i-STENTORE

innovative Energy Storage
TEchnologies TOwards increased
Renewables integration and
Efficient Operation

D2.2 – SERVICES CO-CREATION, BUSINESS MODELS, FUNCTIONAL SPECIFICATIONS, AND REFERENCE ARCHITECTURE (1st VERSION)

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Abstract	This deliverable includes the first specification and design of the business models for i-STENTORE, the first identification of functional specifications for standardized data access and exchange and the first conceptual version of the i-STENTORE software Reference Architecture
Keywords	Business Models, Functional Specifications, Reference Architecture

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TABLE OF ABBREVIATIONS AND ACRONYMS

Acronym	Definition
(A)PV	(Agriculture) PhotoVoltaic
(B)ESS	(Battery) Energy Storage Systems
(B)UC	(Business) Use Case
(D)SO	(Distribution) System Operator
(H)ESS	Hybrid Energy Storage System
(I)IoT	(industial) Internet of Things
AD	Architecture Description
AI	Artificial Intelligence
API	Application Programming Interface
AWS	Amazon Web Services
BSPs	Balancing Service Providers
CEN	European Committee for Standardisation
CP	Charging Point
CS	Central System
CSA	Coordination and Support Actions
DB(S)	DataBase (System or Server)
DC/DC	Direct Current to Direct Current
DEI	Digitizing European Industry
DER(A)	Distributed Energy Sources (Architecture)
EMAM	Electric Mobility Architecture Model
EM-ISA	e-mobility Information System Architecture
EMS	Energy Management System
EPES	Electric Power and Energy Systems
ERP	Enterprise Resource Planning
EU	European Union
EV	Electric Vehicles
FL	Flexible Loads
FMS	Furnace Monitoring System
FR	Flexibility Register
FSP	flexibility Service Provider
GDPR	General Data Protection Regulation
GWAC	GridWise Architecture Council
HBAM	Home and Building Architecture Model
HOCS	Hierarchical Operation and Control System
HTTP	Hypertext Transfer Protocol
HVAC	High Voltage Alternating Current
HVDC	High Voltage Direct Current
ICT	Information and Computer Technologies

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IDSA	International Data Spaces Association
IEGSA	Interoperable European Grid Services Architecture
IPT	Investment Planning Tool
LIB	Lithium-Ion Battery
LIFO	Last-In-First-Out
Li-Ion	Lithium-ion
LTO	Lithium Titanate Oxide
MAF	Maritime Architecture Framework
MCDA	Multi-Criteria Decision Analysis
MO	Market Operator
MQTT	Message Queuing Telemetry Transport
NGSI-LD	Next Generation Service Interface – Linked Data
NISD	Network and Information Systems Directive
NMC	Nickel-Metal Hydride
OCPP	Open Charge Point Protocol
OLE	Object Linking and Embedding
OPC	OLE for Process Control
PLC	Programmable Logic Controller
PV	Photovoltaic
PVPP	Photovoltaic Power Plant
RA(M)	Reference Architecture (Model)
RAF	Reference Architecture Framework
RAMA	Reference Architecture Model for Automotives
RAMI	Reference Architecture Model for Industry
RES	Renewable Energy Sources
REST	REpresentational State Transfer
RoCoF	Rate of Change of Frequency
RT-HIL	Real-Time Hardware-In-the-Loop
SCADA	Supervisory Control And Data Acquisition
SGAM	Smart energy Grid Architecture Model
S-MP-AC-SCOPF	Stochastic Multi-Period AC Security Constrained Optimal Power Flow
S-MP-OPF	Stochastic Multi-Period Optimal Power Flow
SO	System Operator
SoC	State of Charge
SQL	Structured Query Language
SR	Spinning Reserves
TCP/IP	Transmission Control Protocol/Internet Protocol
TSO	Transmission System Operator
UI	User Interface
V2G	Vehicle to Grid

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VESS	Virtual Energy Storage System
VPP	Virtual Power Plant
VPN	Virtual Private Network
VRFB	Vanadium Redox Flow Battery

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EXECUTIVE SUMMARY

The i-STENTORE project encompasses a large number of stakeholders in the electricity sector. The goal of the project is to examine the integration of diverse storage solutions and their combinations. Innovative storage systems will be showcased and their co-operation with the integrated assets will be co-optimised, placing the reliability, the power quality, the cost-efficient operation and the maximisation of the assets' lifetime as end-goals. Also, it aims to implement a Reference implementation which combines modern smart energy architecture models in the energy domain along with the participation of a variety of emerging roles in a common European (EU) Data Space. It will do so while addressing concerns of trust, security, sovereignty, and interoperability in data exchange and application services. In addition, standardisation, security, legal, and privacy topics are highlighted.

In its novel exploration, i-STENTORE dives into the intricacies of developing business models for ESS outlining their multi-faceted nature, highlighting their critical role in integrating renewable energy sources and enhancing grid reliability. The document also explores and meticulously dissects various business models, ranging from single-use to multi-use applications, underscoring their significance in the broader context of Europe's transition to a climate-neutral economy. The research further delves into the functional specifications for standardized data access and integration which is pivotal in establishing a harmonized framework for data exchange, facilitating efficient and effective utilization of energy storage systems. It encompasses a thorough analysis of prior projects, offering a comprehensive understanding of the challenges and opportunities in data standardization within the energy sector.

i-STENTORE will introduce an umbrella framework aiming to showcase stand-alone and hybrid storage solutions highlighting the multi-purpose use of storage, not only as an energy buffer, but also as an active grid component capable of providing services and contributing to grid resilience, stability and efficient operation. In furtherance of the effectuation of this vision, this deliverable describes the process of deriving a requirements-based Reference Architecture. This is done while leveraging on the experiences of a multitude of preceding and co-evolving European projects and initiatives. First drafts for Reference Architecture (RA) components are included.

To showcase the reference architecture, we suggest splitting it into the orthogonal concerns of energy and smart energy domain architectures. As the basis for the Data Space Reference Architecture, we chose BRIDGE DERA 3.0 and Smart energy Grid Architecture Model (SGAM). In order to connect it to the energy use cases, we suggest a mapping of Harmonised Electricity Market Role Model entities to IDSA RAM Energy Domain Data roles as a starting point for the Energy Domain Reference Architecture. Finally, in view of the need to converge technical implementations to align with the Reference Architecture and each other, this Deliverable also includes a summary of the as-of-writing current technical components of WP3 with respective interfaces wherever possible.

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1 INTRODUCTION

1.1 PURPOSE OF THIS DOCUMENT

Deliverable D2.2 "i-STENTORE services co-creation, business models, functional specifications and Reference Architecture (1st version)" is the first result of the joint activities of WP2 and especially Tasks 2.3, 2.5 & 2.6. This deliverable includes the early specification of the distinct services that will be provided by the integrated storage systems deployed in the project and also the services provided by the VPP (Virtual Power Plant) and other project tools. Moreover, the initial business models governing the operation of the systems and facilitating their access to markets will be defined based on the Use Cases (UCs). Focus of this deliverable is also to present the i-STENTORE technical components (building blocks) and an initial component convergence which will be an integral part of the Reference Architecture design. In other words, the purpose of this document is to list the requirements for the Reference Architecture, and the methodology to obtain it. Furthermore, as mandated by the grant agreement, it shall consider RAs from relevant and related EU projects, and architectural models from coordinated projects and efforts. This document produces a basis to develop the final RA in Deliverable D2.4. To this end, this document will leverage insights from all WP2 tasks but also development of WP3 components.

1.2 RELATED ACTIVITIES

As mentioned, this document serves as the basis for the development of the RA in the period succeeding the publication. Therefore, this section does not only list links that are strictly related to the synthesis of this document itself but all foreseen sources to the final product of WP2, that is the RA. These links are depicted in Figure 1. The remainder of this subsection is a description of said depiction.

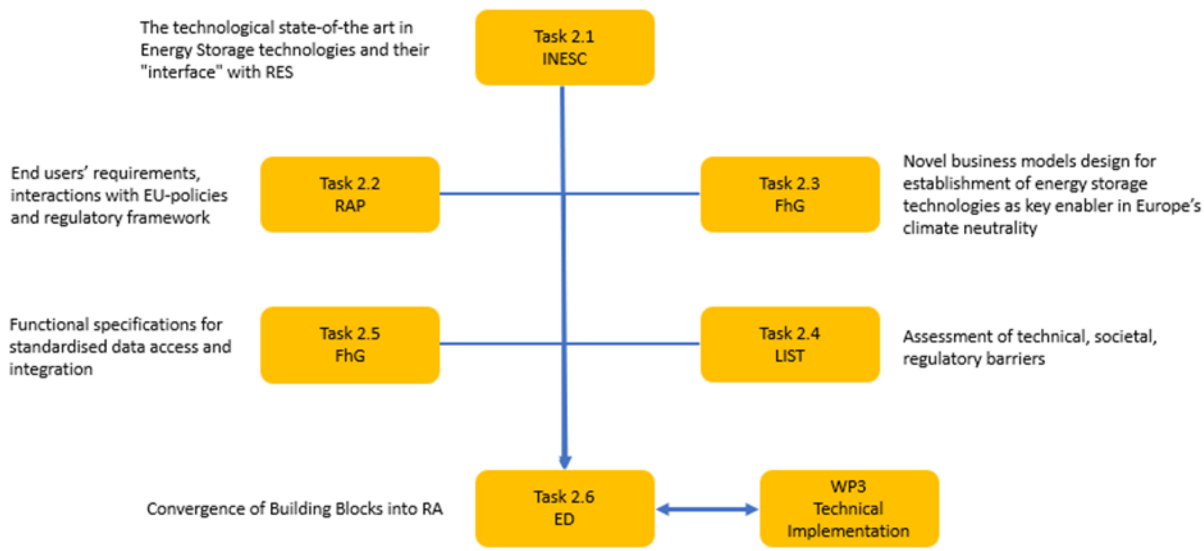

FIGURE 1: RELATED ACTIVITIES.

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All results of other WP2 tasks can be considered as inputs to T2.6:

- **T2.1** "The technological state-of-the-art in Energy Storage technologies and their 'interface' with RES" and the corresponding D2.1 "SOTA analysis, barriers, regulatory framework and use cases' descriptions"
- **T2.2** "End users' requirements, interactions with EU-policies and regulatory framework" and the corresponding D2.1 "SOTA analysis, barriers, regulatory framework and use cases' descriptions" with a focused consideration of use-cases.
- **T2.3** "Novel business models design for establishment of energy storage technologies as key enabler in Europe's climate neutrality".
- **T2.4** "Assessment of technical, societal, regulatory barriers".
- **T2.5** "Functional specifications for standardized data access and integration".
- **T2.6** "Reference Architecture tailored to an open and modular European energy system for optimised storage technologies use leading to increased flexibility" the actual RA implementation task.

It is important to note that the Reference Architecture and more importantly the technical convergence should reflect the i-STENTORE building blocks and their interfaces as a clear guide for the outcome of the whole project, by providing practical development guidelines and a solid system & software architecture, as early as possible.

1.3 DOCUMENT STRUCTURE

The remainder deliverable is structured as follows:

- **Chapter 2** discusses the role of ESS in balancing and integrating renewable energy into power grids. It emphasizes the importance of ESS in enhancing grid reliability and stability and explores various business models and functions associated with ESS, including single-use and multi-use applications, trading services, system services, and operational requirements for business models.
- **Chapter 3** includes a methodology for integrating these systems and examines the i-STENTORE pilots. The chapter focuses on creating a standardized approach for data access and integration in relation to ESS, thereby facilitating more efficient and effective use of these systems in various applications.
- **Chapter 4** describes the methodology to design (develop) the Reference Architecture. We explain the 4+1 views model and its merits. Furthermore, we describe ISO 42010 and how based on it we can extrapolate an accepted vocabulary in the system architecture context.
- **Chapter 5** summarizes the i-STENTORE Business Use Cases based on D2.1.
- **Chapter 6** covers the diverse set of architecture models that can serve as an inspiration for a consolidation in the i-STENTORE RA as required by the grant agreement.

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- **Chapter 7** describes European Data Space RAs that serve as the basis of the Data Space aspects of i-STENTORE implementation. These are among others GAIA-X, The IDS Reference Architecture Model, OPENDEI, and the FIWARE Smart Energy Model.
- **Chapter 8** showcases related projects such as INTERRFACE, PLATOON, BD4NRG, ATTEST and OneNet.
- **Chapter 9** aims at supporting the convergence of technical developments. It provides an overview of technical components which will be implemented by the technical work packages (WP3).
- **Chapter 10** presents the actual technical i-STENTORE building blocks convergence, albeit as a high-level concept for this deliverable version.
- **Chapter 11** presents an initial approach to the integration guidelines in an attempt to aid developers in providing software that can be integrated with as little friction as possible.
- **Chapter 12** examines the UCs from the viewpoints of data privacy, cybersecurity and ethical and legal concerns. Subsequently, adequate RA requirements are derived.
- Finally, **chapter 13** concludes the deliverable results and outlines the next steps.

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2 NOVEL BUSINESS MODEL DESIGN FOR ESS ESTABLISHMENT

In the era of renewable energy dominance, the importance of efficient and adaptable storage solutions has become increasingly evident. Recognizing this critical need, the i-STENTORE project has embarked on a ground-breaking mission to revolutionize the integration and hybridization of various storage technologies through the power of digital solutions. With a strong focus on reliability, power quality, cost-efficient operation, and asset longevity, i-STENTORE aims to optimize the cooperation between innovative storage systems and integrated assets. In i-STENTORE, a comprehensive framework will be introduced, showcasing both stand-alone and hybrid storage solutions that highlight the versatile applications of storage beyond its traditional role as an energy buffer. Instead, storage will be positioned as an active grid component capable of providing valuable services that contribute to grid resilience, stability, and efficient operation.

2.1 INTRODUCTION

Task 2.3 deals with the development and evaluation for ESS and business models that can be defined. The first research step will identify the existing revenue opportunities for ESS and economic barriers to a wide-scale storage penetration. As a second step, potential future use cases and related business models will be assessed with a focus on single-use. Multi-use storage deployment and associated business models will be developed as a third step. This results in reduced storage capacity investment needs and a lower footprint from storage production.

At a glance:

Chapter Summary

i-STENTORE targets the development of future multi-use applications and related business models for ESSs.

Key Exploitable Results

Business models for energy storage technologies towards international market penetration

Quantified Targets and Verification

- >6 single-use business models defined
- >10 multi-use business models defined
- > 4 multi-use business models evaluated and tested in detail

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2.2 ESS TECHNOLOGIES

Energy Storage Systems (ESS) encapsulate techniques for capturing, storing, and distributing energy from diverse solar, wind hydroelectric and other renewable and conventional power sources. Critical for integrating renewable energy into the power grid, ESS smoothens energy distribution, directly mitigating time variability. Additionally, it enhances grid reliability and stability, and offers backup during power outages.

ESS includes Chemical, Thermal, Pumped Hydro, Battery, and Compressed Air Energy Storage Systems (CAESS), each possessing unique benefits and shortcomings. For instance, Chemical and Pumped Hydro storage have high energy densities but need to be improved by material costs and location demands. Meanwhile, Thermal storage and CAESS are cost-effective but require significant storage capacities.

Choosing the optimal ESS depends on the use case and location. Battery storage is suited for small-scale applications like homes and small businesses, while utilities and industrial facilities might necessitate robust systems like Pumped Hydro storage or CAESS.

Present challenges include high costs relative to conventional power generation methods, and power grid integration. Yet, anticipated increases in renewable energy demand and technological advancements predict a cost reduction. Developing advanced energy storage materials and technologies is critical to enhancing performance and cost-effectiveness.

ESS is instrumental in renewable energy integration into power grids, thus crucial for a low-carbon economy transition. Ongoing research could make ESS more efficient and cost-effective, potentially pivotal for the energy transition and sustainability. Furthermore, ESS plays a significant role in the transportation sector, particularly with Electric Vehicles (EVs), and can facilitate micro-grids in remote areas, providing reliable and sustainable energy sources.

In conclusion, ESS is a linchpin for transitioning to sustainable energy, promising efficiency, cost-effectiveness, and significant contributions to a sustainable future.

2.2.1 Business Models

The definition of business models [1], [2] as used throughout this work for the usage application of battery storage technologies can be described as:

A business model is a conceptual structure to describe the operation and requirements for a functional application that delivers value. This model then serves as a blueprint that specifies the methods of a use case to employ the resources and gain financially viable solutions. It encapsulates a given set of parameters combined in function to determine gains throughout operation.

With this definition, the following will be a thorough analysis of business models for battery storage systems.

