provides a big data analytics toolbox for optimized energy system management.
    - OneNet: Focuses on cross-platform data exchange for flexibility markets.
    - InterConnect: Implements IoT-enabled data exchange for smart grid devices.
    - INTERRFACE: Facilitates real-time cross-border energy market data exchange.
    - XFLEX: Implements data interoperability via integrated flexibility management tools and common data models (CIM, SAREF, etc.).
- **Strengthening cybersecurity and resilience of energy systems:**
  The following projects concentrate on enhancing cybersecurity and resilience, with a particular emphasis on the provision of safety to critical energy infrastructure, encompassing both cyber- and physical assets:
    - ENERGYSHIELD: Develops a cybersecurity toolkit for energy systems.
    - eFORT: Addresses grid resilience through secure technologies and real-time threat management.
    - CyberSEAS: Enhances cybersecurity for critical energy infrastructure.
    - ELECTRON: Focuses on grid resilience and cybersecurity measures.
    - SDN-MICROSENSE: Develops secure software-defined networking for microgrids.
    - OneNet: Implements network traffic monitoring and cybersecurity protocols for cross-platform data exchange.
- **Advancing grid operations, asset management and infrastructure resilience:**
  The following projects predominantly focused on enhancing the operation and management of grid assets by leveraging cutting-edge technologies, advanced data analytics, and decision-making tools. By incorporating innovations such as real-time monitoring, predictive analytics, and automated control systems, they scope in optimizing grid performance, improve efficiency, and ensure greater reliability and resilience in energy networks. Additionally, they contribute to more informed decision-making processes, enabling better long-term planning and dynamic management of grid resources:
    - Ebalance+: Enhances grid flexibility through smart-grid technologies and market mechanisms.
    - STREAM: Focuses on low-voltage grid flexibility and innovative services.
    - NEWGEN: Develops new HVDC cable solutions and monitoring systems for grid reliability.
    - AGISTIN: Optimizes energy storage systems and grid integration architectures.
    - BD4OPEM: Provides tools for grid monitoring and predictive maintenance.
    - EUniversal: Improves grid operations by integrating distributed energy resources.
    - FARCROSS: Aims to improve cross-border grid operations and optimize electricity transmission.
    - ENFLATE: Focuses on grid flexibility through innovative market services.
    - 2LiPP: Develops hybrid energy storage systems to transition power plants away from fossil fuels.
    - HVDC-wise: Focuses on advancing HVDC transmission technologies for cross-border grid resilience.
- **Promoting decarbonization and enhanced RES integration:**
  These projects principally centred on the integration of RES and the reduction of carbon emissions through innovative energy solutions. The following projects incorporate advanced technologies (e.g., smart grids, energy storage systems (ESS), and demand-response mechanisms, etc.) to promote clean energy penetration into the system:

    - PARITY: Integrates DERs into smart grid systems for optimized flexibility management and decarbonization.
    - AGISTIN: Promotes energy storage and renewable integration for grid users.
    - INTERRFACE: Facilitates renewable energy integration through cross-border data exchange.
    - INTERSTORE: Develops energy storage solutions to support renewable integration.
- **Development of innovative tools for energy services and markets:**
  These projects focus mostly on developing new tools and technologies to enhance energy services and support energy markets.
    - Platone: Provides tools for energy market services and grid flexibility.
    - OneNet: Provides tools for market participation and grid services at a European scale.
    - EUniversal: Develops tools for integrating DER into energy services.
    - BD4NRG: Provides tools for AI-based analytics and decision-making in energy markets.
    - FlexCHESS: Develops energy storage systems to provide flexibility in markets.

The most common focus area among the researched projects is indicated as the “advancing grid operations, asset management, and infrastructure resilience”, with 10 projects’ core subjects being on this domain. The next most addressed area is the “Interoperability and data sharing platforms”, with 8 projects. “Enhancing flexibility and market participation through integrated platforms” is another key area of focus, with 7 projects, while “Cybersecurity and resilience of energy systems” follows closely, with 5 projects. Lastly, “Decarbonization and RES integration” includes 4 projects. These focus areas reflect the key priorities for digital transformation in the energy sector.

Several projects emerge as cross-category initiatives, reflecting their multi-faceted approach to addressing energy system challenges. OneNet, for example, appears in multiple categories specifically featuring in four of them. This project focuses on creating an open architecture that integrates energy systems across Europe, facilitates cross-platform data exchange, enhances market participation, and ensures cybersecurity measures for data exchange, making it an all-inclusive initiative for the future of energy systems. Similarly, XFLEX falls into two categories, where it integrates decentralized energy resources into markets while ensuring interoperability via common data models, providing a unified platform for flexibility management. EUniversal also spans multiple categories. The project focuses on integrating DERs to optimize grid operations while providing tools to support energy services. BD4NRG is another versatile project, featuring in three categories, since it provides a big data analytics toolbox for system optimization while supporting advanced decision-making through AI-driven tools. Finally, BeFLEXIBLE enhances flexibility and stakeholder cooperation but also supports data interoperability by implementing platforms for data exchange and services integration, touching upon two categories.

4.2 Key Challenges and Opportunities from Literature and Survey

Digitalization is rapidly transforming the energy sector, much like many other industries. Solutions such as EVs, solar panels, and heat pumps are increasingly integrated with smart technologies that generate data and allow for remote control. By 2030, the number of active IoT devices worldwide is expected to exceed 25.4 billion, with 51% of households and SMEs in the EU already equipped with smart electricity meters. This surge in smart technology adoption presents both significant challenges and opportunities [20]. Insights from the survey results of EU surveyed projects highlight key factors essential for the sector’s successful digital transformation and assist on the further development of the project’s KB.

Key challenges include issues of interoperability, where inconsistencies in data formats and communication protocols hinder seamless integration across diverse platforms and legacy systems. Cyber-physical reliability and resilience also pose significant concerns, as increased digitalization brings new vulnerabilities and cybersecurity risks. Additionally, managing large volumes of data, ensuring data quality, and navigating complex regulatory frameworks further complicate the digitalization process.

Digitalization poses several challenges; however, considerable opportunities also arise from it. The integration of real-time monitoring, predictive maintenance, and advanced data analytics significantly enhances decision-making, improves system efficiency, and increases flexibility potential. Many projects surveyed demonstrate how flexibility markets and business cases, aligned with grid constraints, can optimize energy management. Furthermore, projects focused on standardization, adoption of smart grid technologies, and the integration of RES into the system offer significant potential to boost energy resilience and overall system performance.

4.2.1 Key challenges and opportunities identified in the literature

The current deliverable aims to analyse the evolution of the energy system in the context of digitalization at pan-EU level, while also considering the individual national cases that comprise it. The energy transition demonstrates a long series of opportunities, coming together with a wide array of challenges and risks across technical, economic, political, and societal domains, with digitalization playing a key role in this process [21]. It is becoming deeply integrated into nearly every aspect of the energy system, affecting both the demand and supply side. Core sectors such as industry, residential, and mobility are increasingly driven by innovations like the Internet of Things (IoT), smart grids, autonomous systems, and others.

The opportunities indicated across these sectors are concentrated in the following categories:

- to support for decarbonization and to improve energy system efficiency
- to enhance flexibility in energy markets
- to optimize system operation
- to create new economic sectors
- to assist in managing the complexities of decentralized energy systems

However, it also brings complexities into energy system planning and operation [22]. These are defined as challenges that arise across various sectors and are generally concentrated in the following core categories:

- decentralization of energy systems
- increased electricity demand to support digital infrastructure
- heightened cyber risks and threats to data privacy
- multitude of different standards, infrastructure and policies across the EU
- potential disruptions in labour markets

In this chapter, comprehensive systemic literature research has been conducted in order to gather and assemble insights in the opportunities and challenges comprising the digitalization part of the energy transition.

The EU has launched an action plan for digitalizing the energy system in 2022 to promote connectivity and interoperability, foster coordinated investments in smart grid technologies, empower customers, enhance cyber security, promote greater efficiency, and design effective governance through joint planning [7].

The transformation of the EU energy system to its future version is primarily based on digital solutions such as artificial intelligence (AI), advanced data analytics, the Internet of Things (IoT), machine learning (ML), and the digital twin technologies (DT), presenting significant opportunities to enhance efficiency in handling the increasing complexity of the energy landscape [23]. The digital technologies are applied across the entire energy supply chain, extending from infrastructure design and operational management to energy production, distribution, and consumption, enabling more effective planning, maintenance, and system optimization.

In the context of digital transformation, the key medium for innovation is considered the seamless streams of data, which need to be shared unimpededly, and flow efficiently across the network. Through the utilization of real-time big data for advanced analytics, digitalization succeeds in accessing and valorising detailed energy-related information (consumption, production, storage, weather data, etc.) and grid performance insight [24].

Secure, efficient, and seamless data sharing benefits a wide range of stakeholders in the energy ecosystem, including suppliers, infrastructure operators, energy service providers, and consumers. This data exchange supports and powers the digital solutions that are driving innovation and optimization within the system.

Digitalization presents significant opportunities, allowing for the implementation of demand-response mechanisms, where energy consumption can be adjusted based on real-time price signals, reducing peak load pressures to the grid, enhancing grid-resilience, providing predictive maintenance, and facilitating the efficient integration of RESs to the system [25].

As digitalization and particularly the digital twin technology grows across various industries, it is enhancing operations and contributing to the broader goals of Industry 4.0 concept [26]. According to literature, the energy sector valorises a lot of benefits from digitalization and the digital twins, seeking to optimize value chains across the overall sector, offering a range of benefits for future development and management [27]. With power systems becoming increasingly complex, digital tools are vital for asset optimization across the sector, from maintenance and production planning to plant efficiency and risk management.

One of the most critical applications of digitalization in energy is simulating the conditions of the grid. This is achieved via the valorisation of DTs, which exploit real-time data, providing the potential for instantaneous management and alleviates grid congestion through suggested reroutes or load adjustments [28]. The literature review indicates that digital twins allow for tuning parameters of Special Protection & Control (P&C) schemes based on several variables, enhancing reliability and reducing blackout risks. Through this technology, the opportunity for a risk-free environment for decision-making can be developed, enabling stakeholders to simulate and implement strategies without impacting the physical grid.

Digital technologies offer the opportunity to optimize maintenance by predicting potential failures and proactively scheduling preventive actions, thereby maintaining grid stability. Continuous updates with real-time data (associated with weather info, remedial issues, etc.) enable monitoring of assets' conditions, scheduling necessary maintenance activities, and predicting failures before they occur. Furthermore, digital twins can forecast power flow changes caused by fluctuations in renewable energy output and demand, assisting on the integration of RES into the system. Additionally, by simulating the impact of renewable energy on the grid, the digital twin technology enables faster commissioning of RES.

Through inertia monitoring, power flow forecasting, and security analysis, digital technologies help assess grid stability and optimize grid topology for future growth, while also offering decision-support capabilities by identifying mitigation actions to address vulnerabilities and optimize operational planning [29].

Digitalization supports the decentralization of energy systems, enabling more efficient monitoring and control of distributed assets, leading to enhanced grid flexibility, resilience, ensuring a balanced energy supply and demand [30]. By analysing data from smart grid technologies, stakeholders can make informed decisions, reduce operational costs, and enhance grid resilience.

Digitalization opens new opportunities for consumer engagement and market integration, since smart meters and connected devices give consumers real-time insights into their energy consumption, enabling them to participate in demand-response programs, and thus elevating them to prosumers. Moreover, digital platforms that support dynamic pricing and peer-to-peer energy trading foster competition and efficiency in the energy market.

In addition to operational benefits, digitalization through digital twins can provide a virtual environment for stakeholder involvement, enhancing transparency and collaboration. Through implementing aspects such as cyber-security analysis, supply chain management, and financial optimization, digitalization further contributes to the robust management of the future energy systems.

The opportunities delivered by digitalization come together with significant challenges that must be addressed to fully realize their potential.

A major challenge identified in the literature is the lack of standardization across energy systems and digital platforms [31], fitting also with. The integration of diverse energy assets is hindered by the absence of common communication protocols and data formats, resulting in data silos that do not efficiently exchange information, complicating efforts to optimize the energy grid. Interoperability is crucial for the seamless operation of interconnected devices and digital solutions, but current technologies and frameworks lack unified interoperability standards, making large-scale integration difficult [32]. In addition, it is evident that no or very low attention has been given to data and model interoperability dimensions, making the energy stakeholders highly reluctant to share data due to regulatory and/or organizational/humans and security constraints.

As digitalization expands and the use of digital technologies increases, the risks related to cybersecurity and data privacy also grow. The energy sector, with its increasing reliance on digital (smart) devices, faces growing vulnerabilities to cyberattacks. Malware, Distributed Denial of Service (DDoS) attacks, and data breaches could significantly disrupt energy systems, as critical assets are exposed to cyber threats. Moreover, the vast amounts of data collected from digital devices to be used in digital twins and other technologies require strict data protection measures [33].

Another challenge is the integration of advanced digital tools with existing legacy systems, since many energy infrastructures rely on older technologies that were not designed to interface with modern digital solutions [34]. The process of upgrading or replacing these systems can be costly, time-consuming, and prone to operational disruptions. Industries that face difficulties in aligning their outdated equipment with new technologies are likely to encounter barriers to achieving full digital transformation. While energy operators have implemented digital models of individual and system-level assets to gain insights into their infrastructure's behaviours and performance, real-time synchronization between digital models and physical assets remains lacking. The current state of the art operates as an "open loop" system, where data flows unidirectionally from the physical asset to the digital model without influencing real-time operations.

The growing complexity of energy systems, especially with the integration of DERs, smart devices, and digital twins, has resulted in an enormous entry of real-time big data. Current infrastructure often lacks the capacity to manage and process these large volumes of data efficiently, leading to issues with data latency and limited scalability. Real-time monitoring is crucial for utilizing digital solutions and particularly digital twins, optimizing grid performance and preventing outages, but inconsistent data formats and slow processing times continue to hinder its effectiveness.

The digitalization of the European energy sector presents significant opportunities while also posing challenges too. It plays a pivotal role in optimizing energy efficiency, reducing waste, and driving decarbonization efforts across the EU. This transformation is expected to positively influence the EUs' core market sectors, including the residential (representing about 26% of EU's final energy consumption in 2022, and one-third of global energy consumption), the industrial (constituting 25% of the final energy consumption in EU in 2022 [35]), the services (accounts for 13.4%), the transportation sector (being the most intense one, accounting for 31% of final energy consumption in EU in 2022 [36]). According to the revised EED [37]**Error! Reference source not found.**, the goal is to reduce the EU's energy consumption by 11.7% by 2030, based on a 2020 reference scenario.

The opposite side of the dual aspect of digitalization associates with the challenges that could be raised in these market sectors, that are matching with the hinders indicated previously.

Figure 4: Digitalization potential on transport, buildings, and industries

The potential of key technologies associated with the digitalization of the different market sectors of EU, can be seen in a summarizing view in Figure 4. The figure provided by IEA [38] takes into consideration the transformative potential of digital technologies in the sectors, while it also reflects the significance and impact of the barriers that may impede the path toward full digitalization.

4.2.2 Key common challenges indicated in the surveyed projects

After reviewing the scientific literature surrounding the theme of challenges and opportunities in energy digitalization, this chapter focuses on the responses gathered by the survey tool. The survey question 14 (A.14) specifically designed to identify challenges anticipated in the implementation of project solutions played a crucial role in extracting the most commonly encountered ones. An analysis and review of the results in Annex B revealed the following key challenges that were mostly identified as hinders to the implementation of the projects' proposed solutions. They are also presented in a hierarchical structure, starting from the most commonly reported in the survey, to the least frequently mentioned:

- Ch1: The challenge of **data privacy and security** is the most commonly identified challenge extracted from the projects' answers**.**

  A significant concern in eight projects, including CyberSEAS, DATA CELLAR, SYNERGY, ENERGYSHIELD, FEVER, EUniversal, INTERSTORE, and ELECTRON.

  Description: As energy systems become increasingly digitalized, protecting sensitive data and ensuring compliance with regulations are vital. The risk of cyberattacks and data breaches grows with the increased connectivity of systems, requiring advanced cybersecurity measures. Projects dealing with smart grids, real-time data exchange, and IoT devices emphasize the critical need to safeguard data privacy and security, with some proposing specific measures like homomorphic encryption, or intrusion detection systems. Furthermore, the consumer related data generated by IoT devices and smart meters should be well safeguarded to diminish ethical and legal concerns of misuse against the wide public, an element will be highlighted in data space projects for energy communities i.e. DATA CELLAR. These consumer data privacy measures will also remove any reservations they may have about adopting IoT technologies, data sharing platforms and participation in flexibility provision.

- Ch2: The challenge of **technological complexity**:

  This challenge is raised by seven projects, including DATA CELLAR, CyberSEAS, FEVER, FLEXCHESS, INTERSTORE, HVDC-Wise, OneNet, and SYNERGY.

  Description: Managing the technical complexity of integrating various energy systems, particularly legacy infrastructure, poses a significant challenge, therefore, projects working with smart grid technologies, IoT, and data platforms face difficulties in ensuring real-time communication and coordination between the diverse systems. Ensuring compatibility across different types of hardware, software, and communication protocols is an ongoing issue, especially in projects that aim to integrate advanced sensors and control mechanisms.

- Ch3: The challenge of **interoperability and standardization**:

  This interoperability challenge is mentioned by five projects, including DATA CELLAR, XFLEX, OneNet, INTERSTORE, and INT:NET.

  Description: The primary issue is achieving seamless integration between different systems and platforms, which is intensified by the previous challenge, including not consistent data formats, communication protocols, and gaps in existing standards (such as CIM [39], SAREF [40], and IEC 61850 [41]). The need for harmonization and standardization is a recurring theme in the surveyed projects, as it is critical for achieving functional and efficient energy systems.

- Ch4: **Regulatory and policy barriers**-related challenges**:**

This challenge is cited by five projects including DATA CELLAR, SYNERGY, INTERCONNECT, FlexCHESS, and INTERRFACE.

Description: Projects report difficulties in navigating the regulatory landscape, especially when it comes to introducing new technologies and energy market innovations. The existing differences in regulations across the EU countries, the slow adaptation of policies, and the compliance with privacy and cybersecurity standards are indicated as common obstacles. Projects working on flexibility markets or smart grid technologies often face challenges aligning their innovative approaches with existing regulations, requiring a push for regulatory reform and harmonization across regions.

- Ch5: The challenge linked with **market acceptance and stakeholder engagement/collaboration**:

  This challenge is noted by five projects including DATA CELLAR, SYNERGY, Platone, CyberSEAS, INTERRFACE.

  Description: A challenge that is faced by these projects is related to gaining market acceptance for new technologies and flexibility markets. Coordinating efforts across multiple stakeholders, engaging consumers, prosumers, and market actors to participate in new energy models often requires considerable educational efforts and incentives, as well as clear communication about the benefits. Inducting workshops, training programs, and targeted outreach are frequently necessary to build understanding and drive participation. Additionally, coordinating across a diverse set of stakeholders, including TSOs, DSOs, regulators, and consumers, can be complex and time-consuming. Establishing effective communication channels, setting common goals, and ensuring smooth collaboration are crucial for the success of large-scale, cross-country EU projects, where seamless stakeholder cooperation is essential.

- Ch6**:** The challenge associated with **investment costs:**

  This challenge is highlighted by two projects which are DATA CELLAR, and FlexCHESS.

  Description: High initial costs for deploying digital technologies, upgrading existing infrastructure, and supporting new energy systems are common concerns, and securing adequate long-term financial resources for large-scale implementation is a recurring issue. The uncertainty around return on investment for digital technologies also acts as a barrier, particularly for smaller energy providers.

Summarizing, **interoperability and standardization** are the most commonly identified challenges in the survey, followed closely by **data privacy and security** and **regulatory barriers**. These challenges must be addressed through technological innovation, regulatory reform, and enhanced stakeholder engagement to ensure the successful digital transformation of the European energy sector.

Table 1 below, is created to offer a clear, concise summary of the challenges identified in the surveyed projects, providing an easy-to-read and reference format.

Project	Ch1	Ch2	Ch3	Ch4	Ch5	Ch6
BeFLEXIBLE						

DATA CELLAR	✓	✓	✓	✓	✓	✓
Ebalance+						
eFORT						
PARITY						
STREAM						
SYNERGY	✓	✓		✓	✓	
XFLEX			✓			
CoordiNet						
ENERGYSHIELD	✓					
NEWGEN						
AGISTIN						
BD4OPEM						
EDDIE						
BD4NRG						
OneNet		✓	✓			
Platone					✓	
InterConnect				✓		
EUniversal	✓					
HVDC-wise		✓				
FARCROSS						
ENFLATE						
int:net			✓			
SDN-MICROSENSE						
CyberSEAS	✓	✓			✓	
ELECTRON	✓					
FEVER	✓	✓				
FlexCHESS		✓		✓		✓
INTERRFACE				✓	✓	
INTERSTORE	✓	✓	✓			

Table 1: List of challenges identified per surveyed project

4.2.3 Key common opportunities indicated in the surveyed projects

The survey question (A.13), which is specifically designed to indicate the opportunities delivered by the proposals developed within the surveyed projects, focuses on (i) how to improve the business processes (system planning/asset management, system operation, energy markets) efficiency, while (ii) facilitating the flexibility and resilience of the EU energy system. Q13 is specifically designed to gather the opportunities defined in the answers to the survey tool and is considered of great importance to form a complete image of the solutions that the projects bring via digitalization.

An analysis and review of the results in Annex B revealed the following opportunities, which are presented hierarchically, starting from the most commonly defined in the survey answers, to the least frequently mentioned:

- Opp1: **Leveraging advanced technologies for achieving decarbonization** is the most commonly recognized opportunity:

This opportunity is noted by the analysis of fifteen projects, including BeFLEXIBLE, DATA CELLAR, SYNERGY, XFLEX, BD4OPEM, BD4NRG, OneNet, INTERCONNECT, EUniversal, INT:NET, CyberSEAS, FEVER, FlexCHESS, INTERRFACE, and INTERSTORE.

Description: Enhanced decision-making, predictive maintenance, and system optimization is enhanced by the advanced technologies developed (or being developed) by the surveyed projects. Via providing real-time data analytics, automation, and efficient management of DERs they accelerate digitalization of the systems, and contribute to the development of more adaptive, intelligent, and resilient energy grid infrastructure.

- Opp2: Delivery of **improved data exchange and interoperability**:

  This opportunity is identified in fourteen projects, including XFLEX, BD4OPEM, PARITY, BD4NRG, OneNet, Platone, INTERCONNECT, EUniversal, INT:NET, CyberSEAS, DATA CELLAR, FlexCHESS, INTERRFACE, and INTERSTORE.

  Description: Ensuring interoperability among different systems and stakeholders is a recurring theme, with projects highlighting the importance of standardized data models and communication protocols that assist in enabling the efficient integration of new energy solutions and services. Improved data exchange also promotes greater grid visibility, market participation, and collaborative efforts among energy actors, driving smoother and more coordinated energy management.

- Opp3: The **real-time monitoring and control** opportunity:

  This opportunity is noted by thirteen projects, including DATA CELLAR, SYNERGY, XFLEX, BD4OPEM, OneNet, INTERCONNECT, EUniversal, INT:NET, CyberSEAS, FEVER, FlexCHESS, INTERRFACE, and INTERSTORE.

  Description: Implementation of real-time monitoring enhances system stability and operational flexibility. This is achieved via enabling continuous data monitoring and automated/assisted decision-making processes. Therefore, optimizing grid operations, allows for faster detection of issues and dynamic responses to fluctuations in supply and demand. This capability enables energy systems becoming more adaptive and resilient, particularly in managing RES penetration and addressing the constantly growing energy demand.

- Opp4: The opportunity of revolutionizing **cybersecurity and data privacy** levels:

  It is highlighted by twelve projects, including CyberSEAS, DATA CELLAR, EDDIE, eFORT, Platone, BD4OPEM, INTERCONNECT, ENERGYSIELD, OneNet, ELECTRON, SDN-MICROSENSE, and INT:NET.

  Description: With the increasing reliance on digital systems and IoT devices, ensuring robust cybersecurity and data privacy is considered of high significance. These projects clearly identify the need to protect sensitive data, ensure compliance with regulations at cross-national level (such as GDPR, ENISA, etc.), while also considering national level (with national cybersecurity authorities, etc.), and developing cybersecurity measures to safeguard against emerging threats.

- Opp5: The provision of **flexibility services and demand-response mechanisms**:

  This opportunity is found across ten projects, BeFLEXIBLE, DATA CELLAR, SYNERGY, BD4OPEM, OneNet, Platone, INTERCONNECT, EUniversal, INT:NET, and FEVER.

  Description: Flexibility services, such as demand-response and the management of DERs and storage systems, highlight significant opportunities enabled by digitalization, delivering effective reduction of peak loads, enhanced energy efficiency across various sectors, effectively managing storage and DERs, while providing real-time flexibility management.

- Opp6: The opportunity to develop and employ **enhanced market mechanisms**:

  This opportunity is considered by nine projects, cited by DATA CELLAR, SYNERGY, EDDIE, BD4NRG, EUniversal, INTERCONNECT, FEVER, FlexCHESS, and Platone.

  Description: Several projects highlight the opportunity to develop enhanced market mechanisms, including dynamic pricing, increased transparency, and greater participation in flexibility markets. The scope of the market mechanisms is to foster competition, promote efficient energy use, encourage both explicit and implicit flexibility mechanisms with concrete pricing structure, and support the integration of RES into the system. This is planned to be achieved by enabling more actors to participate in energy markets (regional and cross-regional).

- Opp7: The opportunity delivered by **new business models (BMs) for flexibility provision**:

  There are six projects demonstrating this opportunity, including BeFLEXIBLE, BD4OPEM, EUniversal, FEVER, INTERCONNECT, and Platone.

  Description: The new BMs support the management of DERs, energy storage, smart home technologies, and flexible pricing strategies, and aim at optimizing energy usage and reducing costs for consumers. BMs also focus on cross-sector opportunities, including EV charging, energy storage-as-a-service (SaaS), and smart home solutions, which provide flexibility, while enhancing consumer engagement.

- Opp8: Promoting **collaboration and stakeholder engagement**:

  This opportunity is highlighted by six projects, which are SYNERGY, OneNet, Platone, INTERCONNECT, INT:NET, and EUniversal.

  Description: It is considered of high significance for the successful implementation of new energy models to encourage collaboration among stakeholders, including TSOs, DSOs, consumers, and regulators. The surveyed projects identify the need for effective communication channels, shared goals, and collaborative efforts to align stakeholders and ensure smooth operations. Stakeholder engagement also plays a role in promoting the adoption of new technologies and fostering trust in innovative energy solutions.

- Opp9: The opportunity for **cross-sector and cross-country integration** of the solutions:

This opportunity is noted by five projects, which are SYNERGY, OneNet, BD4NRG, INTERCONNECT, and INT:NET.

Description: Cross-sector and cross-country integration is emphasized as an opportunity for creating more coordinated and comprehensive energy management systems. By facilitating the sharing of solutions and technologies across sectors (such as transport, healthcare, and residential), projects are able to leverage synergies and promote the widespread adoption of digital energy solutions. Additionally, cross-country collaboration supports the standardization and replication of solutions at an EU scale.

- Opp10: The potential for **standardization and regulatory support** extending to the digitalization:

  This opportunity is displayed in four projects, this are XFLEX, BD4NRG, INTERCONNECT, and INT:NET.

  Description: Standardization of data models, communication protocols, and regulatory frameworks is seen as a key opportunity for scaling digital energy solutions across the EU. By promoting standardization and compliance with regulations such as GDPR and EU-wide data spaces, projects can ensure consistent implementation of new technologies, reduce integration costs, and support the replicability of energy solutions across different regions and sectors.

In summary, the most frequently identified opportunity across the surveyed projects is the **utilization of advanced technologies to drive decarbonization efforts**. This trend highlights the key role of innovation in achieving cleaner energy systems. Closely following are opportunities related to **real-time monitoring and control**, which enable more efficient and responsive grid management. Additionally, the potential to improve **interoperability across systems** is another significant opportunity, emphasizing the importance of seamless communication between diverse energy technologies to enhance overall system performance and integration.

Table 2 is shaped for a clear summary of the opportunities occurred in the surveyed projects, providing an easy-to-read and reference format.

Project	Opp1	Opp2	Opp3	Opp4	Opp5	Opp6	Opp7	Opp8	Opp9	Opp1
BeFLEXIBLE	✓				✓		✓			
DATA CELLAR	✓	✓	✓	✓	✓	✓				
Ebalance+										
eFORT				✓						
PARITY		✓								
STREAM										
SYNERGY	✓		✓		✓	✓		✓	✓	
XFLEX	✓	✓	✓							✓
CoordiNet										
ENERGYSHIELD				✓						
NEWGEN										
AGISTIN										
BD4OPEM	✓	✓	✓	✓	✓		✓			

EDDIE				✓		✓				
BD4NRG	✓	✓				✓			✓	✓
OneNet	✓	✓	✓	✓	✓			✓	✓	
Platone		✓		✓	✓	✓	✓	✓		
InterConnect	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
EUniversal	✓	✓	✓		✓	✓	✓	✓		
HVDC-wise										
FARCROSS										
ENFLATE										
int:net	✓	✓	✓	✓	✓			✓	✓	✓
SDN-				✓						
CyberSEAS	✓	✓	✓	✓						
ELECTRON				✓						
FEVER	✓		✓		✓	✓	✓			
FlexCHESS	✓	✓	✓			✓				
INTERRFACE	✓	✓	✓							
INTERSTORE	✓	✓	✓							

Table 2: List of opportunities identified per surveyed project

5 High-impact factors identified

Chapter 5 focuses on the key factors that bear a significant impact on the digitalization and modernization of energy systems, as identified across the surveyed projects. Through detailed analysis, several critical gaps and opportunities have been highlighted, spanning data exchange, cyber-physical infrastructures, system planning, grid operation, and energy market integration. Each sub-chapter dives into a specific aspect of these encounters, providing in-depth insights and indicating potential solutions for bridging. The aim is to offer a comprehensive understanding of the high-impact factors that influence the successful digital transformation of the energy sector.

5.1 Analysis of data exchange gaps and proposed solutions

To evaluate the high impact factor of data exchange, while working towards populating the content of the project's KB, the two-way stream illustrated in Figure 1 is implemented as well. The paths include the (i) systemic desktop research that is conducted to concentrate the literature-based content, and the (ii) targeted set of questions that were addressed by the surveyed projects.

5.1.1 Data exchange gaps identified in the literature

As the economic and strategic benefits of data sharing gain increasing recognition, it is becoming a global movement to encourage the integration, openness, and exchange of data across the various sectors and industries. This trend is driving the transformation of traditional sectors, encouraging deeper collaboration between industries, and enhancing social service management. The gaps in data exchange under the digitalization of the energy sector are gathered and presented through a desktop systemic literature review.

Key gaps in data exchange hinder the full realization of the opportunities indicated in Table 3. As outlined in these sections of the deliverable, the primary challenges identified relate to two main categories, the gaps in interoperability and cybersecurity. These gaps are linked to the diverse communication protocols and standards valorised across energy systems, DERs, smart grids, and traditional energy infrastructure. The gaps in standardization-lacking create data silos and limit the ability to integrate systems seamlessly across the grid. The literature research [42] highlights the same two gaps-categories as the most identified ones, indicating that without harmonized communication interfaces, integrating emerging technologies into the broader energy ecosystem becomes difficult.

Another key gap commonly indicated in literature is the difficulty in integrating heterogeneous data sources. Since the energy sector increasingly relies on real-time data from sensors, smart-meters, and other IoT devices, merging this data across different systems remains problematic, as data is often inconsistent, or incompatible. This gap is particularly definite in decentralized energy systems, where data integration is critical for optimizing operations but often falls short due to differing time scales, data formats, and communication technologies [30]. As a result, while digital platforms can gather massive amounts of information, the inability to effectively merge and interpret this data hinders the optimization of energy flows and demand forecasting.

Data privacy and security concerns are another significant gap identified in the literature [21]. The increased data sharing across multiple platforms and stakeholders, ranging from utility operators to consumers, makes cybersecurity risks more evident. In that perspective, the lack of robust cybersecurity frameworks has been identified as a major gap limiting the trust required for widespread data exchange and digitalization.

Efficiently processing and analysing real-time data is essential for dynamic grid management, especially with the increasing penetration of intermittent RES, like wind and solar power. Processing real-time and large volumes of data to achieve scalability is proving to be a challenge.

Finally**, regulatory barriers and market fragmentation** worsen the gaps of data exchange. The lack of comprehensive regulatory frameworks that mandate or incentivize data sharing across market participants is not unified in cross-country level, leading to fragmented digital ecosystems, where data is either proprietary or inadequately accessible, thereby limiting collaboration and the integration of advanced digital solutions.

In the context of addressing the regulatory barriers, the EU DSO is working jointly with ENTSO-E to define standards in specific domains of digitalization, such as smart meters and demand-response (e.g., through the Network code on Demand Response and its implementing regulation). Therefore, forming an extended, horizontal profile of standardization in these areas.

5.1.2 Data exchange gaps identified in the surveyed projects

The questions from the T2.1 research questionnaire addressing this issue can be categorized into two groups: those aimed at identifying existing gaps under the questions Q8 (A.8), Q10 (A.10), and Q11 (A.11); and Q12 (A.12), which specifically focused on the solutions provided, developed, and implemented by the projects to address and bridge these gaps. An analysis of the review of the results (as outlined in Annex B) revealed the following categories of gaps, which are presented in a hierarchical display, starting from the most commonly reported in the survey, to the least frequently mentioned:

- Gap1**: Inconsistencies indicated in data formats** among systems and devices
  This type of gap in data exchange is identified in eleven projects, including DATA CELLAR, eFORT, PARITY, SYNERGY, Platone, INTERCONNECT, EUniversal, INT:NET, CyberSEAS, ELECTRON, and FEVER.

  Description: The most commonly occurred gap in data exchange is indicated in the lack of consistent data formats across systems and devices, which hinders seamless integration of the proposed solutions. Different databases, platforms, and systems use varying data schemas, which results in difficulties when aggregating or analysing the data. This inconsistency requires standardization across data formats to facilitate effective data exchange.

- Gap2**:** The gaps in **information models**

  Identified by ten projects, indicated in DATA CELLAR, eFORT, PARITY, SYNERGY, Platone, INTERCONNECT, EUniversal, CyberSEAS, FEVER, and FlexCHESS.

  Description: The projects implementing CIM lack the proper documentation of use cases and the assessment on whether such information model satisfies them. For readers' facilitation purposes, as common information model (CIM) [39] is considered the definition provided by ENTSO-E [2] regarding grid model data exchange, defining that "The CIM for grid model exchange enables exchanges for the data necessary for regional or pan-European grid development studies, and for future processes related to network codes" [43]. The communication channels and feedback loops for implementers to contact actors defining the standardized information models in the energy industry like the CIM need to be strengthen and disseminated. The projects demonstrating this type of issue report gaps in how different systems represent data, leading to interoperability issues that could be solved by increasing collaboration initiatives such as the organization of interoperability (IOP) tests and hackathons. In some cases, the metadata is not correctly represented in the information model (i.e., description of relevant classes and attributes, use of linked data technologies, etc.), thus leading implementers to rely on side, non-standardized technical specifications.

- Gap3: The gaps indicated with **communication protocols:**

  This gap is identified in ten projects, noted by DATA CELLAR, eFORT, PARITY, SYNERGY, Platone, CyberSEAS, ELECTRON, FEVER, FlexCHESS, and INTERRFACE.

  Description: Communication protocols refer to a "set of rules and procedures that govern the exchange of data between smart devices, including technologies that demonstrate their own transmission range and considerations based on the deployment environment". Communication protocols vary widely across systems, with legacy systems still relying on outdated or proprietary protocols, posing inconsistencies regarding real-time data exchange, which is critical for dynamic decision-making and system responsiveness. The projects point out the need for standardized and more robust protocols to manage modern energy systems' real-time data demands effectively [44].

- Gap4: The gaps associated with **interoperability**:

  Identified by the nine projects, DATA CELLAR, SYNERGY, PARITY, Platone, INT:NET, EUniversal, CyberSEAS, FEVER, and FlexCHESS.

  Description: Interoperability remains a major challenge across different systems and databases due to variations in data formats, information models, and communication protocols. The need for common standards and a unified approach to data exchange is emphasizing the gaps in semantic and technical interoperability preventing the smooth integration of data, especially across energy actors like TSOs, DSOs, and consumers.

- Gap5: The gaps related to **semantics**:

  This gap category is identified by six projects, including DATA CELLAR, SYNERGY, INTERCONNECT, INT:NET, CyberSEAS, and Platone.

  Description: Semantic interoperability refers to ensuring that different systems understand and interpret data in the same way. Projects frequently point out the lack of alignment between different ontologies and data structures, which creates a need for mapping and harmonizing ontologies across platforms to enable meaningful data exchange.

- Gap6: Gaps related to **security and privacy protocol** in data exchange:

  Identified by five projects in the survey, PARITY, SYNERGY, CyberSEAS, ELECTRON, and FEVER.

  Description: The increasing complexity of energy systems and the introduction of more connected devices, security and privacy protocols are often lacking, or insufficiently implemented. The projects emphasize the importance of robust security frameworks to protect sensitive data and ensure compliance with privacy regulations like GDPR.

- Gap7: Limitations regarding **real-time data exchange:**

  This gap is identified by five projects, including SYNERGY, Platone, CyberSEAS, FEVER, and FlexCHESS.

  Description: Real-time data exchange is crucial for effective grid management and flexibility services; the above projects identify a lack of infrastructure to support this issue. Without real-time capabilities, energy systems cannot respond swiftly to changes in demand, limiting their ability to ensure grid stability and optimize energy resources.

- Gap8: Discrepancies associated with **data granularity**:

  Identified by two projects, which are PARITY, and SYNERGY.

  Description: Data is collected at various levels of granularity across devices and systems, which creates challenges in aggregation and analysis. These discrepancies make it difficult to perform accurate and comprehensive decision-making processes, as some systems may collect more detailed data than others, leading to inconsistent insights.

Table 3 is developed to present a clear and summarizing view of the gaps that are identified in the survey.

Project	Gap01	Gap02	Gap03	Gap04	Gap05	Gap06	Gap07	Gap08
DATA CELLAR	✓	✓	✓	✓	✓			
eFORT	✓	✓	✓					
PARITY	✓	✓	✓	✓		✓		✓
SYNERGY	✓	✓	✓	✓	✓	✓	✓	✓
Platone	✓	✓	✓	✓	✓		✓	
InterConnect	✓	✓			✓			
EUniversal	✓	✓		✓				
int:net	✓			✓	✓			
CyberSEAS	✓	✓	✓	✓	✓	✓	✓	
ELECTRON	✓		✓			✓		
FEVER	✓	✓	✓	✓		✓	✓	
FlexCHESS		✓	✓	✓			✓	
INTERRFACE			✓					

Table 3: List of Gaps identified per surveyed project

5.1.3 Data exchange solutions

Based on the responses to Q12 (A.12) of the survey regarding solutions to the identified data exchange gaps, the following list of solutions are structured. The most commonly occurred ones are presented in a hierarchical order, ranked by frequency and accompanied by detailed project-specific information:

- Sol1**:** Adoption of **merged standards for data exchange**:

Identified by fourteen projects, including SYNERGY, XFLEX, BD4OPEM, BD4NRG, OneNet, Platone, InterConnect, EUniversal, INT:NET, CyberSEAS, ELECTRON, FEVER, FlexCHESS, and INTERRFACE.

Description: These projects proposed merging and adopting industry standards such as CIM, DCAT, USEF/UFTP, and SAREF. These standards help ensure consistent data formats, improve semantic interoperability, and facilitate smooth integration across energy systems. For example, an extension of the CIM model is used to cover battery systems, pan-European regional coordination process (such as security analysis or capacity calculation), PV systems, CHP, P2G, and P2H systems, while adoption of SAREF models and semantic technologies in energy devices and appliances is leverages as well.

- Sol2: Proposal for **developing interfaces and adapters for TSO/DSO and customer integration**:

  Identified in thirteen projects, SYNERGY, XFLEX, BD4OPEM, BD4NRG, OneNet, Platone, EUniversal, INT:NET, CyberSEAS, ELECTRON, FEVER, FlexCHESS, and INTERRFACE.

  Description: The projects deliver the proposal for creating new interfaces and adapters to enhance real-time data exchange and better integrate TSOs, DSOs, and customers. These interfaces will enable seamless participation in demand-response programs, flexibility services, and grid coordination. In this context, a middleware solution could be developed to enable real-time coordination between TSOs, DSOs, and customers. While data exchange specifications for boundary points between TSO and DSO data models already exist, they should be further enhanced.

- Sol3: Implementation of **cross-sector and cross-border integration in reference architectures**:

  This type of solution was considered in twelve projects, SYNERGY, XFLEX, BD4NRG, OneNet, Platone, EUniversal, INT:NET, CyberSEAS, ELECTRON, FEVER, FlexCHESS, and INTERRFACE.

  Description: Integrating solutions to enhance system flexibility and scalability of cross-sector and cross-border components into reference architectures is a common practice in these projects. Some projects focus on cross-border data exchange and cross-sector analytics to enhance grid flexibility and resilience, while others organized interoperability tests and Network Code profiles CIM extension for Regional Coordination processes (e.g., CGMES v3.0 and the “Network Code Profiles” extension to the CIM to harmonize energy services across Europe, helping stakeholders align with cross-sector needs.

- Sol4: Developing enhanced **real-time data exchange with low-latency communication protocols**:

  There are seven projects demonstrating this solution, including SYNERGY, XFLEX, EUniversal, FEVER, FlexCHESS, INTERRFACE, CyberSEAS.

  Description: These projects aim to improve real-time data exchange by developing low-latency communication protocols and enhancing real-time processing tools. These tools are essential for flexibility services, grid balancing, and immediate response to grid need. Solutions for low-latency communication protocols to improve real-time coordination are designed and implemented. A solution for high-performance data processing tools to enhance real-time data exchange for grid operations was presented as well.

- Sol5**: Modernization** and **standardization** of energy infrastructure and IT platforms:

  This solution was demonstrated by five projects in the survey, which are BD4NRG, OneNet, INT:NET, ELECTRON, and InterConnect.

  Description: Modernizing energy infrastructures and standardizing IT platforms are seen as critical factors for accelerating the creation of efficient flexibility systems. There are solutions emphasizing the importance of standardizing energy platforms and infrastructure to ensure compatibility and promote the scalability of flexibility services, while other project promotes the use of standard frameworks to ensure alignment between energy system upgrades and IT improvements. As reference of already existing energy platforms: The European energy platforms Picasso [45], Mari [46], TERRE [47], and the ENTSO-E Transparency Platform [48] serve as prime examples of Cross-Border Energy Data Sharing Platforms, facilitating efficient coordination and data exchange across national borders to ensure the stability and optimization of the electricity grid.

- Sol6: Proposal for enhanced cybersecurity measures APIs and Middleware solutions for the optimal integration of legacy systems:

  There are four projects with this solution, which are SYNERGY, BD4OPEM, XFLEX, and Platone.

  Description: The above projects recognize the challenges of integrating legacy systems with modern data management tools and propose middleware solutions or APIs to bridge the gap. Middleware solutions are introduced as solutions to integrate legacy systems into the modern data architecture, ensuring that older systems can still contribute to flexibility services. Others developed APIs to connect DSOs with consumers and ensure legacy systems' compatibility with modern platforms.

A summary of the solutions for the identified gaps is presented in Table 4 below. This table provides a comprehensive overview of the proposed solutions.

Project	Sol1	Sol2	Sol3	Sol4	Sol5	Sol6
BeFLEXIBLE						
DATA CELLAR						
Ebalance+						
eFORT						
PARITY						
STREAM						
SYNERGY	✓	✓	✓	✓		✓
XFLEX	✓	✓	✓	✓		✓
CoordiNet						
ENERGYSHIELD						
NEWGEN						

AGISTIN						
BD4OPEM	✓	✓				✓
EDDIE						
BD4NRG	✓	✓	✓		✓	
OneNet	✓	✓	✓		✓	
Platone	✓	✓	✓			✓
InterConnect	✓				✓	
EUniversal	✓	✓	✓	✓		
HVDC-wise						
FARCROSS						
ENFLATE						
int:net	✓	✓	✓		✓	
SDN-MICROSENSE						
CyberSEAS	✓	✓	✓	✓		
ELECTRON	✓	✓	✓		✓	
FEVER	✓	✓	✓	✓		
FlexCHESS	✓	✓	✓	✓		
INTERRFACE	✓	✓	✓	✓		
INTERSTORE						

Table 4: List of Solutions to the gaps identified per surveyed project

A comparison between the literature review and the surveyed projects, reveals a strong alignment in identifying data exchange gaps as a high impact factor in the digitalization of the energy sector. Both analyses highlight interoperability, standardization, and data integration as critical barriers that hinder the full realization of digital energy systems.

The literature emphasizes the need of addressing gaps in interoperability and standardization due to diverse communication protocols and data formats across energy systems, DERs, and traditional infrastructure. Similarly, the surveyed projects confirm these issues, reporting difficulties in achieving consistent data formats and information models, leading to fragmented systems. Both sources advocate for adopting industry-wide standards (i.e., CIM, DCAT, SAREF, SHACL, etc.) to facilitate seamless data exchange.

Inconsistent data formats, timescales, and communication technologies complicate data merging and hinder optimization. Both the literature and the survey results underscore the challenges of integrating heterogeneous data sources, particularly in decentralized energy systems. Surveyed projects suggest solutions such as low-latency communication protocols and standardized interfaces, reflecting the literature's recommendations.

Data privacy and security concerns are another key overlap. The literature emphasizes the need for strong security protocols to build trust among stakeholders, while surveyed projects propose enhanced cybersecurity measures to address gaps in security and privacy protocols, ensuring compliance with regulations like GDPR.

Regulatory barriers and market fragmentation also emerge as significant themes. Both the literature and surveyed projects note that fragmented regulatory frameworks across countries exacerbate data exchange challenges, creating isolated ecosystems. Both sources call for cross-border data exchange and regulatory alignment to overcome these barriers.

In conclusion, the surveyed projects validate the findings from the literature, indicating a high degree of alignment between theoretical frameworks and the real-world. Both sources agree on the critical barriers and propose similar solutions, reinforcing the need for harmonized standards, improved security, and regulatory cohesion to advance the digitalization of energy systems.

5.2 Analysis of gaps in the cyber-physical digitalised pan-European grid

5.2.1 Analysis of gaps in cyber-physical digitalized pan-European grid identified in literature

The digitalization of the pan-European grid, integrating physical infrastructure with cyber capabilities, demonstrates gaps, discussed widely in the available scientific literature, particularly revolve around **interoperability**, **cybersecurity**, **resilience**, and **real-time data monitoring**.

A recurring issue in the literature is the lack of standardization and interoperability across the European grid. The grid's infrastructure involves various vendors, systems, and national boundaries, all of which use distinct communication protocols and data formats, preventing the seamless data exchange and integration of assets and smart technologies in cross regional level [49]. In addition, literature highlights that the digitalized energy grid, now faces risks such as malware attacks, data breaches, and Distributed Denial of Service (DDoS) attacks. Critical assets such as substations, transformers, smart meters, and control systems are vulnerable, and there is an urgent need for comprehensive cybersecurity frameworks tailored to protect both cyber and physical elements of the grid [21]. In addition, supply chain vulnerabilities, particularly related to third-party services, further intensify these risks.

In addition, serious threat to grid stability constitutes the cyber-physical attacks, which simultaneously exploit digital vulnerabilities to cause physical disruptions [50]. This kind of attacks can trigger cascading failures across the grid, as seen in past incidents like the Ukraine grid cyberattack [51]. Despite the criticality of these threats, the literature points to gaps in real-time detection and response mechanisms. Current systems struggle to detect and mitigate cyber-physical threats efficiently, especially with the growing complexity of DERs and decentralized grid operations.

Another significant gap in scope of the pan-EU grid scenario, is indicated in the ability to process and integrate data across various grid systems effectively. Real-time monitoring is essential for grid resilience; therefore, the vast amounts of real-time data being produced by the digital devices, (sensors, smart meters, IoT devices, etc.) which are becoming part of the grid, need to be supported. Though, current systems often face issues with data latency, scalability, and inconsistent formats, which hinder the effective use of dynamic monitoring and predictive analytics necessary for grid optimization and fault detection [52].

The European grid faces additional complexity due to regulatory and market fragmentation across different countries. Each country demonstrates varying degrees of grid digitalization, and there is no unified regulatory framework enforcing cybersecurity or interoperability standards. This lack of cohesion complicates the adoption of advanced digital solutions across the entire grid, leaving it vulnerable to inefficiencies and potential security risks [21].

In the context of European Union through, the commission together with other entities presented a new cybersecurity strategy [53] at the end of 2020, covering the security of essential services such as hospitals, energy grids and railways, while extending to securing the ever-increasing number of connected devices from domestic, business and the industrial sector. The strategy focuses on assembling a collective capability to respond to major cyberattacks, while working with partners around the world to ensure international security and stability in cyberspace. The strategy uses the collective resources and expertise available to the EU and Member States to address via the most effective way the cyber threats. A comprehensive analysis of the regulatory framework on digitalizing the EU energy sector is provided in section 3 of the current document.

Finally, the increasing use of smart meters and IoT devices indicates the collection of sensitive data, while there is a lack of robust data protection frameworks, presenting risk of privacy violations. Compliance with regulations such as GDPR is critical but difficult to maintain across a fragmented, multi-country grid [52].

To conclude, the literature highlights critical gaps in the cyber-physical digitalization of the pan-European grid, particularly in areas of interoperability, cybersecurity, real-time monitoring, resilience, and regulatory alignment. Addressing these gaps will require a concerted effort to standardize communication protocols, implement advanced cybersecurity measures, and create unified regulatory frameworks across Europe. Without these efforts, the pan-European grid's digitalization risks falling short of its potential to enhance efficiency, resilience, and sustainability.

5.2.2 Analysis of gaps in cyber-physical digitalized pan-European grid indicated in the surveyed projects

The responses to Q15 (A.15) of the survey can be categorized into three types: (i) affirmative responses, where projects have either made or are actively developing advancements in cyber-physical systems; (ii) negative responses, where projects indicate no engagement with cyber-physical developments; and (iii) non-responses, attributed either to the early stages of project maturity, limiting the availability of relevant data, or to restrictions imposed by data privacy policies. Table 5 provides a summary of the surveyed projects' responses regarding their contributions to cyber-security-related advancements.

Project	positive	negative	no answer
2LiPP			✓
BeFLEXIBLE			✓
DATA CELLAR	✓		
Ebalance+			✓
eFORT			✓
PARITY			✓
STREAM			✓
SYNERGY			✓
XFLEX			✓
COORDINATE			✓
ENERGYSHIELD			✓
NEWGEN	✓		
AGISTIN			✓
BD4OPEM	✓		
EDDIE			✓
BD4NRG	✓		
OneNet	✓		
Platone		✓	

InterConnect	✓		
EUniversal		✓	
HVDC-wise	✓		
FARCROSS			✓
ENFLATE			✓
int:net		✓	
SDN-MICROSENSE	✓		
CyberSEAS	✓		
ELECTRON	✓		
FEVER	✓		
FlexCHESS		✓	
INTERRFACE	✓		
INTERSTORE			✓

Table 5: Responses on project advancements in cyber-security developments

Question 15 of **Error! Reference source not found.** bears also the sub-questions Q15i and Q15ii, aiming respectively on (i) the cyber-physical assets addressed and the risk mitigation indicated by the survey answers, and on (ii) the cyber focus-areas of the pan-EU grid.

Analysing the responses provided by the surveyed projects in Annex B, the following categories of cyber-physical assets are addressed in the context of improving the reliability and resilience of the electricity grid:

- Frameworks associated with **data management systems and cybersecurity:** This category includes secure access to data and AI models, ensuring compliance with GDPR and data privacy regulations. Blockchain technology is also employed to enhance data integrity and trust. The projects emphasize continuous monitoring, secure data exchange, and dynamic risk management through guidelines (e.g., NISTIR 7628). These projects are:
    - DATA CELLAR: Data platforms ensuring secure access to datasets and AI models, with a focus on cybersecurity and GDPR compliance.
    - BD4NRG: Governance and cybersecurity management tools, following NISTIR 7628 guidelines for data access policies and continuous monitoring.
    - CyberSEAS: Blockchain technology for ensuring data integrity and trust, along with real-time monitoring and advanced cybersecurity frameworks.
    - ELECTRON: Federated learning models and decentralized SIEM for cybersecurity, along with blockchain-based transaction systems for data security.

- Focusing on the **physical grid assets:** These projects address the physical elements of the grid, particularly HVDC cables, distribution grid components, and hybrid AC/DC systems, assets that are designed to improve resilience and reliability by mitigating risks such as cable failures, grid disturbances, and overloads. What is of high significance, is that HVDC-WISE specifically focuses on reducing outages and enhancing grid reliability through optimized system design and protection mechanisms:
    - NEWGEN: HVDC cables, insulation systems, and global monitoring systems designed to mitigate cable failure risks (e.g., partial discharges, insulation breakdown).
    - BD4OPEM: Distribution grid components, focusing on grid disturbances, predictive maintenance, and overload management.
    - HVDC-WISE: HVDC architectures and technologies integrated with hybrid AC/DC systems, aiming to enhance reliability and resilience against disturbances.