2.2.2 Classification of functions

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A potential classification can be identified as the following:

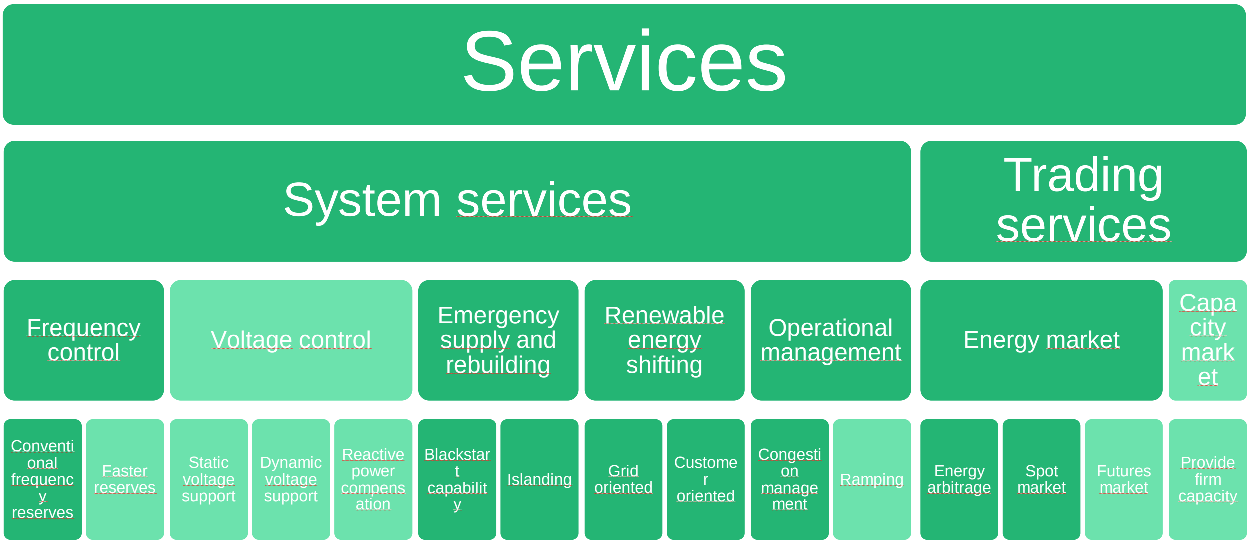

FIGURE 2: CLASSIFICATIONS OF SERVICES [1].

Further dimensions exist on which batteries can be classified, e.g., the point of operation of a battery storage, such as behind-the-meter (BTM) and front-the-meter (FTM) [3].

BTM refers to a consumer focus and is not foreseen to supply additional value on grid-oriented applications but rather on customer-oriented ones. Depending on the point in the electricity value chain and voltage level, taxes and charges are added [3].

FTM applications affect the electricity flows in front of the electricity meter (e.g., at the grid connection point). There is non-consumption characteristic in FTM, only withdrawal and temporary storage of energy. Due to the grid and system serving character of FTM applications, the electricity costs for exchanged energy are subject to favourable conditions [3].

2.2.2.1 Operational requirements for business models

The operational requirements can greatly vary between the different use-cases that can be applied for a storage system. Nevertheless, it is important to mention, that this also offers the opportunity to operate on several applications simultaneously to gain additional revenue streams. While each use case may have its distinct operational demands, a versatile storage system can be a significant asset, enabling market structures to diversify their offerings. By adapting and optimizing for multiple applications, they can not only enhance their operational efficiency but also broaden their market reach.

TABLE 1: OPERATIONAL REQUIREMENTS FOR BUSINESS MODELS [1].

Business model	Power capacity $[MW]$		Discharge duration $[h]$		Response time $[sec]$	
	Min	Max	Min	Max	Min	Max

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Frequency containment	1	100	0.25	1	0.001	15
Day ahead arbitrage	40	400	1	10	60	3600
Black start	5	50	1	5	1	60
Peak shaving	1	500	4	8	60	1800
Self-sufficiency	0.001	1	2	6	60	3600
Consumption arbitrage	0.05	10	5	11	60	3600

This table elucidates the diverse operational parameters for various business models, shedding light on their power capacity, discharge duration, and response time ranges.

Further division can be also made between the two operation modes, online and offline. In online mode, the battery storage system is continuously connected and actively participates in the grid or energy system. It remains online and ready to supply or absorb power as needed. Online operation is commonly used for applications such as frequency regulation, peak shaving, load shifting, and renewable energy integration. The battery system responds to signals or commands from the grid, adjusting its charging or discharging behaviour to support grid stability, balance energy supply and demand, or provide ancillary services. In offline mode, the battery storage system is disconnected from the grid or energy system and not actively participating in power supply or demand. It remains in a standby or idle state, not providing any energy-related services. Offline operation is typically employed for backup power applications, where the battery system remains dormant until there is a grid outage or an emergency situation. Once an outage occurs, the battery system is activated to provide power and support critical loads until grid power is restored.

2.2.2.2 Elucidation of business models

Frequency Containment:
Overview: This model is essential for maintaining the grid's balance by ensuring that frequency stays within desired limits. It operates in a narrow capacity and response time range.
Market Access: Providers will need rapid communication systems and contracts that ensure they are compensated for the quick and often short-term energy contributions. Integration with ancillary services markets is crucial.

Day Ahead Arbitrage:
Overview: This model involves purchasing energy when prices are low, storing it, and then selling it when prices increase. It requires a more extended discharge duration and a wider capacity range.
Market Access: To ensure profitability, real-time energy pricing data and trends are essential, alongside predictive algorithms to anticipate price fluctuations. Integration with energy trading platforms will enhance market accessibility.

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Black Start:
Overview: Vital for grid restoration after blackouts, this service ensures that power stations can be restarted without relying on the external grid.
Market Access: Collaboration with grid operators is paramount, with contracts in place that compensate for the standby and delivery of the required rapid energy injection.

Peak Shaving:
Overview: This model helps in reducing energy consumption during peak demand times, which can prevent blackouts and reduce energy costs.
Market Access: Providers can collaborate directly with large energy consumers, like manufacturing plants, or with utility companies to ensure energy provision during peak times.

Self-sufficiency:
Overview: Typically adopted by microgrids or isolated units to maintain their energy supply without relying on the primary grid.
Market Access: This model is best suited for regions with unreliable grid access or for entities aiming for green credentials. Partnerships with renewable energy providers can further enhance the appeal.

Consumption Arbitrage:
Overview: Similar to day-ahead arbitrage but more consumer-centric, it involves consumers adjusting their energy consumption based on price signals.
Market Access: Integration with smart grid technologies and home automation systems will allow consumers to automate energy consumption based on real-time price data.

2.2.2.3 Functional specifications analysis

Interconnectivity: Systems must be equipped with interfaces that allow seamless communication with the grid, other energy sources, and energy trading platforms.

Scalability: Given the vast range in power capacities mentioned (from 0.001 MW to 500 MW), it's essential for systems to be scalable to cater to different market needs.

Response Time: With ranges from milliseconds to hours, energy storage systems will be presenting varying levels of responsiveness. This suggests the existence of a combination of advanced sensors, real-time data analytics, and efficient energy delivery mechanisms.

Discharge Duration: Systems must be optimized for both short and extended discharges, necessitating flexible energy storage solutions and efficient management algorithms.

Operational Modes: Systems need to be able to switch between online and offline modes efficiently, ensuring energy availability when required and conserving energy when not.

Reliability and Safety: Given the critical nature of some services, such as black start and frequency containment, high reliability levels are crucial. Safety mechanisms, especially in high-capacity scenarios, are paramount.

Integration with Renewables: The resulting storage solution(s) to be able to integrate with various renewable energy sources, optimizing energy storage and delivery based on the variability of these sources.

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2.2.2.4 Value creation

The process of value creation can be also classified according to Table 2.

TABLE 2: OVERVIEW OF THE VALUE CREATION BY APPLICATION [4].

	Application	Creates value for	Standalone	BTM
System services	FCR aFRR mFRR RR Black start	TSO	Yes	Indirect*
Trading services	Energy arbitrage Spot market	Producer/supplier, large customers	Yes	Indirect*

As described the different applications will also lead to value creation for different applications users. Excluded in here is the operator of the BESS, which in turn will gain revenue streams from the different application. In the last column it is noted that a third party, e.g., an aggregator, will be needed to enable BTM BESSs to participate.

2.2.3 Functions of BSS (Single-use Application)

In the following description, the single use application for battery storage technologies is evaluated based on their operation for a single function.

2.3 SYSTEM SERVICES

Under the term system services fall all operation schemes with the major contribution to secure a safe and reliable operation of the system. Considering a stable system, there would likely be no such need, nevertheless due to variability of the changing feed-in or consumption situations such services are greatly needed. To attain a safe operation, the instantaneous feed-in and consumption of electricity must balance at all times. If such conditions cannot be satisfied, there is a mismatch in the grid frequency. In order to regain the base frequency, the activation of control reserves is requested by the Transmission System Operators (TSOs). Such services are described by the term of frequency control. Further stepping into the system operations, there exists a hierarchy of response mechanisms, from primary to tertiary reserves, designed to swiftly counteract any frequency deviations. Additionally, voltage control, another crucial system service, ensures optimal power flow by adjusting reactive power in the network, thus maintaining voltage levels within specified limits and ensuring grid stability.

2.3.1 Frequency control

It is an FTM Application that aims to balance the grid frequency around its normal value. It involves the use of products like frequency containment reserve (FCR), automatic Frequency restoration reserve (aFRR), and manual Frequency restoration reserve (mFRR) to stabilise the grid frequency [4]. Battery energy storage is well suited for the FCR application due to its

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quick response times. Participants in the FCR market must comply with regulations and requirements, including providing symmetrical power in both positive and negative directions. The operation of energy storage units in FCR requires maintaining an energy buffer and a capacity higher than the offered FCR capacity.

2.3.1.1 Primary control market

Description

Battery storage technologies are entering the market for controlling the frequency due to their fast operational principles. Control reserve is procured by Transmission System Operators (TSOs) to balance differences between the actual energy consumption and generation. Positive control reserves balances times where demand exceeds supply, meaning additional power must be fed into the grid. Vice versa, negative control reserves are required when energy supply exceeds demand and excess power can be drawn from the grid. Storage systems can be essential players on this market, as they can provide both positive and negative primary control energy, which is necessary for the prequalification.

Point of Operation

Frequency containment reserve and frequency regulation in general are FTM applications with the task to balance the grid around its nominal value [3].

Operational requirements

TABLE 3: REQUIREMENTS FOR CONTROL MARKETS.

	FCR	aFFR / mFFR
Tender period	daily (since 2020)	daily
Tender date	Day-ahead (since 2020)	Day-ahead
Deadline for submission of bids	8 a.m.	8 a.m. / 10 a.m.
Product time slices	Six (four consecutive hours)	Six (four consecutive hours)
Criterion for award of contract	Power price	Pay-as-bid
Call criterion	Solidarity principle	Energy price
Minimum size	1 MW	5 MW
Offer increment	1 MW	1 MW
Direction	Symmetrical (both directions must be offered)	Positive and negative can be offered separately

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Likeliness for stacking

The provision of frequency containment reserve enables the operator of a battery storage to furthermore apply on other markets, such as intraday trading. The FCR call made by the TSO is according to the solidarity principle, which in turn means there can be times, where there is unused storage capacity. Nevertheless, there must be great care taken, as an overbooking of the storage capacity could lead to a violation in the FCR application, which would not just result in penalties to pay but furthermore in the exclusion from further participation on the FCR market.

Lifetime and degradation

The operation toward the provision of FCR causes a fast change between charging and discharging processes and can therefore stress the battery and hereby lead to non-negligent degradation effects. Nevertheless, differences exist among storage technologies, as the application is more suitable for batteries that can withstand high C-rates [5] In the M5BAT research project [6] cyclic stable batteries like lithium-ion batteries have shown a lower degradation in comparison to the less cyclic stable lead-acid batteries.

Cost

The costs associated with the operation on the FCR market is tightly bound to the initial investment, which should span over the operation period. Despite the degradation costs that were described in the previous section, there are initial investment costs that increase incrementally, as the operation on the FCR market is also an incremental MW bidding.

Operation mode

Online, due to the unpredictable FCR provision over a time, it is necessary to track the system online. In case of large deviations arising from the desired range for the state-of-charge, it is necessary to buy or sell energy on the intraday market.

2.3.1.2 Secondary and tertiary control market

Description

However, when it comes to the secondary and tertiary control energy markets, which require longer energy provision and slower activation times, ESSs find less favourable conditions due to the higher minimum pre-qualified power of 5 MW. Despite these challenges, the unique capabilities of ESSs still make them a compelling choice for the primary control energy market.

Operational requirements

The requirements for the operation on the secondary market are described in Table 3. In general, it can be said that the operational requirements especially towards the activation time for batteries can be met in all periods [7]. The higher complexity is due to the larger power and energy capacity requirements that must be met to operate in these markets. Thereby, Battery Storage Systems (BSSs) must comply with these larger sizes, and it can be said that energy storage units must have higher capacity for the aFRR/mFRR than for FCR. Furthermore, the BSS must at least enable the activation for 60 minutes and in extreme cases the call can last for 4 hours. This results in the minimum size of 2 MWh per MW of marketed power. In practice, batteries tend to have to be designed even larger to provide aFRR independently.

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As for the mFRR, in case of frequency deviation that can be prolonged for more than 15 min, aFRR is replaced by mFRR to offer aFRR again. Full power must be available 15 min after activation and the coverage period is 4 quarter-hours or up to several hours in case of several incidents [8]. The operation for mFRR is also subject to longer lasting activation periods that make it harder for operation.

Point of Operation

As described for FCR also the application on the secondary and tertiary frequency regulation markets are subject to a FTM application.

Likeliness for stacking

Operating in the aFRR and mFRR market can be partly hard to predict, but also offers potential for the additional stacking of other applications. Since the TSO never requests negative and positive aFRR at the same time, storage facilities can even hold positive and negative SRL at the same time, which can be described as a multi-use operation already.

Lifetime and degradation

The aFRR market is influenced by the provision of energy for a longer lasting period, which results in larger Depth-of-Discharge (DoD) cycles that can potentially degrade the battery to a larger extent. Despite a great potential is seen in the application of aFRR, the degradation cost of the battery cannot be neglected and must be considered in the business model.

Cost

The requirements as indicated above also result in higher investment costs as a larger sizing of the battery is needed in order to participate. Furthermore, the degradation costs must also be considered, especially when providing large energy capacities.

Operation mode

Online, again, the operation depends on information like the SOC that is time-dependent.

2.3.2 Renewable energy shifting

As the generation by renewable energy sources (RESs) is strongly dependent on the intermittent feed-in by solar and wind power, a stable energy system must be able to mitigate these challenges by an efficient handling with storage options. For this purpose, peak shaving can enable to shift the energy consumption in times and to leverage the peak demand.

2.3.2.1 Peak shaving

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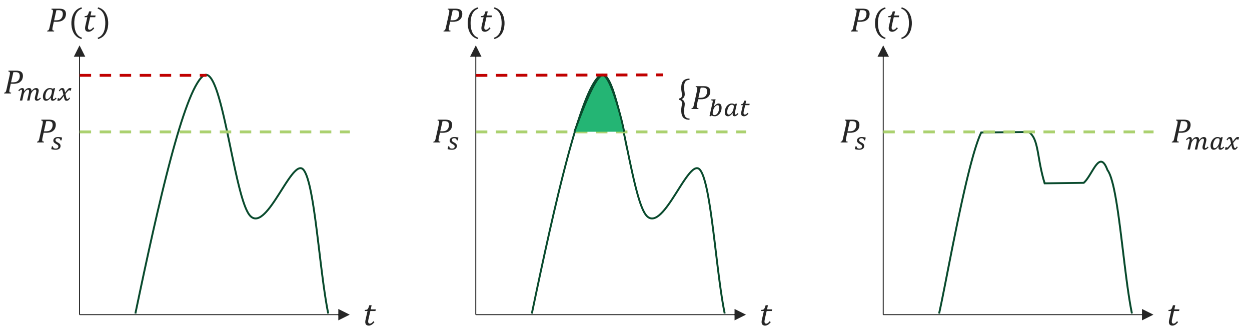

FIGURE 3: SCHEMATIC PEAK SHAVING OPERATION OF BATTERY STORAGE SYSTEM.

Description

In the electricity system a distinction can be made between large-scale and small-scale electricity customer. The operation of large-scale customer will however affect the network operation with greater influence, as the instantaneous shift of energy consumption by large-scale customers is a greater threat to the electricity system in comparison to small-scale customers, e.g., households. The grid planning phase is based on the peak consumption of industrial customers, thereby a reduction in their consumption could potentially reduce the electricity grid charges.

- Peak shaving
- 7,000 hours' rule
- Atypical grid usage

High peak electrical loads generated by industrial consumers result in significant grid tariff charges, thereby substantially inflating electricity costs. This phenomenon arises due to the tariff system considering not only the total electrical energy utilized but also the peak power drawn from the grid. Consequently, any reduction in peak loads directly translates to monetary savings.

For a plethora of industrial customers, apart from the energy procured, the highest annual load peak plays a significant role in the computation of electricity costs. Alternatively, should the demand markedly increase during particular months, the monthly load peaks are accounted for instead of the annual load peak. The calculation of the grid fee is predicated on the 'capacity price' which is levied on large industrial consumers whose demand crosses a designated threshold. A reduction in peak load, therefore, results in immediate financial benefits.

Evading unpredictable load peaks on the consumer end yields additional benefits for the overarching energy system, including a significant alleviation of strain on electricity grids. Given that the grid infrastructure is designed to accommodate the maximum load scenario, intelligent load management strategies can potentially obviate the need for grid expansion to a certain extent. Moreover, with reduced outputs, the associated losses also diminish. In the case of a more consistent electricity demand, the need for expensive and inefficient peak-load power plants is lessened, thus facilitating the realization of climate goals.

There are several methods for reducing peak loads, one of which includes the shutdown of production plants. However, given the sensitivity of production processes, this represents a

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significant disruption and should ideally be circumvented. As such, energy storage serves as a viable alternative. This approach involves the discharging of batteries during periods of impending peak loads, and their recharging during periods of lower loads. Additionally, infrastructure systems and energy storage mechanisms from the thermal sector (e.g., Combined Heat and Power (CHP), heat storage, and cold storage) are employed to enhance the potential for load reduction. It is, however, crucial to ensure that the primary function of these facilities (such as heat provision) is not adversely impacted in the process.

Point of Operation

The point of operation for the application of peak shaving is classical front-the-meter, as the intention is to reduce the grid impact in terms of high peak power demand. Hereby, the grid connection power capacity can be reduced significantly, as the grid is seized due to its major power provision.

Likeliness for stacking

Peak shaving can be easily accompanied with other applications, as the time-of-use is very limited to a small fraction of the timeframe (typically a day). In general, peak shaving is only linked to the usage of industrial processes that require large quantities of power for a limited time.

Cost

The cost of provision for peak shaving are linked to the required sizing to apply for the reduction of grid tariffs. The sizing can be determined from the electricity load profile and respective economic parameters [9].

2.3.3 Emergency supply and rebuilding

In case of a major failure of the power system, its restoration requires options that can operate autonomously and without further adding of energy. Storages can be such a technology that allows to start up on their own.

2.3.3.1 Black start capability

Due to the investigated large-scale deployment and integration of renewable energies, the power system is jeopardized due to the massive ramp-up of RES generation following typically the solar influx, but nonetheless also the usual intermittent nature which is hard to cope with. Following the issue of system stability, in the worst case there would be a blackout of the electricity system or at least a partial blackout of interconnected areas. In order to regain electricity, those areas would have to have resources that can be started without the supply of external power. In the recent time, mostly fossil generation was able, but as part of the phase out, such technologies will no longer be in the generation mix. To take over this crucial task, storage systems can play a vital role [10].

TABLE 4: COMPARISION BETWEEEN TRADITIONAL BLACK START (DIESEL AND GAS BASED) AND INNOVATIVE BLACK START (BASED ON BATTERY ENERGY STORAGE) [1].

Type of black-	Availability of black	Timescale to start up	Capability of instant	Supply resilience of	Voltage control	Frequency control

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start service	start service		aneous loading	black start service		
Traditional	$\geq 90\%$	$\leq 2h$	$\geq 35MW$	≥ 10	$\pm 10\%$	$47.5 - 52Hz$
Battery energy storage based	$\geq 80\%$	Sub-seconds	$\geq 100MW$	≤ 10	$\pm 10\%$	$47.5 - 52Hz$

Among several technologies, the following were identified for the provision of black start capability:

- Pumped hydro energy storage
- Electrochemical energy storage
- Thermal energy storage
- Mechanical and thermo-mechanical energy storage
- Hybrid energy storage

The study [10] presents a comprehensive review and comparative analysis of energy storage methods for black start services, particularly in systems integrated with renewable energy plants. It finds pumped hydro and lithium-ion batteries (LIB) to be the most promising technologies currently, due to their large capacity and short response time respectively. Other potential technologies such as flow batteries, Flywheel Energy Storage (FES), High-Temperature Thermal Energy Storage (HT-TES), Liquid Air Energy Storage (LAES), and Compressed Air Energy Storage (CAES) also exhibit certain advantages.

The comparative analysis highlights the effectiveness of a hybrid energy storage system, combining large-scale storage (HT-TES, LAES, CAES) with smaller-scale systems offering quick ramping speed (LIB, flow batteries, FES). Such a hybrid system can initiate black start processes rapidly, deliver high power over extended periods, and fully restore power, while also providing additional grid services like frequency regulation, peak shaving, and voltage control, thereby increasing profitability.

Operational requirements

In Table 5 is a comparison presented with key indicators for the black start provision.

TABLE 5: COMPARISON OF DIFFERENT ENERGY STORAGE TECHNOLOGIES [1].

Energy storage technology	Storage capacity $[MWh]$	Power capacity $[MW]$	Energy density $[\frac{Wh}{L}]$	Response time	Discharge time	Round trip efficiency [%]
LIB	100	500	200-600	Seconds	Minutes-hours	90
Flow battery	100	100	20-70	Seconds	Hours	70

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HT-TES	1000	100	270-340	Hours	Hours	60-70
LAES	1000	100	120-230	Minutes	Hours	60
FES	100	500	25-200	Seconds	Minutes	85
CAES	10000	500	2-6	Seconds-minutes	Hours-days	70-80
PHS	10000	1000	0.1-2	Minutes	Days	70-84

The comparison indicates that especially storages with a larger storage capacity but also high-power capacity leading to 1C rates, will be suitable for operation. This is also indicated by the currently procured black start power plants, e.g., in Germany where Hydropower is used for these processes followed by gas and coal power plants, which are fossil-based and will therefore be vanished in future years.

Point of Operation

The operation is a front-of-the-meter application due to the complexity of the processes. Using distributed small storages for the grid restoration was analysed in micro-grid environments, however it is due to the complexity of the process not been applied to large-scale grids.

Likeliness for stacking

The likeliness for stacking is due to the current non-transparent tendering process between a TSO and a suitable black start power plant hard to indicate. Despite the growing potential for the grid restoration reserves, unless there are reliant parameters for the revenues published hard to estimate. Thereby the likelihood for stacking cannot be fully quantified. However recent projects in combination with power plants are showing a successful demonstration [1].

Cost

The cost of operation would primarily hinge on the choice of energy storage technology, its maintenance requirements, and the prevailing market rates for electricity during grid restoration. It's also essential to factor in the long-term depreciation of these storage systems and the potential technological advancements that might lead to cost reductions in the near future.

2.3.3.2 Islanding operation

A term that is more used in a combination with micro grid operation is the islanding capability of a storage system. It describes the fully independent operation without further exchange to upper grid level. In comparison with the black start capability, it is not used for the purpose of grid restoration processes but rather for the supply of a local grid area. A proof-of-concept was introduced recently in Germany. In the project it was evaluated whether a medium voltage grid can be fully operated after a switch-off from the main grid [11]. Interestingly, this

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single-use application was already combined to a multi-use application, as within the normal operation, the battery storage system is prequalified for the primary control power market.

Operational requirements

The operational requirements are linked to the operation of the micro-grids and their requirements for an independent operation. In general, the parameters depend heavily on the local supply task. If a micro-grid contains large loads, the sizing of the battery will be large as well. The balancing of the battery should be at least sufficient to handle small to medium deviations for the nominal grid frequency.

Point of Operation

The point of operation would also depend on whether a swarm operation of small, decentralised batteries is intended or if a single point of operation is being used. In the first case a FTM operation is needed with different requirements to the regulatory, whereas in the second case a BTM operation would be considered, where new requirements arise.

Cost

The cost would be dependent on the size of the battery for balancing the mismatch between generation and load per time step. If a battery should be sized to handle the mismatch between renewable power generation from fluctuating sources like solar or wind power, then the sizing especially for night periods or with even further restrictions for seasonal periods are quite exhaustive.

2.3.3.3 Grid boosters

A recent concept foresees that grid boosters will be integrated at transmission level aiming towards a higher utilisation rate of the existing grid infrastructure. Due to the (n-1)-criterion, a system is bounded to be operated even in case of the failure of one core element of the transmission system. In such situations there should be no following equipment failure due to e.g., thermal increases. The grid booster pilots are battery storage systems that are integrated into the control systems of the transmission grid operators in order to implement a new curative grid management technology. The battery storage facilities are thus exclusively available for grid operation and not for electricity trading. In the event of a disturbance in the transmission grid, the battery storage units can react quickly and counteract the overloads caused by the disturbance.

Such a system was approved within the German network development plan in 2021 for the target year of 2035[1]. A potential storage solution included the deployment of a 250MW/250MWh battery storage in the southern part of Germany. Despite there was no economically viable solution found, the project was approved. In the network development plan, a project can be approved if its net benefit to the society can be amortized within the project's lifetime. Due to the fast implementation, it was seen as a benefit to the system.

Operational requirements

The operational requirements have several dimensions, e.g., if the output by the battery is requested within short times, the battery must withstand high C-Rates as well as high output

[1] https://www.eon.com/en/about-us/media/press-release/2023/amprion-and-eon-launch-the-world-s-first-decentralised-grid-booster.html

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power from the one hand side and from the other hand side, the congestion to be cleared could last for several hours during high feed-in periods. Thereby the operation features high performance Intervals, nevertheless it also has long idle periods for example, in where the battery is either almost empty or fully charged, depending on the site of the power line. This is also a challenging aspect that needs to be considered, when planning the battery operation.

Point of Operation

The point of operation is a classical BTM operation, where the service is positioned at the grid side.

Cost

The costs are associated mainly with investment costs that occur due to the large power provision that is necessary in times of grid congestion. The battery must withstand high C-Rates and the operation has long standing times, in where the battery has several idle times.

2.3.3.4 Sector integration

With the shift towards renewable energy also in the provision of heating or cooling by the means of e.g., heat pumps, the demand for electricity can easily excel the current peak power generation or even jeopardize grid stability. Thereby thermal storage systems play a vital role in optimizing the energy consumption of industries and residential applications. Storing surplus heat or cold in storage facilities and releasing it throughout the day can be employed in large-scale power plants but also in small-scale residential applications. Thermal energy storage systems can help to reduce curtailment and improve the self-consumption of electricity produced by renewable energy.

Operational requirements

For the operation, a storage medium is necessary, which is used to store thermal energy and to release it at a later stage. However, the classification of the thermal energy storage system describes the different ways of the operating principles. Thermal energy storages can be divided between sensible heat, latent heat and thermochemical energy storage [12]. As for the materials, it could be for example molten salts to be phase changed or even well-known technologies like concrete [13].

Point of operation

Thermal storage systems for district heating and cooling demand can be applied to both front-the-meter and behind-the-meter applications. FTM applications would be used for the self-consumption optimisation of renewable energy produced and stored for heating or cooling purposes. However, heat storages can also be used for energy arbitrage or network deferral as presented by the recent study of IRENA[2].

Point of operation

District heating and cooling demand can be applied to both front-the-meter and behind-the-meter applications

[2] https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Nov/IRENA_Innovation_Outlook_TES_2020.pdf

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Cost

Costs for heating and cooling applications are currently hard to estimate.

2.4 TRADING SERVICES

Trading services can gain much attention due to the volatility of prices on the electricity markets such as the day-ahead but also the intraday markets. Operators of storage technologies can make use of the high price spreads within a single day.

2.4.1 Energy Arbitrage

Considering the energy arbitrage operation, where a storage system owner would like to buy electricity at cheap prices to sell it again at a higher price, this business model needs to take into account several constraints for example of the trading period at the different markets. In general, markets with a higher volatility return higher revenues due to the larger price spreads that occur during individual days [14]. In here was also identified that the C-Rate which describes the power-to-energy ratio is at almost one third, which indicates that only a third of the energy capacity is needed for the power to be installed. This limits the storage technologies that fall into this term.

Energy arbitrage requires for an increased profitability that the efficiencies for charging and discharging, as well as most important for the standing losses are quite high, as otherwise energy losses would jeopardize the profitability. This limits the technologies that are used for energy arbitrage.

Operational requirements

The operational requirements are bound to the minimum bidding quantity which is 0.1 MWh. From 2018, new options are so called loop blocks which are two blocks that are executed or rejected if successful which allow to bundle buy and sell blocks. This is especially useful for storage activities, as they reflect both the storage phase and the generation phase and ensure that energy is only traded if available on the level of the battery [15].

Point of Operation

The point of operation would be dependent again on whether a single standalone storage is considered or an aggregate virtual battery. In the first case a BTM operation and in the second there is a FTM operation possible.

Cost

The costs are reliant on the period of storing energy, thereby the energy standing losses but also on the efficiency and degradation losses. However, the sizing of the battery can be chosen freely.

2.4.2 Spot market trading

It is an FTM application that takes advantage of the price differences in the wholesale electricity market for arbitrage opportunities. In Germany, there are three spot markets: intraday-continuous (IDC), intraday auction (IDA), and day ahead auction (DAA). The focus here is on IDC market due to its higher price fluctuations and battery storage systems' fast

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response times. The goal is to buy electricity at low prices and sell it when prices are higher. Compliance with market requirements and the consideration of historical price signals are important for successful spot market trading.

2.4.3 Peer-to-peer trading

This describes the electricity trading between different peers, which in turn describes electricity consumers. If these consumers have generation facilities, they are referred to as prosumers (producing consumers). In peer-to-peer trading, not only can excess electricity be traded between consumers and prosumers, but also the flexibility provided by the energy storage systems. In this context, the boundaries between consumer/prosumer are softened and extended to the community. This leads to models where Energy Management Systems no longer decide on the consumer level, but on the community level on the generation units, energy storage and consumers.

2.5 MULTI-USE OPERATION

When being operated towards a single-use application, most batteries fail to reach profitability in their operation [15].

TABLE 6: MULTI-USE OPERATION COMPATIBILITY (■ FULLY, ■ PARTIAL, ■ NONE).

	Primary control	Secondary control	Peak shaving	Black start capability	Islanding operation	Grid boosters	Energy arbitrage	Spot market trading	Peer-to-peer trading
Primary control		Partial	Fully	Fully	Fully	Partial	Partial	Partial	Partial
Secondary control			Fully	None	None	Partial	Partial	Partial	Partial
Peak shaving				Partial	Partial	None	Partial	Fully	Fully
Black start capability					Fully	Fully	Fully	Fully	Fully
Islanding operation						Fully	Fully	Fully	Fully
Grid boosters							None	None	None

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Energy arbitrage									
Spot market trading									
Peer-to-peer trading									

This resulted in the promising approach to combine multiple single-use storage systems for multi-use applications. The resulting operation modus results then in a higher utilisation rate, as well as temporal usage of the battery, which in turn results in additional revenue streams that can be activated. In the following table different single-use applications are being evaluated and compared towards the applicability. In Table 6 there are several applications presented and evaluated towards being fully applicable, only partial due to regulatory barriers or similar and finally towards not being able to be stacked at all. Chosen following multi-use applications will now be further discussed.

2.5.1 Primary Control + Secondary Control

The provision of both applications in the frequency control market seems up to now unlikely. The reason lies in the scaling for the different applications. In primary control, the application is power-based requiring small energy but high-power rates, especially with high charging and discharging rates. In comparison, for the secondary control there are higher values in terms of energy required. In general, such battery storage systems exist, and the trend anticipates an increase in both power and energy capacity. However, this comes at a cost, and up to now, no existing framework has been found, that classifies the combination of primary and secondary control as cost-beneficial.

2.5.2 Primary Control + Peak Shaving

The combination of primary control and peak shaving was examined in [16] stating that the approach increases the net profit of the batteries significantly. In the case study, a framework was created to evaluate the outcome of the installation of a 1 MW, 1 MWh battery storage system and led to the following results in 2020:

TABLE 7: EXPECTED MONTHLY COSTS AND REVENUES OF THE TWO SITES WITH AND WITHOUT BATTERIES [12].

Scenario	Peak Power [MW]	Peak Costs [k€]	Average FCR Capacity [MW]	FCR Revenues [k€]	Electricity Cost [€]	Total net profits [k€]
Without batteries	1.91	24.9				

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Only Peak Shaving	1.35	17.5			197	7.2
Only FCR	2.09	27.3	1.80	15.6	118	13.1
FCR & Peak Shaving Combined	1.96	25.5	1.76	15.2	177	14.4

Table 7 compares costs for four different situations: no batteries, batteries for peak shaving only, batteries for frequency control reserve (FCR) only, and batteries doing both. The table was created using monthly averages from different power use and frequency situations. The "Peak Power" column shows the expected highest power use in a month. "Average FCR Capacity" shows the average FCR over the month. "Total Net Profits" is the outcome by taking peak costs without batteries and subtract the combined peak and electric costs minus the FCR earnings from the other situations.

When only used for peak shaving, batteries can drop the power peak by 560 kW, cutting peak power costs by 7,200 euros. When just doing frequency control, batteries give a max FCR capacity of 1.80 MW on a monthly basis, earning 15,600 euros. However, this also ups the peak power to 2.09 MW, dropping net profits to 13,100 euros. Yet, when using batteries for both FCR and peak shaving with our method, they keep the peak power at 1.96 MW, while still giving 1.76 MW of average FCR capacity. This makes a net profit of 14,400 euros a month. In all these situations, the extra electric costs of the batteries are negligible.