  - FEVER: DERs, power electronics devices (PEDs), smart meters, and SCADA systems for real-time grid monitoring and secure trading.
- Enhancing **monitoring and controlling systems**: The solutions include network traffic and infrastructure monitoring, protection of communication protocols (e.g., IEC61850), and tools for managing secure data exchange. Dynamic monitoring systems enable real-time decision-making and enhance the overall security of the grid's cyber-physical layers:
  - OneNet: Network traffic and infrastructure monitoring tools, with risk mitigation strategies including cryptography, identity management, and traffic filtering for secure data exchange.
  - SDN-MICROSENSE: Substation bus and process control systems, with a focus on securing communication protocols such as IEC61850 and protecting against process bus attacks.
  - INTERRFACE: Advanced grid service platforms and communication protocols for dynamic monitoring and secure operation of the grid's cyber-physical layers.
- Provide **risk mitigation and threat detection tools**: These projects develop tools for predictive maintenance, real-time threat detection, and dynamic rating systems that assess the grid's capacity and vulnerability. They propose comprehensive cybersecurity frameworks and continuous monitoring to ensure grid resilience and reliability in response to potential threats:
  - EUniversal: Tools to identify vulnerabilities and mitigate risks from extreme events in distribution networks, focusing on resilience improvements.
  - FEVER: Predictive maintenance systems and integration of DERs, combined with comprehensive cybersecurity frameworks for real-time threat detection and grid protection.
  - CyberSEAS: Threat intelligence platforms for continuous monitoring and response to potential cyber-attacks, along with dynamic rating systems for real-time grid capacity assessment.

Regarding the second part of Q15 (Q15ii), which focuses on the cyber aspects of the pan-EU grid, the categories and key areas of significance closely align with those identified in the first part (Q15i). The overlapping focus areas emphasize a consistent strategic approach, highlighting the interconnection between the cyber-dimensions and broader grid operational priorities. Though, there is one extra category that populates the list associated with Q15ii, which are:

- The potential **cross-border collaboration:** This category emphasizes the importance of sharing threat intelligence, best practices, and standardized protocols between countries to improve collective defence against cyber threats. The projects covering this area are:
  - FEVER: Promoting cross-border collaboration for sharing threat intelligence and best practices in cybersecurity.
  - INTERRFACE: Ensuring standardized communication protocols for better coordination and threat monitoring across the pan-EU grid.

Overlapping concerns are identified across several key areas regarding the cyber-physical digitalized pan-EU grid concept. These concerns are identified in both streams towards forming the KB (Figure 1). Both sources highlight interoperability as a major obstacle, noting that the lack of standardization in communication protocols and data formats hinders seamless integration across different systems and regions. Similarly, cybersecurity vulnerabilities emerge as a critical concern in both the literature and project findings. The literature points to threats such as malware attacks and DDoS incidents targeting critical infrastructure, whereas the projects emphasize the development of tools for real-time threat detection and secure data exchange.

A key area of alignment is the gap in real-time data monitoring. Both the literature and the surveyed projects identify scalability and data latency issues in processing the large volumes of real-time data generated by IoT devices and smart meters, which limits the effectiveness of predictive analytics and grid resilience. Additionally, the regulatory and market fragmentation cited in the literature is confirmed by the projects, particularly regarding the need for cross-border collaboration and unified cybersecurity frameworks across the European grid.

However, while the literature emphasizes gaps in overarching regulatory alignment and strategic resilience, the surveyed projects demonstrate more concrete advancements in specific areas like blockchain for data integrity and federated learning models for cybersecurity, offering promising solutions that are underrepresented in academic discourse. The surveyed projects also introduce cross-border collaboration as a new category, which is less prominent in literature but increasingly relevant for the pan-EU grid's future cybersecurity strategy.

5.3 Analysis of Gaps and Opportunities in System Planning and Grid Operation

In the present section, gaps and opportunities is considered in the sense of problems and proposed solutions thus it is worth mentioning the following:

System planning processes are called upon to integrate massive RES and electrification of sectors, in a well-coordinated manner. Looking into the research and innovation projects analysed, there are several applications of optimal DER connections, in a way that ensure integration through efficient data exchange and operation control. This is a challenge that SOs will be facing to achieve the decarbonization challenge. However, the system planning process mainly address either the distribution level or the transmission level, especially the issues of hybrid AC/DC grids. There is a need to provide a coordinated methodology applicable for system planning and cost benefits analysis at transmission and distribution levels. This need of coordinated planning is becoming more apparent because several edge grid assets are DC-based (batteries, PVs, EVs, home appliances etc.) while HVDC long transmission lines/cables is becoming an excellent solution for interconnection challenges and mitigation of public discontent to new grid infrastructure. Digital models/twins and AI technology, and especially the concept of federated architectures, can provide a proposition to address this gap, ensuring interoperability and cooperation among systems. A new methodology for coordinated system planning that both TSO and DSO can use would be beneficial, as well as the Identification of missing communication adapters that prevent efficient data exchange between TSOs, DSOs, market operators and other stakeholders.

Policymakers should adopt strategies that unlock grid investments and create incentives for modernization. In several projects, it has been mentioned a lack of sufficient incentives to promote new technology and digital systems Investment. An update cost benefit analysis framework to incorporate non-wire solutions and digital systems, as well as reimbursements not only for CAPEX but for TOTEX and innovations/digitalization grid upgrades.

Harmonized standards for data exchange and interoperability across the energy value chain are essential for efficient system operation. Through the analysis of the findings of the projects, it has been mentioned that there is a lack of standards and interoperability technology, such as common tooling enabling backwards and forwards standard version compatibility, especially in respect to the legacy systems of grid operators. Further cooperation of energy stakeholders is needed for overcoming the issues around incompatible communication protocols and model data exchange formats. This will facilitate the smooth integration of modern digital technologies with the legacy systems in the EU.

System operators should leverage the benefits of digitalization while implementing robust cybersecurity measures to minimize any new digital operational risks. In several projects new digital solutions have been generated that optimize the control of DERs and test scenarios of interaction with DSO to provide flexibility services. The intelligent IoT devices and digital platforms integrated can continue supporting efficiency and security with real time exchange of data during system operations and the balancing challenge. At community/residential scale, Building Management Systems (BMS) are installed to control and monitor the technical systems and services of a building, like AC, lighting, ventilation, and hydraulics. However, the frameworks for collection and handling of data, as well as the development of AI and machine learning tools, can generate new threats for cyber-attacks. At the same time, increased focus on cybersecurity risk assessments, with proactive and reactive capabilities is essential to ensure the security of power systems. Digitalization should not generate new vulnerabilities and jeopardize the energy systems but should enhance resilience and reliability.

Digital solutions should be valorised to maximize the usage of grid assets and their capabilities. The electricity grids have been designed to operate with safe margins regarding power rating and loading. There are various possible digital and sensor-based solutions for improving the utilization of the finite resource of the cross-border transmission lines and certain viewpoints should be considered, such as the available surplus transfer capacity, operational safety, economical aspects, legal authorization process. Several applications have been developed and tested in European projects, however there is a need to include digital solutions in system planning and operation developments for optimizing capacity usage.

A skilled workforce well-versed in digital technologies is essential for the future of the energy sector. In most countries, the liberalization of the energy sector and smart grid deployment has occurred in the last couple of decades. Since the pace of digitalization is really fast, there is already a need for a high number of digitally skilled workers across the entire energy sector, in companies with different roles in the value chain i.e. producers, suppliers, operators, regulators. Especially in system operation practices IoT and data exchanges for real-time control and decision-making at all voltage levels is transforming to fully digitalized process, in respect also with modern grid assets in the field. In the grid assets management, the maintenance personnel need to pass their expertise to the next generation of skilled workforce in order to enable them to adapt the legacy equipment with the digital upgrades. This can be managed in a systematic way in the system operator’s business processes. Governments and policy makers need to ensure they manage the impacts of increased automation on personnel through reskilling and incentivising on-the-job training.

5.4 Analysis of Digitalization Gaps and Opportunities in the Interconnected Energy Markets

Digitalization is increasingly considered as a key enabler to the decarbonization and the democratization of energy systems in general, and of electricity systems in particular. In fact, the massive adoption of new and more powerful digital technologies and communication systems allows getting and treating larger amounts of data, connecting more and more equipment and implementing more complete and adequate control algorithms. Altogether, these moves pave the way to the increasing installation of renewable energy sources, the participation of larger amounts of end users in different sorts of market mechanisms and these changes are already definitely contributing to reduce GHG emissions within the electricity sector. Digitalization is also creating the conditions to electrify several energy demands powered until now by other energy vectors and it is empowering end consumers thus turning the relation between generation and demand more symmetrical and the markets more competitive.

In the context of interconnected energy markets, digitalization plays a crucial role in enhancing the efficiency, reliability, and sustainability of Europe's energy system. Interconnecting Energy Markets at European level can optimize the use of renewable resources and balancing supply and demand more effectively. This interconnection not only enhances energy security by allowing countries to rely on their neighbours during shortages or peak demand periods but also fosters competition, leading to more competitive energy prices for consumers.

Furthermore, interconnected energy markets support the EU's climate goals by facilitating the integration of renewable energy sources, reducing the need for fossil fuel-based power generation. Overall, the development of a pan-European grid service architecture is essential for creating a resilient, flexible, and sustainable energy future for Europe.

Before enumerating some of the challenges, opportunities and gaps raised by the increasing digitalization of interconnected energy markets, and according to IEA [21], digitalization in the context of energy markets is related to three main aspects as follows:

- **Data gathering** – the reduction of the cost of sensors and data storage devices is creating the conditions to collect larger volumes of data, both by the increasing number of monitored points and variables and by the increasing sampling frequency that can be eventually adopted.
- **Data treatment** – because of the previous aspect, larger volumes of data must be transmitted and treated. In this context, rather than just transmitting large quantities of data to increasingly more powerful control centres, it seems much more adequate and efficient to adopt hierarchical structures in which raw data recorded locally is immediately subjected to some preliminary treatment, and the treated data then transmitted to higher-level structures. In any case, the volumes of data to treat (due to the increasing number of sensors and to the increase of the sampling frequency) will certainly be enormous thus requiring the development of data analytics techniques and new computing capabilities. Still related with data, power and energy system engineers must carefully decide on what type of aggregated information will be produced based on raw data. This information should be meaningful in terms of enabling operators or end users to understand the key aspects of the energy systems while ensuring that they will not be sunk in large amounts of information that is impossible to assimilate in due time.
- **Communication links** – as inferred from the previous two aspects, in parallel to the development of the existing infrastructure of energy systems, it is necessary to implement increasingly powerful communication links and data exchange mechanisms among machines and different sorts of devices and powerful interfaces with humans. As mentioned before, it will be pointless having an operator submerged in large amounts of untreated and raw data which raises the question of how to aggregate data without losing its meaning and its capacity to represent events in energy systems.

Having addressed and characterized these three aspects, the rest of this section details some of the challenges, opportunities and gaps raised by the increasing digitalization of energy systems in general and of interconnected electricity systems, in particular:

5.4.1 Increased management efficiency

The increased digitalization of energy systems and markets can contribute to increasing the efficiency of the sector, making logistics more efficient and thus contributing to reducing the energy prices. As a challenge, this electricity price reduction can induce demand transfers from other energy vectors to electricity or, if this price reduction is general to all energy vectors, it can originate a rebound effect of consumption increase and subsequent price increases.

The digitalization of power systems can help to counteract this eventual rebound effect given that generation companies can more easily spot supply problems and develop better quality forecasts, both regarding the demand and the available renewable resources. This will enable them to adopt lower cost generation strategies and to more accurately match generation with demand so that unbalances are minimized.

5.4.2 Electrification of other activities

The progressive reduction of GHG emissions to counteract climate change is certainly a well-established goal within EU countries. It is now well accepted that the electricity sector is perhaps the economic sector that is displaying improved performance in terms of increasing the use of renewable resources.

On the other hand, it is well understood that the increase in share of renewable sources in terms of the entire energy demand cannot be accomplished without acting on the transportation sector. This means that at least for passenger cars, it is expected that the number of EVs will continue to increase, but maybe not at so fast a pace that was expected some years ago. This means that some fossil fuel traditional demands are moving to electricity, thus increasing the electricity demand. In turn, this will likely change the shape of demand diagrams, and it will require more investments in several areas of the electricity systems.

5.4.3 Increase of the use of renewable energy sources

The reduction of GHG emissions is being supported by the increasing use of renewable sources as PV, wind, biomass, biofuels and geothermal (in this case, in specific locations), and also other less mature technologies such as wave energy. The presence of increasing capacity associated with these technologies is challenging and several countries have included in their National Plans for the Energy and Climate very ambitious targets in terms of the percentage of electricity from renewable sources in the generation mix. This certainly requires more advanced forecasting algorithms, larger amounts of data must be collected, treated and communicated eventually at higher frequency rates than today. Once again, digitalization can be the enabler to this new power system operation of current electricity markets.

Several years ago, national governments adopted subsidized tariffs to induce investments in renewable sources. This typically represented an additional cost to consumers, but this strategy was not questioned since the installed capacities were still small. Then, technologies got more mature, and the installed capacities started to rise, and, as mentioned previously, they will increase even more in the next years. This means this subsidization approach is no longer sustainable and new wind and PV units, as well as the existing ones when the subsidization period ends, will have to bid in electricity markets or get bilateral contracts.

This means that the number of generation agents in the market will increase, several of them having very reduced or even zero marginal costs. As a result, electricity markets will become more competitive with some daylight hours having very reduced, zero or even negative prices, while in some other-hours prices will peak when the marginal technology becomes a CCGT, for instance.

This evolution makes the operation of electricity markets more challenging in several ways. On the one hand, traditional thermal units become less used, will have lower revenues and this will make these investments riskier. However, several simulations indicate that at least in some periods these units are still necessary to balance the system which means that other payment mechanisms apart from the marginal market price should be adopted. This clearly suggests the adoption of capacity payments, as it is under study in several countries. On the other hand, the larger presence of intermittent sources and the reduction of the installed capacity in traditional large power stations will likely reduce the inertia in the system eventually creating new control problems in power systems. This suggests the development of new marketed and paid products, or the payment of already existing products currently provided under a mandatory and non-paid scheme in several countries. Inertia, flexibility and Frequency Containment Reserve, FCR, are just three examples of such items.

Although the development of such markets is expected to be challenging in terms of data and control approaches, it will contribute to create new streams of money to several players eventually contributing to break even some investments.

5.4.4 Increasing investments

The digitalization of power systems is creating the conditions to increase the installed capacity of renewable sources and to electrify several demand segments until now powered by other energy vectors. This will require large investments in grid equipment, as it is forecasted to connect large offshore wind parks, large PV farms, sometimes concentrated in some geographical areas with higher energy potential.

In addition, the increasing number of EVs will also pose challenges to distribution networks because these LV and MV grids have not enough capacity to supply large amounts of simultaneous demand.

As an opportunity coming from digitalization and the availability of more data regarding the operation of grid equipment and machinery, it will be possible to develop and implement better quality preventive maintenance mechanisms so that the operational stress is reduced, and the equipment lifetime is extended. This will contribute to reducing the cost of operation as well as the investment requirements in the long term, with positive impacts on the regulated grid tariffs.

5.4.5 Impacts on grid tariffs

Due to the large grid investments that will be required, the grid tariffs paid by end consumers to remunerate regulated grid companies for these costs will likely increase. To tackle this issue and to turn this transition smother from this point of view, it is important to move from pure dumb-charging approaches of EVs to more controlled and supervised charging schemes so that the peak demand does not exceed the existing grid capacity.

This will certainly require more data gathering, more communication links between end users and the DSOs, and more powerful control algorithms. Once again, all these developments can be enabled by the increased digitalization of power systems.

5.4.6 Investments on storage systems

The connection of large, and in several cases intermittent sources, such as wind parks and PV farms, can be connected to existing networks or can reduce required grid investments if storage devices are installed in those units.

This will allow electricity injections in the grid to be controlled, decoupling these injections from the instant of generation and, for instance, moving parts of the electricity generated in PV farms in daylight hours to evening periods when the demand is typically large. This can contribute to reduced electricity prices during the whole day and not just during daylight periods.

5.4.7 New structures, actors and regulations

The development of digitalization and more efficient communication links is enabling the connection of more new units using renewable energy sources. Some of these units have large installed capacities but several others are small units for self-consumption at the industrial or domestic levels, namely connected to MV or LV grids. This means that the traditional top-down structure of power systems has changed to a more decentralized one with an increasing installed capacity connected at the MV and LV levels.

This also means that many traditional end consumers are becoming prosumers and inject the electricity produced in excess regarding their local demand in the grids. As a result of digitalization, power systems are becoming democratized, and end consumers can be empowered. Digitalization allows consumers to have better control over their energy usage, access real-time data, and participate in demand response programs, which can lead to cost savings and more sustainable energy consumption [54].

This is particularly relevant since end consumers start being paid for the mentioned injections and have the possibility of interacting in a more transparent and easy way with retailers and grid companies (for instance providing feedback, changing commercial and contractual arrangements or even moving from one retailer to another one in a simpler and faster way). This also means that the relation between the two extreme sides of the power system structure, generation and demand, is becoming more symmetric, that is, conditions are being created for the demand to be more responsive to the price so that electricity markets become truly competitive, and the aggregated demand curve displays a less vertical shape regarding what happened in the past. Digital technologies like the Internet of Things (IoT), smart appliances, and smart grids can optimize energy consumption and distribution, leading to more efficient and flexible energy systems [55].

This move requires new regulations since traditional consumers can now become net producers in some periods. On the other hand, as determined by EU regulations, several EU countries have already in place in their national legislations the figure of Energy Communities and Renewable Energy Communities, RECs, as a way to boost the use and the installation of renewables. Although several RECs are already in operation in several countries, there is ongoing research related to how to allocate locally produced energy to the participants, it being clear that more accurate and fair allocation techniques require more data and more measurements to be collected and treated.

5.4.8 New products, new markets

It is expected that in the next few years new products will be marketed as is the case for inertia and Frequency Containment Reverse (FCR), and flexibility. Flexibility is expected to become a relevant product in the next few years as a way to address the variability of some renewable sources. In this sense, it can correspond to a new tool to be used by TSOs or DSOs to help them manage power systems with a large share of units using renewable resources. This means that specific markets will have to be developed for these products either at the regional or national levels or eventually involving several interconnected countries.

On the other hand, the progressive shut down of large coal stations and the increased presence of renewables will eventually create the conditions to reform the existing day-ahead markets. These markets operate the day before for every hour of the next day. If we take the example of the Iberian Electricity Market, the gap between gate closure and the last hour of the next day is 36 hours. This large gap was eventually necessary when large slow response coal stations were on. However, as these units are being decommissioned, the reasons to maintain day ahead markets with a so large gap are no longer valid. This evolution towards more volatile and dynamic power systems suggests the substitution of the present day ahead markets by several intraday markets with smaller time gaps, much more adjusted to the generation technologies currently in use. This would also allow intermittent units to obtain better quality forecasts due to the reduction of the forecasting horizon, so that they would bid on these intraday markets with more firm generation values.

Finally, these better forecasted generation values would contribute to reduce imbalances, so that TSOs would have the chance to reduce the volume of reserves to be procured and contracted, and this would reduce this component on the final tariffs paid by end users.

5.4.9 Interoperability and digital applications

The electricity sector has very distinctive features in the sense it includes regulated activities together with other provided under competition, generation and retailing.

On the other hand, historically it is a sector in which large utilities, TSOs and DSOs are very concerned with data access security so that it is most common to have proprietary and closed systems which turns the digitalization of the systems and the increase of cooperation and the implementation of communication links even more challenging and simultaneously very timely. The development of a common European energy data space can foster innovation by enabling better data sharing and collaboration among stakeholders [56].

The management of power systems can profit from the experiences from other sectors in using computer science techniques as blockchain tools, digital platforms and digital twins. Altogether, these tools will contribute to ensure the security of the access while facilitating and turning it more transparent.

5.4.10 Larger interconnections between national systems

It is one of the goals of the EU energy policy to develop the internal market of electricity. This requires well established interconnection grids to allow electricity exchanges so that the transmission networks are neutral regarding generation investment and commercial decisions. This means that congestion should be reduced as much as possible so that electricity becomes a homogenous product along interconnected systems.

If we take the case of the Iberian Peninsula, the planned investments on offshore and PV units for the next 10 to 15 years can only be justified by demand increases (given the expected electrification of existing economic sectors, by the development and installation of electrolysers and the expected sharp increase of electricity demand in desalinisation units, for instance) or by the possibility of exchanging electricity excesses with central European countries. Furthermore, as defined in the

ENTSO-e Regional Investment plan of the CSE region [57] the SEE countries like Greece and Bulgaria are urged to proceed with massive grid reinforcement in order to allow the desired renewable energy flows across them and achieve their NCEP targets. These aspects require the elimination of bottlenecks at the transmission level driven by new investments in interconnections between national systems.

This would also require that national TSOs become more cooperative eventually using a pan-European grid service architecture. More data shall be collected and treated enabled by the increased digitalization of the energy sector. Apart from the physical infrastructure, national or regional electricity markets should progressively move to pan-European approaches so that more competition can be introduced while ensuring and maintaining high level of operational security standards.

The main aspects to be considered are the possibility to implement common regulations and standards across all EU Member States. This includes the Capacity Allocation and Congestion Management (CACM) Regulation, the Forward Capacity Allocation (FCA) Regulation, and the Electricity Balancing (EB) Regulation [58].

In addition, market rules for coupling and balancing need to be aligned and standardized for helping the optimization of cross-border transmission capacities and ensure efficient electricity trading across borders, including at the same time a more efficient management of supply and demand, reducing the need for costly reserve power and enhancing grid stability [59].

As several researchers indicate and in line with the experience of operating small isolated systems as islands, it is very difficult to decarbonize isolated systems, but it becomes much easier to increase the use of renewable energy sources in large interconnected systems given their diversity and the possibility of some of them backing up some others.

5.4.11 Additional Benefits – Economical and Social Impact

Interconnection of energy markets and the digitalization of the energy sector not only cover technological aspects but also impact on economic and social aspects.

In fact, the digitalization in the energy sector offers significant cost reduction benefits by enhancing logistics efficiency and enabling real-time monitoring of supply issues. With advanced data analytics and IoT technologies, energy companies can accurately forecast energy surges and demand patterns, allowing them to produce the exact amount of energy required. This precision not only reduces waste but also optimizes resource allocation, leading to substantial cost savings. Additionally, real-time data enables quicker response to supply chain disruptions, minimizing downtime and ensuring a more reliable energy supply.

Improving infrastructure and services is another critical advantage of digitalization. Predictive maintenance, powered by AI and machine learning, allows for continuous monitoring of equipment and machinery, identifying potential issues before they lead to failures. This proactive approach reduces physical stress on infrastructure, extending its operational lifetime and reducing maintenance costs. By minimizing unexpected breakdowns and optimizing maintenance schedules, digitalization ensures that energy infrastructure operates more efficiently and sustainably.

Furthermore, digital transformation significantly enhances customer interaction by providing more accessible and responsive feedback mechanisms. Through digital platforms, customers can easily communicate their needs, report issues, and receive real-time updates on their energy usage. This improved interaction fosters a better customer experience, as companies can tailor their services to meet individual preferences and address concerns promptly. Enhanced customer engagement not only builds trust but also encourages more active participation in energy-saving initiatives, contributing to a more sustainable energy ecosystem.

The customer engagement implies taking into account the social acceptance of the energy digitalization. In order to have a high-rate and trust it is important to provide transparency, engagement, and tangible benefits for the customer communities.

Involving stakeholders and the public early in the planning process through consultations and open forums can help address concerns and build trust. Clear communication about the benefits of digitalization, such as improved energy efficiency, cost savings, and enhanced grid reliability, is essential. Additionally, demonstrating the positive environmental impact, such as reduced carbon emissions and better integration of renewable energy sources, can garner support. Providing direct benefits to local communities, such as job creation, infrastructure improvements, and educational programs, can further enhance acceptance. Lastly, ensuring robust data privacy and cybersecurity measures can alleviate fears related to digitalization, fostering a sense of security and confidence among the public. By addressing these aspects, energy digitalization initiatives can gain broader social acceptance and support.

5.5 Identify the EU-legislative Related Barriers Regarding Energy Digitalization

The ongoing energy crisis has not only disrupted global energy markets but also posed severe challenges to the EU's climate and energy objectives. The crisis, fuelled by geopolitical tensions such as the Russia-Ukraine war, has exacerbated the EU's dependence on imported fossil fuels and highlighted the urgent need for energy diversification and resilience. This dependence has made the EU vulnerable to market volatility and price shocks, complicating its transition to a sustainable energy future. The REPowerEU plan, designed to reduce reliance on Russian fossil fuels and increase the share of renewable energy to 45% by 2030, represents a crucial step toward energy independence. However, the rapid escalation of energy prices and supply disruptions has forced the EU to temporarily revert to fossil fuels, undermining its climate commitments [60].

A significant challenge in this context is the contradictory behaviour of large oil companies, which have leveraged the crisis to achieve record profits from fossil fuel sales. In 2022, major oil corporations reported substantial earnings and subsequently scaled back their renewable energy targets. This regression threatens the EU's climate goals and underscores the need for stronger legislative oversight and incentives to keep renewable energy investments on track. Despite the ambitious targets of REPowerEU, there is a lack of robust enforcement mechanisms and financial incentives that can compel energy companies to prioritize renewable energy over fossil fuels [61]. Moreover, geopolitical factors such as global inflation, supply chain disruptions, and the weaponization of energy supplies have intensified the EU's energy security concerns. The EU's long-standing reliance on imported energy, particularly natural gas from Russia, has exposed the region to significant risks. The need to secure alternative energy supplies has prompted the EU to explore new partnerships and diversify its energy mix, including accelerated investments in renewable energy and energy efficiency. However, this transition is fraught with challenges, including the need for substantial infrastructure investments, rapid scaling of renewable technologies, and navigating complex legislative landscapes that vary across member states [62]. The energy crisis has also emphasized the importance of integrating digital solutions, such as digital twins, into the energy sector to enhance grid management and stability. Digital twins can provide real-time monitoring and control, forecast supply-demand imbalances, and improve the resilience of energy systems during volatile market conditions, thus playing a critical role in mitigating the impacts of the crisis. To address these challenges, TwinEU advocates for merging standards for data exchange and developing robust interfaces between TSOs, DSOs, and other stakeholders, such as standardizing the way boundary points, and reference data are exchanged both by TSOs and DSOs. These measures are crucial for handling the increased volatility in energy supply and ensuring coordinated responses to disruptions. The integration of these standards and interfaces is a strategic priority to overcome the current legislative and technological gaps.

Digitalization is a cornerstone of the EU's strategy to modernize its energy sector and meet climate goals. The integration of digital technologies such as smart grids, advanced metering infrastructure, and AI-driven energy management systems is essential for achieving a more flexible, efficient, and resilient energy system. However, the current legislative and regulatory frameworks across the EU present significant barriers to energy digitalization. One of the primary issues is the lack of harmonized regulations across member states, leading to fragmented approaches to digital energy solutions [63].

Currently, EU member states operate under different regulatory standards, which impedes the seamless integration of digital energy technologies. For example, the deployment of smart grids and advanced metering infrastructure is uneven across the EU, with some countries leading in adoption while others lag significantly behind. This inconsistency creates challenges for data sharing, interoperability, and cross-border energy trade, ultimately hindering the development of an integrated digital energy market. Furthermore, regulatory gaps concerning data privacy, cybersecurity, and data sovereignty pose additional challenges, as these issues are critical for the widespread adoption of digital solutions in the energy sector [63].

Technological barriers further complicate the EU's digitalization efforts. Outdated infrastructure, lack of investment in modern digital technologies, and limited interoperability between legacy systems and new digital solutions hinder the full realization of a digital energy ecosystem. For instance, many existing energy grids were not designed to accommodate the bidirectional flow of energy and data required by smart grids, making it difficult to integrate renewable energy sources and manage energy demand in real time. The EU's legislative frameworks often fail to address these technological shortcomings, leaving critical gaps in the support needed for digital innovation and transformation within the energy sector [20]. Moreover, there is an urgent need to align the legislative landscape with emerging digital technologies such as AI, blockchain, and IoT, which hold significant potential to optimize energy management, reduce consumption, and enhance grid stability. The current regulatory environment does not provide clear guidelines or incentives for the adoption of these technologies, leading to a cautious approach among energy companies and investors. Without clear and supportive regulatory frameworks, the EU's energy sector risks falling behind in the global race toward digitalization, which is essential for achieving the twin goals of energy security and sustainability [64].

The EU's ambitious climate and energy targets are supported by several key initiatives, including the Action Plan for Grids, the Renewable Energy Directive III (RED III), and the reformed Electricity Market Design. These legislative efforts aim to modernize the EU's energy infrastructure, promote renewable energy, and create a more integrated and competitive energy market. However, significant gaps remain between these legislative initiatives and the practical requirements for advancing energy digitalization [65].

The Renewable Energy Directive III (RED III) is designed to boost the share of renewables in the EU's energy mix, setting ambitious targets for renewable energy generation and consumption. However, RED III does not sufficiently address the role of digital technologies in facilitating this transition. The directive lacks clear provisions on how digital infrastructure investments, such as those needed for smart grids, energy storage, and digital energy management systems, should be prioritized and integrated into the broader energy strategy. This oversight hinders the potential for digital solutions to enhance the efficiency and effectiveness of renewable energy deployment.

Similarly, the Action Plan for Grids emphasizes the need for increased investment in grid infrastructure to support the EU's energy transition. While the plan recognizes the importance of enhancing grid flexibility and capacity, it falls short of addressing the digitalization required to manage these complex systems in a renewable-dominant environment. Key digital tools, such as AI-driven demand-response systems and blockchain-based grid management, are not adequately integrated into the plan, leaving significant opportunities for improving grid management and stability untapped.

The reformed Electricity Market Design seeks to introduce market-based solutions to address the challenges of energy flexibility and storage. While this framework makes strides toward creating more transparent and competitive energy markets, it does not fully incorporate the technological advancements needed to optimize market operations through digital solutions. The design does not adequately address the integration of digital tools that can enhance energy trading, grid balancing, and real-time energy management, creating a disconnect between market reforms and the digitalization imperative **Error! Reference source not found.**.

TwinEU, as a leading project focused on digital twin technologies, can play a critical role in addressing the identified legislative and regulatory gaps. The project can leverage advanced digital tools and technologies to facilitate a more integrated, efficient, and resilient energy system across the EU. Some specific solutions are presented below:

- **Digital Twin Technology for Enhanced Grid Management**: TwinEU can develop digital twins of energy grids that simulate, monitor, and optimize energy flows in real-time. This technology enhances the EU’s ability to manage grid flexibility, predict supply-demand imbalances, and integrate renewable energy sources more effectively, providing policymakers with insights to update legislative frameworks accordingly.
- **Standardization of Digital Energy Systems**: TwinEU can advocate for and contribute to the standardization of digital energy infrastructure across the EU. By creating common standards for data sharing, cybersecurity, and system interoperability, the project can help overcome the current regulatory fragmentation. Standardization will enable smoother cross-border energy trade and cooperation, which is essential for a fully integrated EU energy market.
- **Blockchain for Transparent and Secure Energy Markets**: Implementing blockchain technology within EU energy markets can improve transparency, security, and efficiency in energy trading.
- **Cybersecurity Frameworks for Digital Energy Systems**: As the EU’s energy systems become increasingly digitalized, the need for robust cybersecurity measures grows. TwinEU can develop advanced cybersecurity frameworks tailored to protect digital energy infrastructure from potential cyber threats, ensuring the resilience and reliability of energy systems.
- **Cross-Border Energy Data Sharing Platforms**: TwinEU can promote the creation of shared digital platforms for energy data exchange among EU member states. These platforms will facilitate more efficient cross-border energy trade and grid integration, addressing one of the significant barriers posed by the current legislative discrepancies.

These solutions provided by TwinEU can help bridge the gaps between EU legislative frameworks and the practical needs of energy digitalization, supporting the EU's broader climate and energy objectives. By aligning digital technologies with existing legislative efforts, TwinEU can significantly enhance the EU's ability to transition to a sustainable and secure energy future.

6 Energy Stakeholders' Requirements

Digital twins are dynamic, virtual representations of real-world energy systems that integrate data from physical assets and processes. By connecting local digital twins to a pan-European platform, TwinEU aims to enhance grid resilience, flexibility, and sustainability, thereby ensuring interoperability and collaboration across the continent.

This chapter summarizes the requirements and expectations that European energy stakeholders have for Digital Twins (DTs). These key requirements have been derived from a thorough analysis of the responses of eighty-six stakeholders to the questions in Annex C, ranging from TSOs, DSOs, aggregators, associations, e-mobility operators, market operators, renewable energy producers, research institutions, technology providers and other small or emerging entities, as shown in Figure 5.

Through their contributions, this chapter provides a comprehensive overview of the current state, existing challenges and future directions for the implementation of DTs in the energy sector. It addresses the technical capabilities of DTs, organizational factors influencing their adoption, regulatory and compliance considerations, data management practices, and the expected benefits of their deployment. Finally, it illustrates how DTs can support Europe's transition towards climate neutrality and a more digitised, secure and efficient energy system.

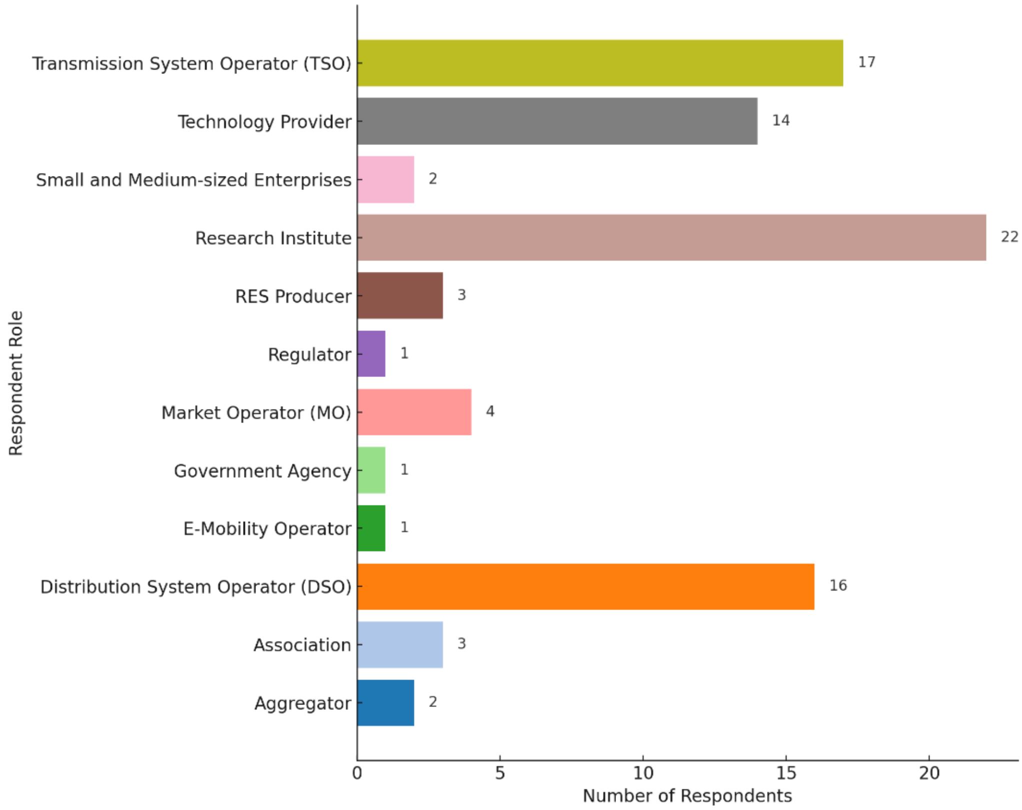

Figure 5 Number of respondents by their role in the energy sector

6.1 Core Capabilities, Limitations, and Desired Features

This section analyses the responses to the questions presented below, in terms of technical capabilities, system limitations and valuable features that stakeholders identify as priorities for the future development of digital twins. This analysis aimed to provide a foundation for understanding how DTs can evolve to meet the dynamic needs of the energy sector. By addressing **current limitations** and **prioritizing valuable features**, future implementations of digital twins have the potential to deliver transformative benefits in terms of **operational efficiency, system resilience,** and **sustainability**.

Question 6	If you already implemented a digital twin, please describe the key characteristics, functions, and technical capabilities (such as performance, reliability, security, etc.).
Question 9	What limitations are you currently facing in terms of observability and controllability?
Question 10	What current limitations exist in your infrastructure and network planning processes?
Question 11	What limitations are you currently experiencing in your processes related to operations and simulations for enhancing grid resilience?
Question 12	What limitations do you currently face in active system management and forecasting?
Question 14	What features would you consider most valuable for future upgrades or new implementations of digital twins?
Question 17	What are the current limitations impacting your processes, especially in terms of observability and controllability, efficient infrastructure and network planning, operations and simulations, active system management and forecasting, data exchange, and cybersecurity?
Question 18	Which features do you think would be most valuable for a new digital twin implementation?
Question 19	What challenges or problems do you face when interacting with other stakeholders, and how could digital twins potentially help address these issues?

6.1.1 Current Capabilities

According to the analysis of the thirty-three responses to Question 6, digital twins in the energy sector already offer a wide range of functionalities and underlying technical strengths. They support grid operations, market simulations, asset management, research initiatives, and more. Key functional areas include:

- **Grid Analysis and Planning:**

Digital twins perform load flow calculations, fault current analysis, and dynamic simulations. They support grid planning, hosting capacity assessments, and scenario testing for future network expansions.

- **Real-Time Integration and Monitoring:**

  By integrating data from sensors, smart meters, SCADA systems, and IoT devices, digital twins provide near-real-time visibility into grid states. This enables proactive operational decisions, such as rapid response to faults and the simulation of short-term operational scenarios (e.g., switching actions, the next possible scenarios in the next 15 minutes, etc.).

- **Advanced Analytics and Predictive Maintenance:**

  Leveraging AI/ML methods, digital twins enhance forecasting of load and generation, support predictive maintenance by identifying potential equipment failures, and optimize maintenance schedules to improve reliability and reduce downtime.

- **Market Modelling and Optimization:**

  Digital twins enable simulations of market dynamics (such as bidding strategies, price formation, balancing mechanisms, and what-if market scenarios) improving decision-making for market operators and other participants.

- **Interoperability and Integration:**

  Designed to work with legacy systems (SCADA, GIS, EMS) and emerging platforms, digital twins use open standards (e.g., CIM) and communication protocols to facilitate smooth data exchange. This ensures effective interaction among TSOs, DSOs, market operators, and other stakeholders, promoting regional coordination and shared insights.

- **Asset Management and R&D Applications**:

  Digital Twins model critical grid components (transformers, lines, substations) at high fidelity, aiding condition monitoring, asset replacement strategies, and infrastructure planning. They also serve as research and development platforms, through hardware-in-the-loop testing and offline simulations, to validate new technologies before deployment.

Technical Capabilities Supporting These Functionalities:

Underpinning the above capabilities are robust technical features that ensure DTs operate efficiently, reliably and securely:

- **Performance and Scalability:**

  Digital twins handle large-scale and complex grids with thousands of nodes. High processing speeds and scalable, cloud-based architectures allow for rapid simulations, real-time decision support, and efficient allocation of computational resources as systems evolve.

- **Reliability and Accuracy:**

  High-fidelity modelling and adherence to industry standards ensure that digital twins accurately represent physical grid conditions. This fidelity underpins reliable simulation results, operational forecasts, and compliance with relevant grid codes and regulations.

- **Security and Compliance:**

Strong cybersecurity measures (encryption, secure access controls, and regular assessments) protect sensitive operational data. Adherence to security directives and policies helps maintain the integrity of critical infrastructure and ensures compliance with data protection regulations.

- **User Interfaces and Visualization:**

  Interactive dashboards, real-time visualization tools, and customizable interfaces make complex data more accessible. These features help operators and other users to quickly interpret analytical insights, respond to operational alerts, and tailor views to their specific roles and preferences.

- **Flexibility and Adaptability:**

  Interactive dashboards, real-time visualization tools, and customizable interfaces make complex data more accessible. These features help operators and other users quickly interpret analytical insights, respond to operational alerts, and tailor views to their specific roles and preferences.

6.1.2 Current Limitations

This analysis synthesizes responses from the survey participants to understand the current limitations they face in various aspects of their digital twin operations. The insights are drawn from responses to five key questions—9, 10, 11, 12, 17, and 19— on observability and controllability; infrastructure and network planning; operations and simulations; active system management and forecasting; and cybersecurity and data exchange. The following list provides a clear understanding of the challenges stakeholders face in their digital twin operations:

- **Data Quality and Visibility:**

  Incomplete or low-quality data, especially at LV levels, limited sensor coverage, and bandwidth restrictions hinder accurate modelling and forecasting

- **Data Exchange and Organizational Barriers:**

  Fragmented data, lack of common standards, and reluctance to share information (due to privacy, security, and commercial concerns) hinder effective data sharing. In addition, a lack of coordination between departments, organisational resistance, skills gaps and a reliance on proprietary systems are slowing down interoperability, the adoption of DT technology and the effective implementation of DTs.

- **Technological and Infrastructure Limitations:**

  Aging infrastructure, legacy IT systems, limited computational resources, and integration complexities with DERs and EV charging infrastructures restrict advanced DT functionalities because they do not produce high granularity data (e.g. analogue energy meters) or have limited control functionalities (e.g. lack of setpoint control for distributed PV generation).

- **Regulatory, Cybersecurity, and Market Factors:**

  Outdated or unclear regulatory frameworks, cybersecurity risks, insufficient incentives, and unpredictable markets complicate DT adoption, because the further definition of roles in the DT process, interrelations of actors for data and model exchanges, as well as support in upfront digital upgrade costs could really limit DT developments.

- **Forecasting and Active System Management Challenges:**

Limited controllability and visibility into DERs, unregistered self-consumption, and outdated forecasting models reduce the effectiveness of active system management. Since forecasting and what-if scenario analyses are major applications of DT (i.e. for the past and current states we have the physical systems, and no need for digital twins), the increased controllability and visibility at the edge of the network can really support the development of DTs.

6.1.3 Desired Features for Future Digital Twins

An analysis of the responses to Question 14 and Question 18 reveals several key features that energy stakeholders consider most valuable for future upgrades or new implementations of digital twins. By incorporating these features, future digital twin implementations can better meet the evolving needs of the energy sector. Stakeholders identified key improvements:

- **Enhanced Data Integration and Real-Time Data Processing:**

  High-quality, standardized data (internally and across actors), real-time simulations, co-simulation with other DTs, and integration of external data sources (e.g., weather) for holistic system views.

- **Advanced Observability, Controllability, and Automation:**

  Improved visibility, fault detection, remote control of distributed assets, intelligent event response, and active system management to ensure resilience.

- **Sophisticated Modelling, Analytics, and AI/ML Integration:**

  High-fidelity, multiresolution models, scenario analyses, uncertainty handling, enhanced forecasting, and predictive insights for flexible planning.

- **Interoperability, Standards, and Adaptability:**

  Adoption of open APIs, IEC standards (e.g., IEC 61850), CIM-based models, and BIM integration, plus scalable architectures that evolve with changing business and technological conditions.

- **User-Friendly Interfaces and Visualization:**

  Intuitive dashboards, GIS-based maps, 3D models, and customizable views, enabling clear, role-specific insights and decision support. By combining 3D modelling with real-time grid data, these intelligent models can serve as a foundation for extended reality (XR) applications, dynamic sensor-based monitoring (e.g., through robotics), and predictive maintenance capabilities.

- **Robust Cybersecurity and Data Governance:**

  Compliance with cybersecurity directives, strong encryption, secure access control, and privacy regulations to foster trust and protect sensitive data

- **Scalability, Cloud-Based Solutions and HPC:**

  Cloud, edge computing, modular architectures, and HPC resources to handle complex, large-scale simulations efficiently and flexibly.

- **Federation of Digital Twins and Collaboration:**

Connected platforms for TSOs, DSOs, market operators, manufacturers, and research centres to support coordination across borders and organisations, harmonized planning, and data exchange.

- **Model Validation, Verification and Auditability:**

  Transparent data sources, scientific validation, auditing, and correctness checks to ensure reliability and trust.

- **Sustainability and Environmental Considerations:**

  Integrating tools to assess environmental impacts, facilitate RES integration, and support decarbonization strategies aligned with EU climate goals

6.2 Regulatory and Compliance Requirements

Navigating the regulatory and compliance landscape is essential for the successful implementation of digital twins in the energy sector. By proactively addressing these considerations, organizations can mitigate risks, enhance security, ensure legal compliance, and unlock the full potential of digital twins to improve operations, planning, and decision-making. An analysis of the responses to Question 7 and Question 15 reveals several regulatory and compliance considerations that energy stakeholders need to address when using and implementing digital twins within their operations. The following summarizes the main themes and insights gathered from the stakeholders' responses.

Question 7	Are there any regulatory or compliance requirements that need to be considered in the use of digital twins within your operations?
Question 15	Are you aware of any regulatory or compliance requirements that need to be considered for the implementation of digital twins?

6.2.1 Key Regulatory and Compliance Considerations

A number of regulatory, compliance and internal policy factors, as listed below, must be considered when implementing digital twins so that organisations can ensure that their digital twins not only deliver operational benefits, but also comply with regulatory obligations, security policies, industry standards and corporate governance principles:

- **Data Privacy and GDPR Compliance:**

  Organizations must comply with data protection laws like GDPR. Handling customer data, especially beyond billing purposes, requires strict adherence to privacy regulations, potentially affecting data granularity and usefulness.

- **Cybersecurity and Critical Infrastructure Protection:**

  Compliance with national and EU regulations on cybersecurity and critical infrastructure protection (e.g., NIS/NIS2 [13], ISO 27001 [67], KritisV [68], BSI-Gesetz [69], etc.) is essential. Robust measures are needed to safeguard digital twins against cyber threats and ensure data integrity. Awareness of new regulations such as the EU Cybersecurity Act and the Cyber Resilience Act is necessary to ensure compliance as well.

- **Grid Codes, Market Rules and Interoperability Standards:**

Digital twins must align with EU Network Codes [70], System Operation Guidelines (SO GL) [71], national electricity laws (e.g., Electricity Law of Cyprus [72]), and standards like IEC 60870-5-104 [73], CIM [39], TASE.2 [74] or OPC UA [75]. Compliance with sector-specific regulations, such as Building Information Modeling (BIM) regulations for infrastructure projects, may be required as well.

- **Data Sovereignty and Unbundling:**

  Regulatory requirements related to data ownership, unbundling (separating supply/generation from network operations), and antitrust laws influence how data is managed and shared. Respecting data sovereignty helps maintain trust and compliance across the energy value chain.

- **Use of AI and Emerging Regulations:**

  Digital twins incorporating AI must be designed to comply with emerging AI-related regulations, such as the forthcoming EU AI Act. Ethical and transparent use of AI, as well as deterministic and trustworthy models, are necessary to meet evolving legal frameworks.

- **Environmental and Market Regulations:**

  Environmental compliance, renewable integration, adherence to market integrity rules (e.g., REMIT [76]), and transparency requirements shape how digital twins are developed and used, particularly in managing and forecasting renewable energy sources.

- **Internal Compliance and Operational Policies:**

  Beyond external regulations, internal company policies also influence digital twin implementation. Some organizations may mandate on-premises deployment rather than cloud-based solutions to maintain control and reliability. Strict access controls, public procurement rules, funding constraints, and intellectual property/licensing considerations (e.g., EU Copyright Policy) further define how digital twins are procured, managed, and operated.

6.2.2 Limitations and Considerations

While meeting regulatory, security and internal policy requirements is essential, there can be a number of practical challenges to digital twin implementation, as outlined below. By proactively recognising these obstacles and planning accordingly, stakeholders can more effectively navigate the complex regulatory environment and ensure that digital twins deliver their intended benefits while maintaining compliance and trust.

- **Data Utility Constraints:**

  If personal data is handled by DT systems, then it must be done in a way that satisfies data privacy and protection rules (e.g. by applying data anonymisation or by applying special permissions. Technical data handled by DT systems does not need to be anonymised to satisfy privacy and protection rules. Any DT system must have some governance which gives its users appropriate controlled access to data, so the availability of the data is controlled. The granularity of the data available to a given user is then whatever the given user is entitled to.

- **Resource and Infrastructure Investments:**

  Meeting stringent cybersecurity and compliance standards often demands significant investments in security infrastructure, specialized expertise, and ongoing monitoring.

- **Complex Regulatory Environments:**

  Multiple, evolving frameworks and standards complicate compliance, requiring dedicated resources to ensure alignment with all relevant directives and practices. . These can be the technical standards evolution for electrification of sectors (i.e. EVs, heat pumps, P2X, electrolyzers, DC-based assets), new regulation to fully enable renewable integration, demand flexibility and sector integration. The DT should be designed and enabled to serve these processes.

- **Technology and Interoperability Trade-offs:**

  Strict adherence to certain standards can limit technological choices and slow integration with innovative solutions. Regulatory restrictions may also reduce the scope of data sharing among stakeholders, affecting interoperability and value creation.

- **Operational Constraints and Internal Policies:**

  Internal rules—such as preferring on-premises deployments, enforcing strict access controls, or facing procurement limitations—further shape how digital twins are developed and operated, potentially reducing flexibility and efficiency.

- **Ongoing Alignment and Skill Development:**

  Continuous education, training, and proactive monitoring of regulatory changes help organizations anticipate new requirements and adjust their strategies accordingly.

6.3 Organizational and Cultural Factors

Questions 8, 16, and 23 examine cultural and organizational factors, stakeholder interactions, and collaboration requirements for the successful implementation of DTs. Through this analysis, the chapter emphasizes that successful deployment extends beyond technical capabilities. It requires a concerted effort to align organizational cultures, build trust among stakeholders, and foster a collaborative environment where knowledge is shared, strategies are coordinated, and outcomes are mutually beneficial.

Question 8 & 16	What cultural and organizational factors could (potentially) impact the adoption of digital twins in your organization?
Question 23	Are there any other specific stakeholders or user groups that you believe should be involved in the development and use of the digital twins? Please specify.

6.3.1 Adoption Challenges and Cultural Factors

Several non-technical hurdles can slow the adoption of digital twins within organizations. These challenges—ranging from resistance to change and skill gaps to issues of trust, awareness, and organizational structures—must be addressed to fully realize the potential of DTs and successful DT adoption.:

- **Resistance to Change and Skill Gaps:**

Employees may be reluctant to abandon familiar methods or doubt the benefits of new technologies. Training, early involvement of staff, and demonstrating practical advantages are key strategies to overcome these barriers.

- **Understanding and Awareness of Digital Twins:**

  The concept of digital twins is sometimes seen as abstract or poorly understood. Increasing clarity through education, training, and highlighting concrete use cases can help teams appreciate the tangible improvements DTs can bring to operations. For example, the need for training of the system operators is defined in the cybersecurity network, where dedicated training is requested for cyber-resilience scenarios.

- **Trust and Confidence in Technology:**

  Some users may distrust the need for DT technology, preferring traditional data sources and human judgment. Providing proof of reliability, demonstrating accuracy in real scenarios, and gradually integrating DT-driven decision-making can build confidence and acceptance.

- **Siloed Structures and Strategic Alignment:**

  Organizational silos, poor communication, and unclear strategic objectives impede integration efforts. Ensuring top-level commitment, aligning DT initiatives with organizational goals, and fostering cross-departmental collaboration help create a more unified approach.

- **Organizational Structure and Decision-Making Processes:**

  Unclear roles , during the DT development and integration, lengthy decision-making processes, and insufficient involvement of middle management can slow or misdirect DT development projects. Defining responsibilities early, streamlining approval workflows, and engaging managers at all levels enhance the pace and direction of implementation.

- **Data Sharing Reluctance and Privacy Concerns:**

  Fears about data security, privacy, and commercial sensitivity discourage open information exchange. The concepts of data spaces, federated architectures and peer to peer exchanges are not very clear to the minds of the involved actors so they are cautious to adopt them. Addressing these concerns with transparent policies, robust safeguards, and clear data-ownership guidelines encourages more collaborative data use.

- **Infrastructure and Resource Limitations:**

  Limited IT capabilities, budget constraints, and competing priorities can restrict adoption. Prioritizing critical use cases, seeking management support, and allocating sufficient resources are crucial steps to ensure that DTs can be deployed effectively and scaled over time.

- **Other Organizational and Cultural Factors:**

  A culture more inclined toward digital innovation generally adapts to DTs more readily, whereas those with low digital affinity may lag. High implementation costs, limited time for training, regulatory constraints on data availability, and uncertainty over the necessity of DTs can also slow progress. Encouraging innovation, covering upfront digital investment costs, carefully managing costs, clearly communicating regulatory requirements, and illustrating the necessity and value of DTs all support a smoother transition. However, in the cases that there is strong determination and planning for digital innovations these hurdles can be overcome.