2.5.3 Primary Control + Black Start capability

Little evidence has been found in literature for this application due to the unforeseen situation of black start situations. In such, it is required to provide the full power at instant time, thereby making it explicitly hard for batteries to operate on the FCR market, while still reserving sufficient power for the black start capability.

Nevertheless, an important idea is to be met, as the coupling can be down including a RES park, e.g. a wind park, which would need a small amount of power to be fed in to start re-operating, once this process is done, the black start can be done via the variable RES [17].

2.5.4 Primary Control + Energy Arbitrage

Nonetheless, the operation of batteries for primary control is constrained to the self-discharge rate and even if assuming a zero-mean FCR signal, the battery would decrease gradually in its SOC. Thereby the possibility must be ensured to recharge the battery during operation [18]. For this reason, energy arbitrage can be executed and further enhanced by using high price spreads over the day.

2.5.5 Black Start capability + Grid Booster

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By the regulation of the ENTSO-E, TSOs are required to procure sufficient black start capability by power plants in the area. Nonetheless, this also applies to the system service of a grid booster that mainly serves the purpose of re-dispatching. Despite the fact, that these services are also expected that the energy balance can only be predicted stochastically, there is great potential that the offering can be made for both applications on the same BESS. Since the grid booster would mainly be operated at a high level for the state of charge and also with a higher level of capacity, this would in turn enable the operation as a grid booster concept.

2.5.6 Grid Booster + Energy Arbitrage

The possibility of offering a grid booster and simultaneously trading on energy arbitrage is up to now not permitted as the operator of a grid booster is the transmission system operator. They are not allowed to operate on the market to gain revenues from energy arbitrage.

2.5.7 Peak Shaving + Spot Market Trading

Combining peak shaving and spot market trading could be highly beneficial. For instance, a battery operator can shave peak demand when electricity prices are high and trade the stored power on the spot market. This multi-use operation increases the revenue streams for the battery storage system, improving its overall economic viability.

Certain technical and regulatory considerations can affect the practicality of this approach. These include restrictions on dual-use operations, possible deterioration of the battery due to increased charging/discharging cycles, and the need for sophisticated control systems to manage these operations.

2.5.8 Peak Shaving + Peer-to-Peer trading

The operation of a BESS in the combined mode of providing both peak shaving and peer-to-peer trading seems to be a promising approach, since the battery utilisation rate in the peak shaving operation is comparably low [16]. Most of its operation is then linked to a temporal restricted period, when the local production of an industrial customer for example exceeds a certain threshold. Bearing in mind the constraints for peak shaving, its operation is power-based and therefore does not require large quantities of energy. Coupling a battery for a combined operation of local peer-to-peer trading would offer the opportunity of local trading with either long-term or short-term contracts. However, it is to be noted that these market contracts are in an early stage, since peer-to-peer trading is related to local energy markets, which in turn does not yet exist.

2.5.9 Primary Control + Peak Shaving + Self-Consumption enhancement

By combining primary frequency control with self-consumption enhancement new revenue streams can be gained from battery storage systems installed behind-the-meter [16], [19]. The operation modus foresees a high dynamic allocation of energy and power capacity for the combined applications.

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2.5.10 Primary Control + Peak Shaving + Energy Arbitrage

Under current market conditions, energy arbitrage trading contributes marginally to the profitability of multi-use operation as the price spreads on the energy markets are too small to justify stronger battery degradation [20]. This however is in conflict between the different BESS technologies.

TABLE 8: ANCILLARY SERVICES OVERVIEW.

		Demo 1		Demo 2		Demo 3		Demo 4		Demo 5	
		Capability to provide	Integrated in i-STENTORE	Capability to provide	Integrated in i-STENTORE	Capability to provide	Integrated in i-STENTORE	Capability to provide	Integrated in i-STENTORE	Capability to provide	Integrated in i-STENTORE
Transmission	Synchronous Inertia	🔴	✗	🟢	✓	🟢	✗	🔴	✗	🟢	✓
	Synthetic Inertia	🟡	✗	🟢	✗	🟢	✗	🔴	✗	🟢	✓
	Fast Frequency Response	🟡	✗	🟢	✓	🟢	✓	🔴	✗	🟢	✓
	Frequency Containment Reserve	🟡	✗	🟢	✓	🟢	✓	🔴	✗	🟢	✓
	Automatic Frequency Restoration Reserve	🟡	✗	🟢	✓	🟢	✓	🔴	✗	🟢	✓
	Manual Frequency Restoration Reserve	🟡	✗	🟢	✗	🟢	✓	🔴	✗	🟢	✓
	Replacement Reserve	🔴	✗	🟢	✗	🟢	✗	🔴	✗	🟢	✓
	Black Start	🔴	✗	🟢	✗	🟢	✗	🔴	✗	🟢	✓
	Voltage/Var Control	🟡	✗	🟢	✗	🟢	✗	🔴	✗	🟢	✓
Distribution	Voltage regulation	🟡	✗	🟢	✗	🟢	✓	🟡	✗	🟢	✓
	Voltage unbalance mitigation	🟢	✗	🔴	✗	🟢	✗	🟢	✗	🟢	✓
	Congestion management	🟢	✓	🟢	✗	🟢	✓	🟢	✓	🟢	✓
	Power smoothing	🟢	✓	🟢	✓	🟢	✓	🟡	✓	🟢	✓

3 FUNCTIONAL SPECS FOR STANDARDISED DATA ACCESS AND INTEGRATION

This chapter concerns Task 2.5 "Functional specifications for standardised data access and integration". It details the functional specifications for standardized data access based on the specific needs and data requirements of several i-STENTORE pilot projects, emphasizing the importance of diverse data and information models to meet the project's broad range of needs.

3.1 MULTI-USE OPERATION

This first section introduces the Task's Methodology, followed by a subsequent report on the completion of its first step, namely the examination of i-STENTORE pilots' data needs. It is concluded by an outlook on the upcoming next steps at time of deliverable submission.

3.1.1 Methodology

Task 2.5 aims to define a set of functional specifications for standardised data access and exchange. They will be handed over to Task 3.4 ("Implementation of data governance middleware and interfaces with existing infrastructure and Systems").

To this end, information from the planned demos is analysed. We examine the data needs, including the types of data used and stored, implemented protocols and privacy provisions etc., which will be used in each of the five i-STENTORE pilots. These parameters will inform the needed requirements for data access and exchange.

After this information is gathered and processed, we focus on the feasibility of data sharing in different scenarios. Independent of use case and source, we evaluate the need for and the feasibility of sharing raw data or processed metadata, forming a picture of the data sharing landscape across the project's demos.

Using these results, the next step tackles the standardisation aspect. We define the interoperability of our requirements with SGAM and IEC, particularly as IEC61850, IEC CIM (IEC61968, IEC61970, IEC62325), COSEM and ETSI TS 103673.

Lastly, we bring together the results to form a coherent set of specifications, which will be handed over to Task 3.4.

The ubiquity of these choices encourages i-STENTORE to proceed similarly. While none of these projects explicitly focus on energy storage, the needs and difficulties of large-scale data sharing remain transferrable, especially when concepts of IDSA and FIWARE are at the base of them all.

We follow this conclusion in the rest of this chapter by beginning with an analysis of the i-STENTORE pilots' data needs, in order to define further specifications for the project as a whole.

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3.1.2 Analysis of I-STENTORE Pilots

This section discusses step 1 of the Methodology described in 3.1.1 – analysis of the i-STENTORE pilots with regards to their data needs. First, a survey was sent out to all the pilots to gather the necessary information. Its results are covered in 3.1.2.1, going into detail about the goals of the survey and the received replies relevant to the development of data access and integration specifications. Subsequently, we consolidate these results to form an overview of the i-STENTORE data landscape in 3.1.2.2.

3.1.2.1 Data Survey

The survey sent out to Pilot Partners regarding their data use was developed in cooperation between Task 2.5 and 2.6. It aims to assess what kind of datasets, interfaces and other predetermined technologies the i-STENTORE System will need to accommodate when it comes to data sharing.

The complete list of questions and prompts each pilot was requested to answer:

- What kind of Data is to be accessed?
- What kind of Data is to be shared?
- What Data is held locally?
- Used Data Formats
- Employed Communication Protocols
- Implemented / planned Privacy provisions
- For all data to be accessed/shared/held locally please provide a sample (if possible) with respective descriptions (in a form of a data template)
- What are the current data sources/platforms?
    - Are data assets and processes used to process and store data identified and inventoried? Please provide this inventory.
- Do the shared data need to be anonymised?
- Please extend the data template with descriptions of potentially new data that may be required or provided in the future.
- Do you perceive potential data format changes?
- Is there a need for data classification?
- Do you need to keep control of the data being sent among the potential different endpoints? (Broker Services for metadata, Clearing House to log in transactions). This applies mainly to the shared data.
- Do you need to apply usage control policies and/or role-based access control policies to the datasets?
- Do you intend to combine data from different data sources? If yes which are the combinations?

- If possible, please draw sequence diagrams of the Use Cases that are involved in your pilot case. You should put the different actors and involved components on top and then draw lines connecting the actors and mention the data exchanges or the processes that are being performed at each step.
    - If not possible, please provide a schematic with the different elements in the demo and the data flows between them and the i-STENTORE platform, including data types and protocols.
- Do you ensure data availability at all times?
- What's the process for integrating new data sources or data types into your system?
- Are there any specific requirements or constraints for data storage and processing?
- What procedures are in place to rectify erroneous data or missing values? (data lineage tracking?)
- Do you have any strategies for data optimization or data compression?
- Is there a data retention policy / backup strategy in place, per case? Do you have a plan in place for managing data life cycle? Is there a contingency plan in case of data loss?
- Are there any data governance standards or best practices that you adhere to? What type of data validation processes do you use?
- Do you use any type of data analytics or business intelligence tools?
- A description of the limitations, if any, of the element or elements that will connect to the i-STENTORE platform, regarding the available communication protocols and the device flexibility
    - is it a closed proprietary solution?
    - is it a device with limited programmability (limited PLC)?
    - is it a fully programmable device (flexible PLC, computer)?"
- A description of the current HMIs, if any, including current functionality and the available alternatives to implement one or modify the existing (APIs available?, closed proprietary solution?, self-developed HMI?)

3.1.2.1.1 Demo 1

The first Demo site is located in Hrastnik, Slovenia at a HRAS facility, and focuses on molten glass thermal storage.

The existing hybrid regenerative glass furnace shall be coupled to a rooftop PV Power Plant (PVPP) and converted to a molten glass thermal storage. This requires upgrades to the furnace control system such as combustion control functionality, simulation of temperature profiles, IR camera scanning, refractory corrosion and batch (carpet) monitoring.

The upgraded furnace control system will be integrated with the upgraded COMS flexibility platform, which will also serve as a connection point to the i-STENTORE platform.

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The main data sources for this demo are the Furnace Monitoring System (FMS), which at time of submission is not yet implemented, but planned for end of 2023, its Energy Management System (EMS), the ERP system and the PVPP inverter management system. Data availability should be guaranteed at all times.

Within i-STENTORE, the overall available flexibility of the plant will be shared through the project's platform. The full list of required and shared data can be found as part of the overall data list in 3.1.2.2.

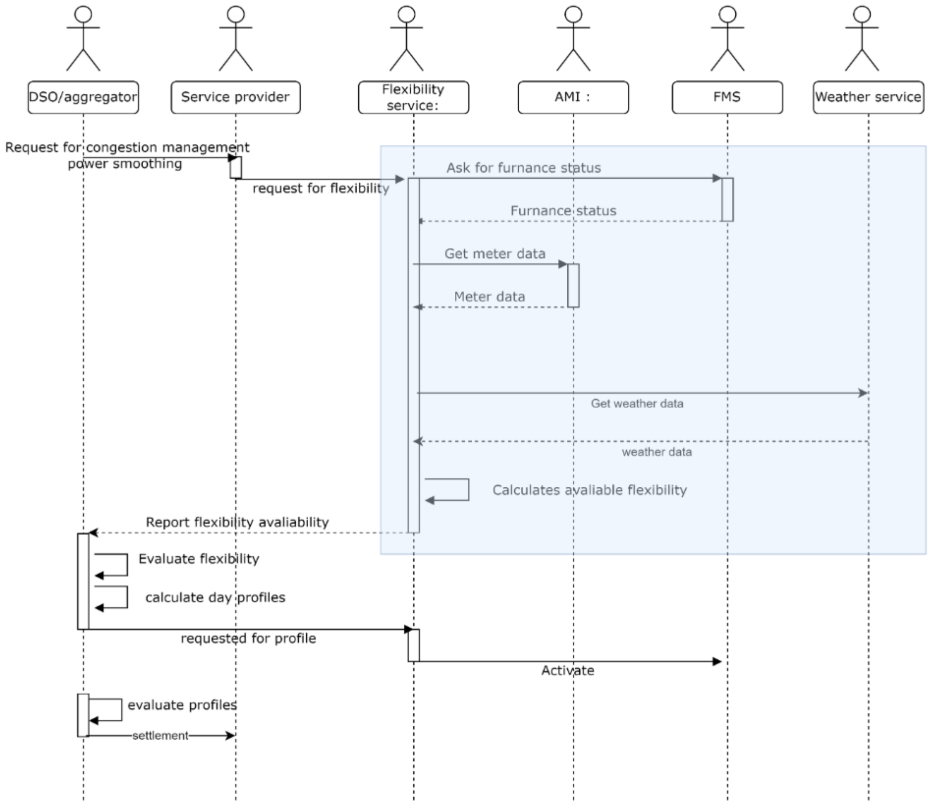

FIGURE 4: COMMUNICATIONS IN DEMO 1.

The only required classification of data is that into internal / confidential and publicly readable data. The publicly available data (available energy flexibility) does not require a special role to read and should be available through the furnace SCADA system (modifiable through WinCC – monitoring and control) at all times.

Other than the FMS validating data by checking against a valid value range, there are no specific governance practices in place.

3.1.2.1.2 Demo 2

Demo 2 is entitled "Pump hydro Storage system combined with BESS" and takes place in Madeira Island, Portugal. The specifics of this demo are described in the following paragraphs.

The Madeira Island power system has an installed capacity of 375 MW, and faces challenges that any small, isolated energy grid encounters. The energy mix is characterized by fossil fuel–

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based and renewable sources. Intermittent renewables have contributed approximately 33% of the generation in recent years. In order to achieve decarbonization it is imperative that renewable energy production increases.

A small and isolated grid has technical and economic constraints, which impede the direct expansion of renewable capacity. Such limitations are more heightened during off-peak periods, where demand variability poses a big challenge. It is within this panorama that the integration of a Lithium-ion Battery and Vanadium Redox Battery emerges as a strategic solution.

The objectives of this demo are described as follows:

- **Minimize Renewables Curtailment:** The incorporation of Li-ion and Vanadium flux BESS has a crucial role in attenuating the curtailment of renewable energy sources, thereby optimizing the generation potential of intermittent renewables.
- **Minimize Dispatched Thermal Groups:** The use of Li-ion BESS in conjunction with hydro units and Vanadium Redox Flow Battery (VRFB) allows increasing grid stability while reducing the dispatched thermal units.
- **Maximize Hybrid ESS Components:** Through the testing of new electrolyte compositions and the implementation of the optimisation algorithm, the Madeira demo will seek to increase the longevity of the HESS, thus reducing operational costs.
- **Maintain Frequency Nadir and RoCoF within the established Limits:** The integration of energy storage augments the power system's ability to respond to frequency deviations and reduce the Rate of Change of Frequency (RoCoF). By preserving these parameters within predetermined thresholds, system stability is safeguarded, ensuring system security.
- **Testing of new electrolytes for the VRFB:** New electrolytes will be tested on-site with the goal of improving the overall performance of the VRFB.
- **Contribute to the Island decarbonization:** The integration of the HESS and the implementation of the multi-temporal optimisation algorithm will contribute to increasing the share of renewables in the island's energy mix, thus contributing to reduce CO2 emissions.

The optimization algorithm's implementation is outlined in Fig. 5. The System Operator (SO) initiates the process by requesting new results from its local server, which, in turn, communicates with the Supervisory Control and Data Acquisition (SCADA) system to obtain updated data. Subsequently, the local server furnishes the INESC TEC virtual machine with the latest data and a request to execute the optimization algorithm.

The INESC TEC virtual machine accesses various types of data required for the optimization process, including:

- Load, reservoirs inflows, solar, and wind generation forecasts, in formats such as txt, csv, and JSON.
- Thermal and hydro units' dispatch data, available in txt, csv, and JSON formats.

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- Vanadium Redox Flow Battery (VRFB) bands for photovoltaic (PV) ramps and Lithium-ion (Li-ion) bands for spinning reserves (SR), transmitted via HTTP/REST API communication protocols.

Following the optimization process, INESC TEC shares essential data with the System Operator (SO), including:

- State of Charge (SoC) set-points for Li-ion and VRFB batteries.
- Synchronous condensers status and renewables operating point information.

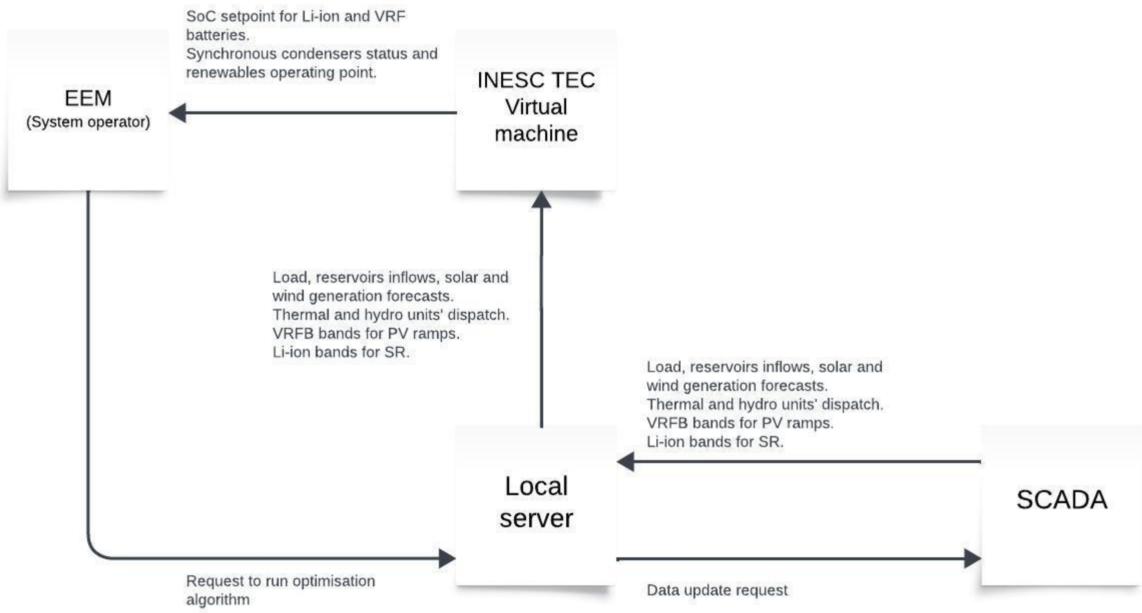

FIGURE 5: DEMO 2 OPTIMISATION ALGORITHM OVERVIEW.

3.1.2.1.3 Demo 3

Located in Spain, Demo 3 aims to bring together several energy storage technologies into a single large-scale VESS.

The separate storage technologies will be coordinated through a hierarchical operation and control system (HOCS) and an interoperable digital platform for energy and grid flexibility services management. After tests and evaluation regarding its quality and effectiveness as well as robustness in case of unexpected failures, the VESS-HOCS system will be integrated into the I-STENTORE digital platform, along with enabling the local DSO's interfaces to employ flexibility services for intelligent schedule generation for optimal asset exploitation.

Regarding data access, several types of forecasting data are needed. Generation forecasting from solar and wind resources as well as the hydro schedule on one side, as well as energy demand forecasting data on the other have to be accessed as well as current market prices and historical market outcomes. On a local level, we retain battery data (SoC, SoH, voltage, current monitoring, etc.) as well as data from PMUs and from the DSO's SCADA.

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Though data sources are generally not inventoried, the most relevant known sources are OMIE and REE data for historical market outcomes, along with the connected BESS, PV and Wind assets and the connected EMS. Data availability should be guaranteed at all times.

The details of data sharing within the Demo itself can be found in Fig. 6.

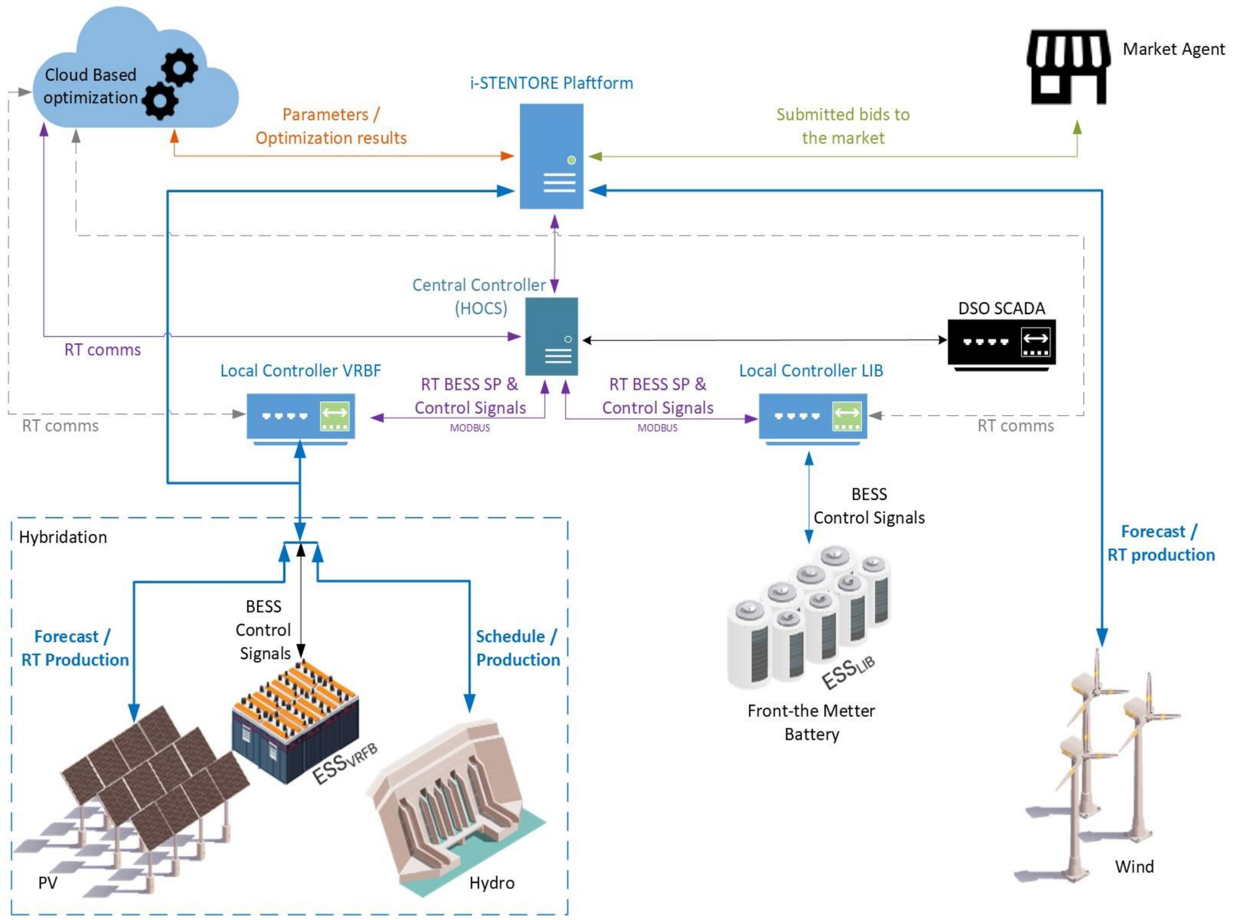

FIGURE 6: DATA SHARING IN DEMO 3.

The handled data is classified into confidential and publicly available data. Confidential data includes e.g., all plant operation and production data, models, layouts and other plant- and/or technology-specific know-how. Access to this information will be only given to specific persons for implementation purposes, and only after obtaining written permission.

3.1.2.1.4 Demo 4

Demo site 4 is located in Italy at Pompei and Cava, covering two multi-charger hubs for EV-Mobility and Energy Services.

The Demo will set up and evaluate both hubs, and integrate storage systems based on PV sources, hybrid supercapacitor/battery technology, battery swap technology and a modular AC/DC Smart Micro-Grid architecture.

The main types of data that need to be accessed therefore are the PVPP power generation, and operation data from EVs and their charging stations. This includes EV state of charge,

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maximum charging / discharging power and energy demand, as well as charging station available power. The needed data is accessed via Open Charge Point Protocol (OCPP), which comes from a GES platform; data availability is not guaranteed at all times.

The handled data is classified into confidential and publicly available data. Confidential data includes e.g., all plant operation and production data, models, layouts and other plant- and/or technology-specific know-how. Access to this information will be only given to specific persons for implementation purposes, and only after obtaining written permission.

At time of submission, some information regarding these questions could not be answered definitively due to changes of consortium partners at the time.

3.1.2.1.5 Demo 5

Demo 5 focuses on an Agri-PV (APV) farm located in Luxembourg, which contains a multi-energy station combining several different resources to be used and expanded during the project.

After modelling its energy processes, the farm's control functionalities will be designed and tested using a digital environment. This is followed by the installation of a utility-scale grid-forming 1MW/1MWh BESS, before i-STENTORE digital platform is deployed and used to managing energy and services in the APV plant.

In order to follow through with the Demo's goals, access to and processing of several types of data is necessary. The overall most important types of data are the PVPP and wind power energy generation, hydrogen electrolyzer process data, and battery metering. Accordingly, the main data sources within this use case are PMUs, Plant Controllers, Smart Meters, and the plant's EMS. In addition, day-ahead market data as well as weather data are required. Data availability should be guaranteed at all times.

Regarding governance, since the Demo 5 platform we will be hosted in AWS, there is a plan to use services like AWS glue and AWS lambda. Usage of IAM policies for fine-grained access control is being discussed.

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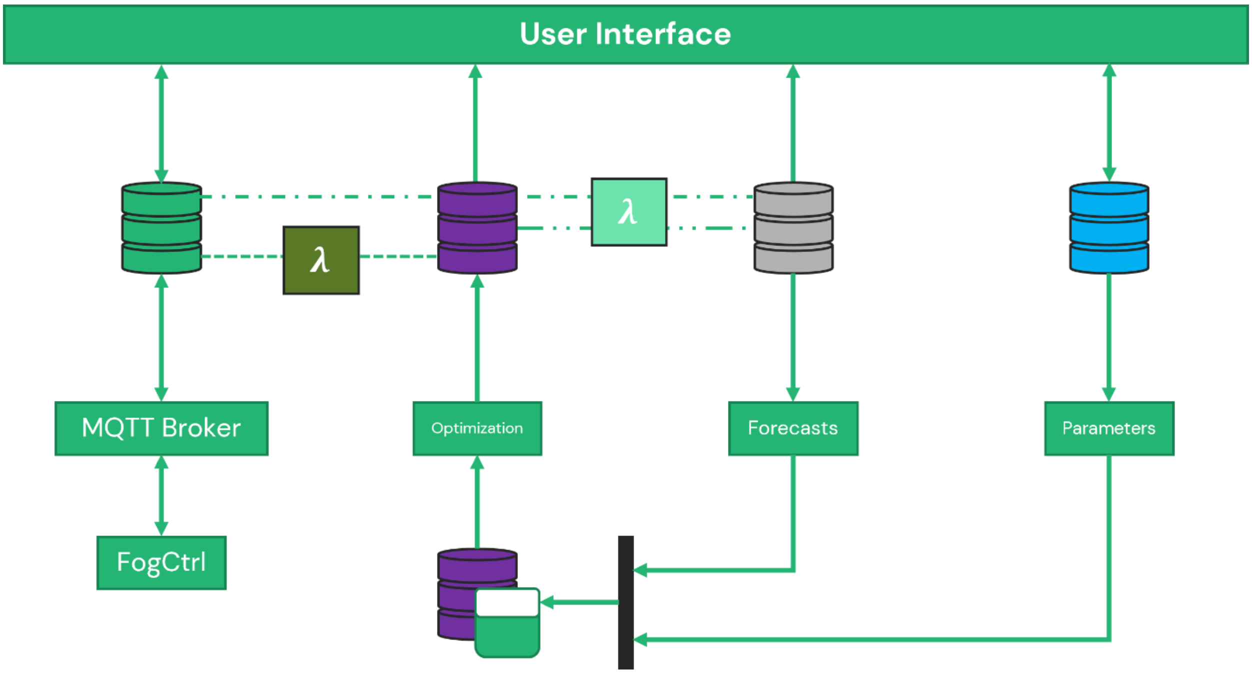

FIGURE 7: DATA SHARING IN DEMO 5.

All operation data, including asset characteristics and parameters are classified as confidential within this Demo. Access to this information will be only given to specific persons or implementation purposes, and only after obtaining written permission.

3.1.2.2 Overview of existing Data Sets and Technologies

i-STENTORE encompasses five Demos with differing goals and purposes. They are set up to cover the breadth of the project's overall goals and are spread out accordingly.

Across the topics of molten glass thermal storage, hydro pump storage, large-scale VESS, EV Multi-Charger Hubs and Agro-PV BESS, it is clear that the type and frequency of data shared will differ. Nevertheless, there are notable commonalities across the structure of the Demos that will be useful to consider for an overarching system.

In general terms, the different kinds of data collected and processed across all Demos can be put together in a simple list:

- Load / Energy Consumption
- PVPP energy generation
- Solar and wind generation forecasts
- Wind generation
- VRFB bands for PV ramps
- Reservoirs inflows
- Energy flexibility
- Furnace energy demand
- Furnace process data

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- Thermal and hydro units' dispatch / schedule
- Li-ion bands for SR
- SoC set-point for Li-ion and VRF batteries
- Synchronous condensers status and renewables operating point
- Historical and current market data
- EV energy demand
- EV State of Charge
- EV max. charging / discharging power
- Charging station available power
- Hydrogen electrolyzer process data
- Battery metering

Additionally, some relevant data sets will be considered as confidential information depending on each pilot. This specifically concerns asset operation data, asset consumption and production data, models and layouts, as well as technology-specific data and know-how.

These kinds of data sets will require special treatment, and specifically require written permission of the respective data owner before use. This also differs by use case – e.g., Demo 2 has not reported any necessity for data classification or usage control. While Demo 3 will definitely consider data regarding the forecast of PV and Wind power as well as the hydro schedule as confidential data.

In addition to the kinds of data to be used, there are also some technologies in place at the Demo sites that can and should be considered in the development of the I-STENTORE system. On the one hand, all five Demos use a very limited set of file formats to manage their data (.json, .csv, .txt), supplemented by SQL databases only in the case of Demo 3. On the other hand, there is a larger number of different communication protocols in use:

- HTTP/REST API
- OPC UA
- OCPP
- OCPI
- OCHP
- OICP
- eMIP
- OSCP
- ISO 15118 (V2G)
- MQTT
- MODBUS
- IEC 61850
- C37.118

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Of these, only the use of HTTP / REST APIs is shared across all five Demos, although MQTT and Modbus are also quite common. Even taking into account the fact that all Demos are still in very early stages at the time of submission, we can conclude that a significant diversity of needs is present across the project's demos. In addition to communicative interoperability, a combination of multiple information- and data models will be necessary to tackle the breadth of data required across the system.

3.1.3 Conclusion and Next Steps

This chapter has followed the methodology of Task 2.5 described in 3.1.1 across its first two stages. We collected and assessed information about the Demos of i-STENTORE itself in order to concretize the project's data needs. The extensive survey answered by the i-STENTORE Demos gave us insight into the kinds of data the project has to handle, as well as its classification and context. The emerging diversity of needs affirmed an aspect also resulting from the previous projects' analysis – that a combination of multiple data- and information models will be necessary to tackle the challenges given by a system of this size.

Following the aforementioned methodology, the next step for Task 2.5 will be an assessment of feasibility of data sharing within the system – investigating by use case and by source the need for sharing raw data and / or processed metadata.

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4 METHODOLOGICAL PROCESS

Our methodological process is based on ISO 42010[3] and the 4+1 Architectural View Model. ISO 42010 defines generally accepted vocabulary in the context of system architecture. This vocabulary serves as the basis of design. Therefore, in this section we summarize the relevant terms of ISO 42010, as well as their relationships. Furthermore, we suggest a concrete methodology to reflect and achieve the Reference Architecture requirements.

4.1 ISO 42010

ISO/IEC/IEEE 42010 is based upon a specific conceptual model – or "meta model" – of the terms and concepts pertaining to Architecture Description in the Software Development and Architecture Context. The conceptual model is presented below using UML class diagrams to represent classes of entities and their relationships. The UML class diagrams serve as a visual aid, simplifying complex relationships and hierarchies within the system architectures, making it accessible even for those who may not have an extensive background in architecture description. Consequently, this enhances the collaborative efforts across different domains and disciplines, fostering a more integrated and cohesive work environment. Fig. 8 captures terms and concepts of systems and their architectures, as a context for understanding Architecture Description.