6.3.2 Stakeholder Involvement

To maximize the benefits of digital twins in the energy sector, involving a diverse range of stakeholders is essential. This diverse involvement promotes innovation, standardization, knowledge exchange, and effective data governance. The 51 responses to question 23 underscore the importance of including various stakeholders in the development and deployment of digital twins:

- **Grid Operators (TSOs and DSOs):** Primary users and beneficiaries of digital twins for grid management and operations.
- **Market Operators: I**nvolved in ensuring compliance, market functioning, and regulatory oversight.
- **Equipment Manufacturers, OEMs, and Suppliers:** Play a crucial role in providing detailed models, data, components, and support for grid equipment.
- **Software Developers and IT Solution Providers:** Essential for developing and maintaining the digital twin platforms and ensuring interoperability.
- **Academia, Research Institutions, and R&D Entities:** Contribute to innovation, development of advanced models, and validation of digital twin technologies.
- **Regulators, Government Agencies, and Standardization Bodies:** Play a crucial role in developing and promoting standards for data exchange and interoperability. Respondents recommend involving harmonization and standardization institutions like VDE, FNN, IEC, CENELEC, CIGRÉ, DSO Entity, ENTSO-E.
- **Industry Associations and Working Groups:** Facilitate collaboration and consensus-building among stakeholders. CIGRÉ and DSO Entity are mentioned in some responses.
- **Cybersecurity Experts and Coordinating Institutions (EE-ISAC):** Ensure that digital twins are secure from cyber threats and comply with data protection regulations.
- **Consumer, Prosumer, Demand Response Aggregators, and Flexibility Service Providers (FSPs):** Crucial for enhancing demand-side management and integrating distributed energy resources. Their participation can optimize the use of distributed flexible assets and strengthen the role of digital twins in energy management.
- **Urban Planners and Municipalities:** Collaboration can support infrastructure planning and the integration of smart city initiatives. Involving policy makers and city councils is suggested.

6.4 Data Management, Exchange, and Standardization

Effective data management, exchange, and standardization are critical components in the implementation and operation of digital twins in the energy sector. The responses to Questions 13, 20, 21, and 22 provide valuable insights into current practices, challenges, and future requirements for data sharing, particularly between TSOs and DSOs. Understanding these aspects is essential for ensuring smooth interoperability, reliable simulations, and informed decision-making across the European energy ecosystem.

Question 13	What are the current limitations on your data exchange processes, specifically between Transmission System Operators (TSOs) and Distribution System Operators (DSOs)?

Question 20	Which stakeholders do you currently need to exchange data with, or foresee a need to exchange data with, particularly concerning network topologies, parameters, etc.?
Question 21	What kinds of data do you currently share, or expect to share in the future, and what are the objectives of sharing this data?
Question 22	Do you currently use or plan to use digital twins to exchange data with external organizations? If so, which ones? Please provide details, such as whether you need to follow specific data exchange standards, etc.

6.4.1 Current Data Exchange Challenges

Stakeholders face several obstacles in data exchange processes, especially between TSOs and DSOs. The 23 responses to question 13 highlight the key challenges as follows:

- Lack of Standardization and Interoperability
- Data Quality and Accessibility Issues
- Regulatory and Compliance Constraints
- Technical Limitations and Legacy Systems
- Limited Real-Time Data Access
- Organizational and Cultural Barriers

6.4.2 Types and Objectives of Data Sharing

The 71 responses to question 21 highlight the specific type of data shared among energy stakeholders and the objectives driving this data exchange. Data exchanged among stakeholders typically includes network topology, load and generation forecasts, asset health metrics, outage information, and market-related data. The primary objectives are to enhance grid stability, improve market transparency, support regulatory compliance, foster innovation, and integrate renewable energy sources more effectively. The types and objectives of shared data are outlined in the list below:

- **Operational and Real-Time Data:**
    - **Grid Parameters:** Voltage levels, current flows, frequency, and other real-time operational metrics are shared to ensure grid stability and efficient operation.
    - **Network Topology:** Detailed network configuration data, including data about lines, transformers, and switchgear, is exchanged for planning and coordination.
    - **Outage Information:** Data on planned and unplanned outages helps coordinate maintenance and minimize disruptions.
- **Market and Economic Data:**
    - **Market Clearing Prices, Bids, Offers:** Sharing these data facilitates transparent market operations and efficient energy trading.
    - **Demand and Generation Forecasts:** Exchanging forecasts supports load balancing, and resource optimization.

- **Asset and Infrastructure Data:**
    - **Equipment Specifications:** Technical details of equipment from manufacturers are shared for modeling, simulation, and maintenance.
    - **Asset Performance Data:** Monitoring data on asset health and performance aids in predictive maintenance and asset management.
- **Consumption and Generation Data:**
    - **Load Profiles:** Data on energy consumption patterns assists in demand response and grid planning.
    - **Renewable Generation Data:** Information on RES output is crucial for integrating variable energy sources into the grid.
- **Regulatory and Compliance Data:**
    - **Reporting Metrics:** Data required for regulatory compliance, performance metrics, and auditing is shared with authorities.
    - **Environmental Impact Data:** Sharing data on emissions and environmental assessments supports sustainability goals and regulatory adherence.
- **Research and Innovation Data:**
    - **Simulation Results:** Academic and research institutions share modeling and simulation data to advance technological developments.
    - **Pilot Project Data:** Data from pilot projects and demonstrations is shared to validate new solutions and share learnings.

6.4.3 Stakeholders Involved in Data Exchange

A broad spectrum of stakeholders participates in data exchange, as identified by the 80 responses to question 20. Beyond TSOs and DSOs, this includes market operators, aggregators, renewable energy producers, technology providers, research institutions, equipment manufacturers, regulators, and others. This diversity highlights the complexity of the energy sector's ecosystem, where each participant depends on accurate and accessible data to optimize operations, ensure system stability, and contribute to a more resilient and efficient energy market.

- **DSOs:** Almost all respondents recognize DSOs as primary stakeholders for data exchange, especially concerning network topology, operational data, and coordination efforts.
- **TSOs:** Crucial for sharing data related to transmission networks, grid stability, and cross-border energy flows.
- **Market Operators (MOs):** Engagement with MOs is necessary for market-related data, including pricing, demand forecasts, and trading activities.
- **Aggregators and Local Energy Communities (LECs):** Becoming increasingly important with the rise of DER.
- **Regulators and Regional Coordination Centres (RCCs):** Compliance and coordination require data exchange with them.
- **Energy Suppliers/Providers and RES Producers:** Data sharing is essential for integrating generation data and ensuring supply-demand balance.

- **Technology Providers and ICT Suppliers:** Data exchange with them supports system integration, software solutions, and technological advancements.
- **Research Institutes and Universities:** Collaborations for research and development involve sharing data for innovation and academic studies.
- **Equipment Manufacturers:** Interaction with manufacturers of grid equipment, storage solutions, and generation equipment is necessary for technical specifications and asset management.
- **E-Mobility Operators and Charging Point Operators (CPOs):** As electric vehicles become more prevalent, data exchange with these stakeholders supports grid management and infrastructure planning.
- **Industrial Consumers and Smart Building Service Providers:** Large consumers and smart building operators require data exchange for demand response, energy efficiency, and grid interaction.
- **City Councils and Environmental Organizations:** Engagement with local authorities and environmental groups is important for urban planning, sustainability initiatives, and regulatory compliance.

6.4.4 External Data Exchange Through Digital Twins

While current direct use of digital twins for data exchange with external organisations remains limited, many stakeholders' express the intention to use them in the future according to the 67 responses to question 22. They anticipate enhanced data integration, real-time monitoring, predictive maintenance, and more efficient collaboration with partners such as TSOs, DSOs, manufacturers, and technology providers. Achieving these benefits, however, depends on the adoption of suitable data exchange standards (e.g., IEC 61850, IEC 61970/CIM, IEC 60870-5-104, IEC 62351, CGMES, MQTT, API-based formats like JSON, and OPC) and compliance with security protocols and data protection regulations.

Despite growing interest, several barriers continue to impede the broad adoption of digital twins for data exchange with external organisations. Technical complexities, a lack of standardized data models, and insufficient expertise or awareness pose significant challenges. Regulatory limitations and privacy concerns further influence data-sharing capabilities. Still, stakeholders envision various use cases emerging as digital twins mature. For instance, TSOs and DSOs plan to leverage them for grid model exchange and operational data sharing; manufacturers seek to improve asset management through predictive maintenance; and research institutions look to facilitate simulation-based collaborations and drive innovation.

As organizations address these challenges and embrace standardization, digital twins are poised to become key enablers of cross-organizational data exchange, fostering a more integrated and informed energy ecosystem.

6.5 Outcomes and Strategic Value of Digital Twins

Digital twins represent a transformative opportunity for the energy sector. They can drive operational efficiencies, enhance strategic planning, and support Europe's climate neutrality ambitions. Insights from Questions 24, 25, and 26 illustrate stakeholders' expectations regarding operational benefits, long-term sector impacts, and contributions to environmental goals.

Question 24	What outcomes or benefits do you expect to achieve from implementing a digital twin in the energy market?
Question 25	Where do you believe a digital twin will have the most significant impact on the future of the energy sector?
Question 26	Considering the EU's target for climate neutrality by 2050 as outlined in the European Climate Law, do you believe that a federation of digital twins can contribute to achieving this goal? If so, how?

6.5.1 Operational Outcomes and Benefits

With 69 responses, Question 24 reveals a broad consensus that digital twins can significantly improve day-to-day operations:

- **Enhanced Grid Management and Efficiency:**

  Stakeholders anticipate better real-time monitoring, scenario simulations, and predictive maintenance, reducing downtime and extending asset lifespans. Accurate load and generation forecasting further streamlines operations, supports cost savings, and enables more effective integration of renewable energy sources.

- **Market Innovation and Transparency:**

  Improved visibility into grid conditions and market dynamics allows for more informed decision-making, compliance with regulatory requirements, and the creation of new services. Clearer insights foster cooperation among TSOs, DSOs, and market operators, ultimately benefiting customers.

- **Stakeholder Collaboration and Data-Driven Insights:**

  Federated data platforms and standardized interfaces facilitate information sharing, support strategic planning, and enhance cross-functional collaboration. As organizations leverage digital twins to break down data silos, they can align operational strategies and investment decisions more effectively.

- **Customer Engagement and Sustainability:**

  By enabling more responsive and reliable energy services, digital twins can improve customer satisfaction and contribute to environmental objectives through greater energy efficiency and reduced emissions.

6.5.2 Strategic Impact on the Future of the Energy Sector

With 81 responses, question 25 provides a comprehensive view of digital twins' long-term influences on the energy landscape:

- **Facilitating Renewable Integration:**

  Digital twins help manage the variability of renewable generation, reducing curtailment and improving the accommodation of high shares of wind and solar energy.

- **Enhancing Grid Resilience and Reliability:**

Advanced modelling and predictive analytics bolster system robustness against disturbances, ensuring a more stable and secure supply.

- **Accelerating Innovation and Technology Validation:**

  By serving as testbeds for new solutions, digital twins enable stakeholders to pilot, refine, and scale emerging technologies faster and with less risk.

- **Informing Market Operations and Regulatory Alignment:**

  Scenario analysis, what-if simulations, and adherence to interoperability standards help align market rules, grid codes, and operational practices, supporting more efficient and transparent market operations.

- **Encouraging Cross-Border Cooperation:**

  Harmonized data models and interoperable digital twins promote coordinated actions between different regions and Member States, fostering a more integrated and collaborative European energy system.

6.5.3 Contribution to Climate Neutrality Goals

With 73 responses, Question 26 indicates strong stakeholder consensus that a federation of digital twins can aid in achieving the EU's 2050 climate neutrality target:

- **Optimizing Resource Use and Reducing Emissions:**

  Digital twins enable more efficient system operation, better forecasting of renewable output, and smarter use of flexibility resources, all contributing to lower greenhouse gas emissions.

- **Supporting Decarbonization Strategies:**

  By modelling low-carbon technologies and forecasting future conditions, digital twins help stakeholders develop and implement effective decarbonization pathways.

- **Enabling Data-Driven Policy and Investment Decisions:**

  Comprehensive scenario modelling informs policymakers, system operators, and investors in making decisions aligned with long-term sustainability goals, promoting resilient infrastructure and market frameworks.

- **Fostering Collaborative Solutions:**

  A federated approach encourages knowledge exchange, best practice sharing, and collective problem-solving, accelerating the transition toward a climate-neutral energy system.

7 Conclusions

7.1 Summary of Findings

The analysis of the smart grid digitalization landscape and associated innovation projects reveals significant insights, which can be categorized into key thematic areas to effectively map and summarize the findings. The identified categories can be branched as follows:

1. Data Management and Interoperability, which is associated with managing vast amounts of data while ensuring seamless integration across diverse systems.
2. Cybersecurity, highlighting the importance of protecting smart grid infrastructure against emerging threats and vulnerabilities.
3. Stakeholder Coordination, including strategies for enhancing collaboration among diverse actors, including utilities, policymakers, and technology providers.
4. Regulatory Aspects, which assesses the regulatory frameworks required to support innovation and ensure compliance across the smart grid ecosystem.
5. Future Development of EU Grids and the Role of Digital Twins, investigating the potential of Digital Twins to shape the future of grids by enabling advanced modelling, optimization, and predictive maintenance.

The key findings derived from the surveys and stakeholders' analyses are designated below, together with the thematic categories that they are relevant to:

- Interoperability challenges have been identified by projects, emphasizing that, in some cases, data silos are created and limitations to integrate digital systems seamlessly across the grid. Legacy systems and heterogeneous standards are also identified as common hurdles to the interoperability issue. (Category 1)
- Heterogeneous data sources, data formats, information models, granularity level, new IoT devices across the network and at grid edge, data privacy and latency in real time processing concerns have been identified as challenges in several projects. (Category 1)
- Standardization of grid assets communication and coordination among System Operators, market participants and consumers are still considered as challenges, while significant progress has been made on a regulatory point of view with Data Spaces regulation and the Demand Response Network Code in the pipeline for official publication. (Category 3)
- System planning methodologies developed in projects are addressing either the transmission or the distribution levels, while they do not propose a coordinated system planning process for both levels, integrating as well with the hybrid AC-DC grid technology. (Category 3)
- There is a lack of clear and substantial incentivization mechanisms to promote new technology and digital systems investments. Cost benefit analysis need to be updated to incorporate the impact of digital solutions, especially in cases where they optimize the usage of grid assets capabilities. (Categories 4&5)
- DT depends on having a low risk of misalignment between the digital model and actual grid conditions to achieve system modelling accuracy sufficient to support operational decision-making and predictive maintenance. There is a need for real-time data integration, handling large volumes of incoming data without delays and high reliability. (Category 1)
- Security is considered an essential technical capability of digital twins, especially concerning the protection of sensitive operational and customer data. A governance model is needed to control who has access to which data. Digital twins for grid operation are adopting encryption

and multi-factor authentication to ensure the system resilience and compliance with regulation. (Category 2)
- The data generated from grid assets, market and operation processes are growing immensely and cloud -based digital-twin architectures are emerging as a credible solution for ensuring scalability and greater computational capacity. (Category 1)
- While data volumes increase, at the same time the stakeholders are expressing a need for more sensors and monitoring equipment to be installed on the grid, since they are still areas of the grid with low observability. This can be related also with the need to increase the smart meters penetration levels across Europe, which is also indicated in related reports, as several countries in Europe (like Greece, Hungary, Germany, Poland and others) still have a smart meter penetration level lower than 20%) (Category 5)
- Digital twin technologies must interface with legacy grid equipment and various data sources. Thus, interoperability is emerging as a significant element of digital twins that will need to integrate smoothly with SCADA, GIS, EMS systems, functioning in a larger operational ecosystem. (Category 1)
- The complexity of the energy systems is extremely high and requires significant computational effort; available computational capacity can limit the scenarios and multi-fault incidents that can be handled by DTs. (Category 1)
- There is a need to improve the real-time forecasting functionalities to forecast the peak loads and rapid demand fluctuations. (Category 5)
- As far as the benefits of DTs are concerned, the stakeholders have great expectations for DTs deployment. Apart from day-to-day operations they see the need to support the grids against natural disasters, equipment failures and cyber-attacks. (Category 5)
- Stakeholders are expecting DTs to facilitate the coordination and data exchange of market actors and support the integration of more renewables in the energy system. (Category 3)
- Stakeholders expressed that DTs would improve their decision making with accurate predictions and calculations of future scenarios and investment prospects (Category 5)
- The smooth integration of modern digitalized equipment with the legacy systems and the generic way data exchange is defined in the network codes have arisen as concerns among stakeholders. (Category 1)
- Engaging regulatory bodies is essential for aligning policies and frameworks with technological advancements in digital twins, ensuring their seamless integration into energy sector operations. (Category 4)
- Stakeholders view digital twins as integral to achieving the EU's climate neutrality target by 2050. They are expected to optimize renewable energy integration, enhance grid efficiency, and facilitate decarbonization efforts. (Category 5)

7.2 Recommendations

Based on the results of the analysis of T2.1 and T2.2, some recommendations for all actors in the energy value chain have been derived using the same categorisation of the findings, while adding some additional categories:

- **Data management and interoperability:** it is crucial to prioritize interoperability and standardization in optimizing energy system digitalization during the developments of new digital tools by technology providers, as well as the implementation of digital grid upgrades by energy stakeholders. Therefore, adopting unified communication protocols and standardized data formats by technology developers and energy stakeholders , alongside advancing the implementation of CIM, DCAT, and SAREF standards, is considered highly effective in enhancing data exchange and integration, while maintaining data quality and security. Moreover, enhanced real-time data integration by strengthening capabilities to gather and consolidate real-time data from sensors, smart meters, and other sources across the distribution network it is relevant to unlock distributed flexibility potential. Having the DTs of the electricity grid which are interoperable with other sectors DTs and Data Spaces that relate with weather phenomena, Geospatial information of the landscape, water and gas infrastructures enables the energy system resilience against extreme phenomena.

- **(Cyber-)security:** To secure critical energy infrastructure, strengthening cybersecurity, and establishing frameworks to counter cyber threats is considered vital. To form the cybersecurity shield, GDPR requirements need to be adhered to safeguarding data privacy, as well as cooperation of energy infrastructure owners/operators and end users to fast deploy all respective cybersecurity guidelines, tools and directives.

- **Stakeholder coordination:** It is considered highly essential to enhance stakeholder engagement for advancing energy systems. This could be achieved, on the one hand, via encouraging collaboration among TSOs, DSOs, consumers, and regulators to address energy challenges. All energy stakeholders should support the joint effort for collaboration, each one from its role/place. On the other hand, by organizing workshops and training sessions by innovation promoters (i.e. in grids by SOs, in markets by MOs, in law by national authorities) to enhance awareness and understanding of new energy models and digital solutions, while promoting more effective participation and adoption.

- **Regulatory aspects:** Harmonization of regulations across EU can help eliminate barriers to cross-border and cross-sector energy collaboration. Policy reforms, that encourage the adoption of digital technologies and attract investments relevant for a more interconnected energy market, are also essential for the transition to a digitalised energy system. The enhanced monitoring and acceleration of national adoption of European regulation together with regulatory sandboxes can assist the fast harmonization and innovations across. Europe.

- **Future development of EU grids and the role of DTs:** The development and valorisation of tools and systems designs that promote the incorporation of RES are key for the decarbonisation of the energy system. Particular attention should be paid to prioritising investments in predictive analytics, real-time monitoring, real-time threat detection and response mechanisms. Such investments help enhancing resilience and ensuring robust protection of the system. Integrating DTs, AI, and IoT enables improved system planning, predictive maintenance, and operational efficiency generating resilience and efficiency gains for the system. System operators should be facilitated to complete their grid upgrade projects and grid digitalisation by the regulators and national authorities with proper incentivisation and acceleration of licensing procedure.

- **Technical configurations of the digital solutions:** Scalability of the technical solutions can be enhanced through the adoption of open-source and cloud-based solutions. Technology companies should make sure that this is well validated during their respective developments. A DT architecture which entails a cloud-based solution also enhances the computational capacity of the adopted system. Another key aspect for scalability deals with the Pan-

European DT adaptability to any reforms in guidelines and regulations about the market operation and connection requests for renewable energies.

- **Market aspects:** The development of dynamic pricing models and flexibility markets empowers consumer engagement and optimizes overall energy management. Innovations in market mechanisms should be promoted by policy makers to enhance capacity markets and provide incentives for flexible energy services, supporting system reliability and efficiency. Flexibility market support enable digital twins to forecast and facilitate flexibility markets, supporting dynamic demand response and ancillary services

- **System modelling:** building a collaborative platform where TSOs, DSOs, market operators and other stakeholders can co-simulate complex market-grid interactions, share data, and jointly analyse scenarios would help an overarching assessment of the system There should be joint efforts by the engaged stakeholders in dedicated activities to define such a framework that will enable the study and evaluation of future scenarios to highlight market opportunities as well as system needs . Furthermore, regulators at national and European level should promote these activities.

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Annex A Task 2.1 Research Questionnaire

Considering the experiences gained from digital perspective from previous projects such as Interrface, OneNet, BD4NRG, TDX-Assist, or CoordiNet, as well as CGM program lessons (CIM/CGMES) where relevant, this task will gather the main projects' outcomes to create a **knowledge base for DEF** focusing more on the information and communication layer of the SGAM architecture. The focus lies on the data interoperability platforms like IEGSA, OneNet connector, int:net maturity model, data-sharing and metadata used between different system operators to support flexibility, standards and interfaces used to enhancing flexibility and improve the efficiency of the overall energy system. **Main gaps** in terms of data models, communication protocols, tool limitations, the missing interfaces and adapters used between system operators, and the data exchanges gaps to support the flexibility needs, are analysed. Finally, we propose **ways for addressing some of these gaps**, e.g., using the merged standards for data exchange, development of interface/adapters for TSO/DSO and customers, integration of cross-sector, cross-border components in the reference architectures and platforms to support flexibilities, etc., that will facilitate enhanced system planning and grid operation while enhancing the flexibility and resilience of the EU energy system. Additionally, the **cyber physical nature** of the digitalised pan-European grid with the related practices of IT and OT convergence in the smart grids, will be outlined, and their **impact on reliability and resilience merits** of the grid will be described, setting the areas to focus for **dynamic monitoring and controllability** of the physical assets and shielding cyber layers of pan-European grid.

Projects Reviewer Information		
1	Name and Surname	
2	E-mail	
3	Organisation	
4	Analysed Project	

A.1 Question 1

1. What is the objective of the project under review? *[provide a brief explanation of the main objectives of this project]*	
Has the project been completed?	

A.2 Question 2

2. Did the project develop **interfaces** and/or **data interoperability** platforms to enhance **flexibility** and improve the **business processes** (system planning/asset management, system operation, and energy markets)?	
References	
If yes, for what are these interfaces? Can you define them in terms of **information** models, timing requirements and **interaction** sequences?	
References	
If yes, provide a brief description or picture of each interface's architecture with a reference to the SGAM model. [Please provide a short description of the interface and reference to the relevant documentation, add lines as necessary]	
References	

A.3 Question 3

3. What were the **key findings** regarding the implementation of standards and interfaces to improve **flexibility** and **business** processes (system planning/asset management, system operation, energy markets)? [Please provide a short description and reference to the relevant documentation, add lines as necessary]	
References	

A.4 Question 4

4. How did the project contribute to the development of **data interoperability** platforms and data-sharing frameworks (e.g. metadata)?	
References	

A.5 Question 5

5. Did the project define **communication** and **data exchange** requirements? [Please describe briefly]	
References	

A.6 Question 6

6. Which **data models** were used? [Please list the models and the corresponding reference]	
References	

A.7 Question 7

7. Which **protocols** and **standards** were applied? [Please list in the table with the corresponding reference]	
References	

A.8 Question 8

8. What specific **gaps** were identified in terms of data format, information models and communication protocols?	
References	

A.9 Question 9

9. Can you provide **examples** of tool **limitations** that were identified during the analysis?

References	

A.10 Question 10

10. What were the significant **missing** interfaces and adapters **identified** between system operators, TSOs, DSOs, and customers?	
References	

A.11 Question 11

11. How were **data exchange** gaps affecting the support for **flexibility** requirements identified and analysed?	
References	

A.12 Question 12

12. What are the proposed solutions for **addressing gaps**? e.g., using the merged standards for data exchange, development of interface/adapters for TSO/DSO and customers, integration of cross-sector, cross-border components in the reference architectures and platforms to support flexibilities, etc?	
References	

A.13 Question 13

13. How do these proposals aim **to improve** the **business processes** (system planning/asset management, system operation, energy markets) efficiency while facilitating the **flexibility** and **resilience** of the EU energy system?	
References	

A.14 Question 14

14. What **challenges** are anticipated in implementing these proposals, and how can they be overcome?	
References	

A.15 Question 15

15. Are there any **developments** in the project that **address the cyber-physical reliability and resilience** of the electricity grid? [yes/no]	
If yes, what are the cyber and physical **assets/elements** that the project addresses?	
References	
If yes, what are the potential **risks** identified in the project that are associated with the cyber-physical nature of the grid, and **how are they mitigated**?	
References	
If yes, what are the identified **focus areas** in the project **for dynamic monitoring and control** to ensure the reliability and resilience of the grid?	
References	
If yes, how can the cyber layers of the **pan-European grid** be effectively monitored and protected from potential threats? What are **the propositions of the project**?	
References	

Annex B Questionnaire Responses Regarding the Projects of EU Energy Digitalisation

The following sections outline the content of each analysed EU research project.

B.1 2LiPP

(Q1) 2LiPP's Project Objective: The 2LIPP project [77] is currently underway, aiming to retrofit the Bornholm CHP plant with a scalable hybrid energy storage system that incorporates three low-cost, sustainable technologies[1]. Managed by an innovative Energy Management System (EMS), these technologies will optimize storage charging and dispatch. This demonstration will prove a new approach to transitioning power plants away from fossil fuels while ensuring energy supply and grid stability. By reusing existing facilities and combining technologies, 2LIPP reduces energy storage costs and improves efficiency. The project also provides feasibility studies to guide utility companies in retrofitting their plants, supporting Europe's renewable energy integration and grid stability.

Project Status: Ongoing

B.2 BeFLEXIBLE

(Q1) BeFLEXIBLE Project Objective: The BeFLEXIBLE project [78] is currently underway, and it aims to increase the flexibility of the energy system, improve cooperation between DSOs and TSOs and facilitate the participation of all energy-related stakeholders. This will be done through the validation and large-scale demonstration of adapted and proven cross-sectoral services, interoperable data exchange platforms for smart grids operation and the creation of the required system architecture framework that will enable the creation of new business models providing additional value to meet consumers' needs in compliance with a stable regulatory framework. The objectives of the project namely are: (i) to design cross-sector business models to enhance flexibility through analysis and validation; (ii) to conduct cost-benefit analysis for flexibility options to ensure profitable, scalable, and replicable business models; (iii) to assess regulatory alternatives based on existing frameworks and the Clean Energy and Fit for 55 Packages; (iv) to foster local flexibility platforms and integrate DSO-TSO coordination platforms; (v) to develop recommendations and solutions from various projects and initiatives; (vi) to create consumer-centric and grid-centric services for deployment and optimization at DEMO sites; (vii) to boost consumer engagement and acceptance of technologies by integrating energy and other services; (viii) to implement exploitation, dissemination, communication, and capacity-building activities to maximize project impact and empower consumers toward prosumer scenarios.

Project Status: Ongoing

(Q2) BeFLEXIBLE interfaces and data interoperability platforms to enhance flexibility and improve business processes:

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[1] (i) molten hydroxide salt storage, (ii) lithium battery which is based on reused car batteries, and (iii) a flywheel, based on non-rare metals and with unprecedented lifetime.

BeFLEXIBLE implements digital platforms for designing a Grid Data and Business Network (GDBN) and defining a system architecture to ensure full data interoperability. The platforms aim to facilitate seamless data exchange and improve operational efficiencies across various energy systems. The project carries out large-scale validation and demonstration of these platforms through multiple pilot tests across different countries, thus being tested in diverse environmental and consumer conditions.

Q2i: BeFLEXIBLE specification of the purposes of the interfaces, along with their definitions in terms of information models, timing requirements, and interaction sequences.

The interfaces ensure efficient and seamless communication between different stakeholders in the energy ecosystem, including DSOs, TSOs, and a broad variety of energy market participants. BeFLEXIBLE creates a GDBN that facilitates the exchange of data across different platforms and systems, thus, the information models include various types of data relevant to grid operations, market transactions, and asset management, ensuring that all necessary information is accurately and consistently represented.

Q2ii: A brief description or illustration of each BeFLEXIBLE interface's architecture of, referencing the SGAM model.

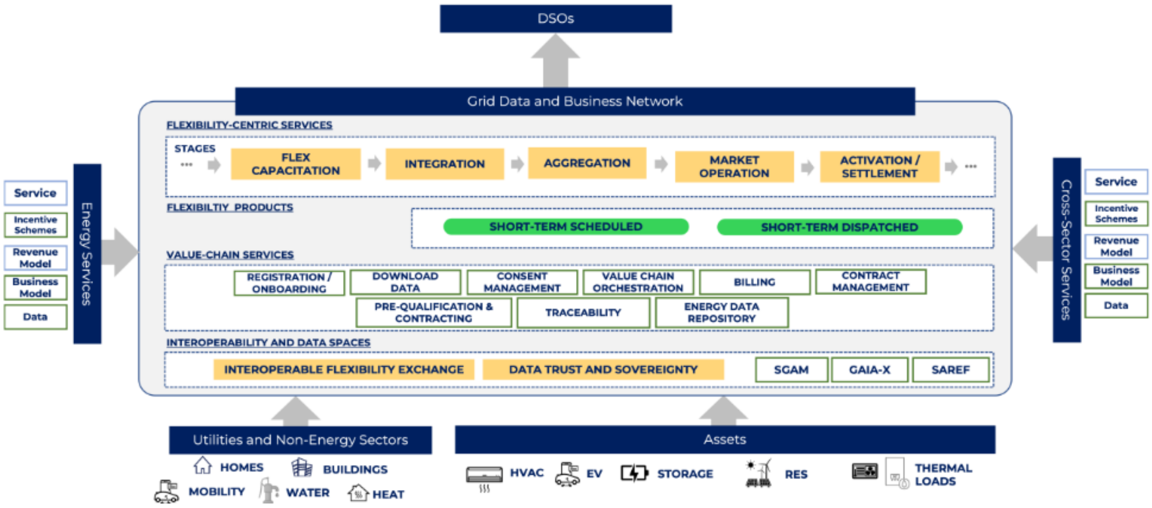


Figure 6: Conceptual design of GDBN architecture

The BeFLEXIBLE Grid Data and Business Network (GDBN) is a digital platform to provide support to all activities in the Flexibility-centric value chain. Its architecture is composed by several logical modules concerning the adoption of the flexibility value chain: (i) the flexibility-centric services, hosting all the services that embody the different phases of the value chain; (ii) the flexibility products, that characterize how the components of the flexibility-centric services module should behave in terms of the flexibility provision; (iii) the value chain services, to support the basic features of the GDBN as an enabler of the value chain (registration, data exchange, contracts management, etc.); and the (iv) interoperability and data spaces module, to provide data interoperability and sovereignty for external services and actors interfacing with the GDBN.

(Q4) BeFLEXIBLE contribution towards the development of data interoperability platforms and data-sharing frameworks.

- It develops and validates interoperable data exchange platforms designed to enhance communication between stakeholders (e.g., DSOs, TSOs, markets), promoting seamless data sharing and integration across different systems and sectors.
- It establishes common metadata standards and ensures data from different sources could be processed.
- It creates open services ecosystem that leverage data-driven services to meet the needs of energy stakeholders, including adaptive, interoperable, and secure services designed to optimize energy management and increase flexibility of the energy system.

(Q5) BeFLEXIBLE definition of communication and data exchange requirements.

To identify data exchange requirements of the GDBN, BeFLEXIBLE had to foresee the information that would be processed. Therefore, it was necessary that an end-to-end methodology was proposed for the provision of flexibility. This is divided into the phases:

- Pre-qualification - dealing with the certification of aggregators and flexible assets, ensuring they are financially and technically able to provide flexibility and participate in flexibility markets.
- Negotiation Preparation - DSO forecasts grid constraints and if potential grid constraints are identified, and it is deemed that flexibility can solve them, the DSO forwards its needs to the market, so that Aggregators can submit bids.
- Market Operation - market clearing is done by the market platform, and final bids are selected by the DSO.
- Activation - flexibility from consumer-side assets is activated.
- Validation & Settlement - flexibility provided by each aggregator is calculated using pre-agreed baselines, resulting in remuneration/penalties to be settled between the Aggregators and DSO. This last phase can be done with or without the support of the GDBN, as decided by the DSO.

(Q10) BeFLEXIBLE significant missing interfaces and adapters identified between system operators, TSOs, DSOs, and customers.

The absence of data-sharing interfaces for real-time TSO-DSO coordination impedes effective balancing of demand-response, congestion management, and RES integration. Additionally, the lack of consumer interfaces and feedback mechanisms, along with the insufficient integration of DERs into the market and the absence of standardized interfaces for energy trading platforms, further enhance these challenges. Furthermore, data security and privacy concerns, including missing authentication and authorization processes, are also significant issues.

(Q13) BeFLEXIBLE proposals for improving the business processes (i.e., system planning/asset management, system operation, energy markets) efficiently while facilitating flexibility and resilience of the EU energy system.

Though the relevant business processes that aim to assess this have been indicated: The Business Models (BM) selected are related to the provision of flexibility to third parties but are not limited to flexibility and try to account for other very linked activities such as the provision of flexibility resources or the management of these resources.

- BMs for DERs provision, including PV systems, BESS, HEMS, WH, HP and HVAC.
- BMs for DERs provision as a Service including Solar-, Energy Storage-, Smart Home-, Charging-, HVAC-as-service.
- BMs to reduce the electricity bills of flexible Consumers including small and large consumers optimizing electricity bills,

- BMs for cross-sector activities including optimizing EV charging, safety/security, healthcare, and social services for residential Consumer, Minimizing non-renewable consumption.
- BMs for the operation of power grid including flexibility acquisition for grid operation and Data acquisition for grid management and control.
- BMs for supplying energy to Consumers including Traditional retailing mode, Retailers managing Consumers’ flexibility.
- BMs for communities including Energy cooperatives, Community flexibility aggregation, and E-mobility cooperatives.

BeFLEXIBLE also brings a role model that indicate the BMs can be characterized by:

- Properly identifying the role model with all the relevant roles involved in the BMs related to the flexibility provision, including cross-sector activities that can provide added value.

B.3 DATA CELLAR

(Q1) DATA CELLAR’s Project Objective: DATA CELLAR [79] is ongoing, and it aims to create a federated energy dataspace to support local energy communities (LECs) in the EU. Using an innovative rewarded private metering approach for easy onboarding, it ensures smooth integration with other EU energy data spaces. The project’s objectives are (i) to develop a dynamic data hub for continuously updated, reliable data; (ii) to implement privacy and cybersecurity measures per GDPR and national regulations; (iii) to provide access to AI models and data-driven energy services to support the energy transition; (iv) to create a data-sharing ecosystem for LECs via a DLT-based marketplace; and (v) to evaluate novel business models with real Energy Community use cases and collaborate with EU initiatives for interoperability testing.

Project Status: Ongoing

(Q2) DATA CELLAR **interfaces and data interoperability platforms** to enhance flexibility and improve business processes:

DATA CELLAR’s core objective is to facilitate the implementation of a collaborative platform that provides a dynamic, interoperable, modular, and secure energy data space, designed to ensure seamless data exchange and integration with other EU energy data spaces. DATA CELLAR incorporates tools to assist in system planning and operational efficiency; on top of that, it includes the marketplace for trading data and pre-trained AI models, which aids in aligning incentives across stakeholders and enhances interoperability. Finally, the project assembles compliance and interoperability with the Gaia-X ecosystem.

Q2i: DATA CELLAR’ specification of the purposes of the interfaces, along with their definitions in terms of information models, timing requirements, and interaction sequences.

The interfaces include a dynamic data hub for real-time and historical data management, AI models for advanced analytics, and a blockchain-based marketplace for trading data and AI models. The project emphasizes standardization, minimal latency for real-time updates, periodic AI model training, and secure, transparent transactions to ensure seamless integration and efficient data exchange among stakeholders and dataspaces.

Q2ii: A brief description, or illustration of each DATA CELLAR **interface’s architecture**, referencing the SGAM model.

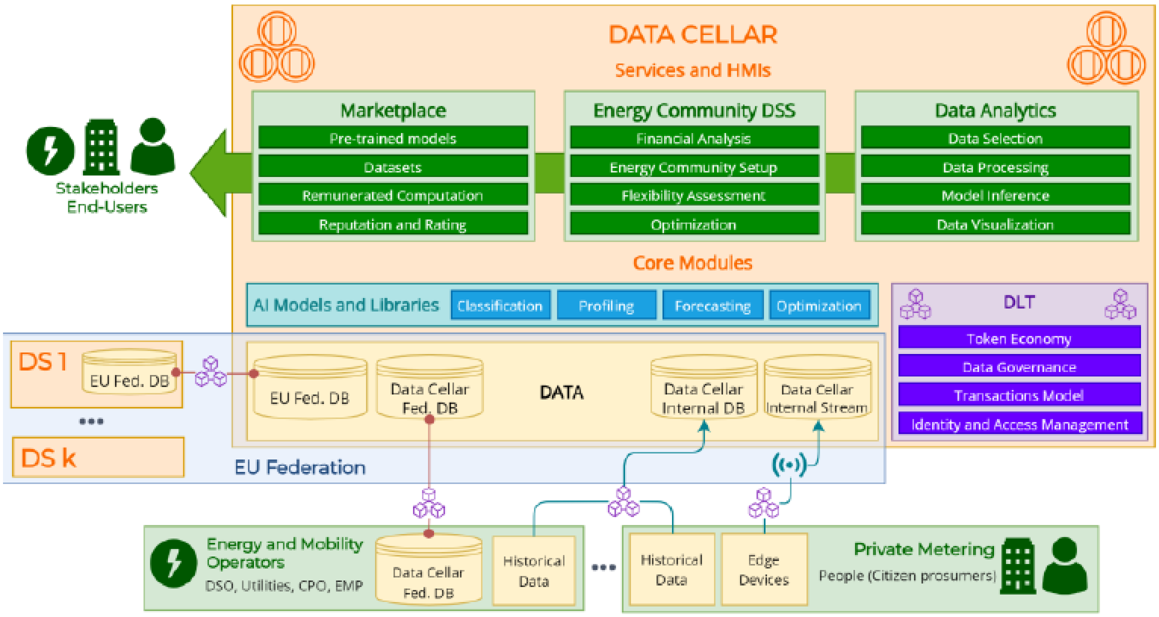


Figure 7: The DATA CELLAR layered architecture

An image is provided with the layering of the processes regarding DATA CELLAR service-oriented architecture. The DATA CELLAR platform presented is composed of three main services with their respective Human-Machine Interfaces:

- The Marketplace where stakeholders, are remunerated for the provision of datasets, direct streams of energy data, or AI models and algorithms. In addition, the transactions for provisioning or supplying data and models is authenticated via various methods among the stakeholders.
- A decision-making assistant system for energy communities' development to support energy utilities, DSOs, and technology providers, supporting users to assess optimal scenarios related to different services. Grid operators will be able to assess the optimal location of resources to improve the operation of the distribution grid.
- A Data Analytics platform to guide the design of data streams through models acquired from the DATA CELLAR marketplace.

(Q3) DATA CELLAR's key findings regarding the implementation of **standards and interfaces** to improve flexibility and business process (system planning/asset management, system operation, energy markets).

According to DATA CELLAR,

- Adoption of standardized data formats and communication protocols enhances the interoperability between various systems and platforms. This allows for seamless data exchange and integration, reducing the time and effort required for data transformation and reconciliation.
- By implementing standardized interfaces, DATA CELLAR facilitates the automation of many business processes, improving efficiency and minimizing human errors.
- Standards-based interfaces make it easier to scale the system and adapt to new business requirements and changes in the technological landscape.
- The use of industry standards and interfaces reduces the need for custom development and maintenance, leading to significant cost savings in both short and long term.
- Standardization ensures data to predefine its quality, improving consistency of data across different systems and making reliable for decision-making processes.

(Q4) DATA CELLAR's contribution towards the development of **data interoperability platforms and data-sharing** frameworks.

DATA CELLAR creates a federated energy dataspace that exploits seamless data exchange and integration among the various platform end-users, through the implementation of standardized metadata formats, the DATA CELLAR -customized data model, and its customized ontology with well-defined taxonomy and metadata.

(Q5) DATA CELLAR's definition of **communication and data exchange requirements**.

The project establishes standardized metadata and data models, i.e., OWL and RDF under the development of the ontology, to ensure consistent data representation and seamless data exchange.

(Q6) **Data models** used in DATA CELLAR.

Various critical factors are considered such as Gaia-X [80] compliance and interoperability and the IDS for domain-agnostic data model, while for the domain-specific the DATA CELLAR customized ontology is used.

(Q7) **Protocols and standards** applied in DATA CELLAR.

DATA CELLAR exploits a series of protocols and standards:

- The CIM connector protocols for consistent data integration and exchange across various systems in the energy sector.
- The OWL protocol from W3C exploited for designing and developing DATA CELLAR ontologies and taxonomies, while a series of formats for metadata storing was used, including RDF.
- Communication standards such as the MQTT and HTTPS.

(Q8) **Gaps** identified in terms of data format, information models and communication protocols in DATA CELLAR.

- Inconsistencies and discrepancies between the ontology and the actual data available in various databases (and validation cases of the project).
- The different data formats and schemas across the databases hinder the seamless data integration, requiring the development of standardization.
- Ensuring semantic agreement between different ontologies and data structures needs mapping and information analysis.
- Interoperability among different data spaces for the seamless data exchange is also another challenge arising due to varying protocols and standards.

(Q9) Examples of tool **limitations** identified during the analysis.

Tools have not yet been developed in DATA CELLAR, though issues are foreseen regarding data integration, accuracy, and interoperability in scope of exploitation.

- Inconsistent data formats require additional pre-processing for integration tools, reducing efficiency.
- Semantic inconsistencies in information models impact the accuracy of ontology and DSS.
- Varying communication protocols impact interoperability solutions, complicating seamless data exchange and collaboration.
- Ensuring data sovereignty and secure exchange is crucial for compliance with GAIA-X standards and identity management is required.

(Q13) DATA CELLAR's proposals for **improving business processes** (i.e., system planning/asset management, system operation, energy markets) efficiently while facilitating flexibility and resilience of the EU energy system.

The proposals of DATA CELLAR enhance the efficiency of the EU energy system by leveraging advanced technologies i.e., big data, AI, IoT, and ML.

- In system planning and asset management, it focuses on integrating and analysing data for better decision-making and utilizing predictive maintenance to reduce downtime and costs.
- For system operations, the proposals emphasize real-time monitoring and control, alongside automated decision-making to streamline processes and improve stability.
- In energy markets, improved transparency and dynamic pricing mechanisms are designed to foster fair competition and efficient energy usage.
- For integrated flexibility services DATA CELLAR proposes to DERs, storage, and demand response programs to quickly respond to supply and demand fluctuations.

(Q14) Challenges anticipated in implementing DATA CELLAR's proposals, and how can be overcome.

Challenges that arise associated with:

- ensuring data privacy and security,
- achieving interoperability and standardization,
- managing high investment costs,
- overcoming technical complexity,
- navigating regulatory and policy barriers,
- gaining market acceptance.

(Q15) DATA CELLAR **has made developments** addressing the **cyber-physical reliability** and **resilience** of the electricity grid.

(Q15i) DATA CELLAR's **cyber and physical assets/elements** that the project addresses, **potential risks** identified in DATA CELLAR that are associated with the cyber-physical nature of the grid, and how the latter are mitigated.

The novel tools provided by the platform assisting on decision-making for the smart management of energy assets are expected to leverage on data-driven methods, managing the engagement of stakeholders for the initial population of data respecting cybersecurity and GDPR and National data handling policy.

DATA CELLAR follows a holistic approach to implement cybersecurity measures at different levels, by considering relevant recommendations from respective organisations. Thus, the objective is to secure, not only the physical storage and DBMS, but also the network communications for exchanging data, as well as the access to the provided end-user services (e.g., datasets and pre-trained AI models).

At the time of the assembling the current deliverable (D2.1), risks have not yet been officially identified and addressed in DATA CELLAR.

(Q15ii) Identified focus areas for **dynamic monitoring and control** to ensure the reliability and resilience of the grid, DATA CELLAR propositions for **effective monitoring and protection of the pan-European grid cyber layers**.

DATA CELLAR has been designed with the aim of creating a data platform to support environmental sustainability through the creation of ECs and new data-driven and user-centred energy services.

Starting from the European Data Strategy, it focuses on topics such as interoperability using open standards, cybersecurity by design, data protection measures according to GDPR and national data processing and digital identity regulations. The project determines KPIs to assess the impact on the reliability and resilience of the grid.

DATA CELLAR contributes to the European Strategy for Data supporting the creation of a data-powered economy and resulting in transformative effects on those sectors which are representative of the European values and rights such as 1) healthcare, 2) cleaner and safer transportation, 3) more inclusion and better public services, 4) new production schemes and more circular and finally 5) improve sustainability and energy efficiency.

B.4 Ebalance+

(Q1) Ebalance+ Project Objective: The Ebalance+ project [81], now completed, focused on enhancing distribution grid resilience and flexibility through smart-grid technologies and market mechanisms. Key objectives included increasing grid flexibility, predicting available flexibility, and designing new ancillary models to promote energy flexibility markets. The project developed an ICT platform ensuring integration and interoperability across electricity domains, providing a market framework for new business models. It incorporated algorithms to manage flexibility, support demand response, and optimize grid capacity. Flexibility solutions included electric storage, V2G systems, SiC power inverters, power to heat, and IoT-based control systems.

Project Status: Completed

(Q2) Ebalance+ **interfaces and data interoperability platforms** to enhance flexibility and improve business processes:

The aim of Ebalance+ is to increase the use of flexibility and resilience of energy networks, by means of an energy balancing platform, which will integrate smart production, storage and consumption technologies. This energy balancing platform is based on a fractal-like hierarchical architecture that replicates the existing grid topology with a bidirectional communication framework, assuring the scalability of the solutions.

Q2ii: A brief description, or illustration of each Ebalance+ **interface's architecture**, referencing the SGAM model.

The Ebalance+ concept comprises a set of relevant components, the management units, that increase the flexibility of the energy platform employing smart-grid solutions. The Figure shows the Ebalance+ SGAM model, represents the five layers of Ebalance+ concept translated into the Smart Grids Architecture Model (SGAM). In Ebalance+, customer premises, DER and distribution grids are considered the domains that comprise the bottom layer. The second layer is composed of the seven technologies developed within Ebalance+ project to increase the flexibility and the distribution grid observability. In the third layer, we can see the management units that control the different fields and components. The fourth layer is where the user's interfaces and the different components exchange information to increase the interoperability for prosumers or increase the grid resilience for Distribution System Operators (DSO). Finally, the business layer is on top, where the main component is the energy aggregator.

The Ebalance+ model is based on a hierarchical architecture to ensure scalability, where each management unit is coordinating a lower level, as shown in the Figure below. The management units and technologies implemented in the Ebalance+ project is described in the Grant Agreement document and the Work Package 3 (WP3). Next, the communication flows between the main components are addressed to define the different levels from the point of view of the communication networking.

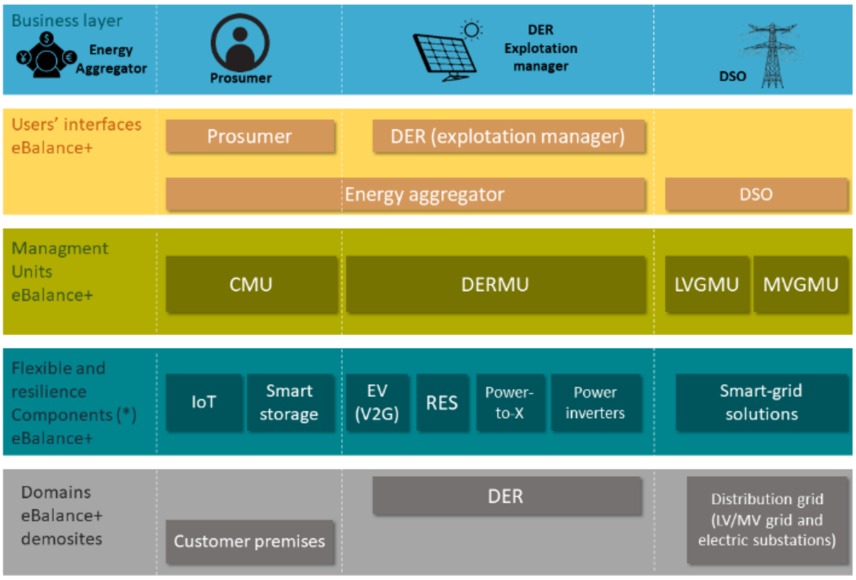


Figure 8: Ebalance+ SGAM architecture

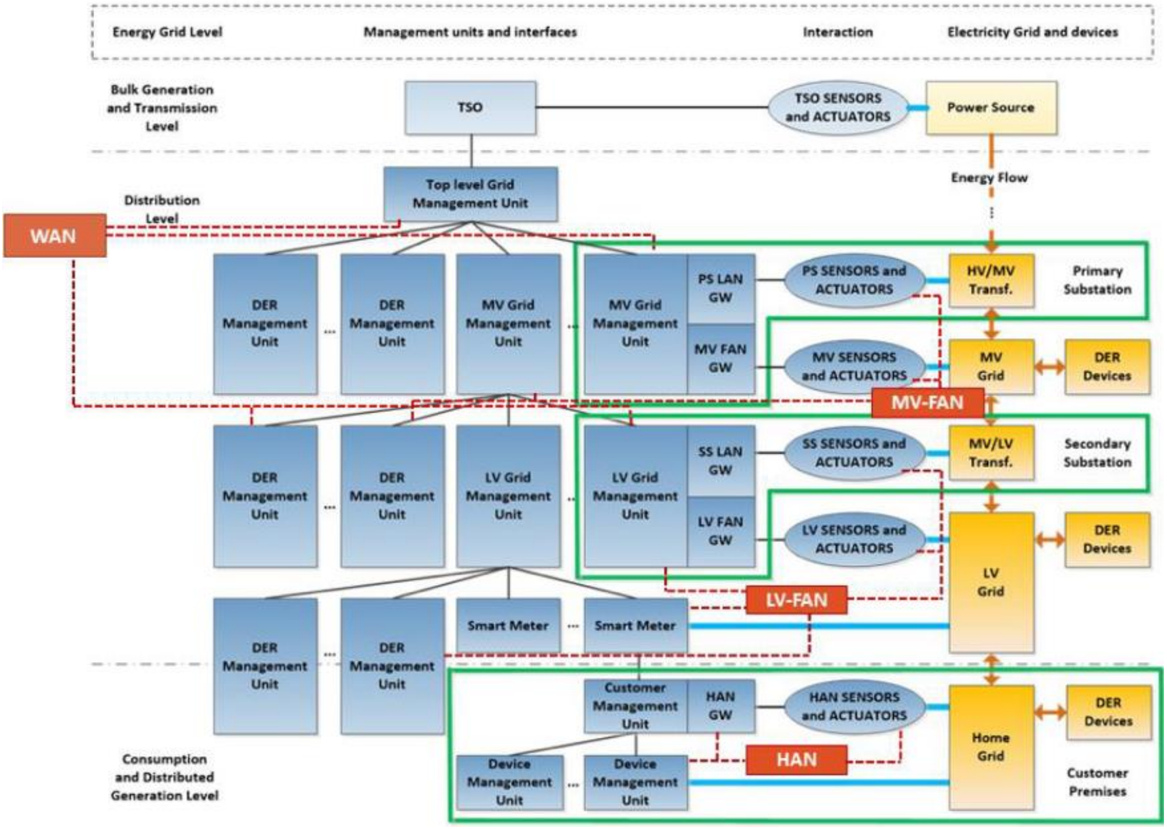


Figure 9: Ebalance+ model

(Q4) Ebalance+ contribution towards the development of **data interoperability platforms and data-sharing** frameworks.

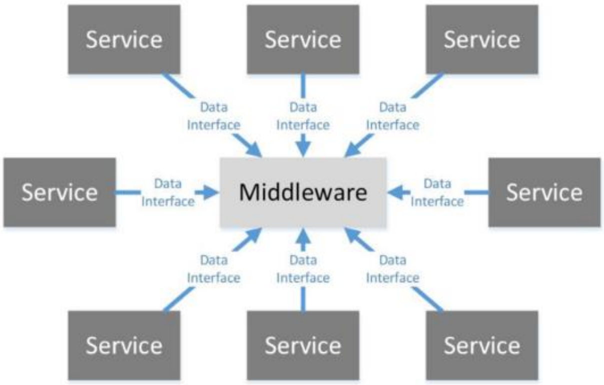


Figure 10: Data exchange middleware

The Ebalance+ system uses a middleware framework that allows the participants to communicate, exchange and store information. The framework stores data in tuple space structures which allows to implement a variety of logical structures that can contain all the information necessary to identify a value, its description, source, and time of creation. The tuple space is accessed by creating variables that can be written, read, or removed. Each variable is further divided into owner spaces. Operations on variables are checked against defined access control policies. By default, each owner can control only their own data. It is possible to grant or revoke permissions to change the default permissions. The variables concept implemented by the framework varies slightly from the general understanding of a variable. The first difference is that by default, each value written to the variable is stored as a separate entry. The second is that data stored in a single variable can have multiple owners. The third difference is that a variable can have multiple fields that are defined when creating the variable. For example, it is possible to create a weather variable that contains fields such as temperature, humidity, or wind. Then, owners can store and share their weather information as they please. The architecture of the framework follows a distributed approach. It allows the participants to store data close to the locations where the data is produced and/or where it might be consumed in order to be processed. The communication is secured through public key infrastructure (PKI).