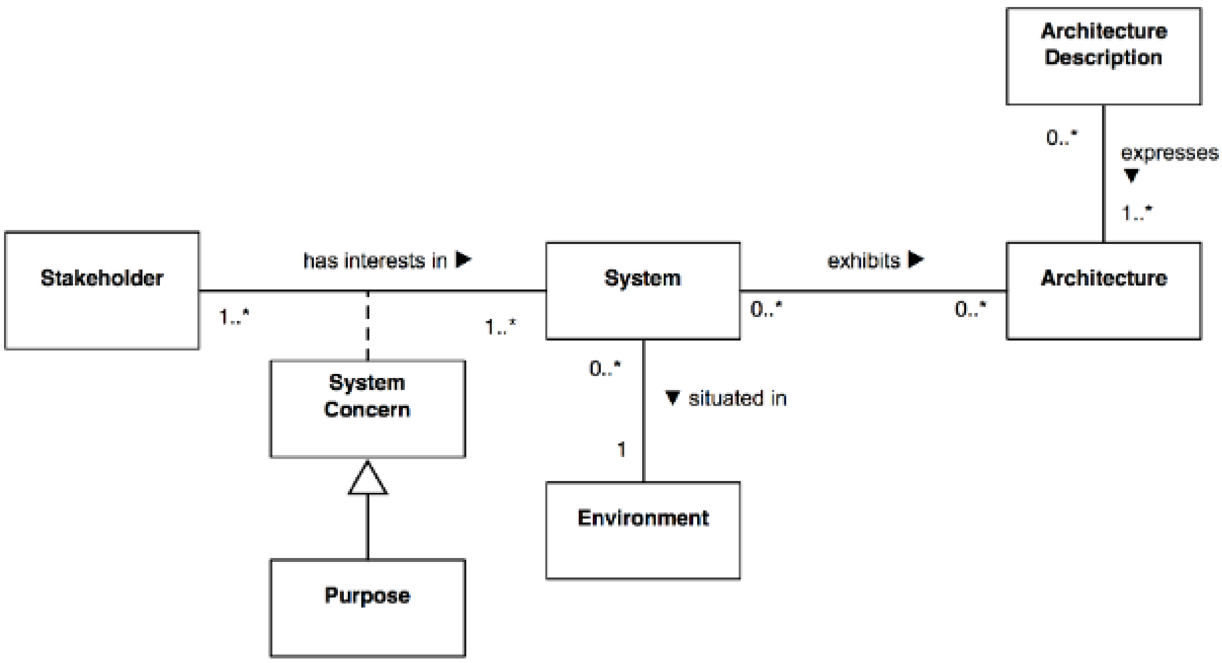

FIGURE 8: ISO 42010 CONCEPTUAL MODEL.

[3] https://www.iso.org/standard/74393.html

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Model elements referring to the diagram:

System: Systems exist. A System is situated in its Environment. That environment could include other Systems. In the Standard, the term system is used as a placeholder – e.g., it could refer to an enterprise, a system of systems, a product line, a service, a subsystem, or software. Systems can be man-made or natural. Nothing in the Standard depends upon a particular definition of system. Users of the Standard are free to employ whatever system theory they choose. The premise of the Standard is, for a system of interest to you, the Standard provides guidance for documenting an **Architecture** for that system.

Stakeholder: Stakeholders have interests in a System; those interests are called **Concerns**. A system's **Purpose** is one very common System Concern.

Environment: Every System inhabits its environment. A System acts upon that Environment and vice versa. A system's environment determines the range of influences upon the system. In the Standard, Environment is intended in the widest possible sense to include developmental, operational, technical, political, regulatory, and all other influences which can affect architecture. These influences are the categorized as the already mentioned Concerns.

Architecture Description: As expected, systems have architectures. An Architecture Description (AD) is an artifact that expresses an Architecture of a System. Architects and other system stakeholders use such descriptions to understand, analyse and compare architectures, often as "blueprints" for planning and construction. ADs are the primary subject of ISO/IEC/IEEE 42010 [27].

Architecture: In the Standard, the architecture of a system is defined as "fundamental concepts or properties of a system in its environment embodied in its elements, relationships, and in the principles of its design and evolution". The definition was chosen

- to accommodate the broad range of things listed above under System: the architecture of X is what is fundamental to X (whether X is an enterprise, system, system of systems, or some other entity); and
- to emphasize (via the phrase "concepts or properties") that a system can have an architecture even if that architecture is not written down.

4.2 4+1 ARCHITECTURAL VIEW MODEL

The 4+1 architectural model, as depicted in Fig. 9, is used to describe software-intensive systems such as the i-STENTORE Platform.

The model stakeholders are the i-STENTORE end-users, developers, system engineers, and project managers. The four viewpoints are the ***Logical*** view, the ***Process*** view, the ***Development*** view and the ***Physical*** view.

Logical view: The logical view is concerned with describing the functionality of the software to the end-user. Model kinds used to represent the logical view include class, state, and object diagrams.

Process view: The process view deals with the communication processes of the system. It addresses non-functional concerns such as concurrency, distribution, integration,

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performance, and scalability. Model kinds used to represent the process view include message sequence charts, communication diagrams, and activity diagrams.

Development view: The development view, also known as the implementation view, describes the system from the perspective of software module organisation. Model kinds used to represent the development view include the package diagram and the component diagram.

Physical view: The physical view, also known as the deployment view, takes the system engineer's point of view. It is about non-functional hardware requirements regarding topology and communication. A model kind to represent the physical view includes the deployment diagram.

Scenarios: The scenarios are a collection of use case descriptions. These use case descriptions illustrate interactions between objects and processes. This viewpoint helps in identifying architecture elements and validating the architecture design [28].

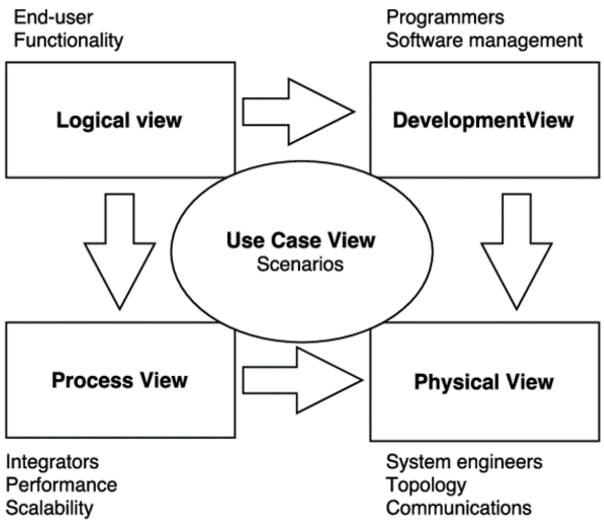

FIGURE 9: THE 4+1 ARCHITECTURAL MODEL.

As per the model description process in steps:

1. The first view to describe is the logical view.
2. For the process view to be derived, classes and their objects must be aligned into tasks and processes addressing concurrency and synchronisation.
3. To obtain the physical view, the processes and process groups are mapped onto processing nodes of a physical computer network. For each dependency between components, there must be a corresponding link between nodes.
4. The logical view also forms the basis for the development view. Each class from the logical view corresponds to a module. Large classes may be decomposed into packages. Collections of classes are grouped into subsystems.

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5. The scenarios are redundant if all other views are finished. It features high-level requirements of the system and aids the elicitation of more refined requirements of the other views. The other views essentially detail how these high-level requirements are realized.

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5 BUSINESS USE CASES

In the current phase of the project, we have progressed in developing and initially standardizing the business use cases, which are detailed below. We recognize the need for further clarification and refinement of these use cases, as the various demos of the project continue to mature and provide valuable data and experience. An elaborative version of these use cases has already been submitted in the content of deliverable D2.1, and we intend to continue our work in improving and revising the use cases based on ongoing developments and the insights gained. In particular, we aim to focus on refining the methodology to ensure that as the demos progress, the use cases are updated and refined to reflect the real-world application and the lessons learned. This iterative process will help in aligning the theoretical aspects of the project with the practical implementation, ensuring a robust and comprehensive understanding of the business use cases.

What follows is a concise encapsulation of the current prevailing status of the use cases:

Agri-PV Farm with Energy Storage (Luxembourg):

- ***Scope:*** Integration of agri-photovoltaic (APV) plant and wind power with a hybrid energy storage system (Li-battery and green hydrogen).
- ***Objective:*** Optimize energy use, provide grid support services, improve grid reliability, and demonstrate the benefits of energy storage in an APV plant.
- ***Actors:*** Luxembourg Institute of Science and Technology, Green Power Storage Solutions S.A., Studio elektronike Rjieka, and CEN Solutions.

Modular Multi Hybrid Energy Storage for E-Mobility (Italy):

- ***Scope:*** Creation of a Multi-Charger Hub for EV-Mobility Service integrating PV source and distributed Energy Storage Systems.
- ***Objective:*** Improve EV Ultra-Fast Charging performance, promote EV mobility, and improve PV grid penetration.
- ***Assumptions:*** Include regulatory and technical assumptions for grid integration and energy exchange.
- ***Actors:*** University of Naples, SAMSO, REEFILA, NIO

Molten Glass Thermal Storage (Slovenia):

- ***Scope:*** Aligning glass melting process with availability of renewable energy sources (RES) and providing ancillary services.
- ***Objective:*** Reduce carbon footprint, increase RES utilisation, and enhance resilience to energy supply disruptions.
- ***Actors:*** Steklarna Hrastnik, Comsensus.

Virtual Energy Storage System (Spain):

- ***Scope:*** Coordinate energy storage systems and a hydropower plant to behave as a single Virtual Energy Storage System.
- ***Objective:*** Optimize storage services, reduce costs, improve renewable energy integration, and demonstrate efficient actor interaction.

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- ***Actors***: Renewable plants owners, BESS owner, and DSO.

Hybrid Energy Storage Integration (Portugal):

- ***Scope:*** Use a hybrid Energy Storage System to increase robustness of Madeira Island power system and facilitate renewable generation integration.
- ***Objective:*** Optimize economic dispatch, minimize renewables curtailment, and maintain frequency and RoCoF within limits.
- ***Actors:*** EEM, Renewable energy companies, and Madeira regional government.

This is a comprehensive overview of various energy storage and management use cases, emphasizing the integration of renewable energy sources, optimisation of energy use, and improvement of grid reliability. The use cases involve a variety of actors, including research institutes, energy storage solution providers, and network operators, demonstrating the collaborative effort required to implement these solutions. This, in turn, highlights the importance of regulatory support, technical compatibility, and the need for innovative energy management platforms to ensure the success of the respective initiatives.

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6 ARCHITECTURAL MODELS

The i-STENTORE Architecture Model will be a three-dimensional architectural framework that can be used to model interactions (mostly exchange of information) between different entities located within the smart energy and especially storage arena. In more detail the design process will focus on the

i) Business aspect (domains),
ii) Architecture aspect (zones) and
iii) Interoperability aspect (levels) as defined in SGAM.

To maintain interoperability between any two components in i-STENTORE, interoperability needs to be considered on five different Interoperability Layers. The first two layers are related to ***functionality***, whereas the lower three layers can be associated with the intended ***technical implementation***. The interoperability layers being used are basically derived by the GridWise Architecture Council (GWAC) interoperability stack [29] [30] [31].

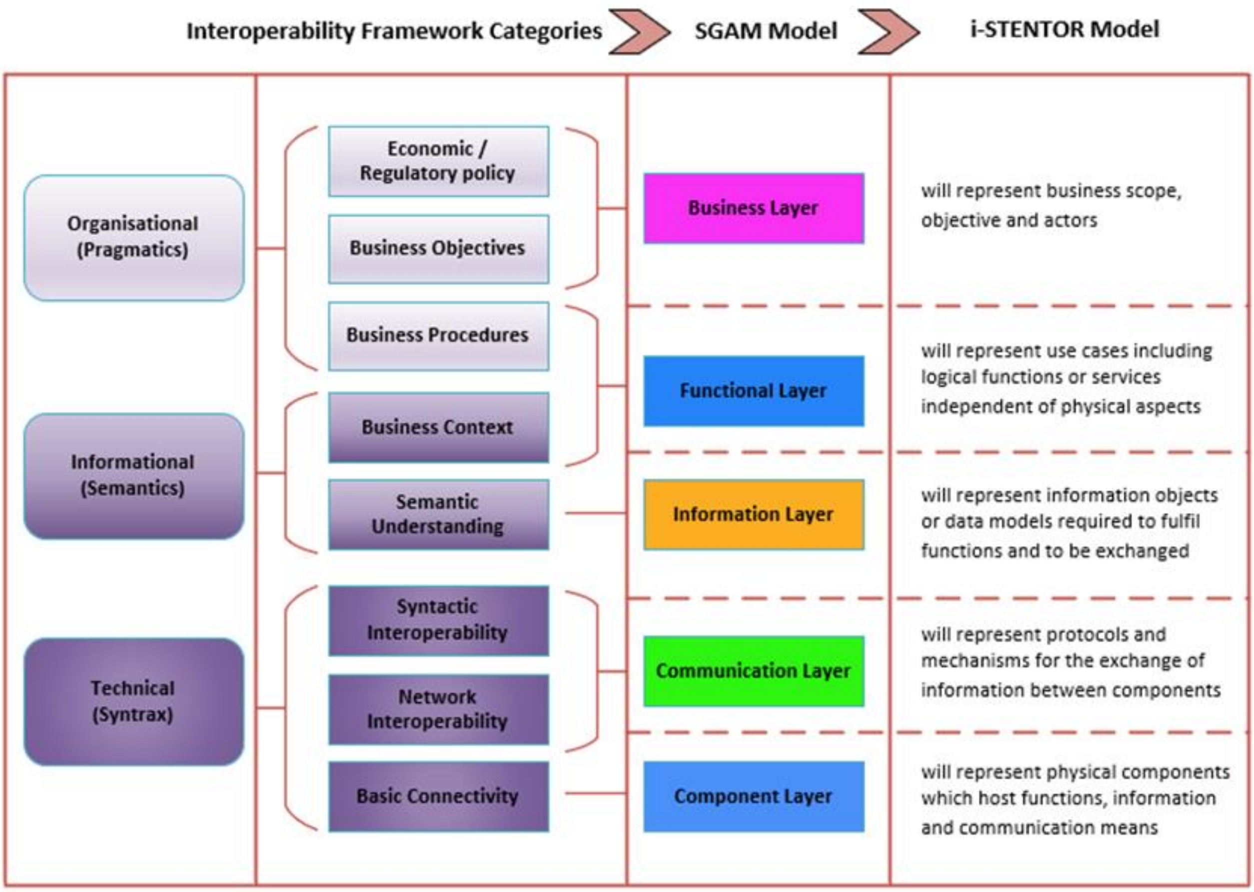

FIGURE 10: REFERENCE ARCHITECTURE DESIGN PROCESS.

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6.1 SGAM

The SGAM (Smart Grid Architecture Model) emerged from the necessity to represent the stakeholders, applications, and systems in future Smart Grids, where cooperation is vital. It was created as a shared model so developers and standardisation bodies have a common understanding of the SGAM. SGAM was created in the European mandate M/490, its formalisation happened first through the CEN-CENELEC-ETSI Smart Grid coordination group (now called SEG-CG as Smart Energy Grid coordination group).[4]

The SGAM is structured into five interoperability layers, each representing specific aspects of the smart grid's design and operation. These layers are designed to address business objectives, processes, functions, information exchange and models, communication protocols, and components. It's important to note that there are interactions and dependencies not only within the same layer but also between different layers. For example, business processes from the business layer are implemented through functions in the function layer, which, in turn, rely on components from the component layer. The proper execution of these functions requires support from data models in the information layer and communication protocols in the communication layer.

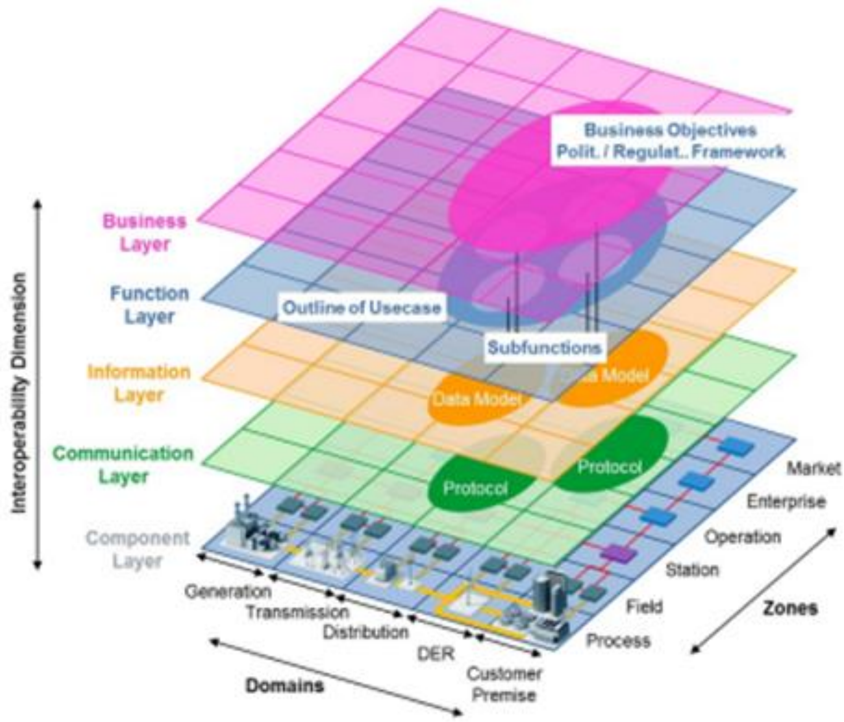

FIGURE 11: THE ORIGINAL SMART GRID ARCHITECTURE MODEL (SGAM).[5]

[4] https://syc-se.iec.ch/deliveries/sgam-basics/
[5] DOI:10.1109/ISGT.2017.8085977

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SGAM creates a standard for technologies used in smart grids, it achieves this by presenting use cases in a technology-neutral manner, allowing for a clear comparison of different approaches and roadmaps from multiple perspectives. Fig. 11 illustrates the original SGAM, where domains include the entire energy conversion process, from generation sites to end-users' premises. Zones delineate the management of the power system, facilitated by information and communication technologies, spanning from process management to market interactions.

Moreover, the interoperability layers in SGAM offer diverse levels of abstraction, ranging from physical hardware to business considerations. This stratification emphasises the interconnections and dependencies that support Smart Grid entities, forming a foundation for their coherent development and operation.

6.1.1 Variants of SGAM

The Information System Architecture for e-Mobility (EM-ISA) represents an early variant of SGAM, with a specific focus on integrating electric vehicles (EVs) into the grid. In this model, domains and zones are created, and an essential addition is made by incorporating human-machine interfaces to capture interactions between human operators and objects. While this extension acknowledges the human element, it abstains from specifying detailed human attributes.

The Electric Mobility Architecture Model (EMAM) maintains most of the original SGAM structure but introduces a distinct electric mobility domain, thereby removing the generation domain. This modification addresses the requirements related to EV integration. Recognizing SGAM's significance for standardisation, two additional reference models were developed using similar architectural principles. However, it's worth noting that these models may differ in their introduced domains and zones, potentially affecting compatibility between them.

Given the potential variations in Smart Grid implementations across countries, efforts have been made to enhance compatibility between different models. For instance, a combination of two state-of-the-art models, the EU's SGAM and the U.S.'s NISTIR 7628, facilitates security analysis right from the inception of the development process.

The Home and Building Architecture Model (HBAM) adopts SGAM's layered approach, introducing various zones and domains adapted to smart homes and buildings' specific concepts. On the other hand, the Reference Architecture Model for Industry 4.0 (RAMI 4.0) is considered the most advanced SGAM derivative. It contains zones and domains relevant to industrial applications and extends interoperability perspectives with an additional layer.[6]

In addition to the previously mentioned variants, two more reference models have been developed using SGAM's foundational design principles. The Reference Architecture Model for Automotives (RAMA) meticulously represents the life cycle of connected vehicles and the associated information technologies. Meanwhile, the Maritime Architecture Framework

[6] DOI: 10.3390/en12081417

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(MAF) is designed to model information exchange among various actors within the maritime domain.

6.2 THE BRIDGE INITIATIVE

The BRIDGE initiative, launched by the European Commission in 2016, is a collaborative community of projects funded under the Horizon 2020 and Horizon Europe programs. This initiative focuses on four key areas: data management, business models, regulation and consumer engagement, which define also the 4 main Working Groups of BRIDGE. The initiative aims to facilitate the exchange of knowledge and best practices among its members. BRIDGE encompasses 155 projects, with 97 ongoing and 58 ended as of July 2023. These projects, focused on the aforementioned four areas, involve 1510 organisations from 39 countries, receiving a total funding of approximately 1.3 billion €.

The initiative involves a wide range of stakeholders, including:

- **Consumers:** residential, professional, public institutions, industries, cities.
- **Regulated operators:** TSOs, DSOs.
- **Local energy communities:** associations, cooperatives, partnerships, non-profit organisations, or other legal entities managed by local shareholders or members that are involved in distributed generation and in performing activities of a distribution system operator, supplier or aggregator at local/regional level.
- **Power technology providers:** hardware manufacturers for power transmissions, distribution, and generation.
- **ICT providers:** software and telecommunication vendors.
- **Research and innovation stakeholders:** research centres, universities, etc.
- **Energy suppliers:** power generators, retailers, ESCOs.
- **Aggregators:** market participants with multiple customer loads or generated electricity for sale.
- **Market operators:** power exchanges, brokers, traders.

Research and innovation actors form the largest group of stakeholders, representing 34.5% of the total. Technology providers, including ICT providers and power technology providers, make up 21.5%, while regulated operators account and electricity market players represent 14.5% and 8.1% of the stakeholders, respectively.

The BRIDGE initiative involves stakeholders from 39 countries, both within and outside the European Union. The UK, Norway, Switzerland, Turkey, India, and other nations participate in various projects, showcasing also international collaboration with the EU. Most BRIDGE projects focus on demonstrations or pilot units of innovative technologies and solutions. These projects span 39 countries, with Spain hosting the highest number of demo sites (60) followed by Italy, Greece, Germany, France, Portugal, Slovenia, and Sweden. Several demos and pilots are also located outside the EU, including in the UK, Switzerland, Norway, Turkey and India.

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BRIDGE projects encompass a broad array of technologies and services. They are categorized into five main groups:

- **Technologies for consumers:** demand-response, smart appliances & metering, heating/cooling peak load management.
- **Grid technologies:** HVDC, HVAC, multi-terminal, protections, HVDC breaker, grid inertia, network management, monitoring and control tools, micro-grid, semiconductor devices and power converters.
- **Small-scale storage technologies:** batteries, electric vehicles, thermal energy storage and flywheels in general connected at distribution level.
- **Large-scale storage technologies:** power-to-gas, compressed air, hydro, and molten salt storage – in general connected at transmission level.
- **Generation technologies:** wind turbines, photovoltaic, solar thermal, biogas, tidal energy, micro-generation, floating offshore wind & PV, Ocean thermal energy conversion.

Technologies for consumers and small-scale storage technologies collectively constitute 50% of the projects. Generation technologies make up 23%, while grid technologies represent 22%. Large-scale storage technology accounts for 4%, and an emerging sustainable energy category covers about 1% of projects. Digitalisation also plays a vital role in BRIDGE projects, addressing technologies for consumers and grid management. Additionally, 66% of projects focus on providing electricity market services, and 62% emphasize ancillary services, reflecting the initiative's commitment to market-oriented innovation.

Among the specific technologies, demand response and smart metering are prominent in technologies for consumers. Network management, monitoring, and control tools are a significant part of grid technologies, with micro-grids gaining increased attention. Small-scale storage technologies prioritize batteries and electric vehicles, while generation technologies focus on photovoltaic systems and wind turbines. Emerging technologies like floating offshore photovoltaic, floating offshore wind, and ocean thermal energy conversion are also explored but at a lower extent.

6.2.1 BRIDGE Data Exchange Reference Architecture (DERA) v3.0[7]

The BRIDGE initiative and more specifically the Data Management Working Group has been working in the latest years towards the design of a Reference Architecture that will be contributing in fostering discussions and implementing practical measures aimed at achieving seamless and business process-agnostic data exchange arrangements at a European level. This effort spans not only within the energy sector but also extends across diverse domains.

Recommendations for the implementation of DERA encompass a comprehensive strategy aimed at fostering interoperability and seamless data exchange on a European scale. To begin, there is a focus on leveraging the Smart Grid Architecture Model (SGAM), enhancing it

[7] European (energy) data exchange reference architecture 3.0.

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by incorporating data governance requirements, particularly from the end-customer perspective. This involves mapping SGAM to reference architectures from various sectors, mirroring successful models such as RAMI4.0 for industry and CREATE-IoT 3D RAM for health. The objective is to establish a basic interoperability vocabulary with non-energy sectors.

A critical aspect involves facilitating a European strategy and harmonizing national regulations. This effort extends to the development of practical tools for cross-sector exchange, encompassing both private and public data. The emphasis is on creating reference models for data space, common data governance, and implementing acts for data interoperability. Collaboration is key in ensuring the success of these initiatives. The recommendation is to foster cooperation among associations, countries, and sector representatives. This involves the establishment of a European data cooperation agency and the restructuring of the Data Management Working Group of the BRIDGE Initiative. The aim is to engage other sectors, extend cooperation beyond EU-funded projects, and collaborate with European Standardisation Organizations. Harmonization remains a central theme, extending to the development, content, and accessibility of data exchange business use cases for cross-sector domains. Aligning role selection is another crucial step, harmonizing data roles across electricity and other energy domains through the development of the Harmonized Energy Role Model (HERM). Functional data processes are defined and harmonized for cross-sector domains, utilizing a common vocabulary, templates, and a repository for respective use case descriptions. Simultaneously, efforts are made to establish a common reference semantic data model, drawing on existing models such as the Common Information Model (CIM) and ontologies like Smart Appliances Reference Ontology (SAREF).

Cross-sector data models and profiles are developed with a specific focus on private data exchange, ensuring open access to model files. The approach remains protocol-agnostic, emphasizing the selection of standardized and open protocols for cross-sector data exchange. Promotion of business process-agnostic Data Exchange Platforms (DEPs) takes precedence, emphasizing interoperability through the development of Application Programming Interfaces (APIs). DEPs are encouraged to explore integration with data space connectors, fostering connectivity with other DEPs, including those in cross-sector domains.

Finally, the narrative suggests the development of universal data applications and open data-driven services. These applications are designed to promote cross-sector integration and are collectively made available in application repositories, fostering a collaborative and inclusive approach to data exchange.

DERA 3.0, as also seen in DERA 1.0, is highlighting the differentiation between Local platforms and Federated Data Space stacks. These two components are interconnected through a software component called the Data Space Connector, which facilitates seamless interconnection and data exchange. A Data Space Connector plays a pivotal role in enabling various IT systems and data-utilizing applications to connect and share data. This functionality proves valuable for integrating data from diverse sources and allows multiple applications to access the same data without the need for duplication. Typically utilizing standardized protocols, Data Space Connectors ensure the smooth transfer of data between different systems, thereby contributing to data consistency and accuracy across all

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connected systems. Beyond reliable and interoperable data exchanges, they enable seamless service utilization.

On the Local side of the architecture, reference is made to existing data platforms, which may belong to individual entities (e.g., a Retailer's data platform), groups of actors (e.g., an Energy Community's data platform), or the broader energy market/system (e.g., the Data Hub for metering data, the Flexibility Register, SCADA, ECCo SP platform from ENTSO-E, and Transparency Platform from ENTSO-E). These platforms already capture and store their own data, typically feeding it into local services for specific applications. The integration of a Data Space Connector into these pre-existing platforms becomes essential for enabling identification, data harmonization, and brokerage towards Data Spaces. The Federated Data Space aspect of the architecture pertains to the indexing of data, making it discoverable and creating a marketplace for trading both data and data services. To achieve this, the Data Space relies on multiple actors and data platforms (as described earlier), federating through Data Space Connectors and offering their data in accordance with predetermined policies.

Figure 12 below shows the DERA v3.0:

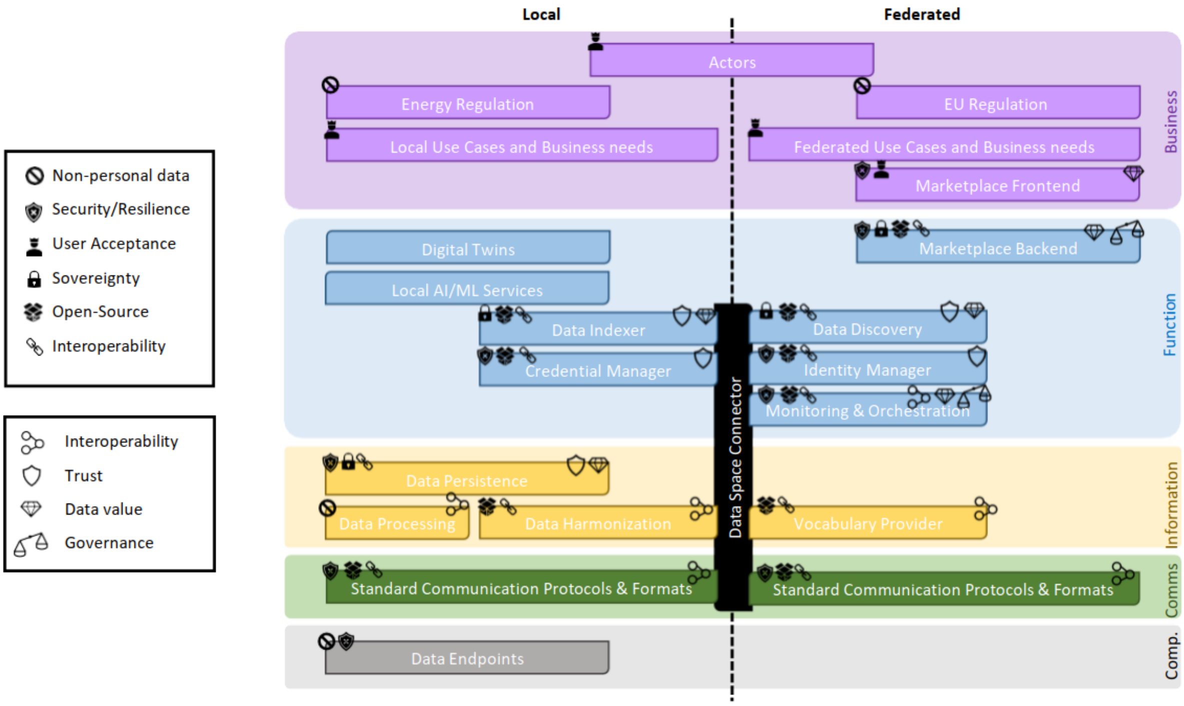

FIGURE 12: DERA 3.0 LAYERED ARCHITECTURE[7]

6.3 I-STENTORE MODEL

i-STENTORE Reference Architecture integrates different storage technologies, generation assets and loads, business models and services in an interoperable manner, enabling the multi-purpose use of storage, fostering RES integration and the optimal utilisation of available flexibility across different energy sectors. The proposed RA aims to extend primarily the Smart Grid Architecture Model through the alignment of key initiatives in the area of Data

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Space architecture modelling (e.g., IDSA and FIWARE) but also leveraging existing ongoing architectures from BRIDGE Data Management WG, H2020 INTERRFACE, BD4NRG, OneNet, etc (to be presented in Section 7). The i-STENTORE interoperable RA serves as the mediator for the seamless and technology-agnostic connection and integration of different storage systems and other interconnected assets (such as RES, loads, controllers, management systems, etc.) with the establishment of a data ecosystem across the energy value chain. The i-STENTORE approach leans merely on soft infrastructure that will lead to a decentralisation and a level playing field for intelligent energy-storage-based applications involving multiple energy stakeholders and systems. The i-STENTORE concept suggests the deployment of a decentralized middleware endowing data sovereignty traits, such as interoperability, portability, security, privacy and trustworthiness, but most importantly discoverability. The latter essentially implies the direct participation of end-users into the so-called 'storage-centric European Energy System' with the subsequent collective benefits for all participants. Figure 12 denotes a visual approach in designing the i-STENTORE reference architecture focusing on the SGAM interoperability layers.

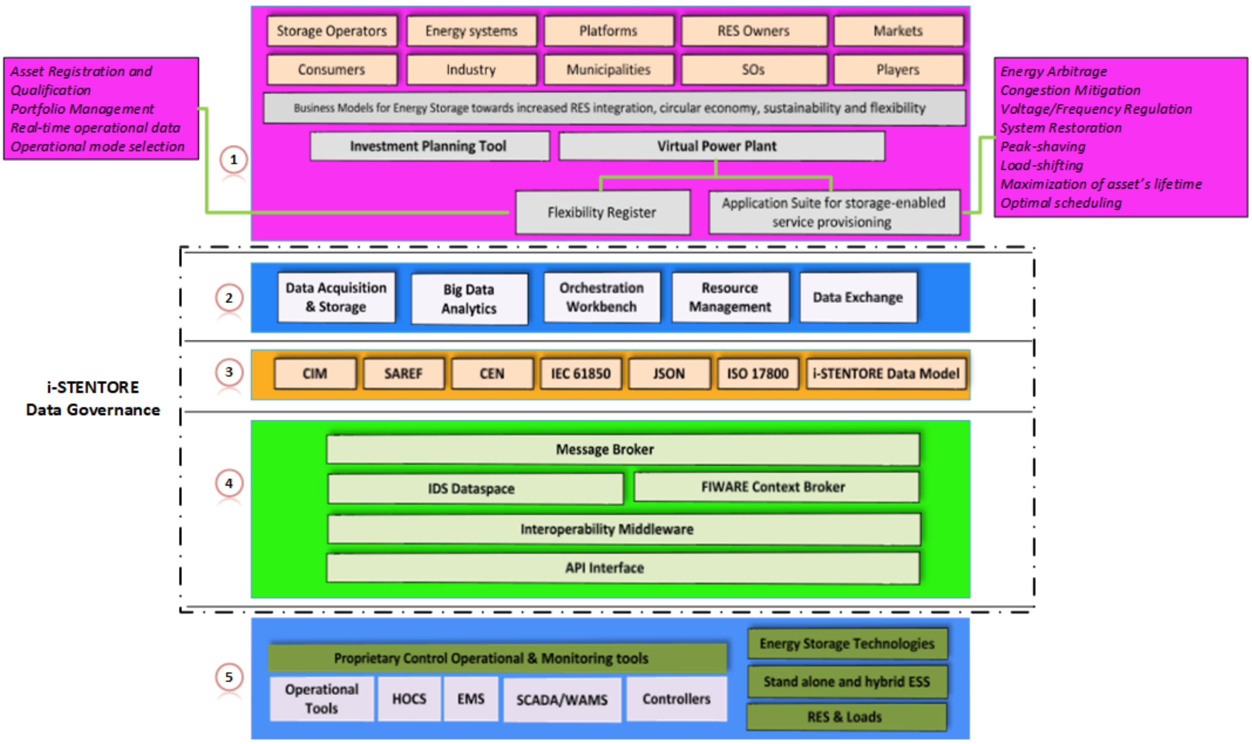

FIGURE 13: I-STENTORE SGAM REFERENCE ARCHITECTURE

Figure 14 depicts an evolved approach to the i-STENTORE reference architecture, taking into consideration the BRIDGE RA model based on the specific project needs and expectations. The end goal is to extend its structure with vertical pillars, containing aspects that are relevant across all the horizontal layers. The current deliverable details which other initiatives and architectures will be considered, and how their ideas will be included in the design of this RA, along with the specific needs of the project at the time.