The services are generic applications and by default, there are no limitations (other than limitations enforced by the operating system) in actions they may perform. In cases where a single machine runs a middleware instance and services that belong to a single user or services that communicate with the middleware server are run on physically separated hardware from the middleware and each other, the threat is minimal. However, in cases where a single machine hosts the middleware and services that belong to different users, there is a risk of malicious services that have the possibility to obtain confidential information such as private keys, databases, passwords, or source code of services that belong to competing users.

To protect against malicious services, the middleware platform implements a utility that is responsible for bootstrapping secure environments for services and running services with adequate privileges.

B.5 eFORT

(Q1) eFORT Project Objective: effort [82] is an ongoing project that aims to modernize electricity networks to reduce blackout frequency and duration, mitigate disruptions, restore services faster, and boost the efficiency of locally produced renewables. Key points of effort include (i) the understanding of the current and emerging vulnerabilities and risks in the EU power grid during its digital and decentralized transition; (ii) the development of a robust electrical power and energy systems (EPES) defence system with secure-by-design technologies for real-time threat management; (iii) the creation of a secure grid framework addressing privacy and data management; (iv) the development of operational technologies to enhance grid resilience; (v) the demonstration and validation up to TRL 5-6; (vi) the analysis of potential replication of eFORT solutions, including cost-benefit analysis and addressing technical and regulatory challenges; (vii) the exploitation of results through business plans and uptake by main EPES players; (viii) and the awareness raising among public bodies and stakeholders about the importance of increasing EPES security and resilience across Europe.

Project Status: Ongoing

(Q2) eFORT **interfaces and data interoperability platforms** to enhance flexibility and improve business processes.

eFORT develops the intelligent that platform comprises the innovative software-based tools of the project and runs on extensive computational resources located in the cloud. It aims to gather information from the field components, harmonize all resources and apply heavy-duty algorithms. Additionally, the platform will allow executing manual or pre-programmed actions over the field components. The core components are:

- Vulnerabilities database
- Interactive visualization tool
- Dynamic risk assessment tools (cyber and physical)
- Self-healing algorithm

Q2i: eFORT specification of the purposes of the interfaces, along with their definitions in terms of information models, timing requirements, and interaction sequences.

These interfaces are defined in terms of information models, timing requirements, and interaction sequences:

- The interfaces are documented in Interface Definition Documents (IDD) or similar, outlining functional definitions, including mechanical, electrical, and data communication characteristics.
- Timing specifications ensure synchronized data exchanges and real-time operations between different system components.
- Interaction sequences define the specific steps and protocols for interactions, ensuring compatibility and coordinated operations across various systems and platforms.

(Q4) eFORT contribution towards the development of **data interoperability platforms and data-sharing** frameworks.

The eFORT implements standardized metadata models, creating interoperable data exchange protocols, and integrating advanced digital technologies such as AI and IoT, enabling seamless data sharing across different systems and platforms, facilitating improved decision-making, real-time monitoring, and efficient resource management.

(Q5) eFORT definition of **communication and data exchange requirements**.

The requirements include the use of standardized protocols and metadata models to harmonize data formats, enabling seamless integration and real-time data exchange.

(Q7) **Protocols and standards** applied in eFORT.

- The EC 62351 and IEC 62443 standards that ensure the security of communication networks within the power grid.
- The ISO 31000 and NIST Frameworks methodologies are used for risk assessment, helping to identify, evaluate, and mitigate risks associated with data exchange and communication in the power grid.
- The OPC UA protocol is employed for secure and reliable data exchange in industrial automation, supporting interoperability and integration across different systems and platforms.
- The RTDS (Real-Time Digital Simulator) which is used for testing and simulating the behaviour of power system components and communication devices, ensuring they meet the necessary standards and protocols for real-time operations.

(Q8) **Gaps** identified in terms of data format, information models and communication protocols in eFORT.

- Data format gaps
- Information model gaps
- Communication protocol gaps

(Q11) How **data exchange gaps** are affecting the support for flexibility requirements identified and analysed.

- The project identifies cybersecurity vulnerabilities in IoT devices and their impact on the grid hindering the flexibility of the energy system by compromising data integrity and availability.

An assessment of cascading effects across functional areas of the EPES (Electric Power and Energy Systems) highlights how data exchange issues can propagate through the system, affecting overall flexibility and reliability.

- The project establishes strategies for secure data collection and DSO-TSO data exchange. Ensuring secure and efficient data exchange between these entities is critical for maintaining system flexibility.
- eFORT develops secure and private data infrastructures that emphasizes to manage confidentiality and ensure data integrity, supporting the flexibility requirements by providing a reliable data exchange framework.
- The development of dynamic risk assessment tools for both physical and cyber layers are aimed at identifying and mitigating risks in real-time assisting in maintaining flexibility by proactively managing potential data exchange disruptions.
- Creating visualization tools and a vulnerabilities database to help stakeholders understand and manage the risks associated with data exchange gaps.

B.6 PARITY

(Q1) PARITY's Project Objective: The PARITY project [83] aims to address the structural inertia of current distribution grids by developing a transactive grid and market framework. This ongoing initiative will create a local flexibility market platform through IoT and blockchain integration, enabling efficient and transparent flexibility transactions. Key features include automated flexibility exchange via smart contracts and blockchain, based on real-time grid constraints and DER flexibility, distributed intelligence with self-learning and real-time control capabilities, dynamic clusters of DERs for real-time P2P transactions and optimized DER flexibility management, and advanced tools for Active Network Management to enhance grid observability and RES hosting capacity. PARITY seeks to integrate diverse DERs within a unified flexibility management framework, combine physical and virtual storage (EVs, batteries, power-to-heat) in a Storage-as-a-Service model, and enable a local flexibility market platform with smart contracts and distributed intelligence. Additionally, it aims to enhance SG monitoring, PQ management, and active network management, validate new business models in real-life environments to engage market actors, and promote PARITY as a next-generation local flexibility market platform through dissemination and knowledge transfer.

Project Status: Ongoing

(Q2) PARITY **interfaces and data interoperability platforms** to enhance flexibility and improve business processes:

To achieve the main objectives, PARITY creates dynamic, flexible, and interoperable systems.

- PARITY develops platforms that ensure different systems and components can communicate and work together effectively using communication protocols and data formats to facilitate seamless integration and interoperability of DERs and grid components.
- PARITY provides real-time data, and its solutions enable more accurate and efficient system planning, asset management, and predictive maintenance, thus utilities and grid operators optimize the use of their assets and reduce operational costs.
- PARITY enhances operation of the electricity grid by utilizing control algorithms for better balancing in the supply and demand.
- Its platforms facilitate the participation of DERs in energy markets through enabling real-time data exchange and automated trading, helping to create more efficient and transparent energy markets, bringing better pricing signals, increased competition, and more opportunities for DER owners to monetize their assets.

Q2i: PARITY's Specification of the purposes of the interfaces, along with their definitions in terms of information models, timing requirements, and interaction sequences.

PARITY uses standardized information models to ensure consistent data exchange across different systems. These models are designed to integrate data from DERs and grid components, including:

- Resource Information: Data on DER types, capacities, locations, operational statuses, and historical performance.
- Grid Information: Details on grid topology, capacity constraints, current loads, and voltage levels.
- Market Information: Real-time and forecasted market prices, demand bids, supply offers, and trading volumes.
- User Preferences: Information related to user preferences, priorities, and constraints for DER operation and participation in demand response programs.

The timing requirements for data exchange are considered for real-time operations and coordination of DERs and include:

- Real-time Data Exchange: Essential for critical grid operations and DER control, requiring updates within milliseconds to seconds.

- Near-real-time Data Exchange: Important for short-term forecasting and market operations, typically occurring within seconds to minutes.
- Periodic Data Exchange: Used for routine data collection, reporting, and analytics, occurring at intervals ranging from minutes to hours.

The interaction sequences include:

- Monitoring and Control**:**
  - Grid operator monitors real-time grid conditions.
  - DERs send status updates to the grid operator.
  - Grid operator sends control commands to DERs for load balancing and voltage regulation.
- Market Participation:
  - Market operator publishes real-time prices and forecasts.
  - DERs and users submit bids and offers based on market conditions.
  - Market operator matches bids and offers and sends dispatch signals to DERs.
- Demand Response**:**
  - Aggregator collects user preferences and constraints.
  - Aggregator sends demand response signals to participate DERs based on grid needs and user agreements.
  - DERs adjust their operation and report back to the aggregator.

(Q3) PARITY's key findings regarding the implementation of **standards and interfaces** to improve flexibility and business process (system planning/asset management, system operation, energy markets).

The critical role of interoperability and standardization in enhancing grid flexibility and efficiency.

- The project emphasized the necessity of standardizing communication protocols and data formats to ensure seamless integration and interaction among various DERs and grid aspects.
- The implementation of smart contracts on a blockchain-based Local Flexibility Market (LFM) platform was identified as a significant advancement. The smart contracts facilitate automated, transparent, and secure transactions of energy and flexibility services, addressing issues of data integrity, which are essential for the broader acceptance and efficient operation of energy markets.
- PARITY developed advanced forecasting and optimization tools for DER operations that provide accurate predictions of energy production/consumption, which are crucial for effective system planning and management. Therefore, grid operators can optimize resource allocation, enhance grid stability, and reduce operational costs.
- The project indicates the distributed intelligence and IoT-enabled DER management tools that enable real-time monitoring and control of DERs, facilitating dynamic response to grid and improving overall system operation. The integration of IoT devices ensures that data is collected and processed efficiently, allowing for more responsive and adaptive grid management.
- PARITY implemented advanced grid monitoring and control mechanisms, including the use of devices like STATCOMs enhancing grid monitoring and stability, in high-RES penetration scenarios.
- The project demonstrates how DERs could participate more effectively in energy markets. The LFM platform and smart contracts facilitate real-time trading and flexibility services, leading

to more competitive and responsive market dynamics, supporting new business models and markets, empowering DER owners in regard of their assets.

(Q4) PARITY's contribution towards the development of **data interoperability platforms and data-sharing** frameworks.

PARITY interoperability contributes to the seamless integration of DERs within the grid. The development of the LFM platform. The project also introduces IoT-enabled DER management tools that provide real-time monitoring and control, leveraging distributed intelligence for autonomous decision-making. Standardized communication protocols and metadata frameworks are implemented to ensure consistent data exchange and integration across diverse systems. Additionally, data analytics and forecasting tools are developed to enhance system planning and asset management, while security measures are put in place to safeguard data privacy.

(Q5) PARITY's definition of **communication and data exchange requirements**.

The requirements defined by the project are allocated in the following categories:

- Interface protocols - applying standard interface protocols to guarantee interoperability and connectivity among various systems and devices.
- Secure communications - channels are a priority, particularly for the management and control of DERs, with protocols and encryption implemented to protect data integrity and privacy.
- Real-time monitoring and control - to enable immediate monitoring and control of grid operations and DERs.
- Data granularity - specific requirements for the granularity of data.
- Metadata standards - to ensure that data from various sources can be harmonized and utilized effectively. Metadata provides contextual information that enhances the understanding and integration of data across different systems.
- Data cleaning and anomaly detection - to maintain the accuracy and reliability of data, cleaning protocols are applied, together with algorithms for detecting data measurement and transmission anomalies.
- User access and Data Transparency - users are given access to their data to verify and adjust inaccuracies, promoting transparency and trust.
- Monitoring and Control - a sequence for monitoring and control activities, where grid conditions are continuously monitored, and DERs send status updates.
- Demand Response - aggregators collect user preferences to send demand response signals to be participating DERs to be adjusted accordingly.

(Q6) **Data models** used in PARITY.

- The Common Information Model (CIM) [39]
- Smart Contracts and Blockchain
- IoT-Enabled DER Management Tools

(Q7) **Protocols and standards** applied in PARITY.

- Common Information Model [39]
- IEC 61850 [41]
- IEEE 2030.5 (SEP2) [84]
- OpenADR [85]

(Q8) **Gaps** identified in terms of data format, information models and communication protocols in PARITY.

- Inconsistent data - lack of consistent data standards across different systems and devices, making it challenging to integrate data from various sources, leading to interoperability issues.
- Data granularity - discrepancies in the granularity of data collection, since different devices and systems have different requirements and capabilities, which confuses the aggregation and analysis of data for effective decision-making.
- Lack of unified information models - can be universally applied across different DERs and grid components, challenging the ability to represent and take data consistently from the energy system.
- Security and privacy - the project identified gaps in the implementation of security protocols.
- Bandwidth and network - due to the big number of energy-IoT devices it leads to higher bandwidth requirements, which the current communication infrastructure may not be able to support effectively, thus causing congestion.

(Q9) Examples of tool **limitations** identified during the analysis [86].

- Complexity and usability Issues of the tools, including the smart contract enabled LFM, whose complexity of the systems and smart contracts was noted as a significant drawback, it caused technical issues and failures, as it was not easily understood by the users.
- Interoperability challenges rose regarding the smart contract enabled IoT gateway with a difficulty to achieve uniformly across different regions and infrastructures.
- Data management limitations in the building-as-a-battery management algorithms, regarding data cleaning and detection of data measurement and transmission anomalies impacting the accuracy of the data used for managing energy resources.
- The design of user interfaces had to account for senior citizens and people with limited technical experience, particularly in residential pilots.

B.7 STREAM

(Q1) STREAM's Project Objective: The STREAM project [87] aims to create an innovative flexibility ecosystem ("STREAM Ecosystem") on the low voltage (LV) grid side of existing power markets, connecting data, technologies, stakeholders, and markets to facilitate flexibility provision. The project objectives are (i) to empower data collection, integration, and utilization of both legacy and open data to enable innovative services; (ii) to develop tailor-made services for end users through the STREAM Ecosystem platform, allowing easy participation in local energy markets; (iii) to design a local market on the LV grid for cross-integration of stakeholders, facilitating cost-effective flexibility services via a standard Device Register; and (iv) to equip network operators and NRAs with new insights to inform grid upgrade and regulatory decisions through a robust flexibility market.

Project Status: Ongoing

(Q2) STREAM **interfaces and data interoperability platforms** to enhance flexibility and improve business processes.

STREAM develops several tools and platforms that are scoped to be hosted in the STREAM ecosystem.

Q2i: STREAM Specification of the purposes of the interfaces, along with their definitions in terms of information models, timing requirements, and interaction sequences.

The STREAM ecosystem which will host the STREAM tools that are thoroughly described:

- *sDATA*- this tool will utilize innovative components built on the top of International Data Spaces (IDS) connectors for ensuring secure and trusted data exchange from the flexibility assets to the flexibility management & aggregation platforms. It will provide the needed open data-driven platform to facilitate data sharing and usage access control from end-users (flexibility assets) upstream to flexibility aggregators/service providers, DSOs and TSOs. sDATA will be a baseline for all data exchange within the STREAM Ecosystem.
- *sMART*- with two different designs: (i) sMART local market, that will introduce a new, user-centric trading facilitation framework on the low-voltage side of power networks to carry out the decision-making processes for before – during – after every period of auctions for flexibility requirements. It will be a central platform for flexibility trading activities – from flexibility services providers who will register their devices, to flexibility capacity aggregators to DSOs. For example, the DSO will be able to send its flexibility requirements through sMART, and thus trigger a local flexibility capacity and availability auction via sMART to solve any constraints or need for ancillary services. (ii) sMART peer-to-peer, this tool will be aimed to orchestrate, coordinate and facilitate data assets versus service exchange, as well as financial and non-financial compensation. It will leverage on the actual TRL-5 implementations developed within H2020 eDREAM project and will make use of Distributed Ledgers Technologies, Blockchain and Smart Contracts to deploy an innovative tokenized solution for orchestrating, coordinating and compensating reciprocal data assets (datasets, ML models, ML algorithms, computational resources for processing, such as cloud, or for storage) against services (e.g. one year maintenance of a heat pump or prioritized access to EV recharging slot) within a financial and barter-like way. Thanks to the adoption of this tool, energy consumers are expected to be further motivated to share their energy consumption data, being rewarded for example with energy and non-energy services.
- *sGRID* – this STREAM tool will provide DSOs with the ability to enhance their management of power network operational risks and challenges with the objective to ensure a safe and reliable long-term operation and low operational costs. For example, due to the increasing addition of variable RES power generation sources to power networks, connection of intermittent power loads (i.e., EV charging stations) and the addition of new technologies (i.e., smart meters), the DSOs are facing increased levels of complexities compared to the more traditional power markets. sGRID will provide DSOs with a tool to estimate the condition of the grid – on its LV side, where the local flexibility market is to be established, and provide the ability to pre-qualify flexibility assets and capacities so they can actively participate within a given local energy market.
- *sENC* – this STREAM tool will empower energy community operators by providing a central energy community, which will provide information about energy community members, their energy and flexibility assets, and provide aggregation of total flexibility capacity, its management, and the offering of such flexibility in the local energy market. sENC will also introduce a bespoke energy member / user mobile app, which will provide each energy community member with up-to-date information regarding the operational aspects of a given energy community that directly pertain to them (i.e., use of flexibility).
- *sPLAN* – based on the developments of the past projects, previously named Value Analysis Tool (H2020 COMPILE, XFLEX) and turn it into a robust decision support tool for the DSOs,

policy makers and the NRAs. Similar to sGRID, sPLAN will focus on enhancing the decision-making processes of DSOs through improved LV grid operation planning activities, analytics and the ability to – in connection with sGRID – provide a range of services through the utilization of flexibility. It will support evidence-based, technology-neutral decision-making in grid planning, comparing the value of the conventional solutions like grid upgrade with the value of their alternatives like flexibility-based energy services.

- *sFLEX* – this STREAM tool will be a central flexibility management system, aimed towards medium- to large-prosumers with reasonably large flexibility assets' capacity. sFLEX will provide them with sufficient levels of information that will empower their decision-making processes to improve the overall energy efficiency of their operations and provide them with the analysis of available flexibility capacity that they will be able to offer upstream to DSOs and flexibility capacity aggregators. Furthermore, it will be used by aggregators to connect various devices of flexibility assets into a large flexibility pool that can be utilized and monetized in multi-service fashion (energy community balancing, DSO and TSO ancillary services, wholesale markets, etc.). The tool will comprise modules like APIs for STREAM Ecosystem integrations, aggregation, analytics (flexibility forecasting and baselines), optimizations (various flexibility products), disaggregating, monitoring, reporting, etc.

Q2ii: A brief description, or illustration of each STREAM **interface's architecture**, referencing the SGAM model.

The STREAM Ecosystem's objective is to promote the use of various flexibility services – as offered by consumers on LV level, to network operators in MV and high voltage (HV) level and the local and wholesale market, enabling them to develop new business models and markets for different types and scales of flexibility services and to interact with various distributed resources in real-time, always using the resources that are technically and commercially most viable in a given moment. New power markets and the interconnected relationships among important stakeholders are becoming more complex in contrast to traditional power markets, which relied on two key service flow streams: transmission and distribution of electricity from generators to consumers, and payment of electricity from consumers to generators. These conventional power market service flows have been disturbed by the ongoing entry of numerous prosumers, aggregators, and other service providers (including e-mobility operators and Internet of Things (IoT) platform managers) on the LV side of the power market structure. To effectively enable these new market circumstances and assure fairness, inclusivity, and cost-efficiency, the supporting services infrastructure must swiftly grow with the new power market designs.

B.8 SYNERGY

(Q1) SYNERGY's Project Objective: The European electricity sector is undergoing a transformation through digitalization, smart meters, renewable energy sources, IoT devices, distributed storage, and electric vehicles. This transformation requires significant automation using machine-to-machine (M2M) technologies, AI, and edge and cloud analytics to enhance network stability and optimization. However, high upfront costs and data complexity pose challenges. The completed SYNERGY project [88] addresses these issues with a novel framework and Big Data architecture. Its objectives include enhancing data integration from diverse sources, facilitating data sharing and trading, promoting advanced analytics with the SYNERGY Big Data Platform, supporting decarbonization and power quality, establishing an analytics services marketplace, generating new insights through data stream correlation, developing innovative energy applications, and creating a data-driven intelligence ecosystem with new business models. These goals aim to improve efficiency, stability, and sustainability in electricity networks while tackling data management challenges.

Project Status: Completed

(Q2) SYNERGY **interfaces and data interoperability platforms** to enhance flexibility and improve business processes.

SYNERGY emphasizes creating a flexible, interoperable platform that integrates data from various sources, facilitating improved business processes and enhanced decision-making capabilities within the energy sector. These are: (i) The SYNERGY Platform; (ii) the SYNERGY Common Information Model (CIM); (iii) the SYNERGY Data Analytics Workbench and Blockchain; (iv) the SYNERGY Living Lab Activities.

- The SYNERGY platform includes apps like Infrastructure Sizing and Grid Planning App, Network Asset Management Optimization App, and others that aid in planning and managing assets efficiently using integrated data and analytics. In a simpler version, the core parts of SYNERGY platform consist of the SYNERGY on-premises environments, the SYNERGY cloud infrastructure, and the SYNERGY energy apps portfolio.
- Apps like Flexibility-based Network Management App and DSO-TSO Common Operational Scheduler help in optimizing network performance and operational scheduling.
- Apps such as Retailer Portfolio Analytics and Management App and Flexibility Analytics and Consumer-Centric DR Optimization App facilitate market participation and demand response optimization.

Q2i: SYNERGY’s specification of the purposes of the interfaces, along with their definitions in terms of information models, timing requirements, and interaction sequences.

Based on the overall structure of SYNERGY Framework Architecture, the interfaces can be defined in terms of information models, timing requirements, and interaction sequences as follows:

Information Models: Designed to provide a standardized way of representing data and ensuring interoperability between different systems and components, including (i) CIM: Defines the semantic concepts, events, relations, and respective data models used across the platform. It ensures that all data exchanged within the platform adheres to a common structure and semantics. (ii) Metadata Schema: Used to describe data assets, including their attributes, ownership, access policies, and licensing information. It is crucial for data discovery, sharing, and management within the Data & AI Marketplace.

Timing Requirements: It is critical for ensuring data processing, analytics, and interactions occur within acceptable timeframes to maintain system efficiency and reliability, including: (i) Real-time Data Processing: The Data Ingestion Service and the Data Analytics Services Bundle, need to handle data in near real-time to support applications like grid monitoring and demand response. (ii) Scheduled Data Processing: Other processes, such as batch data ingestion or scheduled analytics jobs, can be executed at predefined intervals based on user configurations and system requirements. (iii) Failure Management: Timing requirements for detecting and handling failures in data processing workflows are essential to ensure system robustness and quick recovery.

Interaction Sequences: Defining how different components and services within the SYNERGY platform interact to accomplish specific tasks, including Data Check-in Workflow, Data Search and Sharing Workflow, Data Analytics Workflow, Detailed Interface Definitions, Data Collection Services

Bundle, Data Security Services Bundle, Data Sharing Services Bundle, Data Analytics Services Bundle, Platform Management Services Bundle, Example Interaction Sequence, Data Check-in Workflow.

Q2ii: A brief description, or illustration of each SYNERGY's **interface's architecture**, referencing the SGAM model.

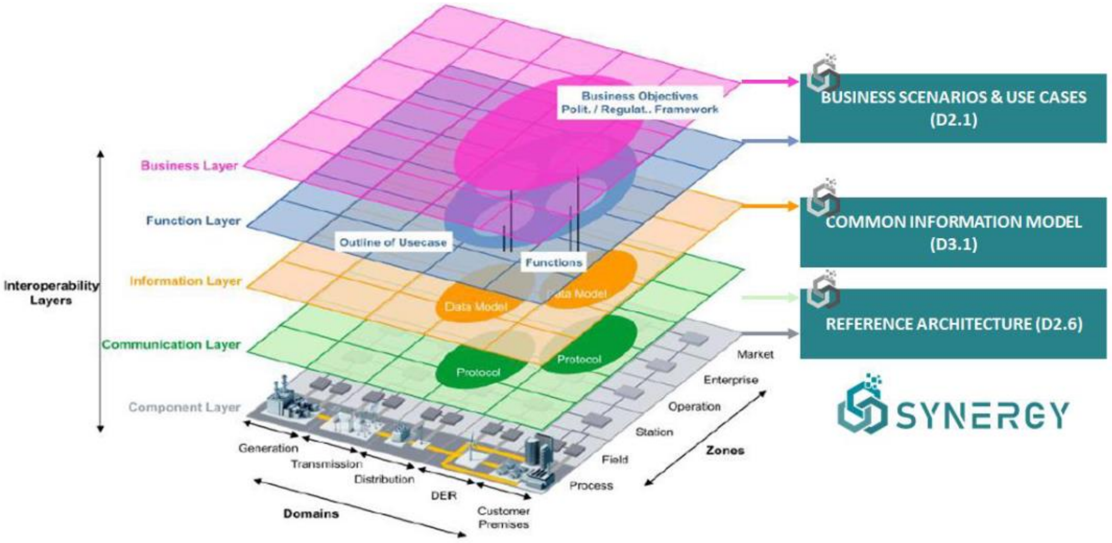


Figure 11: SGAM architecture of SYNERGY

(Q3) SYNERGY's key findings regarding the implementation of **standards and interfaces** to improve flexibility and business process (system planning/asset management, system operation, energy markets).

SYNERGY regarding standards application:

- The SYNERGY platform relies on the CIM to ensure semantic consistency and interoperability across various components and services. The CIM provides a standardized way of representing data, which is crucial for ensuring that data from different sources can be integrated and used effectively.
- The platform incorporates robust data governance standards, including data anonymization, encryption, and access control mechanisms, ensuring data security and privacy, essential for building trust among stakeholders and enabling secure data sharing.
- SYNERGY architecture aligns with the SGAM and the BDVA reference architectures, ensuring the platform follows industry's best practices and standards, facilitating interoperability and integration with other systems.

SYNERGY using interfaces to improve flexibility:

- The platform's architecture includes several data services bundles i.e., *Data Collection*, *Data Security*, *Data Sharing*, *Data Matchmaking*, *Data Analytics*, *Data Storage*, and *Data Governance*. They provide well-defined interfaces that ensure seamless integration and operation within the platform.
- The API Gateway provides standardized interfaces for external applications to interact with the SYNERGY platform, enabling other systems and applications to retrieve data, execute analytics, and access platform functionalities, enhancing flexibility and integration capabilities.

SYNERGY Business Process:

- It includes applications i.e., Infrastructure Sizing and Grid Planning App, Network Asset Management Optimization App, etc., leveraging integrated data and advanced analytics to optimize asset management and system planning processes.
- Apps like Flexibility-based Network Management App and DSO-TSO Common Operational Scheduler provide tools for optimizing network performance and operational scheduling. These tools use real-time data and advanced algorithms to enhance system operation efficiency.
- The platform supports energy market activities through apps like the Retailer Portfolio Analytics and Management App and Flexibility Analytics and Consumer-Centric DR Optimization App.

(Q4) SYNERGY's contribution towards the development of **data interoperability platforms and data-sharing** frameworks.

SYNERGY influenced data interoperability and sharing via adopting and extending the CIM for semantic consistency and developing a comprehensive metadata schema for data discovery and governance. The platform implements robust anonymization and encryption services to ensure data security and privacy and facilitates secure data sharing through its Data & AI Marketplace that supports smart contracts and blockchain for transparent transactions. Additionally, the project introduces advanced analytics capabilities via the analytics workbench and secure experimentation playgrounds, allowing data analysis while maintaining data integrity, Thus, enhancing flexibility, improving system planning, asset management, system operation, and energy market processes, fostering efficient and secure data integration and utilizing across the energy sector.

(Q5) SYNERGY's definition of **communication and data exchange requirements**.

SYNERGY defines requirements to ensure interoperability and efficient data management, adopting widely accepted data standards and formats, including JSON, CSV, XML, and CIM for consistency across systems. Data is collected from diverse sources such as APIs, historical databases, IoT devices, and energy markets, and stored in a secure, scalable cloud infrastructure. Adhering to FAIR principles, metadata is created following DCAT and Dublin Core standards, enhancing discoverability and interoperability. The platform includes robust data security measures like encryption and anonymization, ensuring GDPR compliance and protecting personally identifiable information. SYNERGY provides APIs for secure data ingestion, retrieval, and management, supporting real-time and batch processing for various use cases. Data sharing is facilitated through the Data & AI Marketplace with role-based access control, allowing secure trading and sharing of data assets. These efforts collectively ensure that data is interoperable, secure, and easily accessible, enhancing flexibility and improving business processes in system planning, asset management, system operation, and energy markets.

(Q6) **Data models** used in SYNERGY.

SYNERGY adopts and extends the CIM. Additionally, SYNERGY followed the Dublin Core Metadata Initiative (DCMI) standards for creating metadata, ensuring data is findable, accessible, interoperable, and reusable (FAIR). The project also used the Data Catalog Vocabulary (DCAT) Application Profile for metadata to enhance data discoverability. Widely accepted data formats such as JSON, CSV, and XML were employed for data exchange, thus SYNERGY created a robust, interoperable platform that supports secure data sharing, advanced analytics, and improved decision-making processes across the energy value chain, enhancing the platform's flexibility and efficiency.

(Q7) **Protocols and standards** applied in SYNERGY.

The protocols used in SYNERGY are: CIM, DCMI, Data Catalog Vocabulary (DCAT) Application Profile, Secure Communication Protocols (HTTPS, SFTP), GDPR Compliance, Anonymization and Encryption Standard, Open APIs, FAIR Data Principles, DCAT and Linked Data Standards.

(Q8) **Gaps** identified in terms of data format, information models and communication protocols in SYNERGY.

In terms of data formats, inconsistencies across different sources and the diverse nature of structured, semi-structured, and unstructured data posed significant challenges. For information models, there was incomplete adoption of the CIM, leading to partial interoperability, and the metadata schema lacked comprehensive attributes for some datasets, affecting discoverability and usability. Additionally, semantic interoperability issues arose due to differences in models across stakeholders. Communication protocol gaps included inconsistent use of secure protocols like HTTPS and SFTP, a lack of real-time data exchange capabilities crucial for immediate insights, and difficulties integrating with legacy systems using outdated or proprietary protocols. Addressing these gaps was essential to enhance data interoperability, security, and real-time processing within the SYNERGY platform.

(Q9) Examples of tool **limitations** identified during the analysis.

Several key gaps are identified in data formats, information models, and communication protocols that needed addressing to enhance data interoperability and platform effectiveness. There are inconsistencies in the use of standard data formats, complicating data integration, along with challenges in handling unstructured data. The partial adoption of CIM across different data sources demonstrates incomplete interoperability, necessitating additional mapping and transformation efforts. Additionally, the metadata schema is not comprehensive enough for some datasets, impacting data discoverability and usability. Communication protocol gaps include inconsistent application of secure protocols like HTTPS and SFTP, limitations in real-time data exchange that are crucial for immediate insights, and difficulties integrating with legacy systems using outdated or proprietary protocols.

(Q10) SYNERGY's significant missing interfaces and adapters identified between system operators, TSOs, DSOs, and customers.

TSO-DSO Coordination Interfaces: *Real-Time Data Exchange:* Lack of real-time data exchange interfaces TSOs and DSOs. This gap hindered effective coordination for grid stability and demand response management. *Flexibility Services Integration:* Interfaces to facilitate the integration of flexibility services provided by DSOs into TSO operations were needed, limiting the ability to optimize grid operations and leverage DERs.

Customer-DSO Interaction Adapters: *Demand Response Participation:* Adapters enabling seamless participation of customers in demand response programs managed by DSOs were inadequate and impacted the engagement of customers in energy-saving. *Energy Consumption Data Sharing:* Interfaces for sharing detailed energy consumption data from customers to DSOs were not fully developed, impacting the accuracy of demand forecasting.

Adapters for Legacy Systems: *Integration with Legacy Systems:* Gaps in adapters needed to integrate modern SYNERGY platform capabilities with legacy systems used by TSOs and DSOs.

Proprietary Protocol Compatibility*:* Missing adapters for compatibility with proprietary communication protocols used by some legacy systems hindered data integration and exchange.

(Q11) How **data exchange gaps** are affecting the support for flexibility requirements identified and analysed.

This was addressed through a variety of methods, including stakeholder consultations, technical evaluations, pilot implementations, and data analytics. Stakeholder feedback and technical audits revealed limitations in real-time data sharing, standardization, and interoperability with legacy systems. Pilot projects and living labs tested new interfaces and protocols, highlighting practical challenges and validating solutions. Data analytics and real-time monitoring identified inefficiencies in data flows, while detailed gap analysis reports documented the findings and provided recommendations for improvement. These gaps impacted delayed response times, inaccurate demand forecasting, limited customer participation, inefficient grid operations, and security risks.

(Q12) SYNERGY's proposed solutions for **addressing gaps**, such as using merged standards for data exchange, developing interfaces/adapters for TSO/DSO and customers, integrating cross-sector and cross-border components in the reference architectures and platforms to support flexibilities, etc.

Adoption of merged standards (e.g., CIM & DCAT) to ensure consistent data formats and semantics, and developing interfaces and adapters for real-time data exchange and coordination between TSOs and DSOs, as well as for customer participation in demand response programs. Also, SYNERGY scoped to integrate cross-sector and cross-border components to support data analytics and scalability, enhance real-time data exchange with low-latency communication protocols, and implement advanced security measures (e.g., encryption and anonymization). Additionally, middleware solutions were proposed to integrate modern data management with legacy systems, along with advanced analytics and visualization tools to improve decision-making and operational transparency.

(Q13) SYNERGY's proposals for **improving business processes** (i.e., system planning/asset management, system operation, energy markets) efficiently while facilitating flexibility and resilience of the EU energy system.

By leveraging advanced data analytics, big data technologies, and AI, SYNERGY integrates and manages vast data, improves forecasting, and optimizes resource allocation and maintenance schedules. The project enhances system operation with advanced control strategies, facilitates efficient and transparent energy markets through new models, and increases grid flexibility and resilience by integrating DERs and demand-side management. By promoting stakeholder collaboration and providing regulatory support, SYNERGY fosters a coordinated approach to energy management, ultimately supporting a sustainable and low-carbon EU energy system.

(Q14) **Challenges** anticipated in implementing SYNERGY's proposals, and how to overcome them.

Challenges such as data integration complexities, cybersecurity risks, regulatory hurdles, stakeholder collaboration issues, and the need for technological infrastructure upgrades. These can be overcome by developing standardized data protocols, robust cybersecurity measures, and adaptive regulatory policies, fostering effective stakeholder collaboration through clear communication and shared goals.

B.9 XFLEX

(Q1) XFLEX's Project Objective: The XFLEX project [89] proposes integrated solutions to optimize the combination of decentralized flexibility assets on both the generation (DER) and demand sides (V2G, power-to-heat/cold, batteries, demand response). This enables all parties, including prosumers, to offer their flexibility in local and wholesale markets, benefiting all actors in the smart grid value chain. XFLEX aims to maintain a stable and secure electricity system with a growing role for variable renewable generation, resilient to extreme climate events. Unlike previous projects focusing on isolated parts of the network, XFLEX integrates and synergizes all energy flexibility sources and technologies, promoting cooperation among smart grid and energy market actors. This holistic approach seeks to create the optimal combination of decentralized flexibility assets and new market mechanisms, providing benefits to all actors.

Project Status: Completed

(Q2) XFLEX **interfaces and data interoperability platforms** to enhance flexibility and improve business processes.

XFLEX focused on integrating decentralized flexibility assets such as DER, V2G, power-to-heat/cold, batteries, and demand response, enabling all stakeholders, including final prosumers to offer flexibility in local and wholesale markets. The tools that the project developed are listed:

- SERVIFLEX Tool - integrated flexibility management tool
- GRIDFLEX Tool - tools for automatic control and observability
- MARKETFLEX Tool - market platform with new market mechanisms
- The XFLEX Platform - a flexible and scalable integrated platform that supports interoperability.

Q2i: XFLEX's specification of the purposes of the interfaces, along with their definitions in terms of information models, timing requirements, and interaction sequences.

Specifying the interfaces and the information models, timing requirements, and interaction sequences:

- SERVIFLEX:

  Purpose - Integrated flexibility management.

  Information Models - Includes data from various decentralized energy resources (DER), V2G, power-to-heat/cold systems, batteries, and demand response units.

  Timing requirements - Real-time data acquisition and processing for immediate flexibility management.

  Interaction sequences - Continuous data collection from DERs, real-time analysis, and dispatch of flexibility resources.

- GRIDFLEX

  Purpose - tools for automatic control and observability.

  Information models - Real-time grid status, flexibility asset status, and control signals.

  Timing Requirements - Millisecond to second-level data processing for grid stability and control.

  Interaction sequences - Real-time monitoring of grid parameters, identification of potential issues, and automatic dispatch of control signals to flexibility assets.

- MARKETFLEX

  Purpose - Market platform and new market mechanisms.

  Information models - Market bids and offers, pricing signals, and flexibility service contracts.

  Timing Requirements - Near real-time processing for market transactions and settlements.

Interaction sequences - Collection of bids and offers, market clearing, dispatch instructions based on market outcomes, and settlement processes.

- The XFLEX platform:

Purpose - Flexible and scalable integrated platform.

Information models - Aggregated data from all flexibility assets, market data, and grid status.

Timing Requirements - Varies based on the component (real-time for grid operations, near real-time for market operations).

Interaction sequences - Integration of data from SERVIFLEX, GRIDFLEX, and MARKETFLEX tools; coordination of flexibility resources; and provision of a unified interface for all stakeholders.

Q2ii: A brief description, or illustration of each XFLEX's **interface's architecture**, referencing the SGAM model.

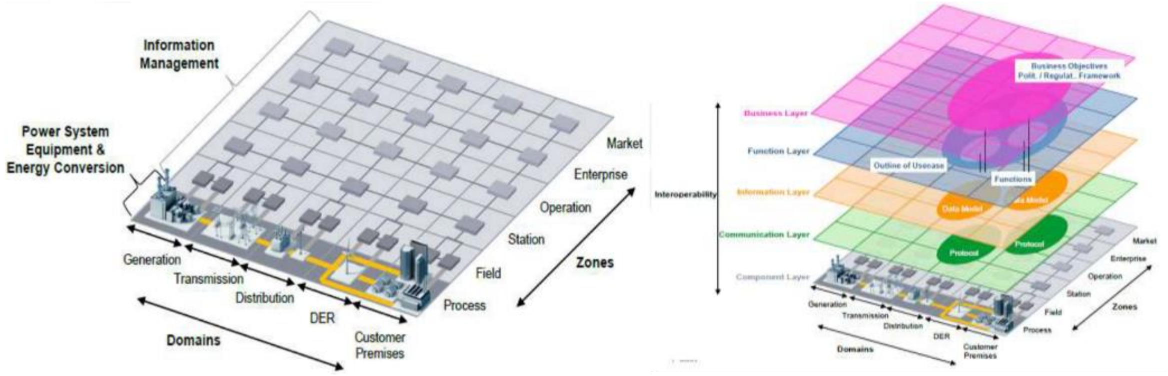


Figure 12: The SGAM and its first layer of XFLEX

The SGAM Layers are combined into a 2-dimensional plane, defined by two axes: electrical processes (domains) and information management viewpoints (zones). A brief overview of the domains and zones is as follows: Bulk Generation (high voltage generation), Transmission (infrastructure for transporting high voltage energy), Distribution (medium to low voltage transmission), Distributed Energy Resource (DERs connected to the distribution grid), and Customer Premises (endpoints of energy delivery at low voltage).

The SG plane's six hierarchical zones ensure framework coherence by following a similar pattern. The Process zone involves energy transformation and equipment. The Field zone handles protection, control, and monitoring of this equipment. The Station zone focuses on substations, followed by the operation zone for grid operation control. The Enterprise and Market zones pertain to enterprise activities and electricity commercialization. After presenting the SGAM Framework's structure, the modelling process for use cases begins with the "analysis" phase, validating UC scenario information. This is followed by developing SGAM layers, zones, and domains. The high-level architecture of XFLEX overall platform is demonstrated in Figure 13.

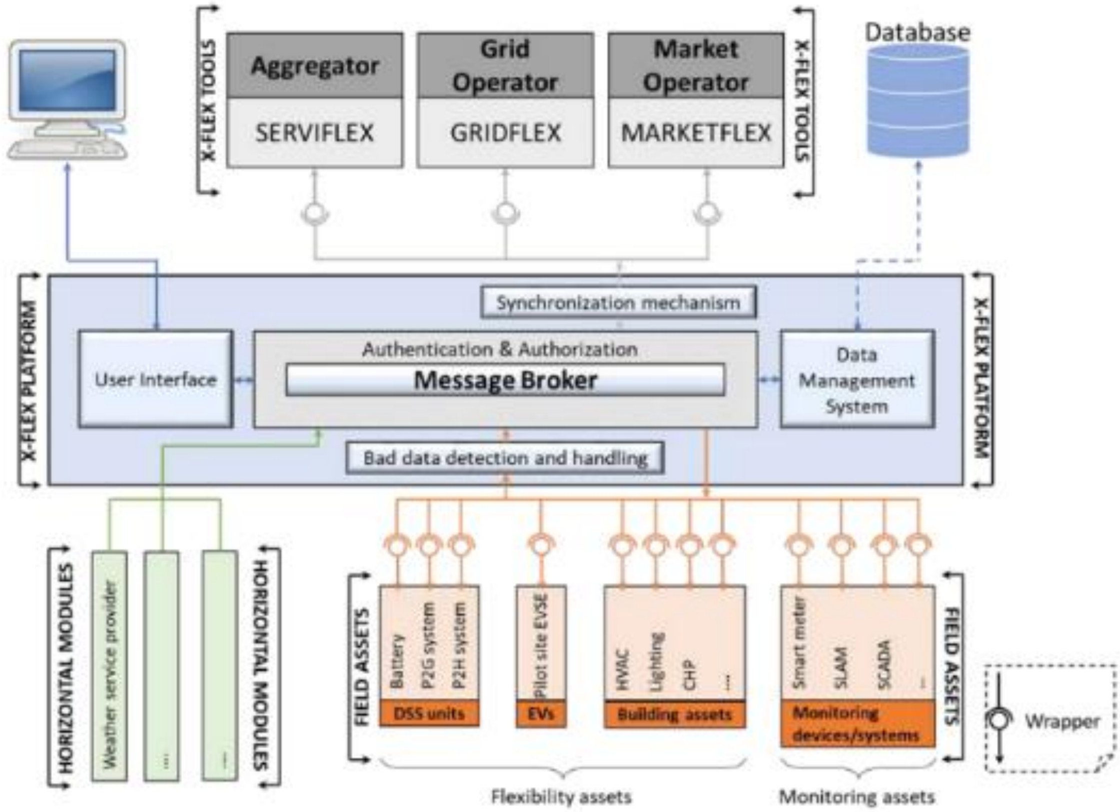


Figure 13 XFLEX high-level architecture

(Q3) XFLEX's key findings regarding the implementation of **standards and interfaces** to improve flexibility and business process (system planning/asset management, system operation, energy markets).

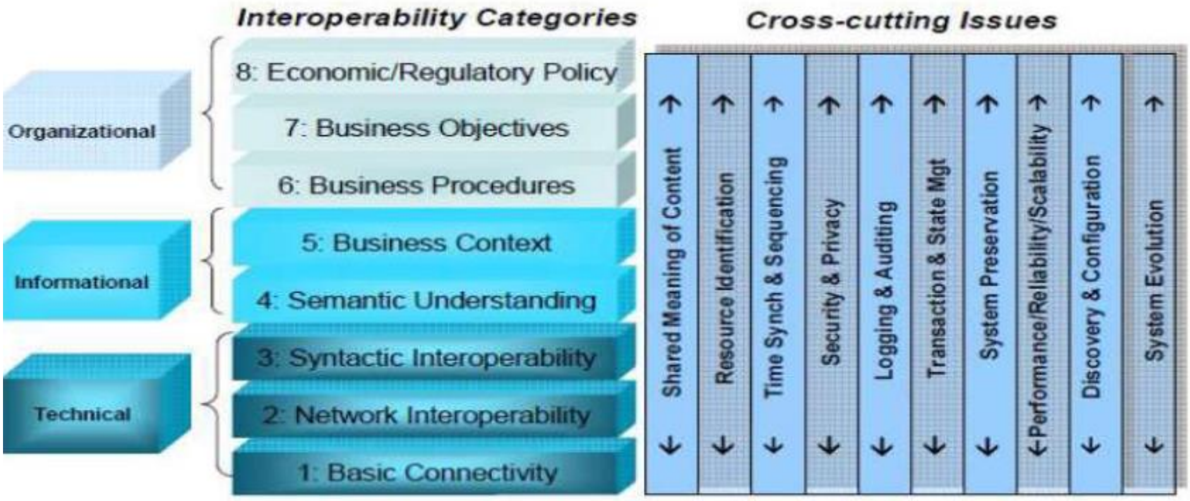


Figure 14 Interoperability Categories

XFLEX successfully demonstrated the integration of decentralized flexibility assets into a unified platform and emphasized the importance of standardized data exchange protocols to ensure interoperability among different technologies and systems. The development of GRIDFLEX provided advanced automatic control and observability capabilities, which are important for real-time grid management and allowed for the continuous monitoring of grid aspects and the rapid dispatch of control signals to manage flexibility resources effectively. MARKETFLEX facilitated new market mechanisms and platforms that enabled various stakeholders, including prosumers, to participate in flexibility markets, thus creating a more responsive and dynamic energy market that can better accommodate fluctuations in supply and demand. The XFLEX platform was designed to be flexible and scalable, accommodating different sizes and types of energy systems, deploying the solutions across various geographical and socio-economic contexts within the EU. By integrating these technologies, XFLEX enhanced business processes via providing better data visibility and decision-making potential, leading to more efficient and effective management of energy systems.

(Q4) XFLEX's contribution towards the development of **data interoperability platforms and data-sharing** frameworks.

XFLEX categorized the interoperability of the platforms to the SGAM.

The project enhanced data interoperability platforms and data-sharing frameworks to improve energy system flexibility and business processes. The tools like SERVIFLEX integrated flexibility management, which utilized standardized metadata frameworks to ensure seamless data exchange between diverse energy resources. The GRIDFLEX facilitated real-time monitoring and control, employing standardized communication protocols to maintain compatibility across the various devices. MARKETFLEX supported new market mechanisms by standardizing data exchange for bids and offers, thus integrating smoothly with existing market systems. The XFLEX platform provided a scalable and flexible integrated solution, employing a unified data model to standardize and facilitate data sharing across the energy value chain. These tools were tested in real-world pilots demonstrating practical interoperability and data-sharing capabilities in diverse settings.

(Q5) XLEX's definition of **communication and data exchange requirements**.

The implementation of XFLEX platform and all its individual components leads to the following requirements on interoperability, information exchange and respective communication infrastructure:

- Communication standards for interaction with distribution network energy resources such as Distributed Energy Generation (DEG), battery storage/ P2H/ P2G systems, Electric Vehicles (EVs) and Building Management Systems (BMSs).
- Communication standards for interaction with distribution network monitoring devices such as SLAMs, SMXs, SCADAs, AMIs etc.
- Standardized data exchange format for communication of relevant market information including tariffs, electricity prices, energy/capacity bids and other data that is shared by retailers, aggregators,
- and other energy market actors.
- Standardized data exchange format for communication of flexibility information such as forecasted flexibility profiles, schedule of operation of flexibility units, etc.
- Standardized data exchange format for communication of grid information such as grid measurements and grid calculations (e.g., power flow, state estimation, congestion forecast, etc.).
- Standardized data exchange format for transmission of activation signals to flexibility sources from grid operators to individual DEG units, storage systems, BMSs and Electric Vehicle Supply Equipment (EVSE).

(Q6) **Data models** used in XFLEX.

The relevant XFLEX project data models and standards that were reviewed and considered are:

- Common Information Model (CIM)
- IEC 61850
- Universal Smart Energy Framework /USEF Flex Trading Protocol (USEF/UFTP)
- Open Change Point (OCPP)
- Smart Application Reference (SAREF) and other Smart Home/Buildings Standards
- Device Language Message Specification / Companion Specification for Energy Modelling (DLMS/COSEM)
- Blockchain standards
- FIWARE

The data models used in the XFLEX platform are: MQTT, AMQP, HTTP, MODBUS, KAFKA and REST API.

(Q9) Examples of tool **limitations** identified during the analysis.

The standards and data models analysed in the previous section can support interoperability between XFLEX tools covering most of the data elements handled by them. However, taking into consideration the XFLEX UCs review conducted in section 2, in some cases there are gaps on the existing standards that may prevent UCs implementation. In this Section these gaps are identified and presented. This process was done in parallel with the data models identification procedure which was carried out under Task 2.4: System architecture definition along with the review of demonstration assets at the different demo sites.

SERVIFLEX: In general, the information objects of SERVIFLEX UCs can be represented by existing standards and data models such as the data objects defined in SAREF, USEF or IEC CIM. However, there are some specific attributes and concepts for the battery, P2X and PV systems that are not covered by existing standards and, for these cases, extensions on CIM and SAREF data model may be built.

GRIDFLEX: Most information objects handled by GRIDFLEX can be covered by existing standards and data models such as CIM, DLMS/COSEM, IEC61850 and USEF. For the information objects that cannot be represented by existing standards, custom data models will be developed.

MARKETFLEX: The information objects of MARKETFLEX UCs will be covered by USEF/UFTP protocol. Some potential differences have been identified between the Traffic Light System (TLS) of USEF and the TLS envisioned in MARKETFLEX. An extension will be provided for these differences to be aligned.

(Q11) How **data exchange gaps** are affecting the support for flexibility requirements identified and analysed.

XFLEX framework will be composed of three major components, namely SERVIFLEX, GRIDFLEX and MARKETFLEX tools:

SERVIFLEX is the tool for flexibility managers. Its main functionality is the analysis and forecasting of flexibility provided by flexibility sources such as generation assets, battery systems, P2G/ P2H/ Power to Vehicle (P2V) technologies and Demand Side Management (DSM)/ Demand Response (DR) schemes. It also provides segmentation, classification and clustering of flexibility sources in order to offer appropriate services to third parties such as the grid operators and the market. Finally, SERVIFLEX is able to control flexibility sources taking instructions from the GRIDFLEX or the MARKETFLEX tools serving the needs of the grid or the market respectively.

GRIDFLEX is the tool for grid and microgrid operators. It aims to promote monitoring (through the integration of data sources – such as SLAM (Smart Low-cost Advanced Meter), SMX (Smart Meter eXtension), SCADA (Supervisory Control and Data Acquisition), or AMI (Advanced Metering Infrastructure) – and the analysis of their metering data), as well as management and control of the grid in an efficient way increasing in parallel the share of Renewable Energy Systems (RES). The tool will provide advanced services and decision support systems to prevent grid congestions (voltage and current issues) and avoid power quality problems, making use of the flexibility sources integrated into the grid. It will also provide optimized services for enhancing electricity grid resilience under extreme events.

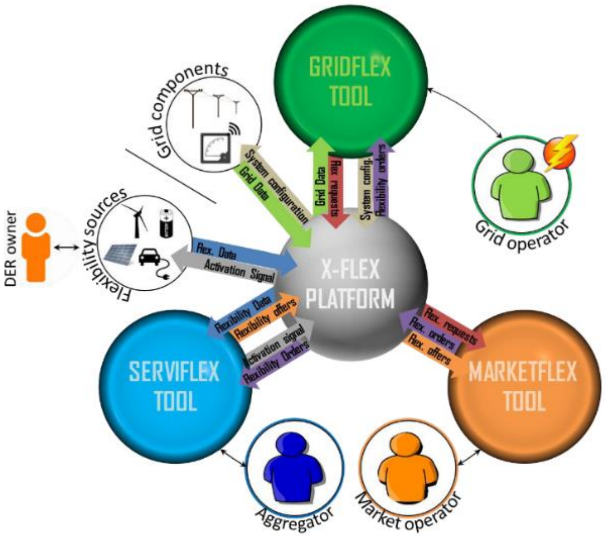


Figure 15: XFLEX platform components

MARKETFLEX tool will facilitate access and participation of energy grid participants (generation, DR, flexibility providers), individually or through an aggregator, on different markets: wholesale, local energy market or ancillary services for Distribution System Operator (DSO) and Transmission System Operator (TSO), in order to improve grid stability and energy supply. MARKETFLEX serves as a link between SERVIFLEX and GRIDFLEX tools. While SERVIFLEX forecasts the flexibility availability and GRIDFLEX forecasts the grid conditions, MARKETFLEX confirms or rejects the activation of flexibility based on technical and economic criteria.

The above-mentioned tools will be integrated into the XFLEX platform (Figure), which serves as a scalable, secure and open ICT (Information and Communication Technology) platform, with interoperable interfaces, for real time monitoring and decentralized control of the energy network. The purpose of this platform is to provide a high-performance and reliable middleware that will integrate and serve as the service bus for all the sub-system, services, and actors of the XFLEX project. This platform will manage and process the heterogeneous and massive data stream coming from the involved distributed energy infrastructure and will serve as the interface for the communication among XFLEX tools and between them and field devices and horizontal modules

The implementation of XFLEX platform and all its individual components leads to the following requirements on interoperability, information exchange and respective communication infrastructure:

- Communication standards for interaction with distribution network energy resources such as Distributed Energy Generation (DEG), battery storage/ P2H/ P2G systems, Electric Vehicles (EVs) and Building Management Systems (BMSs).
- Communication standards for interaction with distribution network monitoring devices such as SLAMs, SMXs, SCADAs, AMIs etc.
- Standardized data exchange format for communication of relevant market information including tariffs, electricity prices, energy/capacity bids and other data that is shared by retailers, aggregators, and other energy market actors.
- Standardized data exchange format for communication of flexibility information such as forecasted flexibility profiles, schedule of operation of flexibility units, etc.
- Standardized data exchange format for communication of grid information such as grid measurements and grid calculations (e.g., power flow, state estimation, congestion forecast, etc.).

Standardized data exchange format for transmission of activation signals to flexibility sources from grid operators to individual DEG units, storage systems, BMSs and Electric Vehicle Supply Equipment (EVSE).

(Q12) XFLEX's Proposed solutions for **addressing gaps**, such as using merged standards for data exchange, developing interfaces/adapters for TSO/DSO and customers, integrating cross-sector and cross-border components in the reference architectures and platforms to support flexibilities, etc.

To address these gaps, XFLEX provided extensions of the existing standards and data models including:

- CIM data model extension to cover XFLEX's flexibility elements
    - CIM extension to cover XFLEX battery systems
    - CIM extension to cover XFLEX PV systems
    - CIM extension to cover XFLEX CHP system
    - CIM extension to cover XFLEX P2G system
    - CIM extension to cover XFLEX P2H system
- USEF/UFTP extension
- SAREF extension to cover P2H/VES system
- Custom XFLEX data models

(Q13) XFLEX's proposals for **improving business processes** (i.e., system planning/asset management, system operation, energy markets) efficiently while facilitating flexibility and resilience of the EU energy system.

The XFLEX project proposes extensions to existing data models and standards:

- CIM Data Model Extensions:
    - Battery Systems: Attributes like battery model, ratedE, and location added to Battery Storage Unit.
    - PV Systems: Based on data model from the Horizon 2020 project PLANET.
    - CHP Systems: Modelled after PLANET project.
    - P2G Systems: Modelled after PLANET project.
    - P2H Systems: Includes Power to Heat Unit and Thermal Storage Unit, modelled for demo site installations.
- USEF/UFTP Extensions:
  Covering areas such as TLS signal data, market bids, LV capacities, voltage, and current profiles.
- SAREF Extension for P2H/VES Systems:
  Integrating building-level devices like HVAC and Domestic Hot Water as thermal storage entities. Requires extensions to cover specific parameters not included in SAREF.
- Custom XFLEX Data Models:

Developed for maintenance, grid information messages, and extreme weather event procedures.

(Q14) Challenges anticipated in implementing XFLEX's proposals, and how can be overcome.

Implementing the proposals for XFLEX battery systems presents several challenges, including:

- Interoperability Issues: Ensuring seamless integration of various smart systems and equipment into the XFLEX framework requires addressing interoperability issues. Different standards and data models need to work together, and extensions to existing standards like

CIM and SAREF may be necessary to cover specific attributes and concepts not currently included.

- Standardization Gaps: Identified gaps in existing standards may prevent the realization of XFLEX use cases. For instance, certain data related to PV systems, CHP systems, battery systems, and P2H systems are not covered by current standards and require extensions to CIM and SAREF models.
- Complex Communication Needs: The communication standards needed for interaction with various distribution network energy resources and monitoring devices, as well as for exchanging market and flexibility information, add layers of complexity to the implementation.
- Validation and Harmonization: To achieve high-level interoperability using CIM, continuous validation methods must be developed, and harmonization between CIM and IEC 61850 standards is required. This involves creating compatible data interfaces between systems based on these two standards.

Overcoming These Challenges:

- Developing Standard Extensions: Address the gaps by developing necessary extensions for existing standards like CIM and SAREF. This involves incorporating new attributes and data models that can handle the specific needs of XFLEX components such as battery, P2G, and PV systems.
- Ensuring Harmonization: Work towards harmonizing CIM with other relevant standards like IEC 61850 to ensure compatibility and smooth data exchange between different systems. This can be facilitated by establishing data interfaces that bridge the gaps between these standards.
- Implementing Advanced Communication Protocols: Utilize advanced communication protocols and standardized data exchange formats to facilitate efficient and accurate data transmission among different components of the XFLEX platform.
- Continuous Validation: Develop and implement validation methods to ensure that the exchanged information conforms to the required standards, thereby maintaining the integrity and reliability of the system.

B.10 CoordiNet

(Q1) CoordiNet Project Objective: The completed CoordiNet project [90] aimed to establish collaboration schemes between transmission system operators (TSOs), distribution system operators (DSOs), and consumers to develop a smart, secure, and resilient energy system. It focused on analysing and defining flexibility in the grid at every voltage level, from TSO and DSO domains to consumer participation. CoordiNet's objectives included demonstrating cost-efficient models for electricity network ancillary services that can be scaled and replicated across the EU energy system, supporting the implementation of current and future network codes on demand-response and storage, opening new revenue streams for consumers and generators to provide grid services, and increasing the share of renewable energy sources (RES) in the electricity system.

Project Status: Completed

(Q2) CoordiNet to specify and develop a TSO-DSO-Consumer cooperation platform.

A service catalogue was created, providing a detailed analysis of how stakeholders exchange information within the Business Use Cases (BUCs) defined by the demos. The service catalogue also clarified the role of the COORDINET market platform and how it was integrated into the information flow between DSO, TSO and other market players. D2.4 [91] also presents the required standards, common interfaces and the requirements for information exchange within the platform.

(Q2i) CoordiNet specification of the purposes of the interfaces, along with their definitions in terms of information models, timing requirements, and interaction sequences.

The SGAM mapping of the architectures used for the BUCs of the CoordiNet demos can be found in D6.5 [92].

(Q3) CoordiNet's key findings regarding the implementation of standards and interfaces to improve flexibility and business process (system planning/asset management, system operation, energy markets).

All the CoordiNet demonstrations found that standardised processes for collecting measurement data and interoperability are necessary, both between grid components and market platforms to enable an efficient and well-functioning market. Currently, there is no common European framework to ensure interoperability between flexibility market platforms. If several separate markets exist, different interfaces and market procedures increase complexity, ICT costs, and the need for IT security measures. Harmonisation of rules and requirements will be important to promote an environment where choices are guided by best practices and can support efficient and secure electricity systems (D6.7 [93]).

(Q7) Protocols and standards applied in CoordiNet:

The common interfaces elaborated in CoordiNet built on ENTSO-E CIM profiles based on the standards set by the International Electrotechnical Commission (IEC):

- CGMES (Common Grid Model Exchange Specification), based on IEC 61970 and IEC 61968
- CIM European Style Market profile based on IEC 62325

Other standards considered by the project include:

- IEC 62559, Use Case (UC) methodology
- IEC 61850

(Q8) **Gaps** identified in terms of data format, information models and communication protocols in CoordiNet

No common European framework was available to ensure interoperability between flexibility market platforms. Different communication protocols were needed depending on the type of the flexibility service provider (FSP) and market participant. This could become time-consuming and costly for SOs as it made communication with different types of FSPs and markets more complex to develop, implement, deploy, update, and maintain. The development of SOs' own approaches reduces interoperability and increase complexity, ICT costs, and time spent for FSPs, leading to market entry barriers and potentially decreased liquidity.

(Q12) proposed solutions for addressing gaps, such as using merged standards for data exchange, developing interfaces/adapters for TSO/DSO and customers, integrating cross-sector and cross-border components in the reference architectures and platforms to support flexibilities, etc.

Formats for smart meter output data should be standardised to ensure that it is possible to increase interoperability between regions and streamline the platforms' interfaces. In the process of defining new standards, a review of existing standards and payloads must be done to ensure that meta-data collection and attributes will be consistent with the needs of new flexibility products. This will lower the overall complexity and cost of integration. Moreover, DSOs and TSOs must agree on standards for data exchange in order to be able to exchange data and information on the market platform.

A consistent architectural description for knowledge retention and exchange is necessary for the integration of complex systems. The application aids for the use case methodology, for the SGAM methodology or the security-by-design approach for the IEC 62559-2 use case template, should be further disseminated and used for documenting and sharing knowledge in the medium term.

The CoordiNet project showed that basic technologies for ICT-based energy transition are available and must be integrated into new energy markets. The fundamental basic architectures must be designed for the long term and should be modular for adjustments in the power system.

(Q15) CoordiNet **has made developments** addressing the **cyber-physical reliability and resilien**ce of the electricity grid.

(Q15i) CoordiNet cyber and physical assets/elements that the project addresses, **potential risks** identified in CoordiNet that are associated with the cyber-physical nature of the grid, and how the latter are mitigated.

Higher levels of interoperability would bring stronger requirements for encryption, secure protocols, etc. Hence, the project recommended enhancing security measures, as the increasing number of available increments possible attack vectors in the grid.

New and innovative solutions must take into account fundamental security requirements in the design of systems engineering not only to initially implement a high level of security, but also to be able to evaluate the effects of IT security on the performance and scalability of solutions. The existing technical solutions should be evaluated cyclically using an ISO 31000-based approach. In particular, new attack vectors and documented vulnerabilities should be reviewed cyclically and addressed through mitigations. The project recommended EU-level efforts should be made to promote an accelerated deployment of monitoring and measurement tools to improve digitalization and grid observability. One of the biggest challenges identified was the installation of monitoring and control devices for the flexible resources and the low voltage network. The process of installing the necessary components was lengthy and was customised for every flexible resource. Monitoring and measurements need to be improved and roll-out facilitated since potential FSP resources are not prepared or equipped to participate in a flexibility market (D6.7).

B.11 ENERGYSHIELD

(Q1) ENERGYSHIELD's Project Objective: ENERGYSHIELD **Error! Reference source not found.** combines the latest technologies for vulnerability assessment, supervision and protection to draft a defensive toolkit that can support the needs of Electrical Power and Energy System (EPES) operators. The main objective of the project is to develop a set of tools such as (i) Vulnerability assessment (VA), which can simulate attacker's behaviour within networks, (ii) Security information and event management (SIEM), which can integrate the different tools and give an overview what is happening in the organization, (iii) Security behaviour analysis (SBA), which can help to assess the actual state of security awareness in organizations (iv) Distributed Denial of Service DDoS detection and mitigation (DDoSM), which can help to detect DDoS attacks on the infrastructure and mitigate them, (v) Anomaly detection (AD), which can analyse the networks and point out unexpected events, (vi) Homomorphic Encryption (HE), which can secure the data exchange between the tools.

Project Status: Completed

(Q2) ENERGYSHIELD **interfaces and data interoperability platforms** to enhance flexibility and improve business processes.

The project mainly deals with software tools for cybersecurity, mainly regarding the IT systems of system operators. The ENERGYSHIELD toolkit exposes a set of REST API that enables the interoperability between the developed cybersecurity tools (i) to (v) mentioned above, and the possible integration with other tool, offering asynchronous message exchange using queues, inter module asynchronous communication, and allowing external system to subscribe to the topics. There is no direct indication of enhancing specifically power system flexibility or other specific business processes of the system operators.

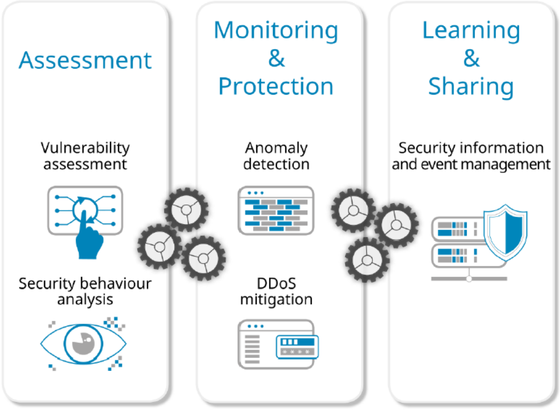


Figure 16: The three modules and the five tools of EnergyShield

Q2i: ENERGYSHIELD’s Specification of the purposes of the interfaces, along with their definitions in terms of information models, timing requirements, and interaction sequences.

The deliverable mentions that 3 APIs connected with the system operators IT systems need to be protected by DDoSM: e.g., for smart metering (AMI), communication with smaller renewables, data exchange with the regulator.

Q2ii: A brief description, or illustration of each ENERGYSHIELD **interface’s architecture**, referencing the SGAM model.

There is no reference to SGAM. The overall toolkit integration diagram is the following.

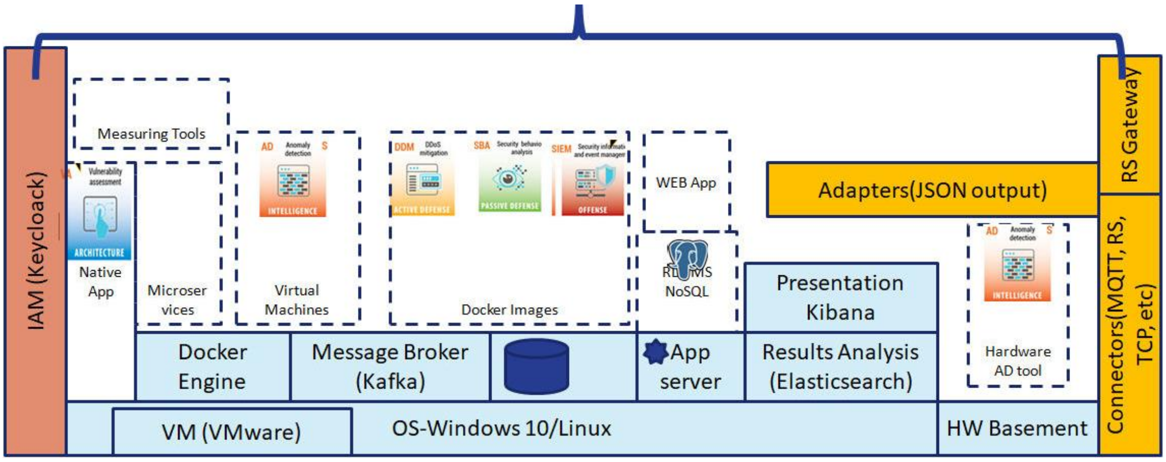


Figure 17: ENERGYSHIELD overall toolkit integration diagram

The ENERGYSHIELD toolkit is organized in several “shelves” or “drawers” and contains hardware components, software components, and communication ports. It is protected by an authentication mechanism.

(Q4) ENERGYSHIELD's contribution towards the development of **data interoperability platforms and data-sharing** frameworks.

The project defines interoperability as "system can exchange information with other systems and use the information that has been exchanged» and ensures the tools exchange capability among the rest of the ENERGYSHIELD components and IT information tools of System operators during field test evaluations.

(Q5) ENERGYSHIELD's definition of **communication and data exchange requirements**.

ENERGYSHIELD tests the cybersecurity tools in the communication of smart metering devices with IT systems of DSOs and validates their efficiency. It practically does not propose any communication or data exchange requirements.

(Q10) ENERGYSHIELD's significant missing interfaces and adapters identified between system operators, TSOs, DSOs, and customers.

The project develops and test tools that include user interfaces mainly for the usage of the tools not to connect SOs and customers: "Web interface: implemented using a combination of HTML, Bootstrap, CSS and JavaScript files to provide a user-friendly interface for all interacting actors of the tool.", "REST API: a web interface allowing interaction of the SBA tool with the rest of the ENERGYSHIELD toolkit or with any other corporate operational system", "Graphical User Interface (GUI): The tool's graphical user interface is called SigaSight, and it provides the user with asset visualization, alerts, and analysis"

B.12 NEWGEN

(Q1) NEWGEN's Project Objective: The EU-funded NEWGEN project **Error! Reference source not found.** will develop and demonstrate new insulation materials, cable manufacturing solutions, online condition monitoring technologies and comprehensive life and reliability modelling tools for the next-generation of extruded high-voltage direct-current (HVDC) cable systems. The project will deliver new space charge mitigating additives for extruded HVDC insulation materials, as well as new industrial cable extrusion solutions for defect-free and cost-effective manufacturing of next-generation thermoplastic HVDC cables. NEWGEN will also provide new pre-fault detection methods and instruments for assessing the health status of extruded HVDC cable systems, as well as comprehensive tools and models for the evaluation of their life and reliability.

Project Status: Ongoing

(Q2) NEWGEN **interfaces and data interoperability platforms** to enhance flexibility and improve business processes.

The project mainly develops new materials and cable designs for HVDC cables, i.e. hardware technologies as well as cable monitoring technologies, while building models for cable lifetime assessment

(Q15) NEWGEN **has made developments** addressing the **cyber-physical reliability** and **resilience** of the electricity grid.

(Q15i) NEWGEN's **cyber and physical assets/elements** that the project addresses, **potential risks** identified in NEWGEN that are associated with the cyber-physical nature of the grid, and how the latter are mitigated.

The projects present methodologies for online global monitoring of HVDC cables, optimized HVDC insulation compounds and cable prototypes that mitigate/diminish the risk of cable failures i.e., partial discharges, insulation breakdown, material failures.

The project presents an online global monitoring system architecture for HVDC cable systems. This is not further explained since there are almost not at all technical deliverables publicly available even though the project is running from mid-2022.

(Q15ii) Identified focus areas for **dynamic monitoring and control** to ensure the reliability and resilience of the grid, NEWGEN propositions for **effective monitoring and protection of the pan-European grid cyber layers**.

The project mentions “Simulated impact on HVDC/AC multilink system and its “firewall” properties.”, from which we understand that they will study the impact on the pan EU grid of their HVDC related developments [96].

B.13 AGISTIN

(Q1) AGISTIN’s Project Objective: The AGISTIN project **Error! Reference source not found.** proposes to develop grid integration architectures for energy storage with on-site renewables and emerging DC end-uses. This follows the DC coupling approach considered in current PV+ storage hybrids, extending it to include end-use, grid users and system integrators. As such, industrial grid users can benefit from the avoidance of additional hardware, reducing costs, improved operational efficiency, flexibility and self-consumption as compared to the AC connection approach. The project will develop control algorithms to coordinate between all three asset classes that will be open sourced for exploitation by system integrators and power electronics OEMs.

Project Status: Ongoing

B.14 BD4OPEM

(Q1) BD4OPEM’s Project Objective: BD4OPEM (Big Data for Innovative and Sustainable Energy Solutions) **Error! Reference source not found.** develops an open innovation marketplace where, through an analytic toolbox that integrates solutions based on artificial intelligence, products and services to improve the monitoring, operation, maintenance and planning of electrical distribution grids are made available to stakeholders.

Project Status: Completed

(Q2) BD4OPEM **interfaces and data interoperability platforms** to enhance flexibility and improve business processes.

The project developed an IT architecture with several “device adaptors” as they call them for achieving interoperability, as a part of the data layer that includes also modules like data harmonization CIM, context broker, data cleansing, storage, data lake, unified API, data management and monitoring.

Q2i: Specification of the purposes of the interfaces, along with their definitions in terms of information models, timing requirements, and interaction sequences.

As mentioned, the “harmonization is accomplished by the implementation of standards and ontologies (e.g. SAREF[1], SAREF4NER[2], FIWARE[3], CIM[4]) framed within ICT and energy domain, offering a common structure for data and fully defined in D3.2”.

Regarding timings, it was not possible to find any information.

The interaction sequences are provided in detailed sequence diagrams of the use cases, 10BUCs and 24 SUCs (D2.3 pg. 93)

Q2ii: A brief description, or illustration of each **interface’s architecture**, referencing the SGAM model.

The project presents a detailed mapping of the BD4OPEM architecture with the SGAM model and the various layers.

(Q3) BD4OPEM’s key findings regarding the implementation of **standards and interfaces** to improve flexibility and business process (system planning/asset management, system operation, energy markets).

The project use cases mainly focus on distribution level use cases at LV and MV, mainly dealing with power quality and disturbance, flexibility forecasting, topological representation and SCADA information mapping, EV to the grid flexibility.

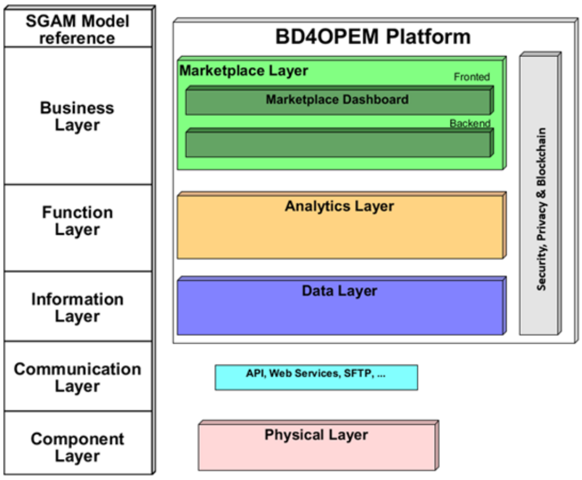


Figure 18: BD4OPEM high-level architecture layering

Regarding key findings, the information we found does not ‘discriminate’ for the standards and interfaces: it presents the details of the main architectural layers and its contents and the results of the pilots. In the demos there were two KPIs presented at project level, (i) Dimension of data providers and volume of data managed (ii) Data coming from renewable technologies evaluating the engagement of many and different users and scalability-replicability potential.

(Q4) BD4OPEM’s contribution towards the development of **data interoperability platforms and data-sharing** frameworks.

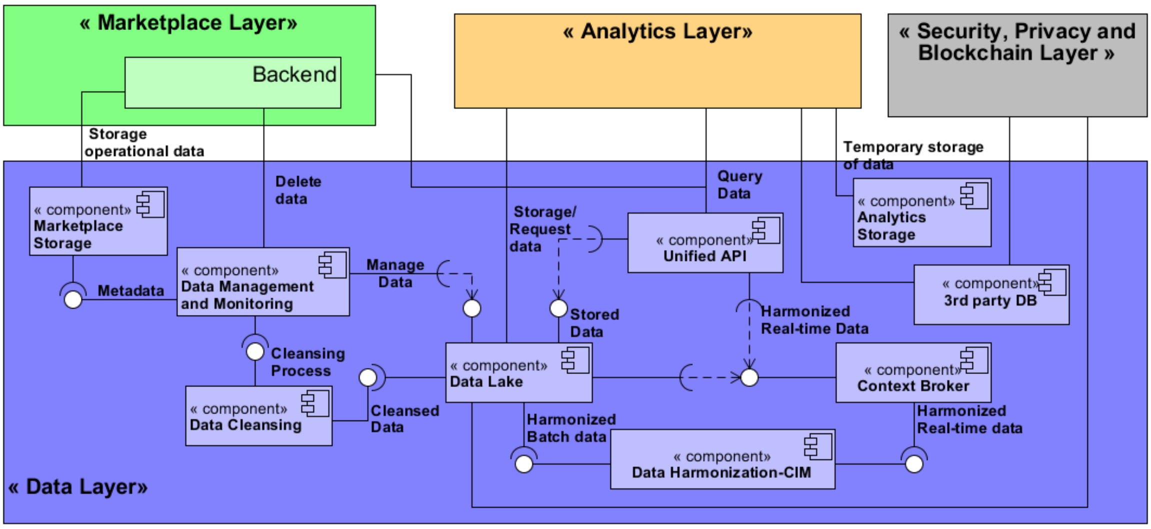


Figure 19: The BD4OPME architecture

The project presented a data layer that provided interoperability with the analytics, marketplace and security layers, mainly hosting the independent tools tested in the demo sites. The architecture is compatible with AMI, SCADA, GIS, EV charging, HVAC with KNX, PV control Wibeee.

(Q5) BD4OPEM's definition of **communication and data exchange requirements**.

The project presents a detailed data layer with a data mediation functionality» act as a facilitator of data exchanges with external APIs for the services built on the Analytics layer, offering transparent integration with external data sources through standard interfaces.

(Q9) Examples of tool **limitations** identified during the analysis.

In the deliverable for the Spanish pilot, it has been pointed out that "First, by having to supply a huge amount of data to different partners made the company realize the state of disorganization and state of quality of the data gathered from the different assets of the grid. The outcome of this is a clear task for ESTEBANELL to create a data architecture that unifies and brings together all data gathered from its sources. This organization facilitates the participation in data marketplaces, enabling a proper treatment of the data internally, more profitable collaboration with other partners, and a better predisposition to open innovation, but most of all, it can facilitate the extraction of information, and hence, the value inherent in the data."

"Related to the issue raised before is the data transfer, and the rising concern of data interoperability and data transparency in the sector. This was extremely visible in two aspects. One refers to the bad quality of data and different formatting issues that make it difficult in a lot of cases the extraction of proper results in the simulations of the services. And the other refers to the process of harmonization needed that also put some difficulties in running the same service for different companies. Finally, through the different services tested in ESTEBANELL's pilot, the DSO was able to extract direct value that was solving specific issues such as the phase connection from the Smart Meters; and data gaps and outliers from timeseries data."

Based on Elektro Celje's reference "we have been collecting vast amounts of data from various sources, including smart meters, GIS systems, and billing systems. Despite this wealth of information, we have not been able to fully utilize it to improve our network operations. We recognize the potential of data to enhance our network management but lack the expertise to extract meaningful insights from it."

Moreover, Elektro Celje mentions "we discovered that our data was not in a usable format. In some cases, it was not clean or standardized, and, in some cases, it was not collected at all. Additionally, there were gaps in the data. Once the data was cleaned and standardized, our partners were able to develop services that could potentially benefit Distribution System Operators (DSOs)."

(Q11) How **data exchange gaps** are affecting the support for flexibility requirements identified and analysed.

The DSOs were facing issues organizing/managing their dispersed data and develop flexibility services. They also mentioned issues for valorisation of real time data "one of the pilot's objectives was to provide real-time data to enable the deployment of high value services. This was an important challenge both in terms of data collection and data integration. Overall, the deployment of the concerned services was complex, but this demonstration brought a lot of insight into this kind of work for future service developers.

(Q12) BD4OPEM's proposed solutions for **addressing gaps**, such as using merged standards for data exchange, developing interfaces/adapters for TSO/DSO and customers, integrating cross-sector and cross-border components in the reference architectures and platforms to support flexibilities, etc.

BD4OPEM is mainly dealing with DSO-consumer interface and in order to deliver specific services addressing the various operational aspects of the DSO. In order to communicate with the main data management layer, the project has developed APIs to connect.

(Q13) BD4OPEM's proposals for **improving business processes** (i.e., system planning/asset management, system operation, energy markets) efficiently while facilitating flexibility and resilience of the EU energy system.

The services developed in BD4OPEM are focusing on data valorisation for flexibility services at DSO level, mainly managing consumer assets related with household loads EV chargers, energy sharing practices at distribution level and disturbances mitigation. Thus, they focus more or less to all aspects of operators, at MV/LV levels, apart from markets that are not established at DSO level yet.

(Q14) Challenges anticipated in implementing BD4OPEM's proposals, and how to overcome them.

The challenges identified has been the poor data quality and, in some cases, (i.e. Slovenian demo) they had to install some additional smart meters to generate some near real time datasets.

(Q15) BD4OPEM **has made developments** addressing the **cyber-physical reliability** and **resilience** of the electricity grid.

(Q15i) BD4OPEM's **cyber and physical assets/elements** that the project addresses, **potential risks** identified in BD4OPEM that are associated with the cyber-physical nature of the grid, and how the latter are mitigated.

The pilots have deployed different services, including grid disturbances simulations services, and predictive maintenance.

The reliability areas identified are mainly disturbances scenarios and predictive maintenance based on data analysis

(Q15ii) Identified focus areas for **dynamic monitoring and control** to ensure the reliability and resilience of the grid, BD4OPEM propositions for **effective monitoring and protection of the pan-European grid cyber layers**.

The focus areas are disturbance simulations, mainly due to congestions, overvoltage, line and transformer overloads

The project mainly focuses on distribution grids, and does not study the impact on the transmission grid and thus to the interconnected European network

B.15 EDDIE

(Q1) EDDIE's Project Objective: EDDIE (European Distributed Data Infrastructure for Energy) **Error! Reference source not found.** introduces a decentralized, distributed, open-source Data Space, in alignment with the efforts of the EU Smart Grids Task Force on Implementing Acts on Interoperability and other European initiatives. The European Distributed Data Infrastructure for Energy (EDDIE) significantly reduces data integration costs, allowing energy service companies to operate and compete seamlessly in a unified European market. Additionally, an Administrative Interface for In-house Data Access (AIIDA) ensures secure and reliable access to valuable real-time data based on customer consent.

Project Status: Ongoing

B.16 BD4NRG

(Q1) BD4NRG's Project Objective: The main objective of BD4NRG [100] is to deliver an innovative smart grid-tailored near real time energy-specific open analytics modular framework which leverages on an open-source highly distributed interoperability reference architecture. BD4NRG enables edge-level AI-based cross-sector analytics for integrated and optimised smart energy grid management, based on seamless data-information-knowledge exchange under respective sovereignty and regulatory principles. BD4NRG evolves, upscales, and demonstrates an innovative energy-tailored Big Data Analytics Toolbox (BD4NRG Toolbox), which contributes to achieve a techno-economic optimal management of Electric Power and Energy Systems (EPES) value chain. This will range from optimal risk assessment for energy efficiency investments planning, to optimised management of grid and non-grid owned assets, improved efficiency and reliability of electricity networks operation, while at the same time contributing to achieve fair energy prices to the consumers and laying the foundations for an EU-level energy-tailored data sharing economy.

BD4NRG
Big Data for Next Generation Energy

Project Status: Completed

(Q2) BD4NRG **interfaces and data interoperability platforms** to enhance flexibility and improve business processes.

Interoperability in BD4NRG relies on specific data connectors to handle different data available in different formats and communication protocols (Rest API, SFTP, IoT protocols, sensor network). It provides interfaces for other third-party energy and non-energy datasets/platforms that wish to federate/integrate with BD4NRG. Interoperability reflects the solution adopted by FIWARE: the interoperability layer is composed by FIWARE-compliant components that accept data from multiple data sources from the same protocol, i.e., MQTT, to provide the information with the same format (NGSI-LD) to any FIWARE-compliant external actors. In this sense, the interoperability proposed is at format and semantic level. The semantic level can be granted by a clear definition of the data model, by means of an appropriate NSGI-LD @context file, which implements the schema of the common data.

Q2i: Specification of the purposes of the interfaces, along with their definitions in terms of information models, timing requirements, and interaction sequences.

The NGSI-LD API is structured into a Core API and an optional Temporal API. In addition, the Registry API consists of the operations to be implemented by the Context Registry. Furthermore, the JSON-LD Context API provides functionality for storing, managing and serving JSON-LD @contexts. All Brokers shall implement the Core API. Temporal API and Registry API can be implemented by a Broker or by a separate temporal component and Context Registry respectively. A temporal component implementing the Temporal API can also be used completely independently of a Broker. The JSON-LD Context API is optional. The managing and serving of @contexts can also be handled by an independent, stand-alone component.

Q2ii: A brief description, or illustration of each **interface's architecture**, referencing the SGAM model.

The Data Sources Layer focuses on identifying and understanding the Big Data provided by numerous sources, including energy sensors and meters, data monitoring and acquisition platforms such as SCADA systems or Building Energy Management systems, databases with historical or real time data, smart grid data exchange platforms and cross-domain information such as environmental information and data coming from public administration services (e.g., related to energy performance contracts). Essentially, this layer includes all the data generating hardware, applications and platforms as described in the Component Layer of the BRIDGE architecture.

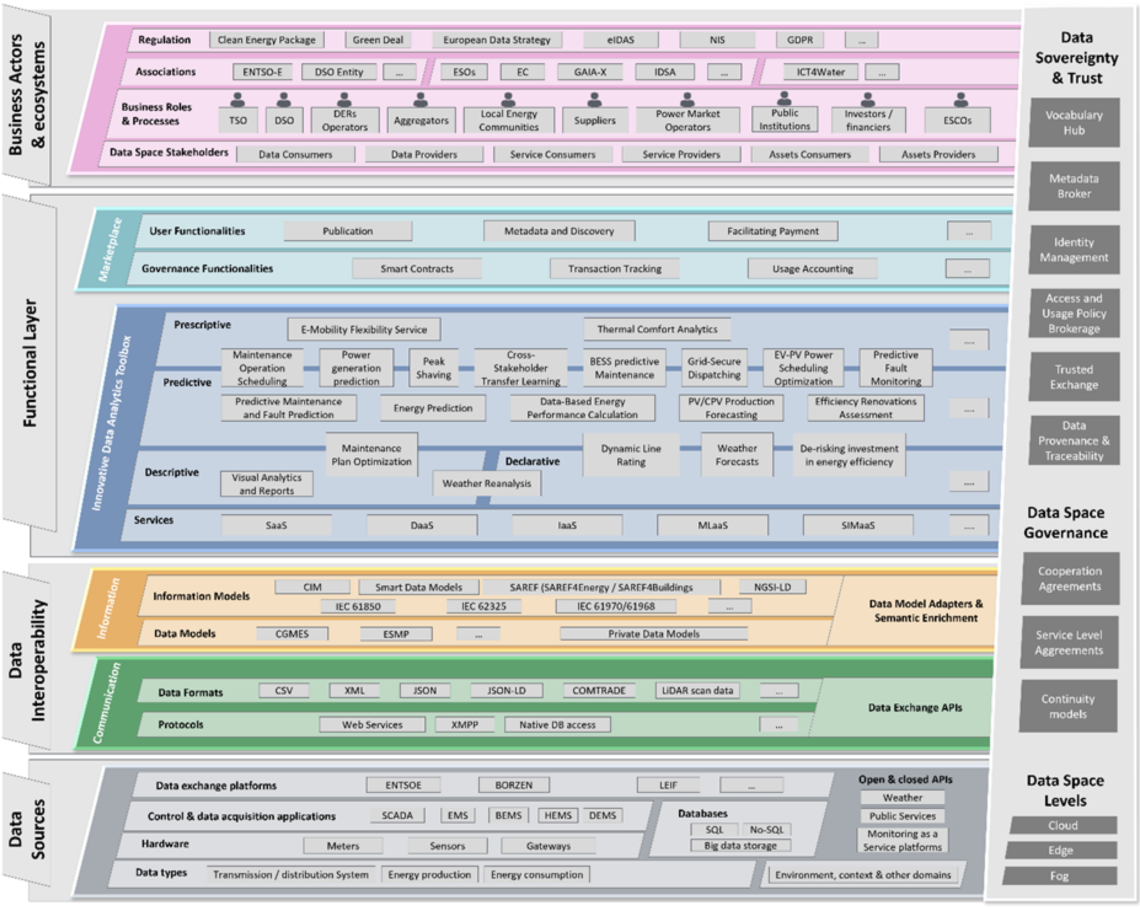


Figure 20: The BD4NRG reference architecture

The Data Interoperability Layer focuses on identifying the communication interfaces with the data sources and corresponding data formats, as well as on providing a set of data and information models which could be followed or used for data transformation, aiming to ensure interoperable data exchange and use.

The Functional Layer deals with application specific rules and decision-making logic as well as services that are executed on the top of the data. This layer represents the “Function” layer of the BRIDGE architecture by consolidating aspects related to data analytics and correspondingly supported functions.

The definition and implementation of the BD4NRG analytics services is performed in WP4. The work

The Business Actors and Ecosystems Layer identifies stakeholders who participate in the data analytics ecosystem and corresponding energy data spaces. They include data providers and analytics services users / data consumers, analytics applications providers and providers of data space enablers and related platforms.

The architecture is organized around three vertical layers that cover specific aspects along the data processing chain and two horizontal layers that are responsible for cross-cutting issues that have impact on the vertical layers. Everything is built upon a common infrastructure. Taking into consideration the Big Data Value Reference Model, the vertical layers do not imply the adoption of a layered architecture model since data can be served to consumers/client applications without being processed.

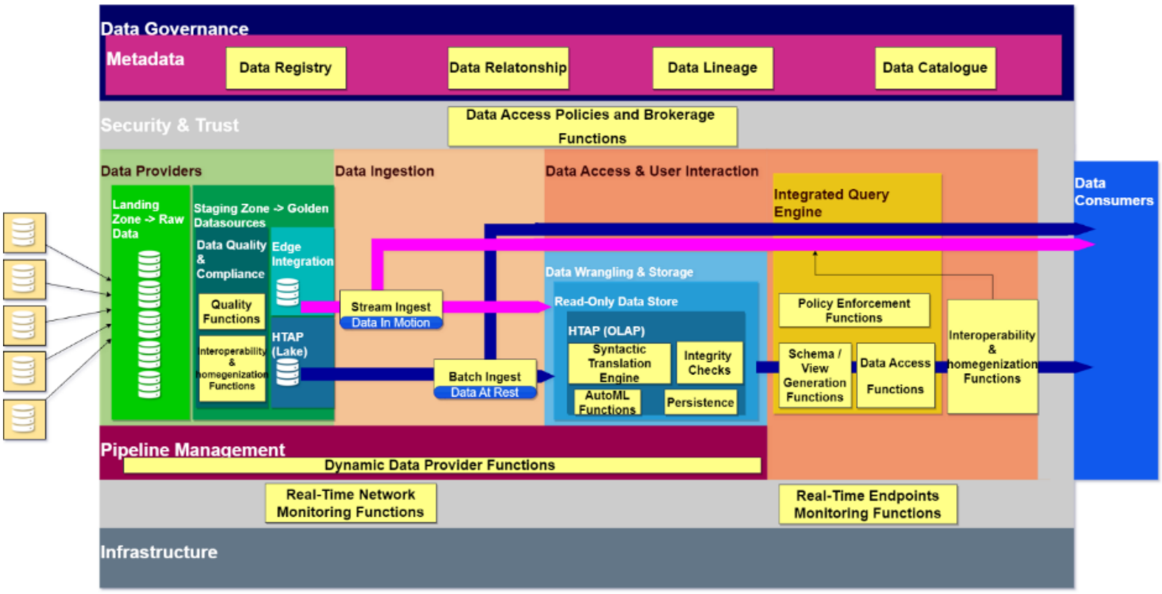


Figure 21: the BD4NRG layer of data flow

The purpose of each layer is here briefly described:

Data Providers: introduces new data into the BD4NRG Data system for discovery, transformation, analysis, and access. The data can come from different sources such as static files (e.g., Comma Separated Values or JavaScript Object Notation), social media, third-party services as well as sensory data from intelligent devices. Raw data is – within this layer – properly processed to create the so-called golden datasets. These datasets are unique data, including all the necessary meta-data, the required quality and following the created interoperability standards to be ingested by the BD4NRG data system.

Data Ingestion & Management: where the data starts their journey i.e., how data can be delivered and distributed within the BD4NRG data system for immediate use or storage. Two main mechanisms are considered, namely: real-time streaming ingestion (for data in motion) and batch ingestion (for data at rest). The specific data ingestion mechanism strictly depends on the application use case.

Data Access & User Interaction: facilitates access and navigation of the data, allowing the generation of different business views to be represented by the data. At the centre of this layer lies a high-performance real time analytics database to support interactive dashboards and analytics platforms while being used as data warehouse. A query engine is also part of the layer and serves as Rapid Application Development (RAD) by presenting fast logical views of data to consumer applications.

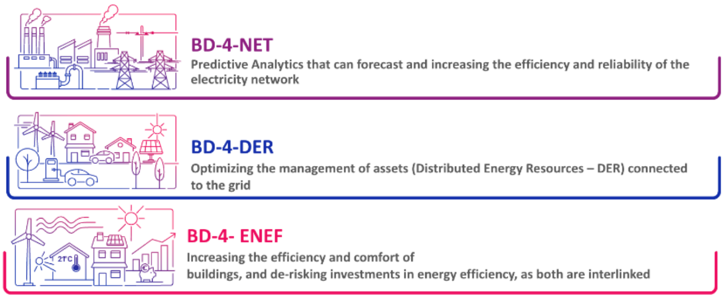
Data Governance: all considered data will be channelized through data governance processes to ensure data stewardship, data classification, data transparency, data discovery, data ownership and data quality by adding business and technical metadata.

Security & Trust is responsible to support and maintain security and trust beyond anonymization and privacy. Data access policies are here defined and enforced as well as dedicated monitoring functions will be also deployed at infrastructure level.

Infrastructure: is the core infrastructure of the BD4NRG data system. The layer deals with networking, computing and storage needs to ensure that large and diverse formats of data can be stored and transferred in a cost-efficient, secure and scalable way. The key requirement of any Big Data storage is that it can handle very massive quantities of data and that it keeps scaling with the growth of the organization, and that it can provide the input/output operations per second (IOPS) necessary to deliver data to applications.

(Q3) BD4NRG's key findings regarding the implementation of **standards and interfaces** to improve flexibility and business process (system planning/asset management, system operation, energy markets).

BD4NRG was aimed at evolving, upscaling and demonstrating an innovative energy-tailored Big Data Analytics Toolbox (BD4NRG Toolbox), and the underlying big data management Framework which significantly contributes to unlock novel cross-stakeholders business opportunities for electricity and other non-energy stakeholders as result of multi-value chain energy-centred data-driven AI-based services.



Predictive Analytics that can forecast and increasing the efficiency and reliability of the electricity network

Optimizing the management of assets (Distributed Energy Resources – DER) connected to the grid

Increasing the efficiency and comfort of buildings, and de-risking investments in energy efficiency, as both are interlinked

Figure 22: BD4NRG toolbox

(Q4) BD4NRG's contribution towards the development of **data interoperability platforms and data-sharing** frameworks.

The value of interoperability specifications was determined by the extent of implementation in the BD4NRG large scale pilots (LSPs). The following arrangements have been made to make this happen:

- Alignment with the three popular initiatives mentioned ensures that implementations or parts thereof also make sense outside of BD4NRG context. This should be an attractive prospect for technical partners.
- Agile standardization and the focus on fit for purpose vocabularies and models ensure that the BD4NRG interoperability specifications serves the needs of the users, not the other way around.
- Setting up a synergy with Semantic Interoperability Toolbox that enables the semantic alignment of data from various users.

(Q5) BD4NRG's definition of **communication and data exchange requirements**.

BD4NRG adopted a solution based on FIWARE technologies by providing common interfaces and open APIs to facilitate the exchange of data and communications between the actors involved.

(Q6) **Data models** used in BD4NRG.

BD4NRG proposes an interoperable FIWARE-based solution as the keystone for all connections between applications/services based on the standardized NGSI-LD API and meta-model, which are viewed as a strong candidate solution to support data interoperability for IoT ecosystems in operational environments.

The NGSI-LD meta-model formally establishes the following NGSI-LD core concepts (Entities, Relations, Properties) based on RDF/RDFS/OWL, and partially based on JSON-LD:

- An NGSI-LD Entity is the informational representative of something (a referent) that is assumed to exist in the real world, outside the NGSI-LD platform. Each instance of such an entity should be uniquely identified by a URI and characterized by reference to one or more NGSI-LD entity types.
- An NGSI-LD property is an instance that maps a characteristic, an NGSI-LD value, to an NGSI-LD entity, an NGSI-LD relationship, or another NGSI-LD property.
- An NGSI-LD relationship is a direct link among a subject (starting point), which can be an NGSI-LD entity, an NGSI-LD property or another NGSI-LD relationship, and an object (end point), which is an NGSI-LD entity.

The ENTIRETY Tool adopts the SARGON ontology by default for provision, govern, discover, and query smart energy domain devices. Furthermore, it maps the SARGON ontology into the core meta-model of NGSI-LD.

SARGON ontology extends Smart Appliance Reference ontology (SAREF) to cross-cut domain-specific information representing the smart energy domain and includes building and electrical grid automation together. SARGON ontology is powered by IEC 61850, and common information model (CIM) standards which are applied to real use cases like monitoring and controlling of electrical grids, controlling of the energy demand in buildings, energy management with residential/non-residential involvement, etc. SARGON may be the starting point for the definition of the BD4NRG data model which will be defined before the third technology release.

Other data models used are Common Grid Model Exchange Standard (CGMES), ESMP, and private data models.

(Q7) **Protocols and standards** applied in BD4NRG.

- CIM (Standard)
- NGSI-LD
- International Electrotechnical Commission (IEC) 61850, IEC 62325, IEC 61970/61968
- Modbus RTU protocol
- MQTT
- Common Grid Model Exchange Standard (CGMES), ESMP

(Q11) How **data exchange gaps** are affecting the support for flexibility requirements identified and analysed.

Given the presence of proprietary solutions and the adoption of proprietary formats and templates that often do not follow existing or evolving standards, communication between the various actors in the European energy system encounters several obstacles in integrating and sharing existing information for the realization of an efficient and manageable flexibility system. Often, small energy system actors do not have enough resources to adapt their technologies and evolve existing ones, creating a brake on the expansion of flexibility systems across the board.

(Q12) BD4NRG's proposed solutions for addressing gaps, such as using merged standards for data exchange, developing interfaces/adapters for TSO/DSO and customers, integrating cross-sector and cross-border components in the reference architectures and platforms to support flexibilities, etc.

The adoption of standards in terms of protocols and data models and vocabularies can firmly contribute to overcoming the gaps between the actors of the European energy system. Investments in the modernization of energy infrastructures and related IT platforms that adopt common, standardised components can certainly accelerate the creation of efficient and effective flexibility systems.

(Q13) BD4NRG's proposals for **improving business processes** (i.e., system planning/asset management, system operation, energy markets) efficiently while facilitating flexibility and resilience of the EU energy system.

Make the participation of all stakeholders in the European energy system simpler and centrally regulated. Promote the evolution and regulation of solutions already implemented at European level either in research projects or locally already adopted by specific communities.

(Q15) BD4NRG **has made developments** addressing the **cyber-physical reliability** and **resilience** of the electricity grid.

(Q15i) BD4NRG's **cyber and physical assets/elements** that the project addresses, **potential risks** identified in BD4NRG that are associated with the cyber-physical nature of the grid, and how the latter are mitigated.

Legal, regulatory and cybersecurity guidelines and principles are incorporated in the design and development of the Data Governance and Management layers.

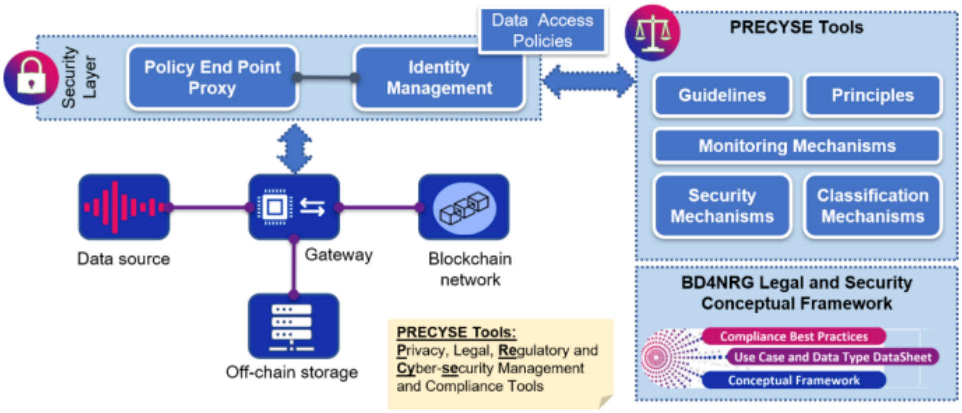


Figure 23: BD4NRG legal and policy

Privacy, Legal, Regulatory and Cyber-security Management and Compliance Tools (PRECYSE Tools) including:

- Guidelines and principles from the Legal and Security conceptual framework addressing and mitigating potential privacy and security concerns.
- Definition and management of the data access policies
- Mechanisms to ensure continuous monitoring to guarantee that conditions are not changing and infringing any of the security guidelines and principles.
- Adoption of the assessment checklist during the development process.
- A list of appropriate NISTIR 7628 cybersecurity guidelines for the overall BD4NRG development process.

(Q15ii) Identified focus areas for **dynamic monitoring and control** to ensure the reliability and resilience of the grid, BD4NRG propositions for **effective monitoring and protection of the pan-European grid cyber layers**.

NISTIR 7628 cybersecurity guidelines for the overall BD4NRG development process have been adopted.

B.17 OneNet

(Q1) OneNet Project Objective: The scope of OneNet [101] is to create a fully replicable and scalable architecture that enables the whole European electrical system to operate as a single system in which a variety of markets allows the universal participation of stakeholders regardless of their physical location – at every level from small consumer to large producers. The project (i) developed an open and flexible architecture for transforming the actual European electricity system, which is often managed in fragmented country – or area – level, in a pan-European smarter and more efficient one; (ii) reciprocally coordinated market and network technical operations closer to real time: (a) among them; (b) across different countries; (c) while maximizing the consumer capabilities to participate in an open market structure. (iii) designed an open IT architecture supported by scalable data management enabling the market structures; (iv) verified in a set of large field tests the concepts and solutions proposed; (v) promoted the results of OneNet in the standardization process for a significant market uptake.

Project Status: Completed

(Q2) OneNet **interfaces and data interoperability platforms** to enhance flexibility and improve business processes.

The project developed the OneNet Framework, a Data Space based framework able to:

- allows cross-countries participation of stakeholders at all levels, from TSOs to DSOs, from small consumers to large producers
- facilitates the platforms integration and cooperation for cross-platform market and network operation services
- makes available and accessible data from different sources (actors) in a secure and trusted way ensuring data ownership and privacy

Q2i: Specification of the purposes of the interfaces, along with their definitions in terms of information models, timing requirements, and interaction sequences.

The OneNet project identified 64 services, in 10 different categories. For each of them, data profiles, actors involved, and data exchanged have been identified.

Q2ii: A brief description, or illustration of each **interface's architecture**, referencing the SGAM model.

The following interfaces can be mapped on the Functional Layer of the SGAM model.

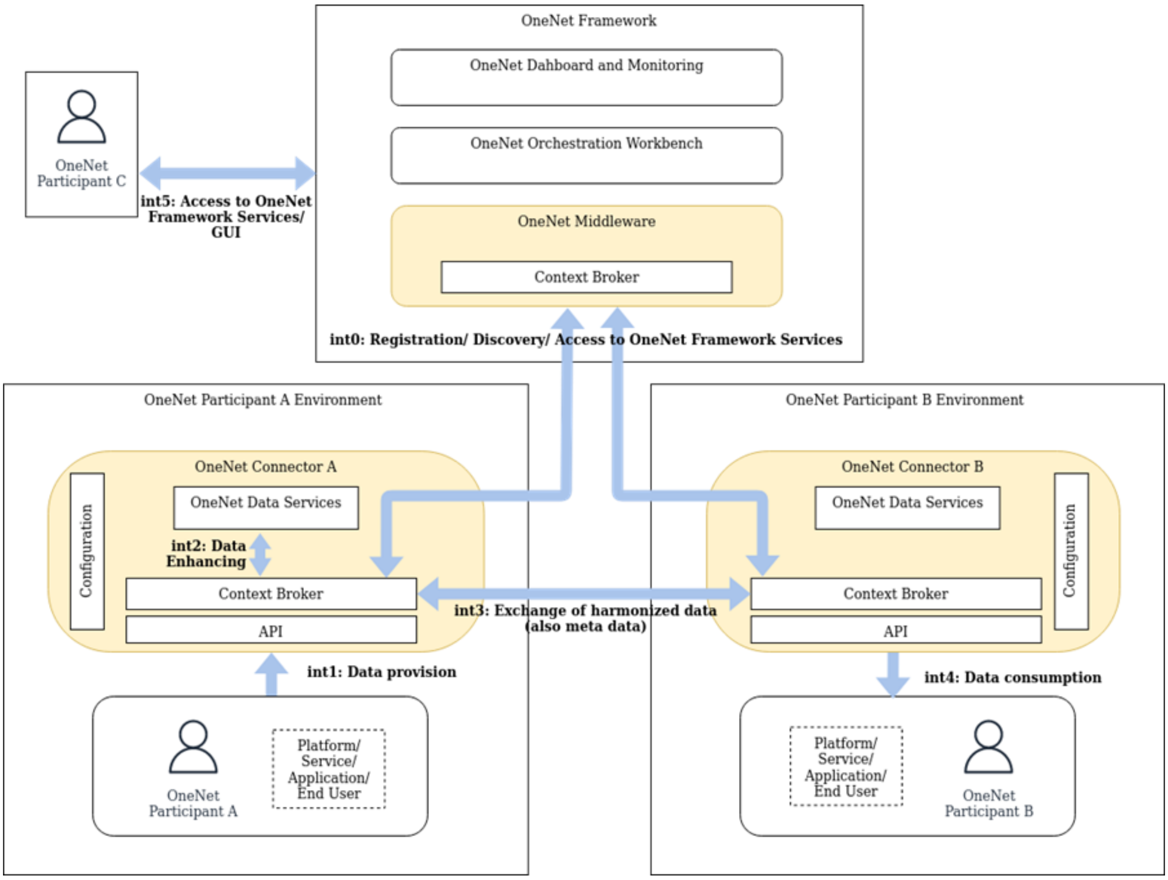


Figure 24 OneNet SGAM model

(Q3) OneNet's key findings regarding the implementation of **standards and interfaces** to improve flexibility and business process (system planning/asset management, system operation, energy markets).

Towards the analysis of the semantic description of flexibility and business processes, it was concluded so far that they can be generally addressed by IEC profiles such as IEC 62325 (ESMP), IEC 61970 (CGMES), IEC 61968 (CDPSM) and potentially by their subsequent enhancements

(Q4) OneNet's contribution towards the development of **data interoperability platforms and data-sharing** frameworks.

The project suggested an extension of the already implemented CIM Profiles for covering the gaps.

In addition, a data harmonization tool for mapping CIM Profiles and NGSI-LD was implemented.

(Q5) OneNet's definition of **communication and data exchange requirements**.

OneNet implements a decentralized approach for communication and data exchange. For any of the cross-platform services identified, specification for data exchange was listed in terms of business objects, data format, data models and actors involved.

(Q7) **Protocols and** standards applied in OneNet.

No analysis of the communication protocols was carried out. IEC Standards were suggested and extended for the data exchange (IEC 62325 (ESMP), IEC 61970 (CGMES), IEC 61968 (CDPSM)).

NGSI-LD standard was implemented for the end-to-end data exchange

(Q11) How **data exchange gaps** are affecting the support for flexibility requirements identified and analysed.

- Lack of communication and data exchange among energy stakeholders can impact on flexibility implementation.
- Lack of standardization is the main gap.
- Small stakeholders (like FSPs) are not ready for cooperate in a standardized way. Lak of technology.

(Q12) OneNet's Proposed solutions for addressing gaps, such as using merged standards for data exchange, developing interfaces/adapters for TSO/DSO and customers, integrating cross-sector and cross-border components in the reference architectures and platforms to support flexibilities, etc.

Use Standards data models and protocol. Adoption of standard market models.

(Q13) OneNet's proposals for **improving business processes** (i.e., system planning/asset management, system operation, energy markets) efficiently while facilitating flexibility and resilience of the EU energy system.

Facilitate the participation of any stakeholder. Cross-country and cross-sector integration can facilitate the re-adoption of already existing solution

(Q14) Challenges anticipated in implementing ONENET's proposals, and how to overcome them.

Lack of technologies. Lack of standards. Proprietary systems instead of open-solution impact on interoperability.

(Q15) OneNet **has made developments** addressing the **cyber-physical reliability** and **resilience** of the electricity grid.

(Q15i) OneNet's **cyber and physical assets/elements** that the project addresses, **potential risks** identified in ONENET that are associated with the cyber-physical nature of the grid, and how the latter are mitigated.

The OneNet Framework includes Network Traffic & Endpoint Infrastructure Monitoring Tool, in order to address cybersecurity aspects during any data exchange among OneNet Participants in the Energy Data Space.

Below the suggestion for risk mitigation and security recommendations

- Regular risk assessment of the system as part of the Information System Security Risk Analysis to identify any security related risks, assess them and define appropriate risk treatment actions (mitigation, acceptance, avoidance, transfer).
- Systems Configuration: Configuring systems following industry hardening standards Installing only services and functionalities or connecting equipment which is essential for the functioning and security of the information system.
- System Segregation: Segregating logically or physically the systems to limit the propagation of IT security incident within the system or subsystem.
- Traffic Filtering: Filtering traffic flows circulating in the system and forbidding traffic that is not needed for the system and that is likely to facilitate attacks.

- Cryptography: Establishing and implementing a cryptography policy and related procedures to protect data confidentiality, authenticity and/or integrity.
- IT Security Administration: Restricting administrative accounts to authorized employees for only “need-to-know” tasks.
- Identity and Access Management: Authentication and Identification and Access Rights.
- IT Security Maintenance: Developing and implementing a security maintenance procedure to ensure that the latest versions of hardware and software are installed. Security requirements should also be enforced in Industrial Control Systems.
- Physical and Environmental Security
- Security Incident Management process: Such a process should include details on the below points:
  - Detection: Detection, Logging & Monitoring, Logs Correlation and Analysis.
  - Computer Security Incident Management: Information System Security Incident Response, Incident Report and Communication with Competent Authorities and Computer Incident Response Teams (CSIRTs).
- Continuity of Operations: Ensuring Business Continuity including Disaster Recovery Management.
- Crisis Management: Crisis Management Organization and Crisis Management Process.

(Q15ii) Identified focus areas for **dynamic monitoring and control** to ensure the reliability and resilience of the grid, ONENET propositions for **effective monitoring and protection of the pan-European grid cyber layers**.

Business processes and data exchange among energy stakeholders at any level. The project proposes to apply and evaluate NISTIR 7628 Smart Grid Cyber Security standard.

B.18 Platone

(Q1) Platone’s Project Objective: Platone [102] developed new methods to improve the observability and flexibility of RES and unpredictable loads. To support energy transition, distribution system operators (DSOs) need innovative tools to handle volatile renewable sources and erratic consumption patterns. Platone introduced a joint data management approach that respects regulatory frameworks and utilizes a multi-layered platform to meet the needs of system operators, aggregators, and end-users. A blockchain-based platform served as the access layer, providing certified measures to all players and breaking traditional access barriers. This certified data and signals supported a new DSO platform to maintain local system integrity and build confidence in flexibility operations. Additionally, an upper-layer blockchain-based open market platform connected the local system to transmission system operators (TSOs), enhancing overall system cost and efficiency. By focusing on grid users' needs and expectations, Platone used blockchain technology to unlock greater response dynamics.

Project Status: Completed

(Q2) Platone **interfaces and data interoperability platforms** to enhance flexibility and improve business processes.

Platone implemented the “Platone Open Framework”, which aims to create an open, flexible, and secure system that enables distribution grid flexibility/congestion management mechanisms, through innovative energy market models involving all the possible actors at many levels (DSOs, TSOs, customers, aggregators). The Platone Framework is an open-source framework based on blockchain technology that enables a secure and shared data management system, allows standard and flexible integration of external solutions (e.g., legacy solutions), and is open to integration of external services through standardized open application program interfaces (APIs).

Q2i: Specification of the purposes of the interfaces, along with their definitions in terms of information models, timing requirements, and interaction sequences.

Platone Open Framework consist of three main components that interact with energy stakeholders at three different level: Market, DSO and Network (including Customers).

For each of these layers specific interfaces were implemented for integrating several data and platforms. The figure described the architecture from a functional view including all interfaces.

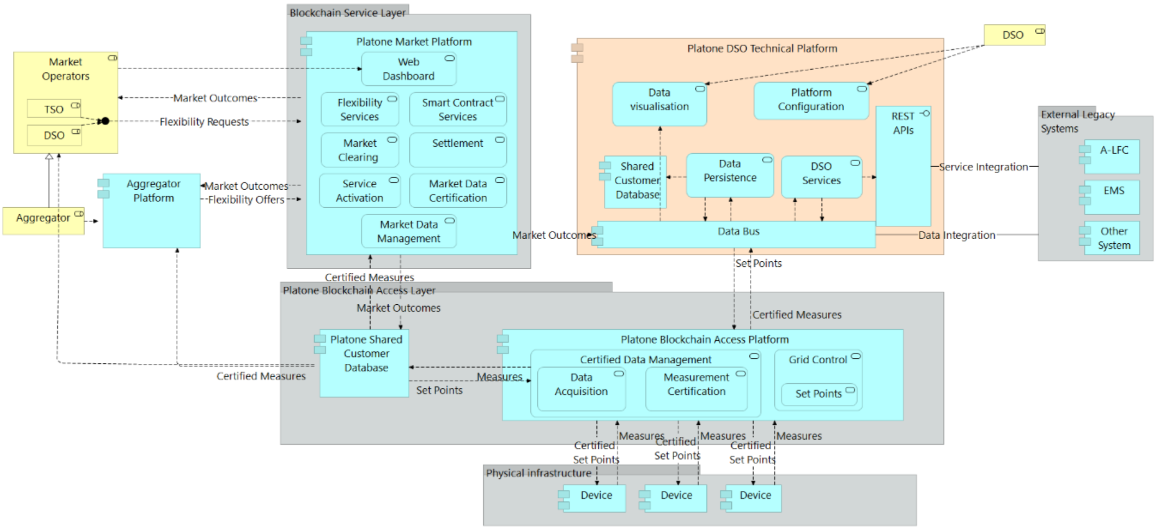


Figure 25 Platone Architecture

(Q3) Platone's key findings regarding the implementation of **standards and interfaces** to improve flexibility and business process (system planning/asset management, system operation, energy markets).

- Standards for data exchange and communication already exist but need to be adopted and extended.
- Business processes must be standardized for energy markets.
- Regulatory Framework must take into consideration innovativeness of the proposed solutions
- DSO must play a more central role in the Flexibility Market

(Q4) Platone's contribution towards the development of **data interoperability platforms and data-sharing** frameworks.

Platone DSO Technical Platform, as shown in Figure 26, based on SOGNO open-source platform, allows the integration of data and existing platform in a standardized way (using standard communication mechanisms and interfaces).

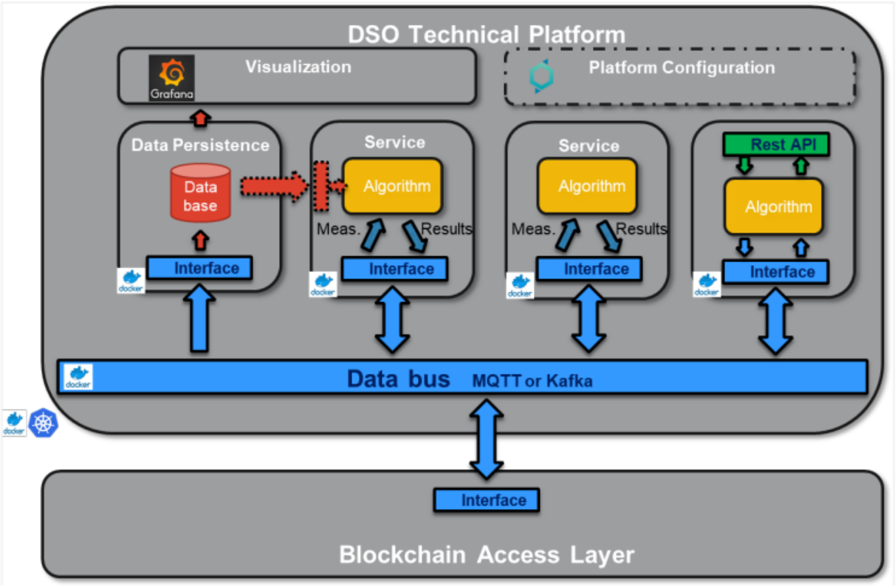


Figure 26: Platone DSO Technical Platform

Platone Blockchain Access Layer, as shown Figure 27, allows to integrate measurements and activation data from and to the network assets (smart meters and PMUs) using standard communication mechanisms and data models (CIM-61968-9).

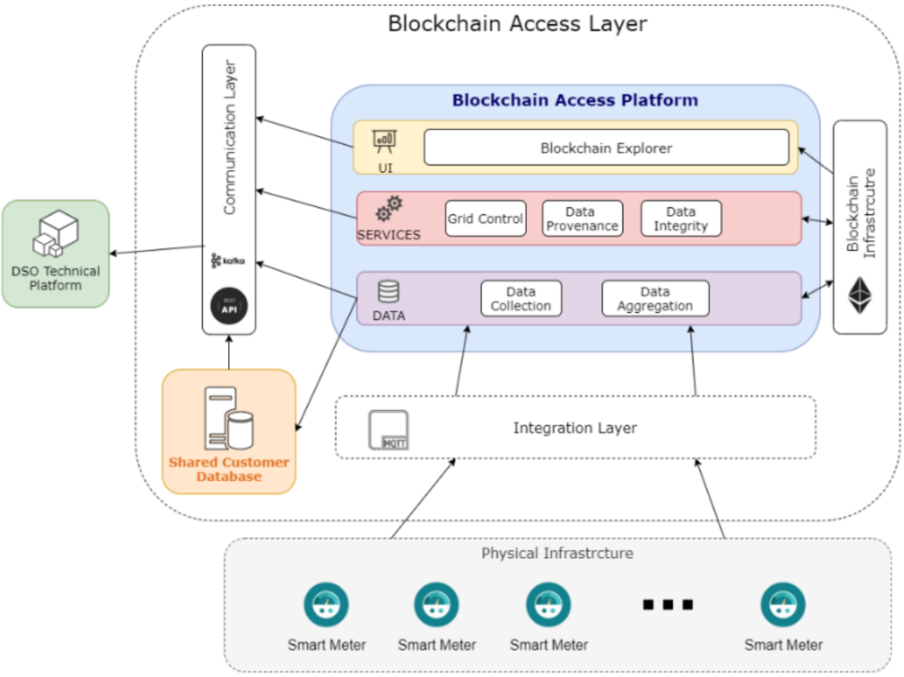


Figure 27: Platone Blockchain Access Layer

(Q5) Platone's definition of **communication and data exchange requirements**.

The project defined non-functional requirements for every platform, including Communication and data-exchange requirements. All the requirements are reported in D2.1.

(Q6) **Data models** used in Platone:

- Market (bids/offer)

- Measurements
- Assets

(Q7) **Protocols and standards** applied in Platone:

The most relevant standards for the Platone Open Framework are IEC 61850 and the CIM-61968-9 standards. Furthermore, the need for further harmonization of internal data models became apparent. The SARGON ontology was identified as a possible solution.

At the demo level the following standards were used:

- IEC 60870
- IEC 62055
- IEC 62325
- MQTT
- Kafka Broker
- REST APIs

(Q8) **Gaps** identified in terms of data format, information models and communication protocols in Platone:

Standardized data format missing for many data exchange. Ontologies and vocabularies must support the data exchange.

(Q10) Platone's significant **missing interfaces and adapters** identified between system operators, TSOs, DSOs, and customers.

- Customers are not actually integrated and involved in the flexibility markets.
- Interfaces among operators (DSOs and TSOs) and aggregators (FSPs) are missing in some countries TSO/DSO data sharing is partially missing.

(Q11) How **data exchange gaps** are affecting the support for flexibility requirements identified and analysed.

- Sharing information among energy stakeholders can facilitate the identification of the flexibility requirements. In particular TSO/DSO coordination and data exchange is the main gap.
- Data privacy and data governance need to be managed.

(Q12) Platone's Proposed solutions for addressing gaps, such as using merged standards for data exchange, developing interfaces/adapters for TSO/DSO and customers, integrating cross-sector and cross-border components in the reference architectures and platforms to support flexibilities, etc.

- Using Flexibility Register for Measurement and Asset data sharing among stakeholders.
- Using open-source solutions in addition to proprietary ones for a simpler integration.

(Q13) Platone's proposals for **improving business processes** (i.e., system planning/asset management, system operation, energy markets) efficiently while facilitating flexibility and resilience of the EU energy system.

Platone implement an open and fair market model (including participation of TSO and DSO as well aggregators) based on blockchain technology for security and transparency. In addition, it leverages on a centralized storage (Shared Customer Database/Flexibility Register) for sharing data across stakeholders.

This implementation should facilitate the participation of players within the Flexibility Market increasing at the same time the grid observability for the DSOs.

(Q14) **Challenges anticipated** in implementing Platone's proposals, and how can be overcome.

- Customer Engagement
- Implementation of a Local Flexibility Market

Local Flexibility Market implementation needs a strong involved of customer (aggregated) and their participation in the market. Customer engagement is a crucial step. Platone involved customers in dedicated workshops and study tours, allowing them to understand the concept of Flexibility and how they can play an active role.

(Q15) Platone **has not made developments** addressing the **cyber-physical reliability** and **resilience** of the electricity grid.

B.19 InterConnect

(Q1) InterConnect Project Objective: The main objective of the InterConnect project [103] was to develop new methodologies and implementations towards the creation of interoperable data exchange mechanisms to interlink devices and systems from buildings and grid. The underlying concept is the Semantic Interoperability, which is the ability that digital systems must exchange data with unambiguous, shared and agreed meaning, a steppingstone for the implementation of the Digital Single Market and enablement of cross domain data spaces. This is supported using ontologies, such as SAREF, and knowledge exchange mechanisms, allowing different providers and companies to offer competitive and cost-effective solutions whilst avoiding lock-ins or closed vertical technology implementations. The main innovation of the project was to foster the adoption of semantic interoperability and to put it into practice on a large scale, deploying technologies and services, validating acceptance by key market stakeholders from domains for energy and smart buildings. Providing semantic expression capabilities was therefore a key requirement for the integration of a digital platform into InterConnect's ecosystem of pluggable, semantically driven platforms and services.

Project Status: Completed

(Q2) INTERCONNECT **interfaces and data interoperability platforms** to enhance flexibility and improve business processes.

Semantic Interoperability Framework (SIF) is a comprehensive toolset that has been designed, specified, and implemented to be used publicly by developers and integrators to enable the creation of several components to enable the semantic data exchange among devices and systems. The SIF utilizes extensive ontology based on SAREF for ensuring that the meaning of data and knowledge representation are the same across all stakeholders and domains representing semantically interoperable ecosystems. The SIF knowledge interactions, communicative acts, and mechanisms for managing data dissemination (recipient selectors) provides integrators the mechanisms for establishing control protocols within and between interoperable ecosystems.

The SIF is replicable, and it is being replicated across pilots in the project, by allowing several connected instantiations of the components. The figure below depicts the logical arrangement of the

SIF's components. While the Service Store is a central component to unite the view from pilots, the Semantic Interoperability Layer and the Service Adapter are distributed components, with multiple instances within and across pilots, thus, to allow the diversity and re-use of interoperable services and data sources.

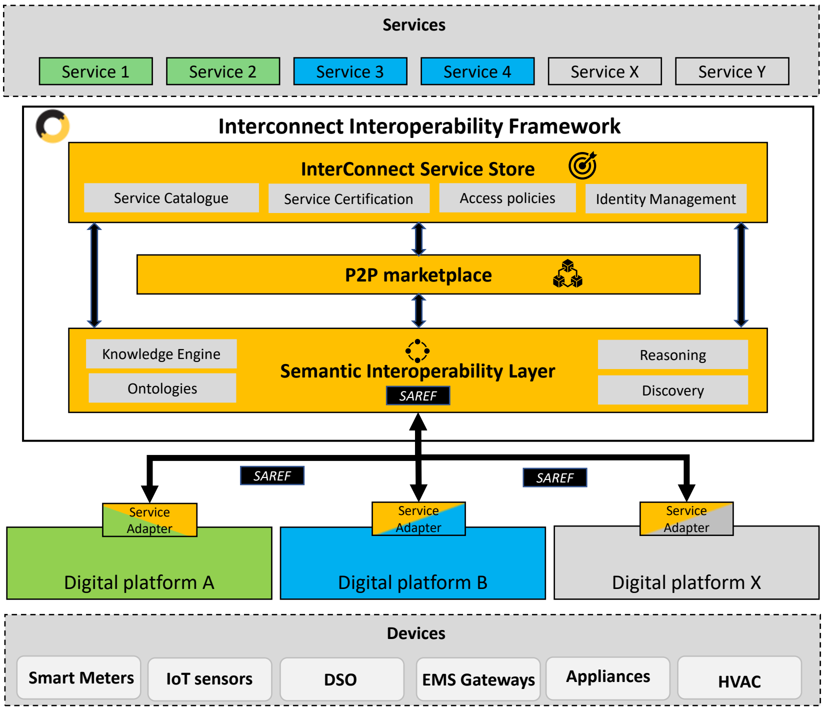


Figure 28: Semantic Interoperability Framework

The SIF concept bundles a set of tools to enable interoperability up to the semantic level, namely: the Service Adapter as the connector adopted by digital platforms via a Service Specific Adapter (SSA); the distributed Semantic interoperability layer, handling knowledge exchange and querying between adapters; the Service Store providing a catalogue of interoperable services, knowledge explorer and certification of services; the P2P marketplace for the instantiation of services devoted to fully distributed applications; and a set of tools to ensure security, privacy and governance transversal capabilities.

Distribution System Operator Interface (DSOi):

The DSO Interface concept and platform developed in InterConnect, as in figure below, facilitates the implementation of DSF and data-driven services, ensuring a standardized bi-directional interaction between DSOs legacy systems and emerging business models such as flexibility aggregators, local energy communities and ultimately prosumers. It also establishes the ground for the interaction with new stakeholders (i.e., Data Brokers) that will

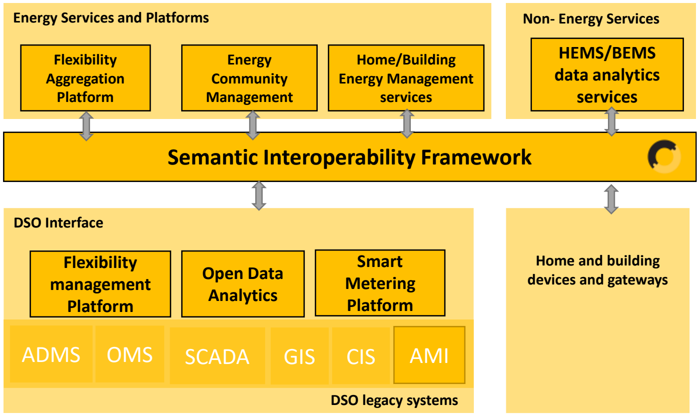


Figure 29: DSO interface and components

create a lot of value both for DSO and consumers data.

The services specified and derived from project use cases involving the DSO are implemented and its SAREF models developed built upon a common framework for interaction with external actors and with DSO legacy systems. The integration of this common framework within the Semantic Interoperability Framework is expected to foster high replicability and allow the agnostic integration of the multitude of technologies used by the different DSOs across Europe.

The DSO interface leverages from the InterConnect SIF, creating a standardized approach to support new services that aim to:

- Establish technology agnostic flexibility procurement processes and enable data exchange with aggregators and flexibility market platforms (external to the DSO domain).
- Use smart metering data to foster local energy communities, DSF-based services and cross-sector integration (e.g., financing of DER projects, green supermarkets, water).
- Leverage from third-party data (e.g., behind-the-meter measurements) to improve network observability and planning, enabling new business models such as data brokers.

Interoperable Recommender (IR):

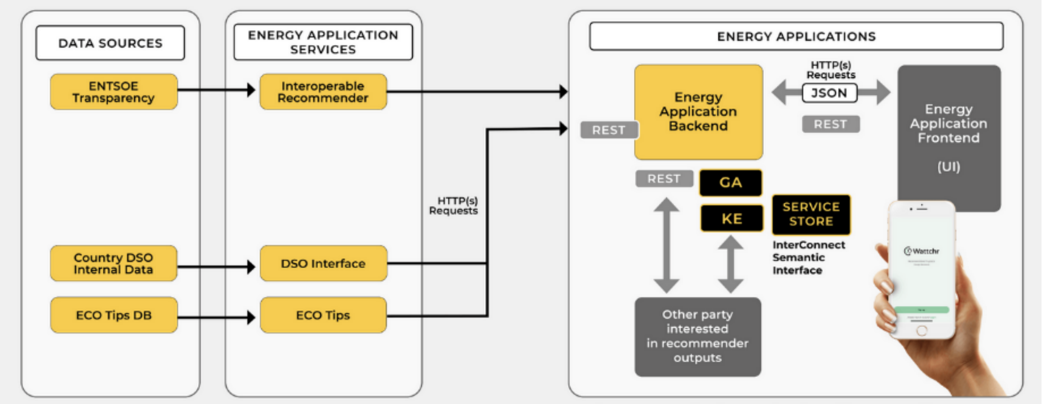


Figure 30: Interoperable Recommender to enable energy applications

The Interoperable Recommender is a data-driven solution aimed at enabling the participation of consumers in enhancing the resilience of the European energy infrastructure. This service harnesses the potential of innovative algorithms and leverages publicly accessible data sources such as the ENTSO-E Transparency Platform to assess country-specific vulnerabilities related to loss of load and generation curtailment.

The Interoperable Recommender main goal is to enable energy applications to empower European citizens with actionable recommendations on a national level, encouraging adaptive energy consumption during periods of expected system vulnerability. The service provides day-ahead hourly recommendations, tailored to meet the unique needs of each country while accounting for interconnections within the broader European network.

The Interoperable Recommender provides:

- a methodology to assess periods of expected system vulnerability in Europe’s energy infrastructure.
- an assessment of system vulnerabilities and determine the best operating conditions for the grid, considering the status of each member state and its neighbours/interconnections.

- the definition country-level actions (increase/decrease energy consumption) during specific hours to enhance resilience.
- a sharing of information with other interested parties with direct integration in separate backends.

Q2i: Specification of the purposes of the interfaces, along with their definitions in terms of information models, timing requirements, and interaction sequences.

Generic Adapter (GA):

The Generic Adapter (figure) is to be instantiated per endpoint (software service, digital platform, device) which needs to be made interoperable. The Generic Adapter provided by the Interoperability Framework can then be customized to specific service types.

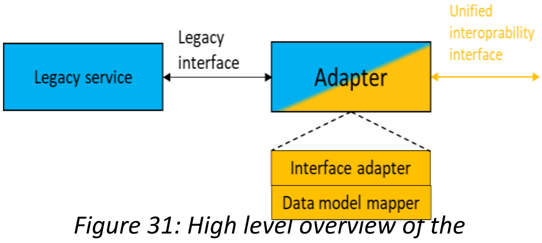


Figure 31: High level overview of the interoperability adapter

Service Specific Adapter (SSA):

The Service Specific Adapter performs mapping of the service interface onto the unified interoperability interface and maps data models onto the SAREF ontology (more details provided in the next subsection). Services equipped with this set of interoperability adapters do not need to know API specification of other interoperable services in order to communicate with them. They need to use/understand the same ontology.

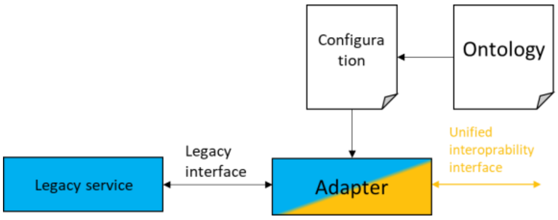


Figure 32: High level overview of the IC interoperability adapter with custom configuration

The SSA provides the capability to devices and systems to be able to support semantic data exchange and to enable the creation of reasoning among computational systems and unlock the automatized interpretability of data by machines. The SAREFization process, includes the following steps (see **Error! Reference source not found.**):

- Address service capabilities and matching them with SAREF descriptions.
- Address service messages and units of measure and match them with SAREF descriptions.
- Candidate graph patterns for services as ways to disseminate service messages and instructions through the semantically interoperable layer.
- Technical integration with the Generic Adapter provided by the Interoperability Framework.

Figure 33: SAREFIzation process

Q2ii: A brief description, or illustration of each **interface's architecture**, referencing the SGAM model.

Secure Interoperable IoT Smart Home/Building and Smart Energy System Reference Architecture (SHBERA), that was derived from:

- The analysis of the SotA: after analysis and consideration of each relevant reference architectures (RAs), it became clear no single RAs scores high enough in all dimensions when ranked by project stakeholders. The focus was then put on reusing and extending useful concepts while attempting to provide a bridge between different domains so that project stakeholders can understand each other in terms of the three dimensions interoperability, ontology, and ICT processing.

- The project's primary and derived requirements, which are the high-level requirements that InterConnect's RA should always comply with. These principles were created to ensure that the resulting RA is a technology-independent and device-agnostic ecosystem.

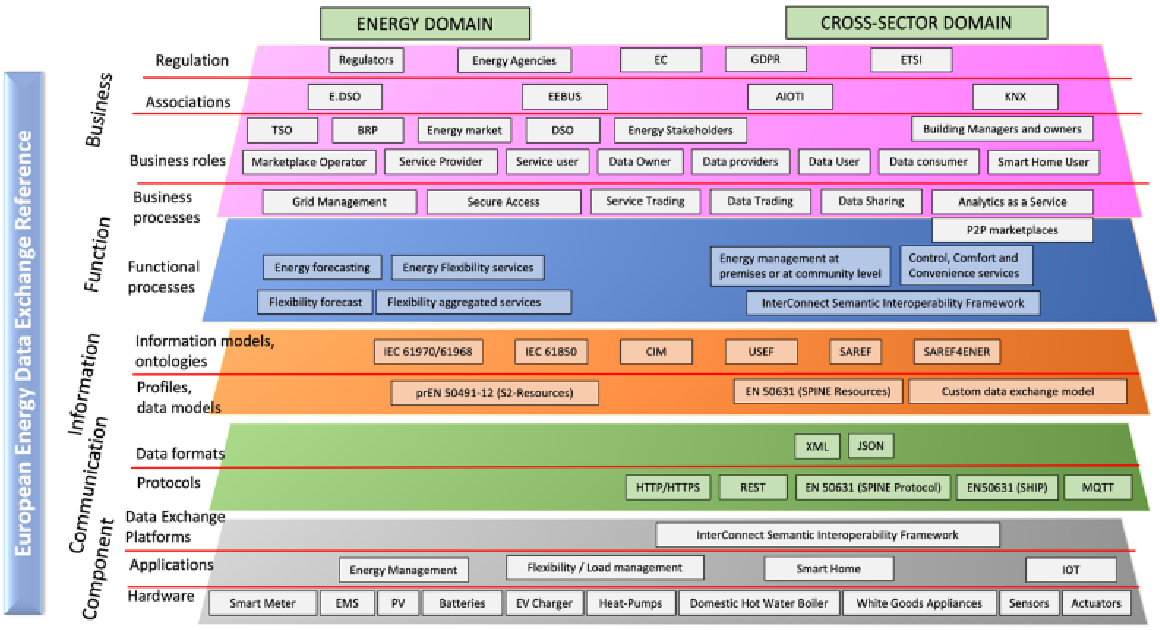


Figure 34: SGAM Reference Architecture

To fulfil the objective of deploying semantic interoperability on a large scale and cross-domain, the first step was to define a reference architecture for the project, that resulted from a detailed state of the art analysis of relevant IoT related reference architectures, extending the well-established concepts to allow a wider coverage necessary to cover ICT processing, ontology mapping and semantic interoperability.

Particularly, the Smart Grid Architecture Model (SGAM), Error! Reference source not found.a three-dimensional architectural framework that supports interactions (mostly exchange of information) between different entities located within the smart energy arena, was used as common ground, as it involves the main actors and roles of the energy system.

The result was the establishment of the Secure interoperable IoT smart Home/Building and smart Energy system Reference Architecture (SHBERA), illustrated in the figure**Error! Reference source not found.**, that also ensures compatibility with other well-established initiatives like Reference Architectural Model Industry (RAMI).The unification portrayed in SHBERA is what enables the implementation of digital services, which can be clustered, according to the context and requirements, supporting multiple implementations focused on devices and systems as well as cloud-based infrastructures. This is what allows different corporate digital ecosystems to be built in a completely modular approach and to take advantage of synergies and developments that can be leveraged by several entities.

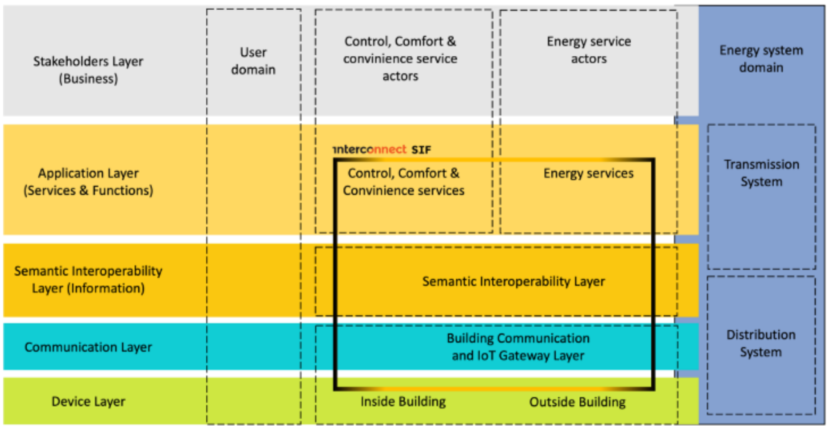


Figure 35: InterConnect Reference Architecture (SHBERA)

(Q3) INTERCONNECT's key findings regarding the implementation of **standards and interfaces** to improve flexibility and business process (system planning/asset management, system operation, energy markets).

Contributions to interoperability (energy and non-energy services for flexibility). The difficulty in achieving a general adoption of Market-based products lies in the lacking regulatory frameworks in the different countries where the pilots are developed, especially when it comes down to exchanging those products with DSOs or TSOs. Clear, stable and ambitious regulations need to be established to create a mature, efficient and effective energy flexibility market.

One key finding is that the use of the main IoT-based standards is fundamental in ensuring the proper mapping between syntactic representations and semantic data models to enable the interoperability that allows knowledge exchange and inference to be implemented, can continue to do so.

(Q4) INTERCONNECT's contribution towards the development of **data interoperability platforms and data-sharing** frameworks.

The following contributions were made:

- ETSI: SAREF/SAREF4ENER extension
- ENELEC EN 50090/KNX
- EN 50561-x (mapping of SAREF)

(Q5) INTERCONNECT's definition of **communication and data exchange requirements**.

Definition of requirements regarding the reference architecture (SHBERA) explained above. InterConnect discriminated between primary requirements and derived requirements. The primary requirements are high-level requirements that the Reference Architecture should always comply with

Requirement	Description
R1	IC Reference Architecture **MUST** be technology independent and device agnostic
R2	IC Reference Architecture **MUST** integrate semantic reasoning mechanisms to exploit the benefits of ontologies and semantic technology in the InterConnect ecosystem

R3	IC Reference Architecture **MUST** include a set of InterConnect-compliant energy and non-energy services, and produce extensions for a mainstream uptake and for testing and applying new business models
R4	IC Reference Architecture **MUST** be based on the latest and most stable industry standards and insights for cybersecurity and data privacy protection
R5	IC Reference Architecture **MUST** enable data exchange between all stakeholders, roles, and their related services

Specific requirements, can be found in the references, regarding the:

- Benefits of ontologies and semantic web technologies
- Inclusion of energy and non-energy business models
- Use of industry standards for security and privacy
- Enablement of data exchange among components

(Q6) **Data models** used in INTERCONNECT.

The main data models use is derived from the standards:

- SAREF (Smart Applications Reference) and extensions (SAREF4ENER, SAREF4BLDG)
- EEBUS SPINE-IoT

(Q7) **Protocols and standards** applied in INTERCONNECT.

- SAREF and its extensions
- SPINE-IoT (EEBUS)

(Q8) **Gaps** identified in terms of data format, information models and communication protocols in INTERCONNECT.

The gaps were centred in the SAREF ontology extensions to cover:

- Smart metering representations (multi-metering)
- Mapping of other relevant automation assets in buildings

Articulation with other IOT-based ontologies:

- Energy Efficiency Prediction Semantic Assistant (EEPSA) ontology
- KNX information model (KIM) ontology

Articulation with other general ontologies:

- Time ontology
- GeoSPARQL ontology
- Unit of measure ontology (OM)

(Q9) Examples of tool **limitations** identified during the analysis.

The main limitations arise from the use of SAREF as the ground ontology to represent assets and systems, which provides a scoped representation of semantic data models. Still the compatibility with other ontologies and semantic representation was deemed possible.

(Q10) INTERCONNECT's significant **missing interfaces and adapters** identified between system operators, TSOs, DSOs, and customers.

This assessment was not carried out as the grid domain was mainly focused to the DSO systems as defined in the DSOi platform.

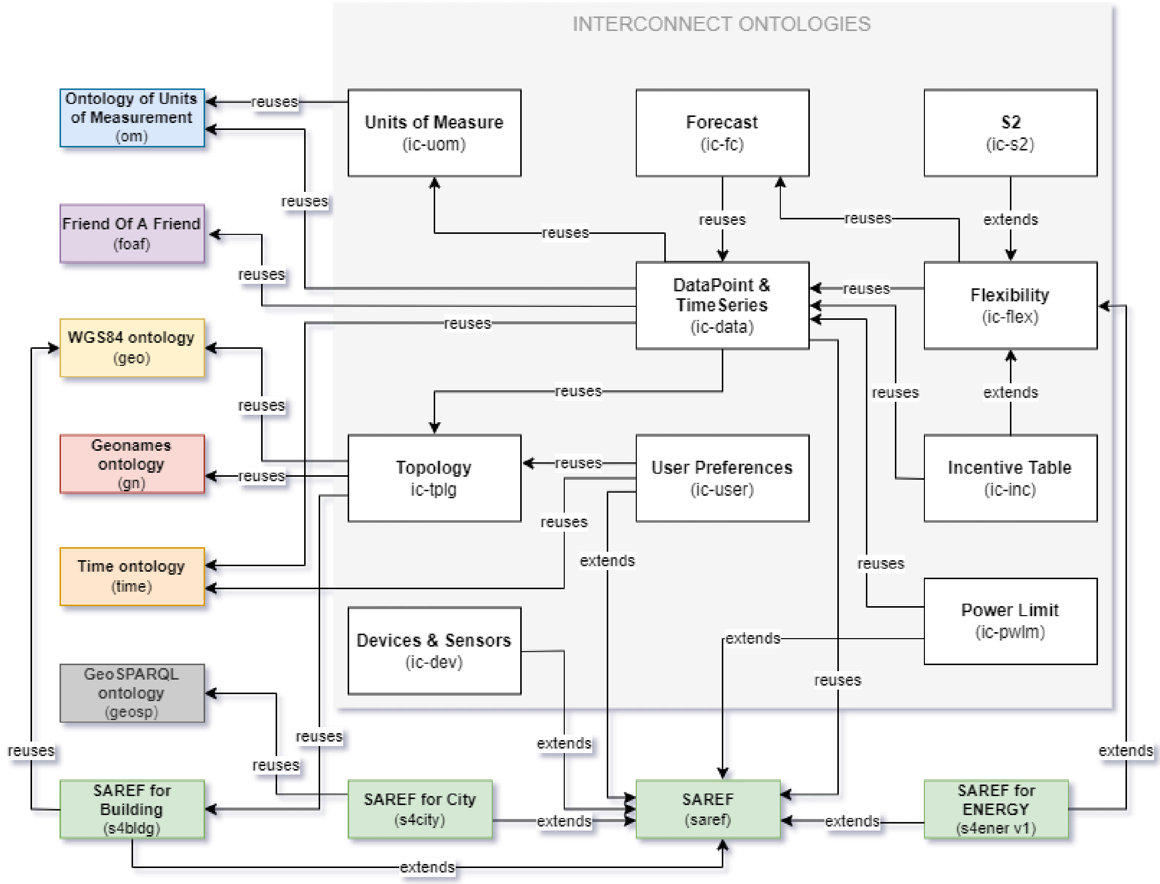


Figure 36: Overview of InterConnect ontologies in relation to SAREF and other existing ontologies

(Q11) How **data exchange gaps** are affecting the support for flexibility requirements identified and analysed.

The requirements for services were mapped in D1.1 the technical requirements were set in D2.1. A gap analysis, covering several aspects of the use of flexibility in energy services. A gap assessment was carried out to prevent a misalignment to the use in practice (demonstrators).

(Q12) InterConnect Proposed solutions for **addressing gaps**, such as using merged standards for data exchange, developing interfaces/adapters for TSO/DSO and customers, integrating cross-sector and cross-border components in the reference architectures and platforms to support flexibilities, etc.

Code of conduct: InterConnect has contributed to the JRC Smart Electricity Systems that publishes, in collaboration with the industry in Europe, a Code of Conduct for Energy Smart Appliances as published [104]. The push for the adoption of semantic technologies, inlaid in EN 50631 where SAREF data models were proposed the underlying methodologies of InterConnect as well to address the gap of the limited adoption of semantic representations by the main manufacturers and integrators of domestic appliances (including thermal).

(Q13) INTERCONNECT's proposals for **improving business processes** (i.e., system planning/asset management, system operation, energy markets) efficiently while facilitating flexibility and resilience of the EU energy system.

Common European Reference Framework (CERF):

Following the adoption of the 'Digitalising the energy system' EU action plan, the InterConnect project was tasked with the role defining a blueprint for energy applications based on the Common European Reference Framework for Energy (CERF). The CERF is an extensive and scalable data and knowledge exchange framework which can be instantiated at different levels in support of innovative and user-engaging mobile applications. To do that, the InterConnect Semantic Interoperability Framework (SIF) and the DSOi were further developed to demonstrate the ability to interconnect consumers, grid stakeholders, devices, and service providers to enable different consumer Energy Applications. In this way, the project developed and validated the CERF in 10 Member States. A first generation of applications was tested in the environment of 3 member states that already had InterConnect large scale pilots up and running. Nine additional countries were involved through a cascaded funding mechanism engaging both project partners as well as third parties to demonstrate the InterConnect solutions.

An overview of the underlying recommendations, divided by topic, is comprised within the table. These are presented following the framework used for the collection and assessment of results from the InterConnect pilots. In their final format, the jointly agreed recommendations consist of a core proposal to be considered for the 2nd generation blueprint for the CERF which itself is beyond the scope of the InterConnect project.

Data Sources	
Technical	Building upon InterConnect solutions will help in the provision of semantically interoperable services and digital platforms that are needed to realize the CERF for energy.
Economic	Defining incentives and revenue mechanisms is essential to leverage data providers' contributions to the CERF.
Social	Fostering social strategies that encourage data owners to overcome their reservations about data sharing.
Regulatory	• Engaging stakeholders in open data initiatives and data sharing agreements is essential to increase the availability of public and common data sources. • Implementing EU legislation and initiatives on data access (e.g. common European energy data space) will be the backbone for the development of the CERF.
Data Repository and exchange	
Technical	• A harmonized process should be followed before integrating existing data repositories to the CERF to guarantee interoperability. • Data providers should partner with service providers to jointly present the real value behind data.
Economic	• Choosing a standard interface logic and data models and developing the energy application from them. • Relying on projects like InterConnect can help speeding up this process and lower the costs.
Social	The access to granular data referring to the specific electricity point of delivery might not be needed to develop the CERF. Aggregated data at higher levels of abstraction might suffice for many applications.

Regulatory	When integrating data repositories, the project recommends ensuring the compliance of the CERF based application with the GDPR
Consumer Application	
Technical	• Enabling a participative approach is essential to motivate end users in participating to the activity. • A simple and direct language - using pictograms and colours – should be adopted to transfer information effectively to end users.
Economic	• Engaging end users to use energy saving applications, it is essential to implement and harmonize regulations that allow access to process signals across the EU. • Individual metering and billing must be enabled to allow for the multiple households within an apartment building to participate in the provision of flexibility services.
Social	• Social responsibility plays an important role for user engagement. As such, it is important to showcase how their involvement yields tangible benefits for the environment. • Simplifying the user experience by implementing automated responses based on the app recommendations is crucial to maintain user engagement over time.
Regulatory	Energy trading in local flexibility markets should be adopted to define the roles, responsibilities and rights of each stakeholder involved in the trading process.
Replication and Scalability	
Technical	Adopting standardized data exchange protocols through CERF can streamline the Energy application development process.
Economic	The access to price signals must be enabled for end users to ensure the replication and scalability of CERF based applications.
Social	• A consensus on data ownership must be reached to ensure that data generated by the customer belongs to the customer. • Knowledge sharing and further development of InterConnect solutions through EU projects and initiatives is essential to build upon these results.
Regulatory	The differences in the transposition of European Directives into national regulations that pose an obstacle to the replication of CERF compliant energy applications across the Union, must be addressed.

(Q14) **Challenges anticipated** in implementing INTERCONNECT's proposals, and how can be overcome.

The main challenge is associated to the regulatory landscape in Europe that has been slow to adapt to the new business and technical use-case that already were shown in InterConnect as well as in other project that the valorisation of the demand side flexibility is not only possible but desirable. The market pull for energy flexibility services is slowed down by the limited regulation in several sectors.

(Q15) INTERCONNECT **has made developments** addressing the **cyber-physical reliability** and **resilience** of the electricity grid.

(Q15i) INTERCONNECT's **cyber and physical assets/elements** that the project addresses, **potential risks** identified in INTERCONNECT that are associated with the cyber-physical nature of the grid, and how the latter are mitigated.

InterConnect defined a coordinated security and privacy practice for future IoT ecosystems, for the integration of smart homes/buildings with smart grids. A global pro-active framework was defined, including:

- a security and privacy-by-design practice (based on AIOTI reference architecture, ISO IoT reference architecture covering the cybersecurity lifecycle such as ISO/IEC 271014, NIST guidelines for smart grid cyber-security-NISTIR 7628- and current privacy-by-design standards); and
- redefinition of governance role and the compliance auditing role.

Given the nature of the project in involving different domains a set of guidelines for privacy and security design and implementation was set in the InterConnect project.

A SPOCS (Security and Privacy Policies Compliance Solution) was defined to cover:

- Governance management
- Data Management
- Risk Management:
- Engineering Management
- Citizen Engagement

To mitigate the impacts regarding the cyber-physical characteristics of the different devices and systems the following threat analyses were carried out by different technology providers and demonstrators:

- Security threat analysis: spoofing, tampering, repudiation, information disclosure, denial of service, elevation of privilege.
- Privacy threat analysis: linkability, identifiability, non-repudiation, detectability, disclosure of information, unawareness, non-compliance

A set of risk models were used to estimate the privacy risk level of the different IT systems, considering the likelihood of breaches and the impact they have in the operation. On these two axes a classification level was proposed to allow a risk map to be created to assess the materialization of the risks and how to respond to them. Several standards were considered to allow a universal assessment of risks in the different domains of the project (i.e., ISO 27400, 27402, 27550, etc.).

B.20 EUniversal

(Q1) EUniversal's Project Objective: The EUniversal project [105] aimed to promote the use of flexibility by Distribution System Operators (DSOs) through the Universal Market Enabling Interface (UMEI), enhancing flexibility in distribution grids to support 50% renewable electricity by 2030 while ensuring supply security and avoiding unnecessary network investments. The project was organized around four pillars. First, UMEI facilitated market-based flexibility services and linked DSOs' active system management with electricity markets. Second, the DSO Toolbox demonstrated new operation and planning strategies, offering over 10 tools for network observability, flexibility assessment, voltage control, and resilience. Third, FSP Engagement provided recommendations for future market designs to improve consumer engagement and mapped different technologies for flexibility services. Finally, the Flexibility Market Design explored various market design options and complementary flexibility mechanisms.

Project Status: Completed

(Q2) EUniversal **interfaces and data interoperability platforms** to enhance flexibility and improve business processes.

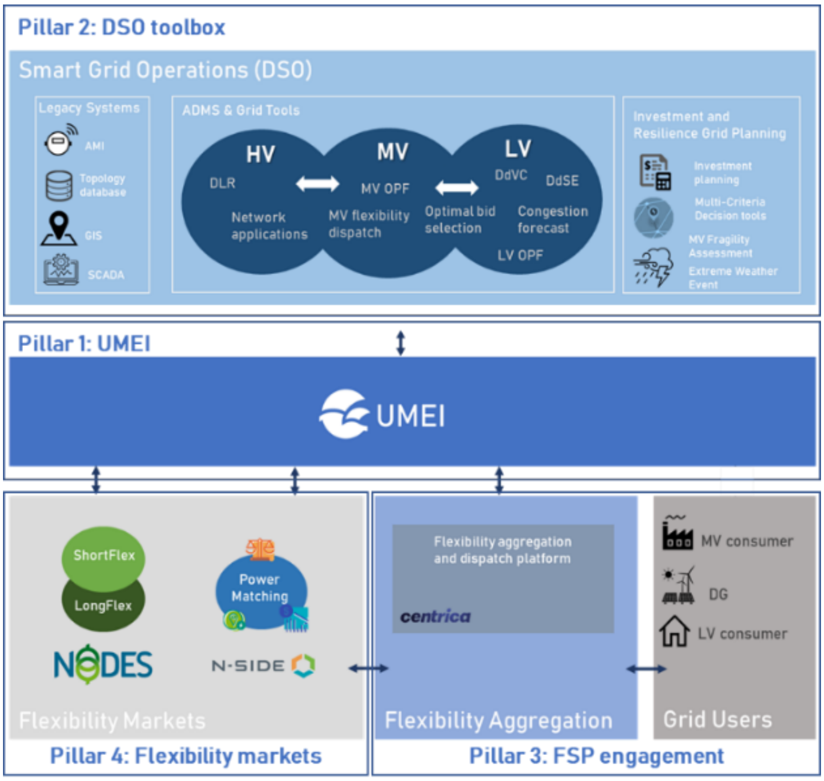


Figure 37 Interaction scheme among the UMEI pillars

The project developed different interfaces that enabled end-to-end demonstration of flexibility provision for system operation support.

The demonstration focused on day-ahead operation planning considering market-based flexibility. Therefore, the interfaces impacted the following business processes:

- Internal DSO data sharing between different systems and applications (e.g. smart metering, SCADA, forecasting)
- Flexibility Aggregation
- Local Flexibility Market operation

Q2i: Specification of the purposes of the interfaces, along with their definitions in terms of information models, timing requirements, and interaction sequences.

Internal DSO data exchange interface – that concentrate data from smart meters, SCADA and MV load and generation forecasting required by the project tools to compute, MV and LV flexibility needs, DSO Day-ahead asset operation plan (OLTC, network reconfiguration, capacitor banks, utility owned storage), MV and LV flexibility bids selection. It also collected Aggregator and Local Flexibility Market Data, collected by the UMEI [106].

UMEI – ensures the DSO data exchange with Local Flexibility Market Platforms and Aggregators, that support the following processes:

Flexibility Needs Assessment – UMEI shares with Local Flexibility Market Platforms Day-ahead flexibility needs, under Flexibility Zones format.

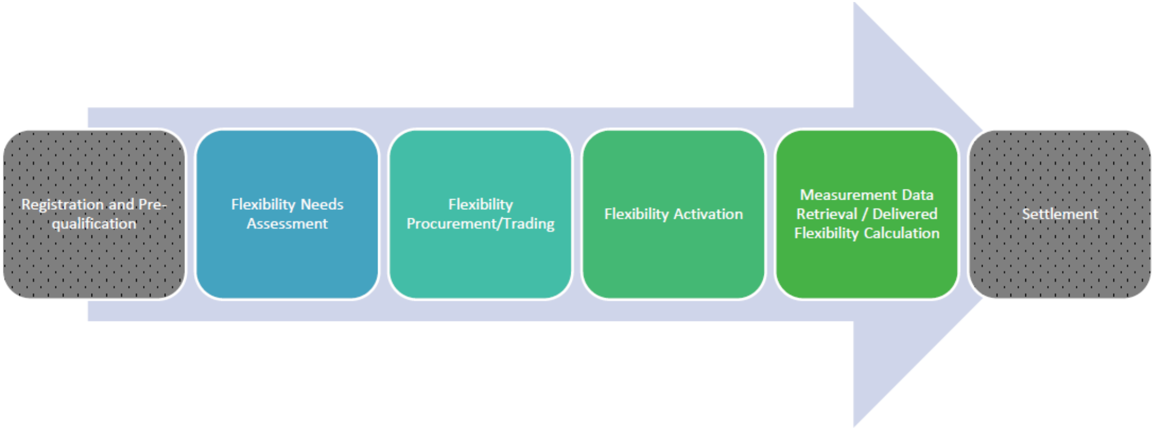


Figure 38 Process steps for registration and pre-qualifications for flexibility activation

Flexibility Procurement/ Trading - UMEI receives from Local Flexibility Market Platforms flexibility offers. After selection by de DSO, it shares with Local Flexibility Market Platforms and Aggregators.

Measurement Data Retrieval/Delivered – Providing meter readings for assets mobilized.

Registration, Pre-Qualification and Settlement not covered by the project.

In terms of timing – mostly day-ahead data exchange was promoted by the interface. However, to ensure proper market operation all the processes needed to run from 00:00 to 15:00 in d-1.

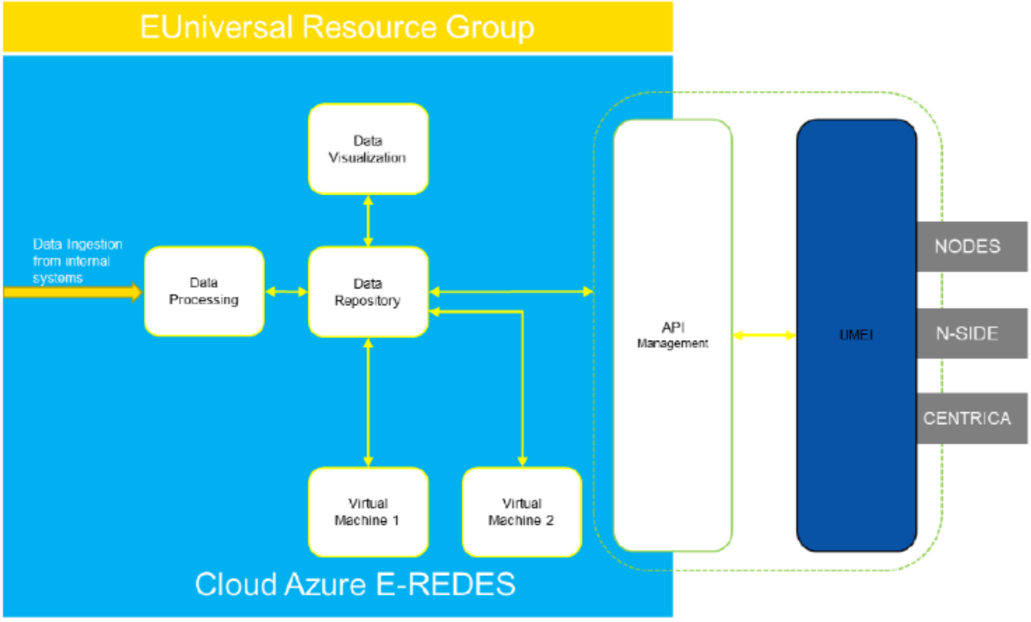


Figure 39 Flexibility process steps covered by the UMEI

The interaction of DSO internal interface and the UMEI is shown below.

Q2ii: A brief description, or illustration of each **interface's architecture**, referencing the SGAM model.

The picture describes the architecture implemented in the Portuguese demo, where it's possible to see the DSO knowledge Database that shares data with DSO Toolbox and with the UMEI. Also, the UMEI assures the interface with market platform and aggregators.

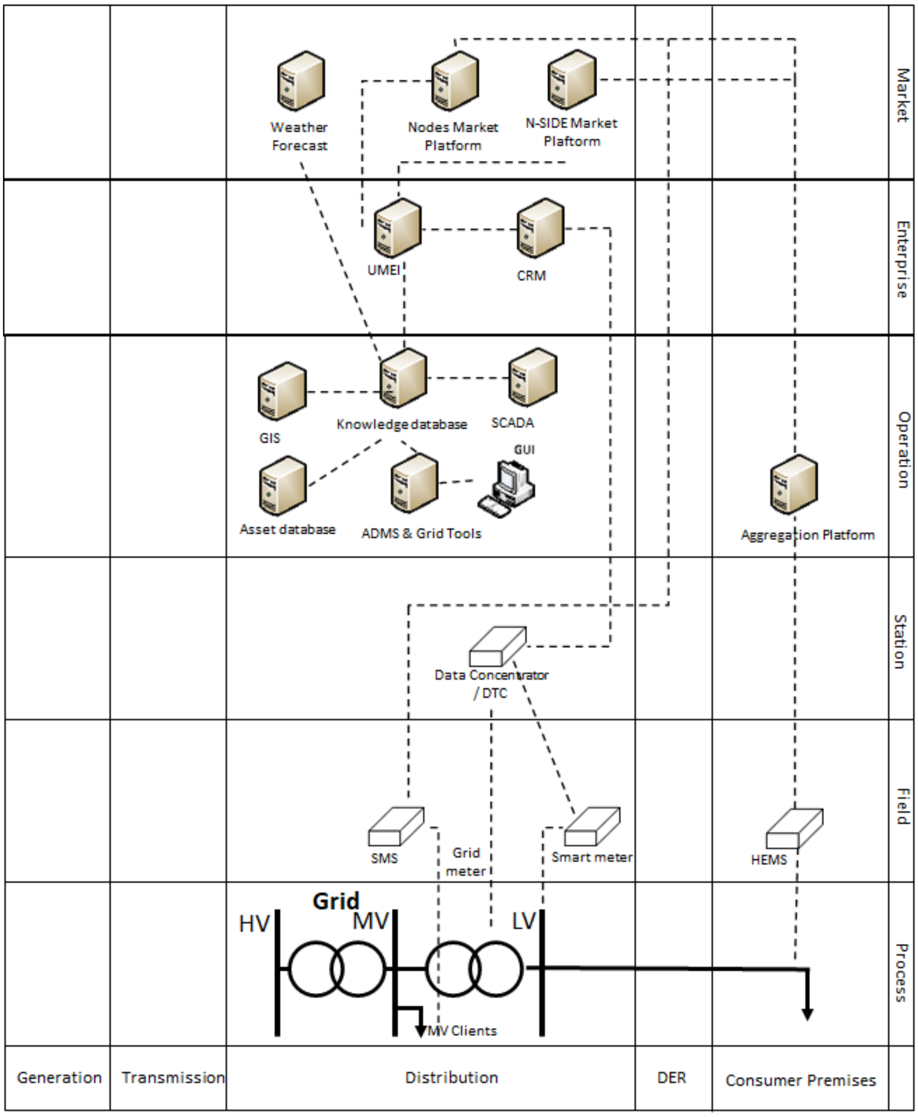


Figure 40 DSO Architecture

(Q3) EUniversal key findings regarding the implementation of **standards and interfaces** to improve flexibility and business process (system planning/asset management, system operation, energy markets).

Although the interfaces developed have not followed specific standards, the following key findings can be derived:

- Implementation of UMEI, as a single channel for different stakeholders interact was well accepted by all actors (DSO, Local Flexibility Market Platforms and Flexibility Aggregation Platform). An appropriate communication model between DSOs, TSOs and other market parties needs to be established that takes into account the flexibility requirements and responsibilities of the parties. Uncoordinated or even conflicting use of flexibility services must be prevented.
- Clear rules and routines need to be set up for stakeholders to exchange data and flexibility services with the DSOs. This can be facilitated through standardization of APIs. Yet, as long as this is not yet in place, it is important to remain adaptable.

- To develop a fully standard/interoperable interface between these actors' flexibility market standards need to be defined, concerning for example explicit flexibility needs, service and product standardization, etc.)
- Within DSO systems promoting horizontal data exchange channels, coming from different systems such as customer relationship management (smart meter data management), SCADA database, and grid models is key to enable testing of new interfaces and applications. This will facilitate establishing new data collection and processing applications.
- For UMEI implementation, a clear mapping of market and DSO processes was key to ensure effective development.

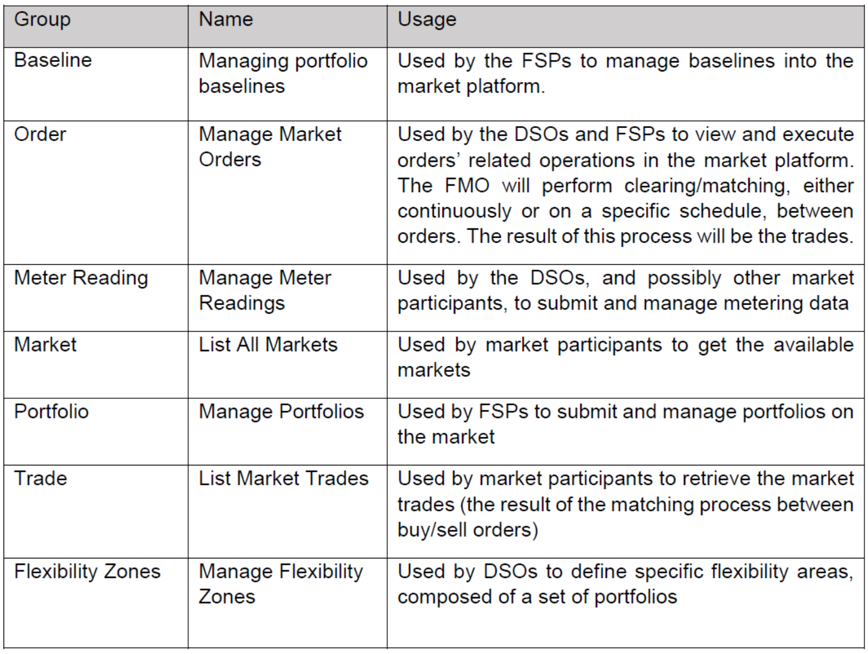
(Q4) EUniversal's contribution towards the development of **data interoperability platforms and data-sharing** frameworks.

The project didn't contribute directly to the development of data interoperability platforms and data-sharing frameworks (e.g. metadata).

UMEI was implemented as an Open Interface already demonstrated, being able to provide future contributions to energy data spaces.

(Q6) **Data models** used in EUniversal.

The main groups of APIs included in the UMEI are described in Table 6 below:



Group	Name	Usage
Baseline	Managing portfolio baselines	Used by the FSPs to manage baselines into the market platform.
Order	Manage Market Orders	Used by the DSOs and FSPs to view and execute orders' related operations in the market platform. The FMO will perform clearing/matching, either continuously or on a specific schedule, between orders. The result of this process will be the trades.
Meter Reading	Manage Meter Readings	Used by the DSOs, and possibly other market participants, to submit and manage metering data
Market	List All Markets	Used by market participants to get the available markets
Portfolio	Manage Portfolios	Used by FSPs to submit and manage portfolios on the market
Trade	List Market Trades	Used by market participants to retrieve the market trades (the result of the matching process between buy/sell orders)
Flexibility Zones	Manage Flexibility Zones	Used by DSOs to define specific flexibility areas, composed of a set of portfolios

Table 6: UMEI overall Structure

(Q8) **Gaps** identified in terms of data format, information models and communication protocols in EUniversal.

Regarding DSO systems, the adoption of CIM could help standardize most of the data exchange requirements. However, load and generation forecasts are not included.

CIM Market was considered. However, considered complex for the requirements of Local Flexibility market data exchange requirements

(Q11) How **data exchange gaps** are affecting the support for flexibility requirements identified and analysed.

Communication of DSO flexibility needs to the Local flexibility markets were not considered by the platforms which adapted their business process and data exchange model.

(Q12) EUniversal's proposed solutions for **addressing gaps**, such as using merged standards for data exchange, developing interfaces/adapters for TSO/DSO and customers, integrating cross-sector and cross-border components in the reference architectures and platforms to support flexibilities, etc.

EUniversal proposed an Open Interface, allowing collaborative development of an interface for DSO, Flexibility Markets, and Flexibility Aggregators. It could also be extended to TSO collaboration.

(Q13) EUniversal's proposals for **improving business processes** (i.e., system planning/asset management, system operation, energy markets) efficiently while facilitating flexibility and resilience of the EU energy system.

The proposed interface enabled the integration of flexibility market-based services in DSO long-term planning, maintenance planning, and day-ahead operation planning, to postpone network investment, and improve voltage regulation and congestion management.

(Q14) **Challenges anticipated** in implementing EUniversal proposals, and how can be overcome.

First of all, the UMEI needs to be maintained to ensure its viability in the long run. To do so, clear ownership of the UMEI beyond the project is important.

Users should follow the API specification presented in GitHub [107]. Although minor adaptations may be introduced in each case, these are to be avoided in order to ease the implementation process.

Data protection and IT security concerns must be considered in the grid as well as for end-users. This should also be considered regarding future developments and possible standardization.

The UMEI offers creative solutions for data transfer (thanks to its distributed approach of data handling and its dynamic flexibility areas) without opening doors for security issues. It is recommended to take further the basic data transfers principles of the UMEI to further ensure data security.

As indicated, the UMEI now covers the key trading market operations. It is a first version which covers the key basis steps to operate any type of platform. Therefore, currently the UMEI is only implemented for the procurement phase. However, if the UMEI becomes a widely accepted API standard for flexibility markets, all operations market participants can do must be covered by the API standard (for example also pre-trading activities such as pre-qualification and registration). These steps are, however, harder to implement in the UMEI due to agreements that are needed regarding standardization of these phases.

Furthermore, development of more process groups for the UMEI, TSO-DSO coordination, Flexibility Register synchronization are needed.

In addition, there might be country specific elements such as the German redispatch that should be accounted for.

(Q15) EUniversal's **has not made developments** addressing the **cyber-physical reliability** and **resilience** of the electricity grid.

The project addresses resilience of distribution networks. No cyber-physical reliability considered.

(Q15i) EUniversal's **cyber and physical assets/elements** that the project addresses, **potential risks** identified in EUniversal that are associated with the cyber-physical nature of the grid, and how the latter are mitigated.

EUniversal has proposed a set of tools to improve operational and long-term grid resilience, providing decision support in long investment decisions to increase the robustness of the grid towards these extreme events, and in terms of planning operation (next days or hours) under these extreme events.

B.21 HVDC-Wise

(Q1) HVDC-Wise Project Objective: The HVDC-WISE project [108] aims to advance hybrid AC/DC transmission grids by developing new reliability and resilience (R&R) planning tools and identifying HVDC-based grid architectures to enhance system performance and integrate new renewable sources. The project focuses on updating power system R&R to reflect the integration of HVDC systems and emerging threats, concentrating on how HVDC technologies can reduce supply interruptions and improve event response. The project will use advanced tools to demonstrate performance benefits and guide HVDC solutions, recommending updates to technical codes and industry practices. HVDC-WISE targets five key objectives: (i) to develop R&R-oriented planning toolsets with HVDC-based grid architecture concepts; (ii) to propose and compare HVDC-based grid architectures for AC/DC systems; (iii) to assess and model emerging HVDC technologies for widespread AC/DC grids (iv) to validate planning toolsets and HVDC architectures in three realistic use cases; and (v) to prepare for industry adoption and deployment of proposed solutions.

Project Status: Ongoing

(Q2) HVDC-Wise **interfaces and data interoperability platforms** to enhance flexibility and improve business processes.

No. Quoting the text available in Section 3.2.8.1 on Interoperability, "HVDC projects are now being proposed that will require, or at least enable, multi-terminal HVDC operation with converter stations from different vendors. Achieving successful multi-vendor multi terminal (MVMT) interoperability will require new approaches to multi-terminal and other supervisory control, specification of interfaces and performance requirements, modelling, analysis, and testing. This need for innovation and new solutions implies some additional risk so there is a need for thorough testing and proving of inter-operability. In HVDC-WISE it is assumed that the challenges of inter-operability will be addressed in other projects, such as the European InterOPERA project and Aquila in GB".

(Q3) HVDC-Wise's key findings regarding the implementation of standards and interfaces to improve flexibility and business process (system planning/asset management, system operation, energy markets).

In addition, the Deliverables publicly available so far do not address, enumerate or describe the standards or interfaces that will be eventually adopted in the project. In fact, HVDC-WISE, at least considering the mentioned three deliverables available so far, is more devoted to technological aspects related with the development of hybrid AC/DC systems together with models to help TSOs planning and operating these systems, rather than addressing issues related with data models, their interoperability or the increased flexibility to manage power systems.

(Q4) HVDC-Wise's contribution towards the development of **data interoperability platforms and data-sharing** frameworks.

As indicated above, HVDC WISE is concerned with technologies and tools to allow the integration of large amounts of renewable generation in European power systems, assuming that most of these new resources will be connected by power electronic interfaces. In this sense, it is not focused on data models nor in interoperability problems or in the resulting increased flexibility as it clearly stated and recognized in section 3.2.8.1 of D2.1, already mentioned in the answer to question 2.

(Q5) HVDC-Wise's definition of **communication and data exchange requirements**.

No, at least the three Deliverables publicly available so far did not address communication and data exchange requirements. It should be noticed that the HVDC-WISE consortium integrates 5 European TSOs, 3 research institutes and 5 universities, that is, it does not include any DSO. This means it is very much focused on the concerns of TSOs in view of the large integration of wind and PV resources and the required grid technologies and on the models required to plan and operate these evolving hybrid AC/DC power systems. This means that communication and data exchange among different operators (for instance in terms of a more refined coordination between TSOs and DSOs) apparently is not a concern in this project.

(Q6) **Data models** used in HVDC-Wise.

See the answer to the previous questions. As mentioned before, data models, standards and interoperability aspects seem not to be within the major concerns or objectives in this project. As indicated in the Figure included the answer to Question 1, WP 5 and WP6 are devoted to the development of simulation tools for Reliability & Resilience oriented expansion planning and operation of hybrid AC/DC power systems and to the application of the developed network expansion planning methodology to use cases. It is then possible that in the context of these two WP aspects related with the required data and its availability and modelling are addressed. However, it happens that HVDC-WISE started in October 2022 and its webpage only contains a preliminary Deliverable from WP5 on the specification of the conceptual architecture of the R&R oriented expansion planning and operation model, describing the existing tools and enumerating for each of them the additional functional and data needs. In any case, this deliverable does not include any information regarding an integrated upper-level global model to represent network data. On the contrary, when enumerating the available expansion planning and operation tools they are addressed in a rather independent way and for each of them the additional functions, enhancements and data are mentioned. This suggests that these tools may eventually use proprietary models confirming that standardization, protocols and interoperability issues are not a major concern, at least until the present phase of this project.

In fact, Section 6 of D2.1 provides brief descriptions of the power function tools to integrate the platform to be developed, several of them based on already existing models and commercial packages implemented in the DIgSilent power factory via the Python API, the PSS/E commercial simulation tool and EuroStag/SmartFlow. In other cases, this section mentions that HVDC-WISE will profit from models that were developed or are under development in other projects as it is the case of the RESILIENT model (it stands for Realistic Event Simulator for International Location-Independent Energy Network Testing, under development in the H2020 EUniversal project) and the network expansion planning tool that was developed in the FlexPlan European project.

However, D2.1 includes a minor section (5.2) on Model Standardization. Quoting the text in this section, "to be able to conduct adequate modelling for R&R analyses, it is necessary that sufficient modelling of equipment is standardised in a format that is agreeable across the industry. The IEC

CIM/CGMES standards have been converged upon in both industry and academia as a standard means for defining power systems models. WP4 will use the IEC CIM/CGMES as much as possible for quasi steady state and RMS models considering the different models and libraries already in existence and the future needs of the project. At the same time, WP4 will explore the potential extension of the IEC CIM/CGMES standards to include dynamic phasor models or EMT models (offline and real-time). If the developed models cannot be contained within the IEC CIM/CGMES standard, an agreed structure among all the partners will be used."

(Q14) **Challenges anticipated** in implementing HVDC-Wise's proposals, and how can be overcome.

This aspect is **not** addressed in the project.

The deliverables available so far identify several challenges regarding the development of hybrid AC/DC power systems ensuring their reliability and resilience in view of connecting increasing wind and PV units. However, these challenges are more related to technological issues as well as with the development of methodologies to perform operation and expansion planning studies to get more insights on the evolving hybrid power systems.

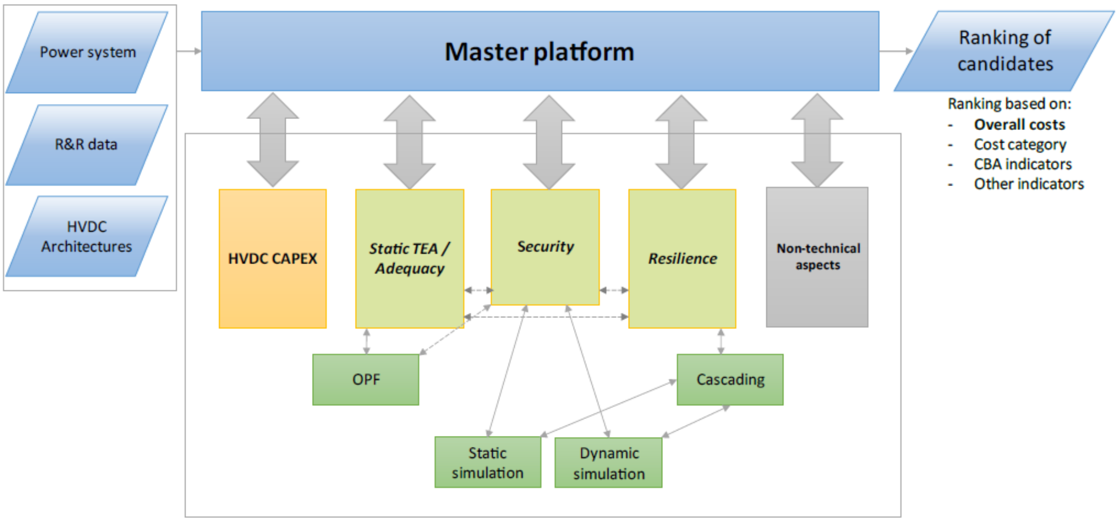


Figure 41 HVDC-Wise high level conceptual architecture

The mentioned technological accent is also very well illustrated in D4.1 on the Identification of Key Technologies, Potential Benefits and Restrictions. This Deliverable "describes building blocks (defined here as "an equipment that can be considered during the planning process") and possible technologies to build them. It also provides considerations on technology readiness levels and how these building blocks and technologies are related to architectures, reliability, and resilience." Therefore, this Deliverable includes three main chapters addressing Building Blocks enabling DC architecture, new building blocks for the AC system with impact on the studies in the Use Cases and Other building blocks.

Considering these building blocks, HVDC-WISE aims at developing a platform to help TSOs in planning the operation and the expansion of hybrid AC/DC power systems as illustrated in the next figure.

(Q15) HVDC-Wise **has made developments** addressing the **cyber-physical reliability** and **resilience** of the electricity grid.

(Q15i) HVDC-Wise's **cyber and physical assets/elements** that the project addresses, **potential risks** identified in HVDC-Wise that are associated with the cyber-physical nature of the grid, and how the latter are mitigated.

HVDC Wise is concentrated on how the integration of HVDC architectures and technologies will be used to move current power systems to new hybrid AC-DC systems and on how these new systems are able to improve reliability and resilience (in this case defined in line with the definition provided by the CIGRE WG C 4.47 as the "ability to limit the extent, severity, and duration of system degradation following an extreme event".

In this scope D2.1 details that "The provision of reliable and resilient access to electricity by energy users is a fundamental objective of a power system and all the various actors involved in generation, transmission, distribution and balancing services. It is affected by many aspects of what these actors do and is a very large subject, covering logistics, asset management, workforce planning, and stakeholder communication and interaction in addition to the definition and implementation of technical standards and codes, design decisions and procurement and commissioning actions. HVDC-WISE will concentrate on technical aspects of R&R in future hybrid AC/DC systems, and on how HVDC architectures and technologies can enhance it and reduce the likelihood of interruptions to supply or make it easier for the impact of events and disturbances to be contained and any interrupted supply to be restored. Threats to R&R that might result from contingencies, malfunctions, or interactions in large-scale HVDC systems will be analysed with the aim of identifying appropriate design of architectures, controls, and protection to ensure that the integration of HVDC does not introduce any new risks. The introduction of HVDC plant into a power system adds new components and types of component and possible outage events that may require security standards to be revised to include additional contingencies and avoided consequences in order that R&R is not degraded. Similarly, grid codes may need to be revised. This will be addressed as part of the HVDC-WISE work.

In general, HVDC plant and systems can enhance R&R relative to today's power systems in the following ways:

- By reducing the likelihood of an outage.
- By minimizing the impact of outages through R&R centred design principles and control methods.
- Through enhanced response to an event or disturbance.
- Through control of system conditions during a restoration process.

The first of the above might most notably be achieved using underground or subsea cables that are, in general, less vulnerable to weather-related outages than overhead lines although repair times may be significantly longer. In many use cases, the desire or need, because of circumstances or public or policy preference, to use cables makes use of HVDC a necessity, e.g. to avoid issues with electrical performance of AC cables or to minimise losses.

In relation to the second point, the effectiveness of HVDC in enhancing R&R depends on how HVDC elements of a combined, hybrid AC/DC system are designed, configured and protected. Topological and technology design choices will influence the extent to which adequacy can be improved through the sharing of disparate resources while the chosen protection philosophy will influence the extent to which individual faults on the system propagate. For example, without DC breakers, a fault anywhere on a multi-terminal HVDC system would lead to a rapid fall in voltage across the entirety of that system and a need for all of it to be isolated by the action of protection on the AC side of each converter station. Thus, while the probability of a fault within a system using underground cables might be lower than if overhead lines had been used for similar distances, the impact of a fault might be greater. A further way in which, in principle, the probability of an outage can be reduced is by better control of power flows and loading across multiple circuits, and better control of voltage. These can both be achieved in a pre-disturbance manner via the controllability of HVDC.

The third and fourth of the above means of enhancement – through post-disturbance responses – relate to the ability of HVDC systems to contribute via, for example, the control of voltages and power flows, the damping of oscillations or aiding energisation. These features in turn depend on how converter controls are designed and operated and on the current rating of converters."

In this context, Section 4 of D2.1 describes different DC network topologies to interconnect different sections of AC grids or to connect large DC units and discusses the influence of these topological aspects on the performance and resilience of the network. It also presents an extensive survey on existing and planned DC links characterizing their architecture, voltage rating, capacity and length over time and discussing the implications on Reliability & Resilience from the identified trends on HVDC links.

Finally, Section 3.3.1.3 of D2.1 on Physical and Cyber Attacks indicates that "The HVDC-WISE project will not focus on specific physical threats but will explore more fully the risks associated with cyber-attacks" detailing that the project will address cyber threats for HVDC controllers and for HVDC communication stations.

This platform will be developed in WP5 and D5.1 provides brief descriptions of several operation and expansion planning tools that are already in use by the members of the consortium as indicated in Section 4 of D5.1 Some of these tools are commercially available and quoting D5.1 "although the methodology aims to be tool-independent, its implementation will rely on pre-existing tools for the quantification of R&R indicators, which will be suitably upgraded for their use during the project. Most of these tools have been used by the partners in past projects; however, …, they must be upgraded to include the proposed HVDC-based grid architecture concepts". These tools include:

- OptTEA Soft Grid – designed to conduct techno-economic analysis and optimization studies on DC networks.
- FlexPlan Tool – to conduct static analysis of AC and DC power grids and its expansion planning along an extended horizon. This tool uses a DC based power flow formulation and it was originally developed in the FlexPlan project. It is based on a Sequential Monte Carlo simulation to select a set of expansion candidates to optimize the social welfare (considering operational and investment costs, the environmental impact and system security issues). The HVDC-Wise consortium now aims at enhancing to enable its integration in the platform to be developed within the project.
- AC-CFM – aiming at simulating cascading failures in static operation mode to conduct resilience analysis. The list of functionalities in Section 4.4.2 of D5.1 indicates that AC-CFM performs "N-k security analysis, where k can be in the order of tens or hundreds of assets, still obtaining a feasible power flow solution".
- D – CFM – it is a dynamic cascading failure model that was implemented in DIgSILENT PowerFactory via the Python API. Section 4.5.1 of D5.1 indicates that "it automatically develops cascading mechanisms, simulates sets of failure scenarios and processes results, and has good scalability, such that it can be easily applied to any power system model".
- HY_ACDC_SIM2 – it is a PSS/E-oriented tool that models Multi Terminal VSC-HVDC systems for power flow and dynamic simulations.

- DPsim tool – aiming at simulating large scale system dynamics based on a dynamic phasor modelling.
- Market Grid Tool Chain – it is a scenario generation and market simulation toolchain that can derive power plant dispatches, by considering exchange capacities, load and RES feed-in time series. It includes hybrid AC/DC power flow calculations and congestion management to identify the redispatch and RES feed-in management to guarantee (N-1) secure grid operation.
- RESILIENT – it stands for Realistic Event Simulator for International Location-Independent Energy Network Testing. RESILIENT is being developed in the H2020 EUniversal project and it is described as "a flexible and modular simulation tool capable of spatio-temporal modelling of extreme weather across transmission and distribution networks. This is coupled with fragility-based models and multi temporal/multi-spatial OPF models for capturing and quantifying the impact of the event on the network using different risk and resilience metrics".
- RELIEF – it is a tool developed in MATLAB environment for resilience assessment that supports both long-term planning and operational planning analyses. As detailed in Section 4.10.1 of D5.1 "it allows for probabilistic modelling of different types of threats, vulnerability of grid components to the same threats, as well as various countermeasures used for mitigation purposes. Combining threat and vulnerability models allows for the identification of the components with the highest failure probabilities, as well as the multiple, dependent, contingencies affecting these components. The tool calculates risk and resilience indicators and provides useful information, such as indications of the grid portions where interventions are needed in long-term planning contexts, or anticipation of critical situations in operational planning contexts".
- EUROSTAG/SmartFlow – it is a dynamic power system simulator (RMS/phasor) developed by Tractebel Engineering, capable of considering multi-terminal and meshed HVDC systems. It is coupled with the SmartFlow toolbox, comprising AC/DC power flow and Security Constrained OPF modules. Eurostag is already used for probabilistic security and resilience assessment, with the consideration of dynamic cascading outage phenomena (including the action of protection systems).

For each of these tools, D5.1 identifies the associated functionalities, the required data, the output, the limitations regarding the analysis of AC/DC systems and the enhancements and model needs that are considered necessary in terms of the HVDC-WISE project. It also addresses opportunities for cross tool integration given that some tools mentioned above address similar problems and should be eventually subject to some integration effort to obtain more complete or generic models (as it the case of the OptTEA Soft Grid and the FlexPlan Tools on one side, or the AC-CFM and the D-CFM on the other).

The HVDC WISE consortium, including five European TSOs (Amprion GmbH, TenneT TSO GmbH, Energinet, Statnett, and SSEN Transmission), has identified several ongoing power system trends that pose potential risks. According to Deliverable D2.1, these include:

- Dominance of Power Electronics: Increased use of power electronics in renewable energy sources and HVDC systems, combined with the phase-out of conventional generators, reduces system inertia and stability.
- Technology Limitations: HVDC converters lack the beneficial behaviours of synchronous generators, and their performance relies heavily on programmable control software. HVDC technology also faces challenges in control and fault management.
- Protection and Control: HVDC systems' control and protection systems act quickly, unlike the slower synchronous generator systems, raising concerns about testing and approval

processes. HVDC converters also have higher fault rates and longer repair times, especially for subsea cables.

- System Stability: Synchronous generators inherently stabilize AC systems, while converters rely on control systems that have limitations, such as needing additional stored energy and current limitation.
- Power Quality: Interactions between HVDC links and other equipment can cause harmonic resonances, impacting system capability. Models for assessing these risks are needed.
- Cyber Security: Digitalization increases dependence on software for grid control, raising concerns about cyber resilience, including protection against attacks and risks from software updates.
- Readiness of Tools and Methods: The project aims to develop new toolkits for assessing reliability and resilience, supporting system planning decisions with advanced analysis tools and real-time environments.

B.22 FARCROSS

(Q1) FARCROSS's Project Objective: The FARCROSS project [109] aims to assist EU to achieve its energy goals by improving cross-border electricity interconnections. This will create a larger market, increase competition, enhance security of supply, and integrate more renewables. FARCROSS connects major energy stakeholders to demonstrate integrated hardware and software solutions, facilitating cross-border electricity flows and regional cooperation. The project promotes advanced technologies to optimize transmission grid assets, increase grid observability, and ensure the safe integration of renewable energy sources. It also includes a regional forecasting platform for better renewable generation and demand response, and tools to optimize capacity reserves and maximize cross-border flows. Additionally, the project addresses non-harmonized national regulations to ensure the full benefits of the technologies.

Project Status: Completed

(Q2) FARCROSS **interfaces and data interoperability platforms** to enhance flexibility and improve business processes.

FARCROSS has developed interfaces and data interoperability platforms to enhance flexibility and improve business processes. These include advanced forecasting tools, capacity allocation, and reserve optimization tools designed to increase cross-border grid services.

Q2i: Specification of the purposes of the interfaces, along with their definitions in terms of information models, timing requirements, and interaction sequences.

The interfaces developed in FARCROSS are used for integrating hardware and software solutions to facilitate cross-border electricity flows and regional cooperation. These interfaces involve advanced forecasting platforms, capacity reserves optimization tools, and wide-area protection, automation, and control systems (WAMPAC). These systems are designed based on specific information models, timing requirements, and interaction sequences to ensure real-time data exchange and interoperability across different platform.

Q2ii: A brief description, or illustration of each **interface's architecture**, referencing the SGAM model.

Each interface architecture in the FARCROSS project is designed following SGAM. For example, the WAMPAC system's architecture integrates PMU data for backup protection and uses the VX-GOOSE model for secure communication. Detailed descriptions and figures of these architectures are available in the project's technical documentation and deliverables.

B.23 ENFLATE

(Q1) ENFLATE's Project Objective: The ENFLATE project [110] supports the European Commission's Clean Energy Package and FiT for 55 policies, aiming to decarbonize the energy system, promote the electrification of heat and transport, and integrate more clean, intermittent generation. Its objectives are to increase the shared use and penetration of renewable energy sources, reduce network operational costs while boosting financial gains, and implement effective power exchange control across regional, national, and EU levels. The project also focuses on improving communication among distributed energy sources, strengthening new multi-sectoral business models, and encouraging consumer and prosumer participation in cost-effective power trading.

Project Status: Ongoing

(Q2) ENFLATE **interfaces and data interoperability platforms** to enhance flexibility and improve business processes.

The project is demonstrating flexibility management solutions that valorise cross sector flexibility resources of end-consumers for providing energy and non-energy services. The developed flexibility platforms will relate to the central IT platform. The software services constituting the ENFLATE Platform Data Management Layer, including the data management bus will be developed. Furthermore, the necessary measures for the resolution of the several data handling, privacy and security issues will be identified and implemented in the following months of the project.

(Q3) ENFLATE's key findings regarding the implementation of **standards and interfaces** to improve flexibility and business processes (system planning/asset management, system operation, energy markets).

The development and implementation of standards and interfaces has not yet taken place. The intention is to deploy flexibility platforms that coordinate heating services with flexibility provision to the electricity system at DSO level, P2P exchange of flexibility among consumers to the TSO and DSO level, mobility services with energy management and charging patterns, health services with energy consumption monitoring.

B.24 int:net

(Q1) int:net Project Objective: The int:net project [111] establishes the Interoperability Network for the Energy Transition, an open, cross-domain community that brings together all stakeholders in the European energy sector to develop, test, and deploy interoperable energy services. This network is designed to continue beyond the project's lifetime, supported by a comprehensive, FAIR knowledge platform and a series of engaging events. As a Coordinating and Support Action, int:net addresses specific Horizon topic requirements by facilitating coordination and alignment of projects, supporting interaction between European and national initiatives, and maintaining expertise in interoperability related to the energy transition. The project focuses on IT/ICT development, standard evolution, virtualization, digital twins, data spaces, and industrial efforts towards interoperability, including ontologies and core models.

Project Status: Ongoing

(Q2) int:net **interfaces and data interoperability platforms** to enhance flexibility and improve business processes.

The project is not developing new interfaces and data interoperability platforms as new products/technologies, it is mainly addressing existing actions and links them together. As mentioned, "The int:net consortium strives to promote holistic interoperability in a future energy system. While it relies on existing means and methods to describe, foster and validate interoperability, it tries to close gaps and to make the topic more tangible for a broad range of stakeholders. Not the least, int:net has identified gaps in collaboration in the field of governance as well as in holistic descriptions of systems. To that end, int:net has set out to add new views and methods to close such gaps."

(Q3) int:net key findings regarding the implementation of **standards and interfaces** to improve flexibility and business processes (system planning/asset management, system operation, energy markets).

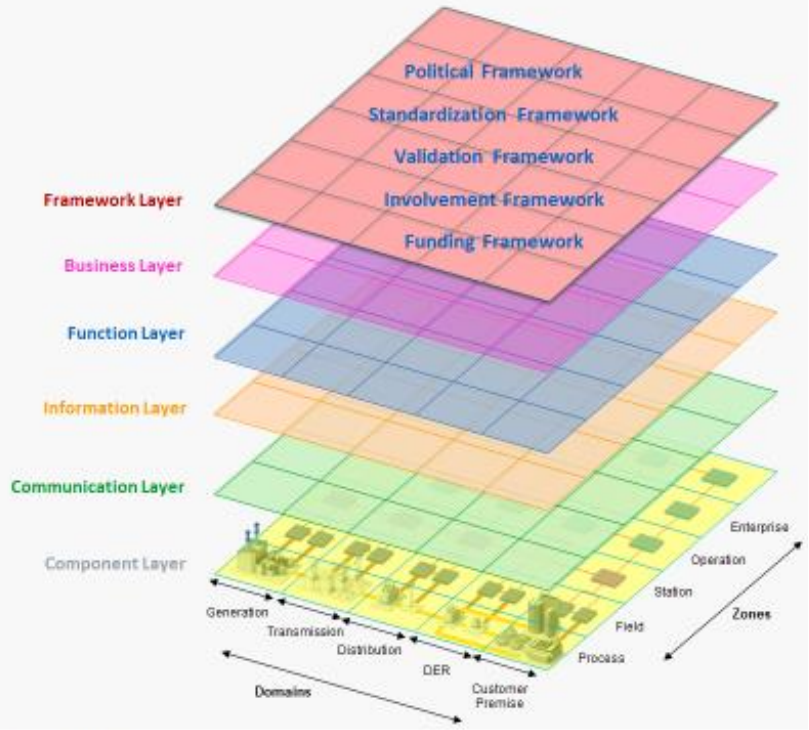


Figure 42 SGAM plus the 6th layer

The int.net projects propose a new layer for the SGAM framework, "The future energy system will be way more complex. Distributed systems explode not only the number of installations but also the number of involved stakeholders. But not only does the number of participants in the system grow, the number of interfaces, dependencies, and potential inconsistencies explodes as well. Political and regulatory, standardization, validation and involvement frameworks need to cope with that situation. In such a governance framework, institutions need to agree which standards shall be mandatory to follow in specific cases. They need to agree on a level of interoperability that shall be mandatory for the implementation in their country or business domain. Owners of funding programs would need to agree on interoperability prerequisites for projects to be funded. The 5th layer of SGAM (business layer) covers some of these aspects with respect to the feasibility of business cases for solutions described on SGAM layers 1 – 4. However, this layer is much oriented to business cases and cannot cover political or regulatory and not at all societal interoperability in broad systems. Therefore, the proposal of int:net is the addition and definition of another SGAM layer. When talking about such a

"6th layer" (see Fig. 4 SGAM plus), interoperability of a broad range of stakeholder groups needs to be addressed, amongst those.

(Q4) int:net contribution towards the development of **data interoperability platforms and data-sharing** frameworks.

The project mentions that targets to promote interoperability and develop an interoperability maturity model:

The project has several objectives, starting with the creation of a common knowledge base and best practices repository based on FAIR principles. This will promote interoperability of energy-related services, data, and platforms. A second objective is the development of an interoperability assessment methodology and the Interoperability Maturity Model (IMM), specifically tailored to European energy services. The project also seeks to harmonize testing procedures and establish a distributed network of interoperability testing laboratories. Finally, int:net aims to foster coordination and support among legal and regulatory entities, promote the adoption of interoperable energy services, data spaces, and digital twins, and collaborate with external initiatives such as, for example Gaia-X and DSSC, BRIDGE and ETIP SNET.

The project developed an interoperability model and provided a GitHub [112] with the related information i.e. "Via this link you can download the artifacts that int:net produced, for example the terminology and definitions used for the int:net Interoperability Model (EMINENT)."

(Q5) int:net definition of **communication and data exchange requirements** [113].

The project is collecting existing approaches in data exchange requirements and developed a Blueprint of Common European Energy Data Spaces, presenting detailed energy use cases i.e. "The success of these use cases is intricately tied to the widespread adoption of energy data spaces, necessitating a detailed examination of data exchange mechanisms, requirements, and the involved actors.

Consequently, to implement the presented use cases, an architecture for the CEEDS is proposed. This architecture envisions the integration of existing data platforms, including legacy systems, through the implementation of a federated data space. Moreover, as the blueprint unfolds, it turns its focus toward identifying and addressing existing challenges in interoperability at technical, semantic, and governance levels. Practical actions and recommendations are outlined, guiding stakeholders on the standards and communication protocols crucial for achieving seamless interoperability.

(Q6) **Data models** used in int:net.

The intent is a coordination support action project, so it mentions that "The int:net is supposed to be a self-sufficient network capable of existing and prospering after the end of the int:net project. To lay a solid foundation, a roadmap to the establishment, organization and practices of the network / community needs to be developed. The int:net consortium is in the process of conducting workshops to develop this roadmap." *"EEBUS describes the communication interface (i.e.,* application, transportation, communication) in order to allow for the interconnection between energy management relevant devices and the corresponding control systems. EEBUS empowers the digitalization of energy transition by creating a data model that ensures cross-domain interoperability among all energy relevant devices and systems.

The main challenge reported by their CEO is to combine independent stakeholders and their differing interests and interactions at the same grid connection point. Each of them wants to influence the operation of energy-relevant devices inside the building with different goals (e.g., cost-optimization, grid-supporting etc.).

The big aim of EEBUS is to introduce standardised communication interface between device manufacturers (device to device) as well as between DSOs and device manufacturers. EEBUS is also texting practical use case implementations and gathering input from regulatory and legislative authorities. Furthermore, test specifications and implementation instructions for bidirectional applications.

(Q7) **Protocols and standards** applied in int:net.

We include extracts from projects deliverables to answer this question.

“In this regard, the CEEDS relies on the harmonization and usage of prominent standards-based data models and ontologies such as SAREF, IEC 61970, IEC 61850, OCPP, Open Data Protocol (OData) and the Common Information Model (CIM).”

“In data spaces where there is data exchange, approaches based on data ontology (highlighting the relations among the data instances) are a requirement in order to avoid silos. External systems cannot know about the relationships unless they are provided with a machine-readable format. RDF is a framework for expressing linked data so it can be exchanged between applications without loss of meaning. RDF allows the expression of simple facts in the form of triples (subject, predicate and object). The subject and the object represent the two resources being related. The predicate represents the nature of their relationship in a directional way (from subject to object). RDF uses URIs to name the relationship between things as well as the two ends of the link. There are various concrete syntaxes for RDF, such as Turtle, TriG, and JSON-LD.”

(Q8) **Gaps** identified in terms of data format, information models and communication protocols in int:net.

Based on the deliverables found the consortium highlights:

“The following list of past activities and existing needs has been identified and underlines the importance to create a lively interoperability ecosystem:

- Various interoperability standards and models for smart grid connectivity have been developed. These solutions need to be further improved. The usability and accessibility of such solutions is important to meet future energy system requirements.
- A comprehensive model for data exchange in advanced use cases between TSOs, DSOs, and other grid users must be adopted and enhanced to enable a flexible and smart energy system. A good exploitation strategy can help to bring all stakeholders together to co-create and collaborate on the missing links for a smart and flexible system.
- More emphasis needs to be given to the functional and business layer of e.g., SGAM while not neglecting the interoperability needs on the data and protocol layers. This can ensure a better understanding of the complexity of the current and future energy system.
- Networks of testing facilities have been developed in the framework of publicly funded projects, but there is a need to harmonize testing procedures, increase the variety of test facilities (and establish a work structure so to continue operation – cooperating on EU and national levels). int:net should create a platform that acts as a focal point for testing interoperability.

- Smart grids standards have been independently developed in EU, America, and Asia and need to be aligned so they do not hinder development and deployment of widely useable, interoperable solutions. A collaboration platform must be established to meet these needs.
- The energy sector should learn from more advanced processes in other sectors (e.g., health) and learn from their success story and possibly adopt their strategies.
- Policymakers and regulatory bodies need innovative models to trigger interoperability without enforcing specific models or standards."

(Q12) int:net Proposed solutions for **addressing gaps**, such as using merged standards for data exchange, developing interfaces/adapters for TSO/DSO and customers, integrating cross-sector and cross-border components in the reference architectures and platforms to support flexibilities, etc.

The project intent organised an Interoperability test (IOP) on Common Grid Models Exchange Standard (CGMES) version 3.0 hosted by ENTSO-E in Brussels. The objective of this test was to foster the harmonization and interoperability of energy services throughout Europe by focusing on the adoption and implementation of CGMES v3.0, an IEC standard (IEC 61970-600-1&2:2021).

"CGMES v3.0, which has been a standard since June 2021, has a wide scope and provides necessary clarifications, forming a stable baseline for future versions. However, it was evident from the test that many vendors, TSOs and DSOs are not fully aware of the benefits offered by this version. Consequently, one of the main conclusions of the test was the need for proactive discussions and knowledge sharing among stakeholders to facilitate a smooth transition to the latest versions of the standards."

Additionally, the test conducted resulted in several propositions for addressing gaps:

- "Conformity assessment emerged as a crucial aspect in ensuring the quality of data exchange and minimizing overall effort"
- "Clear communication, both internally and externally, and strict planning by stakeholders implementing business processes were identified as crucial factors for success."
- "A clear commitment by utilities to implement the standards/specifications designed to meet requirements was emphasized as a key driver for progress."
- "Establishing a robust framework for aligning standardisation processes with implementation needs emerged as a critical requirement."
- "Facilitating access to validation tools and ensuring uniform usage across vendors were considered crucial aspects for business processes."
- "The maintenance of existing test data, the release of declassified models from TSOs and ensuring data quality were recognized as vital factors in enabling the interoperability community to conduct robust testing.

(Q13) int:net proposals for **improving business processes** (i.e., system planning/asset management, system operation, energy markets) efficiently while facilitating flexibility and resilience of the EU energy system.

The int:net proposes the Common European Energy Data Spaces approach (CEEDS) which is related to 5 Business Use Cases for business processes in the energy market i.e. The BUCs correspond to:

- Use case #1 – "Collective self-consumption and optimized sharing for energy communities"
- Use case #2 – "Residential home energy management integrating DER flexibility aggregation"
- Use case #3 – "TSO-DSO coordination for flexibility"
- Use case #4 – "Electromobility: services roaming, load forecasting and schedule planning"

- Use case #5 – “Renewables O&M optimization and grid integration”

(Q14) **Challenges anticipated** in implementing int:net proposals, and how can be overcome.

It is mentioned that interoperability and conformity are related processes. To successfully implement business process and have interoperable interface between different applications, there is a need to have clearly defined use cases; have detailed knowledge of the requirements; develop standards; perform tests (interoperability tests) to test the standards; define conformity assessment process for the standards; organize communication with all involved parties; require conformity assessment for applications to validate their conformity against a standard or set of standards; require conformity assessment for utilities to validate their readiness to conform with a business process”

(Q15) INT:NET **has not made developments** addressing the **cyber-physical reliability** and **resilience** of the electricity grid.

From the deliverables and material examined, we could not identify any relation with cyber-physical reliability and resilience.

B.25 SDN-MICROSENSE

(Q1) SDN-MICROSENSE’s Project Objective: SDN-microSENSE [114] aims at providing and demonstrating a secure, resilient to cyber-attacks, privacy-enabled, and protected against data breaches solution for decentralised Electrical Power and Energy Systems (EPES). All designed, developed, and tested technologies should consider the latest related research findings and maintain high compliance with current industrial standards (e.g., IEC standards).

Project Status: Completed

(Q2) SDN-MICROSENSE **interfaces and data interoperability platforms** to enhance flexibility and improve business processes.

The project aims at monitoring the substation process bus, preventing/detecting cyber-attacks instead of proposing new interfaces and data interoperability platforms to enhance flexibility and improve business processes of system operators. The improvements are achieved via improving cyber resilience.

(Q7) **Protocols and standards** applied in SDN-MICROSENSE.

The project monitors the operation of protocols such as Modbus, DNP3, IEC61850, IEC60870-5-104.

(Q15) SDN-MICROSENSE **has made developments** addressing the **cyber-physical reliability** and **resilience** of the electricity grid.

(Q15i) SDN-MICROSENSE’s **cyber and physical assets/elements** that the project addresses, **potential risks** identified in SDN-MICROSENSE that are associated with the cyber-physical nature of the grid, and how the latter are mitigated.

The project demonstrates the developed technologies in 6 pilot use cases and the involved assets are:

- the Substation local networks (UC1): Investigating attacks occurring at the station bus network where traditionally little or no network monitoring takes place

- Process control attack vectors (UC1): Investigating attacks occurring at the process bus. Process bus networks should only ever be reachable from station bus networks by way of interaction among RTUs, PLCs and ultimately IEDs.
- State estimation and Automatic generation control (UC2)
- Power plant and substation (UC3)
- PV systems and prosumers premises (UC5, UC6)

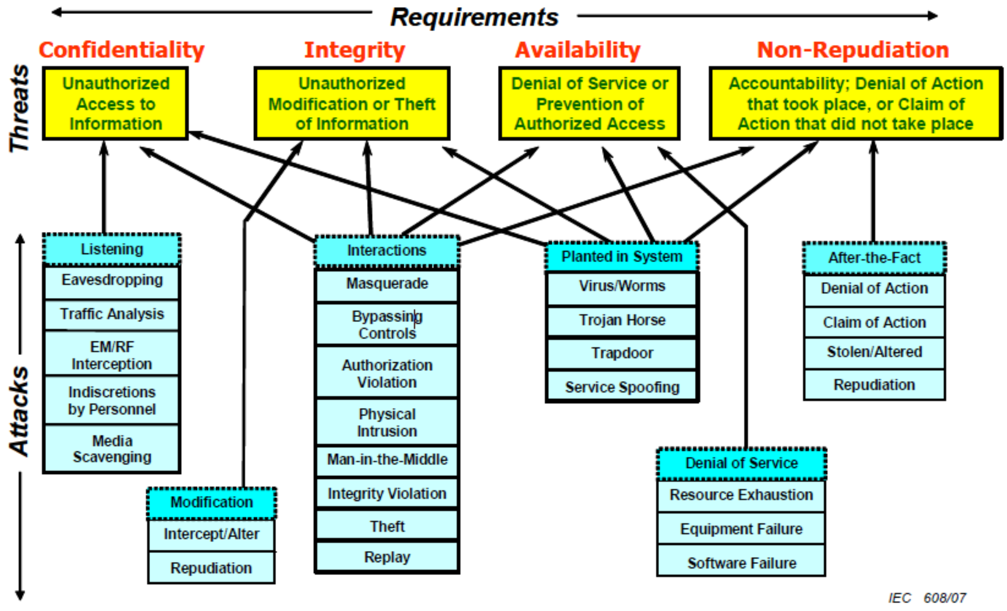


Figure 43 Map of requirements-potential threats for electronic devices

The project is following for its activities on the IEC62351-1. The most typical attacks to an Intelligent Electronic Device (IED) are the following:

- Deny Service (DOS). The most common is to saturate the communication channels. However, it can also be accomplished by injecting invalid firmware or configuration or by inserting a malicious program to stop internal daemons.
- Access to the IED for theft of information.
- Identity Fraud. Take the control of an IED to generate unauthorized actions in the electrical components of a substation (for example to generate a blackout), provide wrong information to the SCADA of the control room, or to get access to other EIDs.
- Message injection. A MiTM attack that intercept authorized messages from the control room and replay them to make the IED

Most of these attacks
use a specific mechanism to
achieve their malicious purpose, these attack mechanisms are categorized by CAPEC3, and the attacks listed above belong to the following categories:

- Abuse Existing Functionality
- Engage in Deceptive Interactions
- Manipulate Data Structures
- Inject Unexpected Items»

(Q15ii) Identified focus areas for **dynamic monitoring and control** to ensure the reliability and resilience of the grid, SDN-MICROSENSE propositions for **effective monitoring and protection of the pan-European grid cyber layers**.

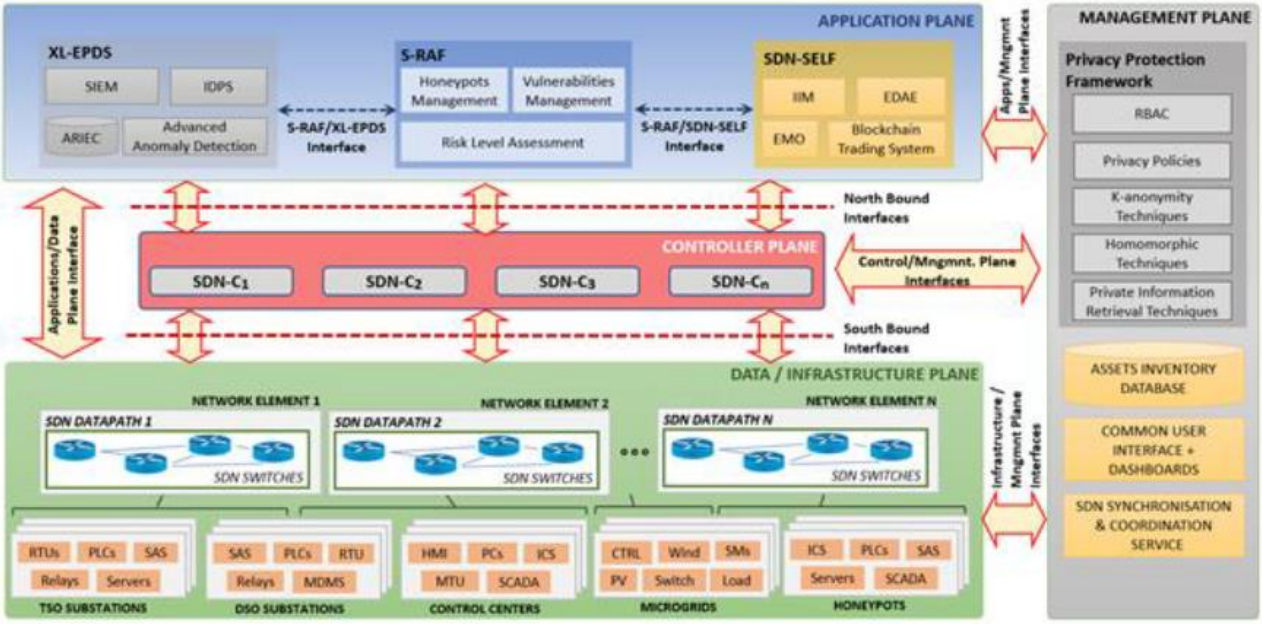


Figure 44 The SDN-microSENSE Architecture

The project focuses on the substation bus and protocols operating the electricity grid such as Modbus, PNP3, IEC61850, IEC61870-5-104

The proposition of the project is basically the tools and ICT architecture that address and mitigate the cybersecurity threats of the electrical power energy systems (EPES)

B.26 CyberSEAS

(Q1) CyberSEAS's Project Objective: The move towards more agile, connected, intelligent and data-driven energy systems, and their interconnection with our day-to-day lives, means that there is a major increase in cyber exposure of energy systems leading to major safety and privacy incidents. The EU-funded CyberSEAS project [115] improves the resilience of energy supply chains by protecting them from disruptions generated by complex attack scenarios. CyberSEAS delivers an open and extendable ecosystem of 30 customisable security solutions providing effective support for key activities, such as risk assessment; interaction with end devices; secure development and deployment; real-time security monitoring; skills improvement and awareness; and certification, governance and cooperation. CyberSEAS solutions will be validated through experimental campaigns consisting of numerous attack scenarios.

Project Status: Ongoing

(Q2) CyberSEAS **interfaces and data interoperability platforms** to enhance flexibility and improve business processes.

The project developed several interfaces and data interoperability platforms to enhance flexibility and improve business processes. These include the Advanced Update Validation Platform (AUVP), Dynamic Rating System (SUMO), Balancing Services Platform, Virtual Cross-border Control Centre, and the MISP Threat Sharing Intelligence Platform.

Q2i: Specification of the purposes of the interfaces, along with their definitions in terms of information models, timing requirements, and interaction sequences.

- AUVP: Ensures the integrity of OT device configuration through firmware control and signing. It uses real-time substation automation data and system logs.
- SUMO: Integrates Dynamic Line Rating (DLR), Dynamic Power Transformer Rating (DPTR), and Dynamic Line Anti-icing (DLAI) for real-time and forecast operations. It uses weather data and power line currents for calculations.
- Balancing Services Platform: Allows Balancing Service Providers (BSPs) to provide ancillary services like FCR, aFRR, and mFFR using AMQP and ICCP protocols.
- Virtual Cross-border Control Centre: Uses the Common Grid Model Exchange Specification for voltage control and loss optimization.
- MISP: Uses JSON format for threat intelligence sharing, supporting real-time exchange of threat data.

Q2ii: A brief description, or illustration of each **interface's architecture**, referencing the SGAM model.

The project categorizes assets into classes derived from the SGAM reference architecture:

- PES Components: Generators, transmission lines, transformers.
- IM Components: Relays, PLCs, IEDs, communication links.
- Communication: WAN, NAN, FAN.
- Information: Measurement data, grid data, market data.
- Functional: SCADA functions, aggregation software.
- Business: Policies, processes.
- Human: Network operators, maintenance personnel.

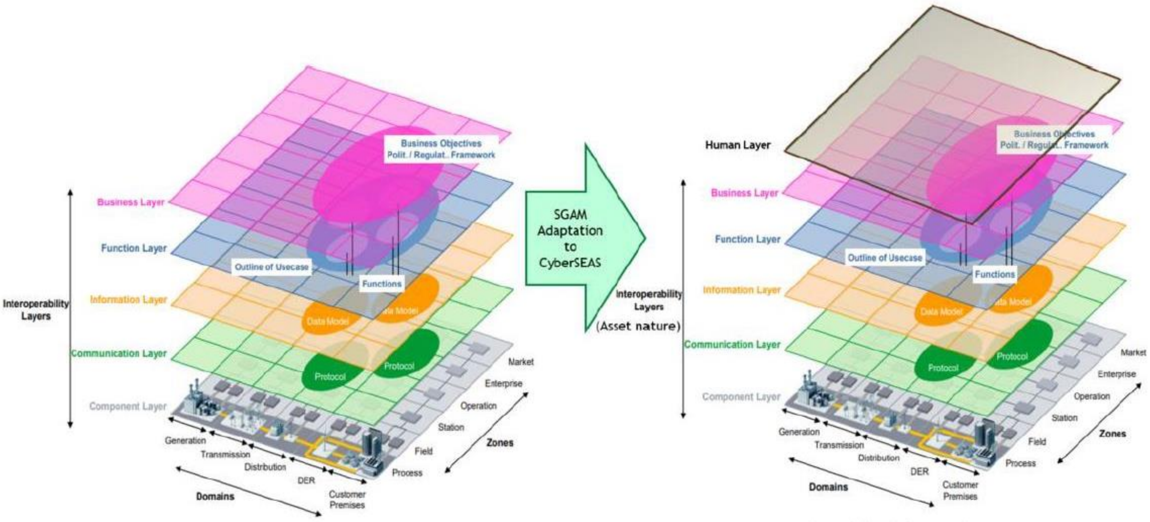


Figure 45: Adaptation of SGAM to categorize asset classes for CyberSEAS

(Q3) CyberSEAS's key findings regarding the implementation of standards and interfaces to improve flexibility and business processes (system planning/asset management, system operation, energy markets).

- The necessity of standardized interfaces for data exchange.
- The critical role of cybersecurity in maintaining the integrity of the energy supply chain.
- The value of real-time data processing and sharing for improving system resilience and operational efficiency.
- Enhanced collaboration and data-sharing mechanisms were found to be essential for effective system operation and market activities

(Q4) CyberSEAS's contribution towards the development of **data interoperability platforms and data-sharing** frameworks.

- Developing real-time cybersecurity monitoring measures.
- Implementing continuous cyber risk assessment support.
- Creating confidentiality-preserving federated machine learning mechanisms.
- Enhancing the use of cyber threat intelligence.
- Developing frameworks for metadata and data-sharing to ensure interoperability across different systems and platforms

(Q5) CyberSEAS's definition of **communication and data exchange requirements**.

The project defined specific communication and data exchange requirements to ensure secure and efficient data flow between various components of the energy infrastructure. This includes protocols like AMQP, ICCP, and SOAP, as well as data formats compliant with IEC standards

(Q6) **Data models** used in CyberSEAS.

- The Common Grid Model Exchange Specification based on the IEC CIM (Common Information Model) for network models.
- Various proprietary protocols for specific data sources, ensuring detailed and precise data modelling for system operations.

(Q7) **Protocols and standards** applied in CyberSEAS.

- AMQP for messaging between systems.
- ICCP (TASE.2) for real-time data exchange between control centres.
- SOAP Web Services for integration of weather data and operational data.
- Common Grid Model Exchange Specification for network models.
- JSON for threat intelligence data exchange via MISP.

(Q8) **Gaps** identified in terms of data format, information models and communication protocols in CyberSEAS.

- The need for standardized data formats to ensure interoperability across different systems.
- Inconsistencies in information models that hinder seamless data integration.
- Limitations in existing communication protocols to handle dynamic and real-time data exchanges efficiently.

(Q9) Examples of tool **limitations** identified during the analysis.

- Challenges in integrating legacy systems with modern cybersecurity tools.
- Limitations in real-time data processing capabilities due to the heterogeneity of data sources and formats.
- Difficulties in achieving seamless interoperability between different platforms and systems

(Q10) CyberSEAS's significant **missing interfaces and adapters** identified between system operators, TSOs, DSOs, and customers.

- Seamless data exchange between TSOs, DSOs, and customers.
- Real-time data sharing and cybersecurity monitoring.
- Integration of various data formats and models to support system flexibility and resilience

(Q11) How **data exchange gaps** are affecting the support for flexibility requirements identified and analysed.

- Pilot implementations and real-world testing scenarios.
- Feedback from stakeholders and system operators.
- Detailed analysis of current data flows and identifying bottlenecks or inefficiencies.

(Q12) CyberSEAS's Proposed solutions for **addressing gaps**, such as using merged standards for data exchange, developing interfaces/adapters for TSO/DSO and customers, integrating cross-sector and cross-border components in the reference architectures and platforms to support flexibilities, etc.

- Developing merged standards for data exchange.
- Creating new interfaces and adapters for seamless integration.
- Integrating cross-sector and cross-border components in reference architectures to support flexibility and resilience.
- Enhancing cybersecurity measures to protect data integrity and confidentiality

(Q13) CyberSEAS's proposals for **improving business processes** (i.e., system planning/asset management, system operation, energy markets) efficiently while facilitating flexibility and resilience of the EU energy system.

- Streamline data flows for improved efficiency.
- Enhance real-time decision-making capabilities.
- Implement robust cybersecurity measures to protect against threats.
- Facilitate better integration and interoperability, leading to more resilient and flexible energy systems.

(Q14) **Challenges anticipated** in implementing CyberSEAS's proposals, and how can be overcome.

- Technical integration issues with existing systems.
- Ensuring data privacy and security.
- Achieving stakeholder consensus on standards and protocols.
- These challenges can be overcome through:
- Pilot testing and iterative refinement of solutions.
- Continuous stakeholder engagement and feedback.
- Adopting a flexible and adaptive approach to integration and standardization.

(Q15) CyberSEAS **has made developments** addressing the **cyber-physical reliability** and **resilience** of the electricity grid.

(Q15i) CyberSEAS's **cyber and physical assets/elements** that the project addresses, **potential risks** identified in CyberSEAS that are associated with the cyber-physical nature of the grid, and how the latter are mitigated.

- OT devices in substations.

- Smart meters.
- Communication devices.
- Remote Terminal Units (RTUs).
- Blockchain technology for ensuring data integrity and trust.
- Cyberattacks on critical infrastructure.
- Data breaches and system integrity issues

How they are mitigated:

- Real-time monitoring and threat detection.
- Implementation of advanced cybersecurity frameworks.
- Regular risk assessments and updating security measures accordingly

(Q15ii) Identified focus areas for **dynamic monitoring and control** to ensure the reliability and resilience of the grid, CyberSEAS propositions for **effective monitoring and protection of the pan-European grid cyber layers**.

- Developing dynamic rating systems for real-time capacity assessment.
- Integrating weather data for predictive analysis.
- Implementing threat intelligence platforms for continuous monitoring and response
- Using advanced cybersecurity tools and real-time monitoring systems.
- Developing collaborative threat intelligence platforms.
- Ensuring continuous updates and improvements to security measures to protect the cyber layers of the pan-European grid from potential threats

B.27 ELECTRON

(Q1) ELECTRON's Project Objective: The primary objective of the ELECTRON project [116] is to deliver a new-generation Electrical Power and Energy Systems (EPES) platform aimed at enhancing the resilience of energy systems against cyber, privacy, and data attacks. The project focuses on risk assessment, federated intrusion and anomaly detection, failure mitigation, energy restoration, and the use of post-quantum cryptography to secure the electrical grid.

Project Status: Ongoing

(Q2) ELECTRON's **interfaces and data interoperability platforms** to enhance flexibility and improve business processes.

The project has developed interfaces and data interoperability platforms aimed at enhancing system flexibility and improving business processes such as system planning, asset management, system operation, and energy markets.

Q2i: Specification of the purposes of the interfaces, along with their definitions in terms of information models, timing requirements, and interaction sequences.

The interfaces developed are designed to support federated learning models for cybersecurity, nanogrid-based prevention and mitigation schemes, and collaborative risk and certification frameworks. These interfaces are aimed at providing decentralized security and integrating various cybersecurity measures. However, specific details about information models, timing requirements, and interaction sequences are not provided in the available sources.

Information Models: The interfaces are defined to manage data exchange and interoperability across different systems and components within the electrical grid. The ELECTRON architecture includes components like the Security Information and Event Management (SIEM) system, Federated Intrusion Detection and Prevention System (FIDPS), and Blockchain Energy Transaction System (BEAM), which facilitate secure and efficient data handling.

Timing Requirements: These interfaces operate in real-time or near-real-time to ensure timely detection, response, and mitigation of cybersecurity threats.

Interaction Sequences: The interaction sequences involve data collection, processing, analysis, and response actions orchestrated by various components such as SDN controllers and AI-based decision support system.

Q2ii: A brief description, or illustration of each **interface's architecture**, referencing the SGAM model.

The architecture of the ELECTRON project's interfaces involves a layered approach based on the SGAM (Smart Grid Architecture Model) framework. This framework ensures comprehensive integration and interoperability across different domains of the electrical grid, including field devices, control centres, and enterprise systems. The physical layer includes components such as smart meters and inverters connected via communication protocols like Modbus/TCP. The data collected from these devices is processed by the Active Distribution Management System (ADMS), which acts as the control centre.

(Q3) ELECTRON's key findings regarding the implementation of standards and interfaces to improve flexibility and business processes (system planning/asset management, system operation, energy markets).

Key findings include the successful integration of advanced cybersecurity measures and compliance with EU cybersecurity policies. The project emphasizes the importance of federated learning and decentralized security information and event management (SIEM) to improve system flexibility and business processes.

(Q4) ELECTRON's contribution towards the development of **data interoperability platforms and data-sharing** frameworks.

The project contributed by developing platforms that support standardized communication protocols and data formats, ensuring seamless data exchange and interoperability across different systems and devices. This includes the use of metadata to enhance the contextual understanding of the data being shared.

(Q5) ELECTRON's definition of **communication and data exchange requirements**.

The project defined comprehensive communication and data exchange requirements to ensure the secure and efficient operation of the electricity grid. These requirements are aligned with international standards such as IEC 61850 and DNP3.

(Q6) **Data models** used in ELECTRON.

- Threat Intelligence Data Model: For capturing information about potential cyber threats and vulnerabilities.
- Network Configuration Data Model: For maintaining up-to-date information about network devices and configurations.
- Security Policies Data Model: For defining and enforcing security policies across the network.

(Q7) **Protocols and standards** applied in ELECTRON.

- IEC 61850: For substation automation and control.
- DNP3: For communication between control systems and field devices.
- Modbus/TCP: For industrial control systems.
- OpenFlow: For SDN communication.

(Q8) **Gaps** identified in terms of data format, information models and communication protocols in ELECTRON.

- Inconsistencies in data formats between different vendors and systems.
- Lack of standardized information models for new types of cyber threats.
- Communication protocols that do not fully support real-time data exchange and dynamic security requirements.

(Q9) Examples of tool **limitations** identified during the analysis.

- Scalability Issues: Some tools struggled to scale efficiently with the increasing amount of data.
- False Positives in Threat Detection: Certain AI models produced a high rate of false positives, requiring further tuning and validation.

(Q10) ELECTRON's significant **missing interfaces and adapters** identified between system operators, TSOs, DSOs, and customers.

- Standardized communication interfaces between Transmission System Operators (TSOs) and Distribution System Operators (DSOs).
- Adapters for integrating legacy systems with modern digital infrastructure.
- Customer interfaces for real-time energy usage monitoring and management.

(Q11) How **data exchange gaps** are affecting the support for flexibility requirements identified and analysed.

Data exchange gaps were identified through extensive testing and simulation of different network scenarios. The analysis focused on the impact of these gaps on real-time data flow and the ability to quickly adapt to changing network conditions.

(Q12) ELECTRON's Proposed solutions for **addressing gaps**, such as using merged standards for data exchange, developing interfaces/adapters for TSO/DSO and customers, integrating cross-sector and cross-border components in the reference architectures and platforms to support flexibilities, etc.

Proposed solutions include developing merged standards for data exchange, creating interfaces/adapters for seamless integration, and incorporating cross-sector and cross-border components to support system flexibility and resilience.

(Q13) ELECTRON's proposals for **improving business processes** (i.e., system planning/asset management, system operation, energy markets) efficiently while facilitating flexibility and resilience of the EU energy system.

These proposals aim to improve business process efficiency (system planning, asset management, system operation, and energy markets) by facilitating flexibility and resilience in the EU energy system through advanced cybersecurity measures and enhanced data interoperability.

(Q14) **Challenges anticipated** in implementing ELECTRON's proposals, and how can be overcome.

Anticipated challenges include ensuring comprehensive cybersecurity across diverse EPES components and managing the complexity of federated learning models. Overcoming these challenges involves continued development and integration of advanced cybersecurity frameworks and training processes.

(Q15) ELECTRON **has made developments** addressing the **cyber-physical reliability** and **resilience** of the electricity grid.

(Q15i) ELECTRON's **cyber and physical assets/elements** that the project addresses, **potential risks** identified in ELECTRON that are associated with the cyber-physical nature of the grid, and how the latter are mitigated.

The project addresses various cyber and physical assets including federated learning models for cybersecurity, nanogrid-based prevention and mitigation schemes, and decentralized SIEM.

Identified risks include vulnerabilities in legacy systems and new cyber threats. Mitigations involve dynamic risk assessment, intrusion detection, and blockchain-based transaction systems.

- Cyberattacks on communication protocols.
- Physical tampering with grid devices.
- Data integrity and confidentiality breaches.
- Mitigation strategies involve:
- Implementing robust encryption and authentication mechanisms.
- Deploying intrusion detection and prevention systems.
- Regular security audits and dynamic risk assessments.

(Q15ii) Identified focus areas for **dynamic monitoring and control** to ensure the reliability and resilience of the grid, ELECTRON propositions for **effective monitoring and protection of the pan-European grid cyber layers**.

Focus areas include dynamic monitoring of the grid, advanced threat detection, and proactive response mechanisms to ensure reliability and resilience.

The project proposes using advanced monitoring techniques, decentralized security measures, and federated learning to effectively monitor and protect the cyber layers of the pan-European grid from potential threats.

B.28 FEVER

(Q1) FEVER's Project Objective: The European Research & Innovation project FEVER [117] will demonstrate and implement solutions that leverage the potential of flexibility in generation, consumption and storage of electricity for optimal management of power grids. Deploying artificial intelligence and ledger technologies, peer-to-peer trading of flexible energies and a toolbox comprising advanced monitoring and prediction algorithms, FEVER empowers distribution system operators (DSOs) to better observe and manage their grids. An ever-growing share of fluctuating electricity generators, such as wind and solar, makes it more difficult to calculate the loads being fed in. Constantly increasing power demand poses an additional challenge. For a secure and resilient energy supply, production and demand need to be harmonized. FEVER meets these challenges by fine-tuning orchestration of flexibilities in generation, storage and consumption. FEVER's objective is to promote optimal management of the power grids in the future energy system based on renewable sources.

Project Status: Completed

(Q2) FEVER **interfaces and data interoperability platforms** to enhance flexibility and improve business processes.

The FEVER project developed several interfaces and data interoperability platforms designed to enhance flexibility and improve business processes in system planning/asset management, system operation, and energy markets. These developments are detailed in various deliverables, including the creation of systems like the Flexibility Trading Platform (FTP), Geographic Information System (GIS), and several others aimed at facilitating the efficient management and trading of flexibility.

Q2i: Specification of the purposes of the interfaces, along with their definitions in terms of information models, timing requirements, and interaction sequences.

- Flexibility Trading Platform (FTP): Manages trading of flexibility.
- Energy Management Systems (EMS): Monitors and controls DER assets.
- Flexibility Management System (FMS): Aggregates/disaggregates flexibilities for trading.
- Power Flow Simulator (PFS): Simulates power flows in the grid.

Q2ii: A brief description, or illustration of each **interface's architecture**, referencing the SGAM model.

- Flexibility Trading Platform (FTP): Centralized control system for flexibility trading. It operates at the market and enterprise layers of the SGAM model, ensuring integration with various grid and market participants.
- Flexibility Service Providing Agent (FSPA): Acts at the field and process layers of the SGAM model, interfacing directly with energy management systems and converting flexibility potentials into marketable offers.
- DSO Toolbox (LRA, SHA): These applications integrate at the operation and field layers, utilizing real-time grid data to perform dynamic loss reduction and fault management.

(Q3) FEVER's key findings regarding the implementation of **standards and interfaces** to improve flexibility and business processes (system planning/asset management, system operation, energy markets).

- Enhanced Grid Management: Implementation of interfaces like FTP and FSPA significantly improved grid stability and operational efficiency through better demand response and flexibility management.
- Data Standardization: Adoption of standards such as CIM (Common Information Model) for grid data ensured interoperability and streamlined data exchange between different systems.
- Scalability and Security: The project highlighted the importance of scalable and secure interfaces, particularly in the context of increasing penetration of DER and the need for robust cybersecurity measures.

(Q4) FEVER's contribution towards the development of **data interoperability platforms and data-sharing** frameworks.

Developing the P2P-FTP platform which utilizes blockchain for secure and decentralized flexibility trading and implementing standardized data models and protocols that facilitate seamless data exchange and interoperability across various energy management and grid systems.

(Q5) FEVER's definition of **communication and data exchange requirements**.

Yes, the project defined specific communication and data exchange requirements. For instance, it established requirements for real-time data exchange, compliance with CIM standards, and the integration of predictive models for flexibility estimation.

(Q6) **Data models** used in FEVER.

- Common Information Model (CIM): For standardized representation of grid data.
- FlexOffer Model: For representing flexibility offers in a standardized format suitable for trading.

(Q7) **Protocols and standards** applied in FEVER.

IEC 61850, ISO/IEC 27001, Blockchain protocols

(Q8) **Gaps** identified in terms of data format, information models and communication protocols in FEVER.

- Inconsistencies in data formats across different systems.
- Need for more robust information models to handle diverse DER capabilities.
- Communication protocol interoperability issues, particularly in real-time data exchanges.

(Q9) Examples of tool **limitations** identified during the analysis.

- Limited scalability of certain EMS tools.
- Challenges in integrating legacy systems with new flexibility platforms.
- Difficulty in maintaining real-time performance with increasing DER numbers.

(Q10) FEVER's significant **missing interfaces and adapters** identified between system operators, TSOs, DSOs, and customers.

- Interfaces for real-time data sharing between TSOs and DSOs.
- Adapters for seamless integration of customer-owned DERs into DSO systems.

(Q11) How **data exchange gaps** are affecting the support for flexibility requirements identified and analysed.

Data exchange gaps were identified through simulations and real-world trials, highlighting issues like delays in data transmission, lack of standardization in data formats, and insufficient granularity of exchanged data. These gaps were analysed in terms of their impact on flexibility market efficiency and grid stability.

(Q12) FEVER's proposed solutions for **addressing gaps**, such as using merged standards for data exchange, developing interfaces/adapters for TSO/DSO and customers, integrating cross-sector and cross-border components in the reference architectures and platforms to support flexibilities, etc.

- Development of Standardized Interfaces: Ensuring all systems comply with common standards like CIM.
- Enhanced Real-time Data Processing: Implementing high-performance data processing tools for real-time operations.
- Integration of Blockchain Technology: For secure and transparent flexibility trading and data exchange

(Q13) FEVER's proposals for **improving business processes** (i.e., system planning/asset management, system operation, energy markets) efficiently while facilitating flexibility and resilience of the EU energy system.

- Enhance Grid Stability: Through better demand response and real-time flexibility management.
- Improve Data Accuracy and Timeliness: Ensuring accurate and timely data for grid operations.
- Increase Market Participation: By enabling more actors to participate in flexibility markets, thus improving overall market efficiency and resilience

(Q14) **Challenges anticipated** in implementing FEVER's proposals, and how can be overcome.

Challenges include:

- Resistance to adopting new standards and protocols.
- Technical difficulties in integrating diverse systems and platforms.
- Ensuring data security and privacy across interconnected systems.

These can be overcome by:

- Conducting extensive stakeholder engagement and training.
- Developing robust integration frameworks and tools.
- Implementing advanced cybersecurity measures.

(Q15) FEVER **has made developments** addressing the **cyber-physical reliability** and **resilience** of the electricity grid.

(Q15i) FEVER's **cyber and physical assets/elements** that the project addresses, **potential risks** identified in FEVER that are associated with the cyber-physical nature of the grid, and how the latter are mitigated.

- Cyber Assets: Blockchain platforms for secure trading, cybersecurity protocols, and data management systems.
- Physical Assets: DERs, PEDs, smart meters, and SCADA systems.

Potential Risks:

- Data Breaches: Mitigated through robust encryption and secure data protocols.
- System Interoperability Issues: Addressed by adhering to universal standards and protocols.
- Real-time Data Latency: Overcome by optimizing data processing and communication frameworks.

(Q15ii) Identified focus areas for **dynamic monitoring and control** to ensure the reliability and resilience of the grid, FEVER propositions for **effective monitoring and protection of the pan-European grid cyber layers**.

- Real-time Monitoring Systems: Enhancing SCADA and AMI for better grid observability.
- Predictive Maintenance and Analytics: Using predictive models for proactive grid management.
- Integration of DERs: Ensuring seamless integration and management of distributed energy resources.

Effective Monitoring and Protection Measures:

- Comprehensive Cybersecurity Framework: Development and implementation of a comprehensive cybersecurity framework that includes intrusion detection systems, firewalls, and continuous monitoring.

- Cross-Border Collaboration: Establishing collaboration among European countries to share threat intelligence and best practices.
- Regular Security Audits and Assessments: Conducting regular security audits and assessments to identify vulnerabilities and ensure compliance with security standards.

Project Propositions:

- Advanced Cybersecurity Tools: Integrating advanced tools and technologies for enhanced security monitoring and threat mitigation.
- Standardized Protocols: Developing and adopting standardized communication and security protocols across the pan-European grid.
- Training and Awareness Programs: Implementing training and awareness programs for all stakeholders to ensure a high level of cybersecurity readiness.

B.29 FlexCHESS

(Q1) FlexCHESS's Project Objective: The large-scale integration of renewable energy sources (RES) has introduced a new operating paradigm. RES are characterized by uncertainty and volatility. Moreover, overloading of transmission and distribution feeders have become more frequent. The curtailment of renewable power generation has thus increased, contradicting the goals for high shares of RES. A valuable solution to these challenges is the introduction of flexibility from flexible resources and loads. In this context, FlexCHESS project [118] proposes cutting-edge solutions based on digital twin concept, Virtual energy storage systems (VESS) and Distributed Ledger Technology (DLT) to revolutionize the existing practices. Based on the aggregation of Connected Hybrid Energy Storage System (CHESS), FlexCHESS improves the grid stability while increasing the profitability of its installations by guaranteeing various ancillary services at the distribution and transmission network levels. FlexCHESS will also ensure the highest level of interoperability of the proposed solutions and enhance the innovation capacity and competitiveness of SMEs and Startups in Europe by unlocking access to meaningful information and co-creating new business opportunities.

Project Status: Ongoing

(Q2) FLEXCHESS **interfaces and data interoperability platforms** to enhance flexibility and improve business processes.

Yes, the project developed various interfaces and data interoperability platforms. The FlexCHESS project aims to revolutionize the existing practices by integrating Digital Twin (DT) concepts, Virtual Energy Storage Systems (VESSs), and Distributed Ledger Technology (DLT) to provide ancillary services at both distribution and transmission network levels.

Q2i: Specification of the purposes of the interfaces, along with their definitions in terms of information models, timing requirements, and interaction sequences.

These interfaces are designed to support various applications such as system frequency support and distribution network voltage support. The information models involve the integration of DERs, VPPs, and energy management systems. There is no information regarding timing requirements and interaction sequences.

Q2ii: A brief description, or illustration of each **interface's architecture**, referencing the SGAM model.

Detailed diagram of the Taxonomy of FlexCHESS is presented in the figure below:

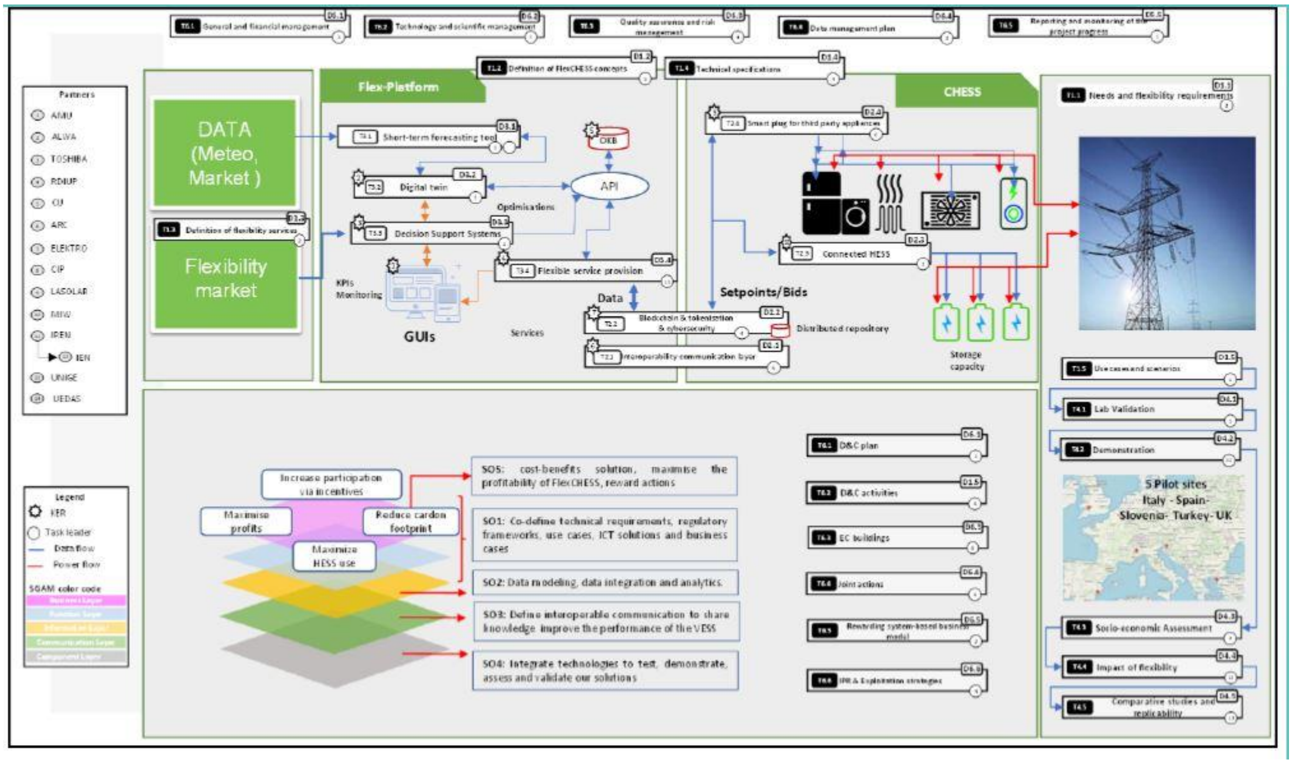


Figure 46 Taxonomy of FlexCHESS

(Q3) FLEXCHESS's key findings regarding the implementation of **standards and interfaces** to improve flexibility and business process (system planning/asset management, system operation, energy markets).

Key findings indicate that the implementation of standards and interfaces significantly enhances system flexibility, allows better integration of renewable energy sources, and improves the overall efficiency of business processes. This includes the adoption of standards such as IEC 61850 for substation integration and IEC 61970/61968 for CIM mapping.

(Q4) FLEXCHESS's contribution towards the development of **data interoperability platforms and data-sharing** frameworks.

The project contributed by developing an integrated platform that supports real-time data exchange and interoperability across different energy systems. This includes the use of advanced metering infrastructure (AMI), IoT-based solutions, and standardized communication protocols.

(Q5) FLEXCHESS's definition of **communication and data exchange requirements**.

These requirements are based on existing standards like IEC 61850 and CIM to support real-time data exchange and system interoperability.

(Q6) **Data models** used in FLEXCHESS.

The data models used include CIM (Common Information Model), IEC61850, SGAM framework and various proprietary models tailored for specific DERs and VPPs.

(Q7) **Protocols and standards** applied in FLEXCHESS.

IEC 61360, ISO/IEC 27001/2022, ISO 27002/2022, ISO/IEC 27701:2019, prEN 17529:2020, ISO/IEC 27019:2017.

Applied protocols and standards include IEC 61850, IEC 61970/61968, and various ISO standards for energy management and communication.

(Q8) **Gaps** identified in terms of data format, information models and communication protocols in FLEXCHESS.

Specific gaps identified include the lack of standardization in data formats across different systems, inconsistencies in information models, and the need for more robust communication protocols to handle real-time data exchange and interoperability.

(Q9) Examples of tool **limitations** identified during the analysis.

Tool limitations identified include issues with scalability, real-time data processing capabilities, and integration challenges with existing legacy systems.

(Q10) FLEXCEHSS's significant **missing interfaces and adapters** identified between system operators, TSOs, DSOs, and customers.

Missing interfaces and adapters were primarily related to real-time data exchange and communication between TSOs and DSOs, as well as between DSOs and end customers. These gaps impede effective coordination and flexibility in energy management.

(Q11) How **data exchange gaps** are affecting the support for flexibility requirements identified and analyzed.

Data exchange gaps were analysed through pilot studies and stakeholder consultations, revealing that inadequate data interoperability and inconsistent communication protocols significantly impact the ability to support flexibility requirements.

(Q12) FLEXCHESS's proposed solutions for **addressing gaps**, such as using merged standards for data exchange, developing interfaces/adapters for TSO/DSO and customers, integrating cross-sector and cross-border components in the reference architectures and platforms to support flexibilities, etc.

Proposed solutions include developing merged standards for data exchange, creating new interfaces and adapters, and enhancing cross-sector and cross-border components in reference architectures to support flexibility.

(Q13) FLEXCHESS's proposals for **improving business processes** (i.e., system planning/asset management, system operation, energy markets) efficiently while facilitating flexibility and resilience of the EU energy system.

These proposals aim to streamline business processes by ensuring better data integration, improving real-time decision-making capabilities, and enhancing the resilience of the energy system through more robust and flexible architectures.

(Q14) **Challenges anticipated** in implementing FLEXCHESS's proposals, and how can be overcome.

Anticipated challenges include technical integration issues, regulatory barriers, and the need for substantial investment. These challenges can be overcome by fostering collaboration among stakeholders and securing regulatory support.

(Q15) FLEXCHESS **has not made developments** addressing the **cyber-physical reliability** and **resilience** of the electricity grid.

B.30 INTERRFACE

(Q1) INTERRFACE's Project Objective: The main objective of the INTERRFACE [119] project is to design, develop, and implement an interoperable pan-European grid services architecture. This architecture acts as the interface between power systems (TSO and DSO) and consumers, facilitating seamless and coordinated operations among all stakeholders to utilize and procure common services efficiently.

Project Status: Completed

(Q2) INTERRFACE **interfaces and data interoperability platforms** to enhance flexibility and improve business processes.

The project has developed interfaces and data interoperability platforms aimed at enhancing flexibility and improving business processes such as system planning, asset management, system operation, and energy markets. These platforms support the integration of advanced grid services and market mechanisms.

Q2i: Specification of the purposes of the interfaces, along with their definitions in terms of information models, timing requirements, and interaction sequences.

The interfaces are primarily designed for system operation, energy market integration, and asset management. They utilize the Common Information Model (CIM) for standardization and interoperability. Timing requirements are structured to support both real-time and near-real-time data exchanges, ensuring timely decision-making and operational efficiency. Interaction sequences follow established protocols to maintain seamless communication between different grid components.

Q2ii: A brief description, or illustration of each **interface's architecture**, referencing the SGAM model.

Detailed descriptions or visual representations of each interface's architecture with reference to the SGAM model is provided in the figure below:

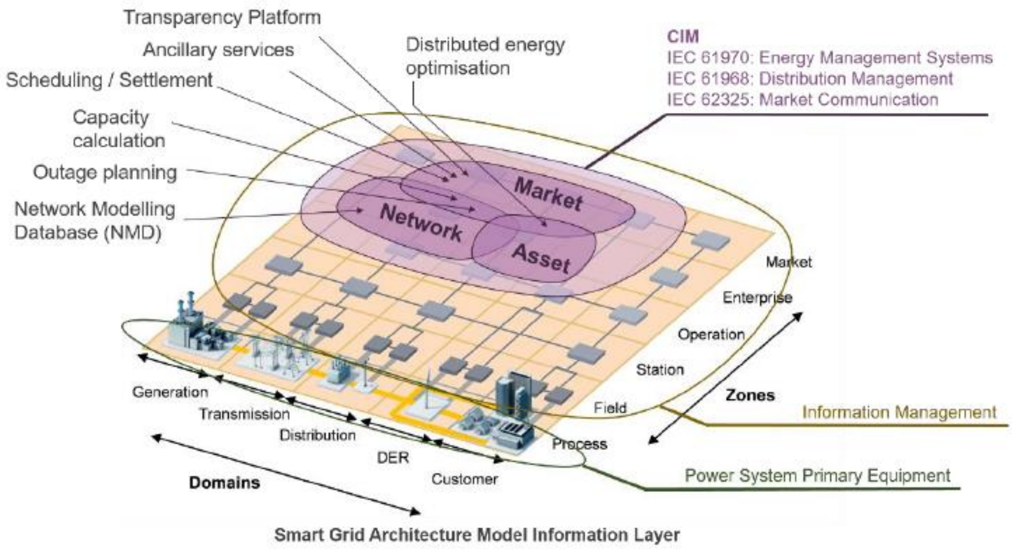


Figure 47: SGAM information layer displaying coverage Common Information Model standards and related business processes.

(Q3) INTERRFACE's key findings regarding the implementation of **standards and interfaces** to improve flexibility and business processes (system planning/asset management, system operation, energy markets).

The project has found that implementing an interoperable grid services architecture enhances flexibility and efficiency in energy markets. It underscores the importance of integrating advanced grid services and developing standardized communication protocols to support coordinated operations among stakeholders.

(Q4) INTERRFACE's contribution towards the development of **data interoperability platforms and data-sharing** frameworks.

The project contributed by developing comprehensive data-sharing frameworks that utilize metadata for effective data exchange. This ensures that different systems can communicate seamlessly, enhancing overall grid management.

(Q5) INTERRFACE's definition of **communication and data exchange requirements**.

The project defines communication and data exchange requirements to ensure the efficient operation of the interoperable grid services architecture. This includes standardized protocols and interfaces for data sharing between TSOs, DSOs, and consumers.

(Q6) **Data models** used in INTERRFACE.

- Common Information Model (CIM): This model is used for energy management to ensure interoperability between different systems. It provides a standardized way to represent power system resources and their relationships.
- SGAM (Smart Grid Architecture Model) Framework: This framework is utilized for ensuring interoperability and standardization across different layers and domains of the smart grid. It helps in mapping and aligning different grid components and their interactions.

(Q7) **Protocols and standards** applied in INTERRFACE.

CIM, IEC61850.

(Q8) **Gaps** identified in terms of data format, information models and communication protocols in INTERRFACE.

The project identifies the need for harmonized communication protocols and standardized data exchange formats to facilitate seamless interoperability among different energy market stakeholders.

(Q9) Examples of tool **limitations** identified during the analysis.

Examples of tool limitations include limited scalability and integration challenges with existing systems.

(Q10) INTERRFACE's significant **missing interfaces and adapters** identified between system operators, TSOs, DSOs, and customers.

Significant missing interfaces and adapters between system operators, TSOs, DSOs, and customers are not detailed in the available sources.

(Q11) How **data exchange gaps** are affecting the support for flexibility requirements identified and analysed.

Data exchange gaps were identified through pilot studies and stakeholder consultations, revealing significant impacts on the ability to support flexibility requirements due to inadequate data interoperability and inconsistent communication protocols.

(Q12) INTERRFACE's proposed solutions for **addressing gaps**, such as using merged standards for data exchange, developing interfaces/adapters for TSO/DSO and customers, integrating cross-sector and cross-border components in the reference architectures and platforms to support flexibilities, etc.

Proposed solutions include:

- Adoption of merged standards for data exchange.
- Development of new interfaces and adapters for better TSO/DSO/customer integration.
- Incorporation of cross-sector and cross-border components in reference architectures.

(Q13) INTERRFACE's proposals for **improving business processes** (i.e., system planning/asset management, system operation, energy markets) efficiently while facilitating flexibility and resilience of the EU energy system.

These proposals streamline data exchange, enhance interoperability, and enable real-time decision-making, improving the efficiency of business processes. They support greater flexibility and resilience by allowing dynamic and responsive energy management practices.

(Q14) **Challenges anticipated** in implementing INTERRFACE's proposals, and how can be overcome.

Anticipated challenges include regulatory and market barriers, high implementation costs, and technical challenges in integrating diverse systems. Overcoming these challenges requires regulatory support, infrastructure investment, and continuous stakeholder collaboration.

(Q15) INTERRFACE **has made developments** addressing the **cyber-physical reliability** and **resilience** of the electricity grid.

(Q15i) INTERRFACE's **cyber and physical assets/elements** that the project addresses, **potential risks** identified in INTERRFACE that are associated with the cyber-physical nature of the grid, and how the latter are mitigated.

Yes, the project addresses the cyber-physical reliability and resilience of the electricity grid by developing a robust interoperable architecture that ensures secure and efficient grid operations. The project addresses various cyber and physical assets, including advanced grid service platforms and communication protocols designed to enhance the reliability and resilience of the grid.

Potential risks include cybersecurity threats and the challenge of integrating diverse grid services. Mitigation strategies involve implementing robust security measures and standardized communication protocols to protect and manage grid operations effectively.

(Q15ii) Identified focus areas for **dynamic monitoring and control** to ensure the reliability and resilience of the grid, INTERRFACE propositions for **effective monitoring and protection of the pan-European grid cyber layers**.

Focus areas include dynamic monitoring of grid operations and advanced control mechanisms to ensure the stability and reliability of the electricity grid.

The project proposes using advanced monitoring tools and standardized communication protocols to effectively monitor and protect the cyber layers of the pan-European grid from potential threats.

B.31 INTERSTORE

(Q1) INTERSTORE's Project Objective: InterSTORE [120] is an EU-funded project that aims to deploy and demonstrate a set of interoperable Open-Source tools to integrate Distributed Energy Storage (DES) and DER, to enable the hybridization, utilization and monetization of storage flexibility, within a real-life environment. InterSTORE plans to address the complexity of various characteristics of storage solutions and technologies by developing an innovative middleware that, while virtualizing the storage technology, will simplify its use from the point of view of integration platform thanks to a technology agnostic approach. The middleware will facilitate the integration of storage creating hardware independent solution, which are critical from a customer perspective, avoiding vendor locked-in solutions. It will also facilitate its use from a monetization perspective making sure that more investments in storage are enabled.

Project Status: Ongoing

(Q2) INTERSTORE **interfaces and data interoperability platforms** to enhance flexibility and improve business processes.

The InterSTORE project developed interfaces and data interoperability platforms aimed at enhancing flexibility and improving business processes. These efforts focus on the integration of hybrid energy storage systems (HESS) and their effective utilization in system planning, asset management, system operation, and energy markets.

Q2i: Specification of the purposes of the interfaces, along with their definitions in terms of information models, timing requirements, and interaction sequences.

The interfaces developed in the InterSTORE project are designed to support various applications including:

- Grid Integration: Interfaces for integrating renewable energy sources and energy storage systems (ESS) into the grid, utilizing standards like IEC 61850 for substation automation and IEEE 2030.5 for energy management systems.
- Energy Management: Interfaces facilitating the communication between DER and utility management systems, ensuring efficient data exchange and coordination.
- Information Models: The project utilizes the Common Information Model (CIM) and IEC 61850 standards for defining the data models and ensuring interoperability between different systems.

Q2ii: A brief description, or illustration of each **interface's architecture**, referencing the SGAM model.

- Grid Integration Interface: Facilitates the connection of ESS with grid control systems using IEC 61850, supporting real-time data exchange and automation.
- Energy Management Interface: Uses IEEE 2030.5 for communication between ESS and energy management systems, enabling effective monitoring, control, and management of energy resources.

(Q3) INTERSTORE's key findings regarding the implementation of **standards and interfaces** to improve flexibility and business processes (system planning/asset management, system operation, energy markets).

- Enhanced Interoperability: Implementation of standards like IEC 61850 and IEEE 2030.5 significantly improved interoperability between different energy systems and devices.
- Improved Flexibility: The standardized interfaces facilitated better integration of ESS, leading to enhanced flexibility in energy management and system operations.
- Operational Efficiency: Standardized communication protocols enabled real-time monitoring and control, improving operational efficiency and responsiveness to market demands.

(Q5) INTERSTORE's definition of **communication and data exchange requirements**.

The project defined detailed communication and data exchange requirements based on existing standards like IEC 61850, IEEE 2030.5, and CIM. These requirements ensure that all components of the energy management systems can communicate effectively, supporting real-time operations and data integration.

(Q6) **Data models** used in INTERSTORE.

- IEC 61850: For substation automation and DER communication.
- IEEE 2030.5: For energy management systems and DER integration.
- CIM (IEC 61968): For utility enterprise systems integration.

(Q7) **Protocols and standards** applied in INTERSTORE.

IEC61850, IEEE2030.5, IEC61958(CIM)

(Q8) **Gaps** identified in terms of data format, information models and communication protocols in INTERSTORE.

- Data Format Inconsistencies: Variations in data formats across different systems leading to integration challenges.
- Information Model Alignment: Need for better alignment and standardization of information models to ensure seamless interoperability.
- Protocol Compatibility: Issues with compatibility between different communication protocols used by various stakeholders.

(Q12) INTERSTORE's Proposed solutions for **addressing gaps**, such as using merged standards for data exchange, developing interfaces/adapters for TSO/DSO and customers, integrating cross-sector and cross-border components in the reference architectures and platforms to support flexibilities, etc.

- Merged Standards: Developing and adopting merged standards for data exchange to ensure consistency and interoperability.
- Interface/Adapter Development: Creating standardized interfaces and adapters for TSO/DSO and customer integration.
- Cross-sector Integration: Incorporating cross-sector and cross-border components in the reference architectures to enhance support for flexibility.

(Q13) INTERSTORE's proposals for **improving business processes** (i.e., system planning/asset management, system operation, energy markets) efficiently while facilitating flexibility and resilience of the EU energy system.

- Enhance Efficiency: By ensuring seamless data exchange and interoperability, thus reducing operational bottlenecks and improving decision-making processes.
- Increase Flexibility: By enabling real-time integration and management of diverse energy resources, enhancing the system's ability to respond to dynamic market conditions.

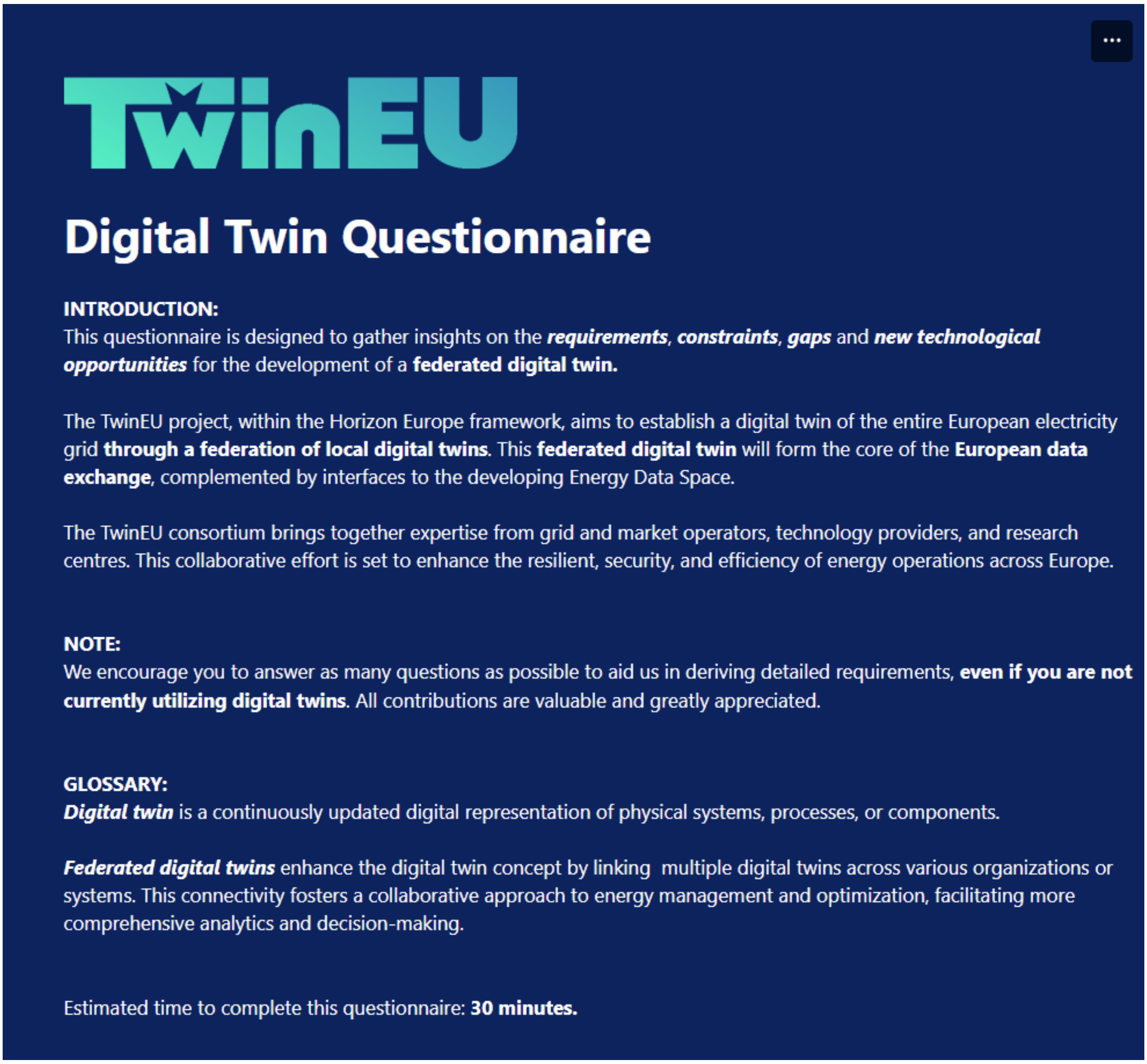
- Improve Resilience: By providing robust data exchange frameworks that support reliable and secure energy system operations.

(Q14) **Challenges anticipated** in implementing INTERSTORE's proposals, and how can be overcome.

- Standardization Adoption: Ensuring widespread adoption of the proposed standards and frameworks across different stakeholders.
- Technical Integration: Addressing technical challenges related to integrating new interfaces and adapters with existing systems.

Annex C Stakeholder Questionnaire

C.1 Questionnaire Introduction



Digital Twin Questionnaire

INTRODUCTION:
This questionnaire is designed to gather insights on the ***requirements***, ***constraints***, ***gaps*** and ***new technological opportunities*** for the development of a **federated digital twin.**

The TwinEU project, within the Horizon Europe framework, aims to establish a digital twin of the entire European electricity grid **through a federation of local digital twins**. This **federated digital twin** will form the core of the **European data exchange**, complemented by interfaces to the developing Energy Data Space.

The TwinEU consortium brings together expertise from grid and market operators, technology providers, and research centres. This collaborative effort is set to enhance the resilient, security, and efficiency of energy operations across Europe.

NOTE:
We encourage you to answer as many questions as possible to aid us in deriving detailed requirements, **even if you are not currently utilizing digital twins**. All contributions are valuable and greatly appreciated.

GLOSSARY:
Digital twin is a continuously updated digital representation of physical systems, processes, or components.

Federated digital twins enhance the digital twin concept by linking multiple digital twins across various organizations or systems. This connectivity fosters a collaborative approach to energy management and optimization, facilitating more comprehensive analytics and decision-making.

Estimated time to complete this questionnaire: **30 minutes.**

Figure 48 Digital Twin Questionnaire

C.2 Questions

C.2.1 Respondent Information

1. Please provide the name of your organization or company:
2. Please enter your full name:
3. Please specify your department and position within the organization:
4. Please provide your primary contact email address:
5. Are you currently utilizing digital twins in your operations?

C.2.2 Information on DTs, Regulations, Limitations, Data Exchange, and Expected Outcomes

These questions are directed to stakeholders based on their responses to Question 5, depending on whether they are currently using DTs or not. This is why some questions are slightly different but are grouped under the same chapter below:

Question 6

If you already implemented a digital twin, please describe the key characteristics, functions, and technical capabilities (such as performance, reliability, security, etc.).

Question 7 & 15

Are there any regulatory or compliance requirements that need to be considered in the use of digital twins within your operations?

Question 8 & 16

What cultural and organizational factors could (potentially) impact the adoption of digital twins in your organization?

Question 9

What limitations are you currently facing in terms of observability and controllability?

Question 10

What current limitations exist in your infrastructure and network planning processes?

Question 11

What limitations are you currently experiencing in your processes related to operations and simulations for enhancing grid resilience?

Question 12

What limitations do you currently face in active system management and forecasting?

Question 13

What are the current limitations on your data exchange processes, specifically between Transmission System Operators (TSOs) and Distribution System Operators (DSOs)?

Question 14 & 18

What features would you consider most valuable for future upgrades or new implementations of digital twins?

Question 17

What are the current limitations impacting your processes, especially in terms of observability and controllability, efficient infrastructure and network planning, operations and simulations, active system management and forecasting, data exchange, and cybersecurity?

Question 19

What challenges or problems do you face when interacting with other stakeholders, and how could digital twins potentially help address these issues?

Question 20

Which stakeholders do you currently need to exchange data with, or foresee a need to exchange data with, particularly concerning network topologies, parameters, etc.?

Question 21

What kinds of data do you currently share, or expect to share in the future, and what are the objectives of sharing this data?

Question 22

Do you currently use or plan to use digital twins to exchange data with external organizations? If so, which ones? Please provide details, such as whether you need to follow specific data exchange standards, etc.

Question 23

Are there any other specific stakeholders or user groups that you believe should be involved in the development and use of the digital twins? Please specify.

Question 24

What outcomes or benefits do you expect to achieve from implementing a digital twin in the energy market?

Question 25

Where do you believe a digital twin will have the most significant impact on the future of the energy sector?

Question 26

Considering the EU's target for climate neutrality by 2050 as outlined in the European Climate Law, do you believe that a federation of digital twins can contribute to achieving this goal? If so, how?