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The **Business Layer** includes the Associations, the Business roles (categories of entities involved in the electricity domain, such as municipalities, consumers, renewable energy source (RES) owners, industry players, and more) and the Business processes (which represent the high-level activities that these roles might engage in, like asset registration, operational data management, optimal scheduling, etc.) The **Function Layer** includes the Functional processes which are the core functions or processes that aid the business processes through the application of the VPP and Investment Planning Tools. The **Information Layer** includes the Information Models (standards or frameworks for structuring and modelling data, like ISO 17800, IEC 61850, etc.) and the Profiles Data models (specific data models like the i-STENTORE data model or the i-STENTORE Semantic Ontologies that fit into the above-mentioned standards). The **Communication Layer** includes the Data formats (i.e., the actual formats in which data might be represented, like XML, JSON, and CSV) and the Protocols (i.e., communication standards or protocols used for data transfer, such as HTTP/HTTPS, REST, MQTT, etc.). Finally, the **Component Layer** includes the Data Exchange Platforms (this likely refers to platforms designed to handle and exchange data, integrating the above layers) the Applications (software or platforms used to control, monitor, and manage the electricity domain processes and data) and the Hardware (physical devices and tools used in the electricity domain, like smart meters, batteries, SCADA systems, sensors, actuators, etc.).

These first versions represent the state of the project and knowledge at the time of writing. Future work will detail how this architecture relates to the technical developments and pilot needs within the project, and how their evolution will update the requirements for the future versions of this RA in the months after deliverable submission.

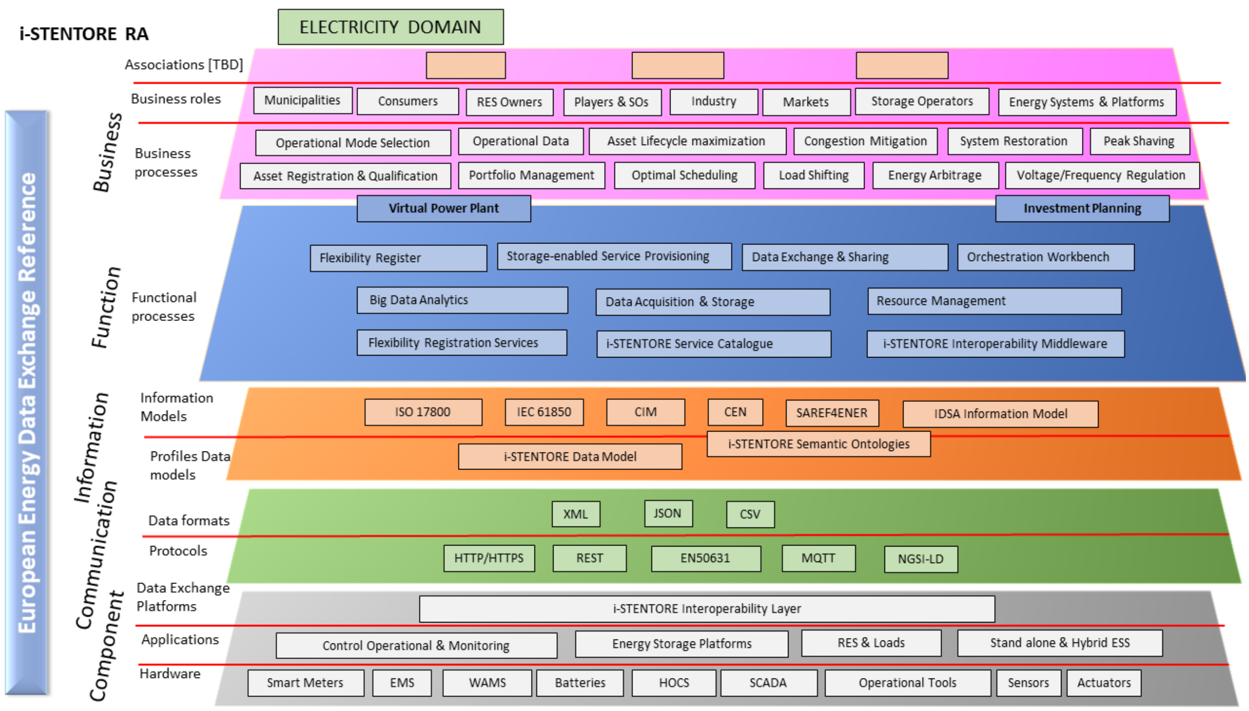

FIGURE 14: I-STENTORE BRIDGE REFERENCE ARCHITECTURE

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7 REFERENCE ARCHITECTURES & RELATED INITIATIVES

7.1 IDS RAM

IDS RAM, or International Data Spaces Reference Architecture Model, is a document that outlines the organisational and technological requirements for the IDS initiative's data infrastructure. The IDS initiative is a European effort that seeks to build a federated, secure, and open data infrastructure for Europe based on European standards and values. [32]

The IDS RAM's primary function is to:

- outline the conceptual framework for inter-organisational data exchange that complies with IDS,
- outline procedures and safeguards for data sovereignty in data ecosystems,
- pay attention to ideas like big data, AI, the IIoT (Industrial Internet of Things), and blockchain technology, and
- place a strong emphasis on certification, security, and governance. This means to specify security standards as well as roles and duties for the data economy and to specify control and enforcement procedures for data usage.

Similar to the aforementioned architectural structures presented, the IDS RAM is built on a **five-layer structure: business, functional, information, process, and system.** The primary elements and facets of the IDS are reflected in each layer. The IDS RAM also employs **three perspectives-security, certification, and governance**-to handle the various stakeholders' concerns. Each viewpoint offers a unique perspective on the IDS RAM. [33]

The IDS Connector, a software module that permits communication and data sharing between various service providers and consumers in the ecosystem, is the primary element of the IDS RAM. The Connector puts into practice the IDS Federation Services, which are a collection of standard procedures for managing identity, trust, policies, catalogues, compliance, and portability. The Federation Services make sure that the IDS values and guidelines are followed by all ecosystem participants. [34]

The IDS RAM is a project that is always being developed and improved. The International Data Spaces Association (IDSA), a global non-profit organisation with headquarters in Belgium, is in charge of overseeing it. The vision, strategy, roadmap, and governance of IDS are defined by the IDSA, which is made up of delegates from many industries and nations. Additionally, the IDSA oversees IDS-related market, standards, and research initiatives.

The IDS RAM is a forward-looking whitepaper that intends to influence data infrastructure in Europe and beyond in the future. It is motivated by the desire to build a secure, dependable, creative, and competitive digital ecosystem. It is predicated on the idea that data is an important resource that ought to be applied for everyone's benefit. [35]

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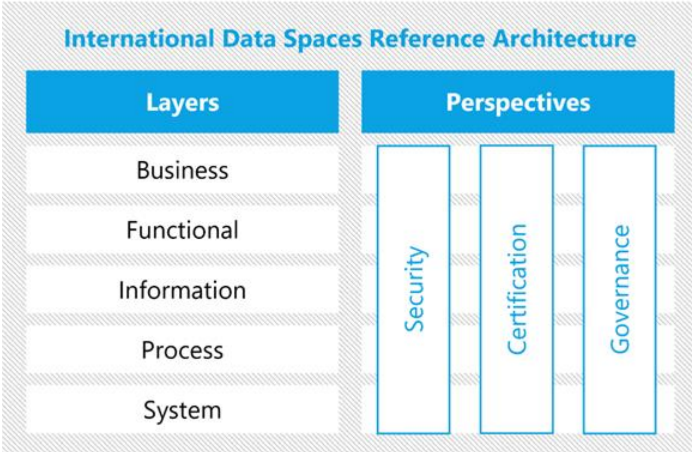

FIGURE 15: GENERAL STRUCTURE OF THE IDS REFERENCE ARCHITECTURE MODEL[8].

7.2 FIWARE SMART ENERGY ARCHITECTURE

With the pressing challenges of global warming and environmental responsibility, a different approach to energy management is needed. FIWARE stands as a solution for this shift, offering a unique solution with open standards and a framework of open-source software platform components [36].

The key to FIWARE's distinctiveness lies in its ability to empower Public Administrations, Utilities, Companies, and Research Institutions to create smart energy platforms rapidly, cost-effectively, and without being tethered to specific vendors. In essence, FIWARE breaks free from the constraints of vendor lock-ins and fosters an environment conducive to sustainable market development[9].

Taking on this responsibility means fostering highly resilient, efficient, and participatory models for energy production and consumption. It's about nurturing self-sustaining "local-energy-community" ecosystems, encouraging individuals to embrace and develop environmentally friendly systems.

To achieve this vision, energy management must transition to a decentralised and democratised model. Each prosumer (those who both produce and consume energy) should have an equal footing alongside traditional energy providers. Power must truly be in the hands of the people, and by the people.

FIWARE has already emerged as a new solution and approach in this regard. It introduces standardised, reusable, and rapidly deployable models for designing smart energy architectures. These models enable the development of versatile solutions and applications,

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[8] Atkinson, R. A., Zaborowski, P., Noardo, F., & Simonis, I. (2022). SMART CITIES–SYSTEMS OF SYSTEMS INTEROPERABILITY AND OGC ENABLERS. ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences, 10, 19-26.

[9] DOI: 10.1109/IOTM.0001.1800022

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facilitating the transition towards participatory energy production and consumption markets. Figure 16 describes FIWARE's architecture and the role of smart-meter aggregator, the energy data is transferred through the context broker to retrieve, translate and store data into the blockchain database adding real-time data into the big data layer. The big data layer is then used to develop the clustering techniques for load, profiling and customer segmentation.

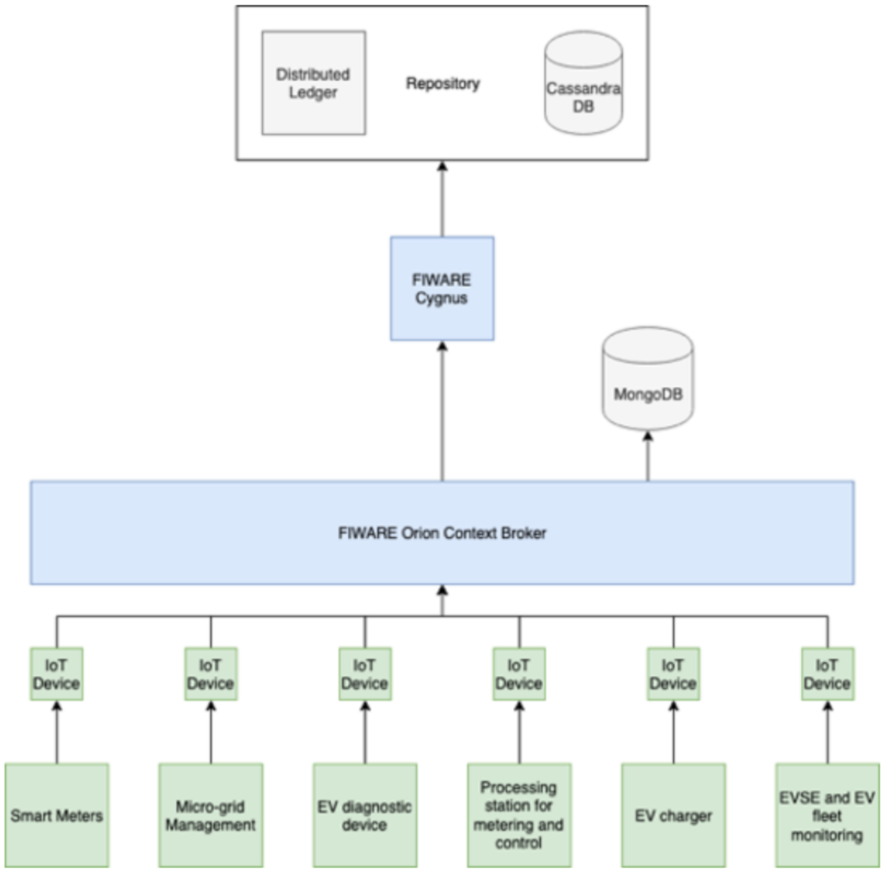

FIGURE 16: FIWARE'S ARCHITECTURE AND THE ROLE OF SMART-METER AGGREGATOR.[10]

FIWARE's strengths encompass[11]:

1. **Open De-facto Standards:** These are essential for cross-domain and cross-border interoperability, allowing for the seamless replication of solutions.
2. **Open Source:** Embracing open-source principles, FIWARE drives the definition of standards through practical implementation and an agile approach.

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[10] FIWARE Context Broker: The engine for future energy systems – FIWARE
[11] DOI: 10.1109/ACCESS.2022.3142894

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3. **System of Systems Approach:** Through common interfaces and data models, FIWARE integrates data-driven systems, no matter how diverse, independent, or autonomous they may be.

The FIWARE's smart grid architecture provides the design and integration of power, communication and control systems allowing a more efficient grid in order to oppose the climate change crisis. The FIWARE allows consumers and organisations to have a role in their energy future.

7.3 GAIA-X

GAIA-X is a European initiative that aims to create a federated, secure, and transparent data infrastructure for Europe, based on European values and standards. It is led by France and Germany, and supported by various stakeholders from the public and private sectors, as well as civil society [37], [38], [39], [O14], [41].

The main goals of Gaia-X are to:

- Enhance the digital sovereignty of European users of cloud services, by allowing them to control their own data and choose their preferred service providers.
- Foster innovation and competitiveness of European businesses, by enabling cross-sector data sharing and collaboration, as well as creating new data-driven services and business models.
- Establish an open and fair digital ecosystem, by using common requirements, standards, and governance models that ensure transparency, interoperability, security, and data protection.

To achieve these goals, GAIA-X develops a RAM that defines the technical and organisational specifications for the data infrastructure. This RAM is based on existing standards and technologies, such as cloud computing, edge computing, artificial intelligence, and blockchain and it also incorporates relevant EU regulations, such as the General Data Protection Regulation (GDPR) and the Free Flow of Non-Personal Data Regulation [42], [43].

The core component of the RAM is the GAIA-X Connector, which is a software module that enables communication and data exchange between different service providers and users in the ecosystem. The Connector implements the GAIA-X Federation Services, which are a set of common functions that provide identity management, trust management, policy management, catalogue management, compliance management, and portability management. The Federation Services ensure that all participants in the ecosystem adhere to the GAIA-X principles and rules [44].

GAIA-X is not a cloud service provider or a cloud management platform. It does not aim to compete with existing cloud offerings, such as those from hyper-scalers. Instead, it aims to link different cloud and edge solutions via open interfaces and standards, to create a network of interoperable and sovereign data spaces. These data spaces are domain-specific or cross-domain platforms that enable data sharing and value creation among various actors. GAIA-X also supports the development of value-adding applications and services that leverage the data spaces and the Federation Services.

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GAIA-X is an ongoing project that is under continuous development and improvement. It is governed by the GAIA-X Association AISBL, which is an international non-profit organisation based in Belgium. The Association consists of representatives from various sectors and countries, who collaborate to define the vision, strategy, roadmap, and governance of the project. The Association also coordinates the research activities, standardisation activities, and the market activities related to GAIA-X.

It is a visionary project that aims to shape the future of data infrastructure in Europe and beyond, and as such, it is driven by the ambition to create a digital ecosystem that is secure, trustworthy, innovative, and competitive. It is based on the belief that data is a valuable asset that should be used for the common good [45].

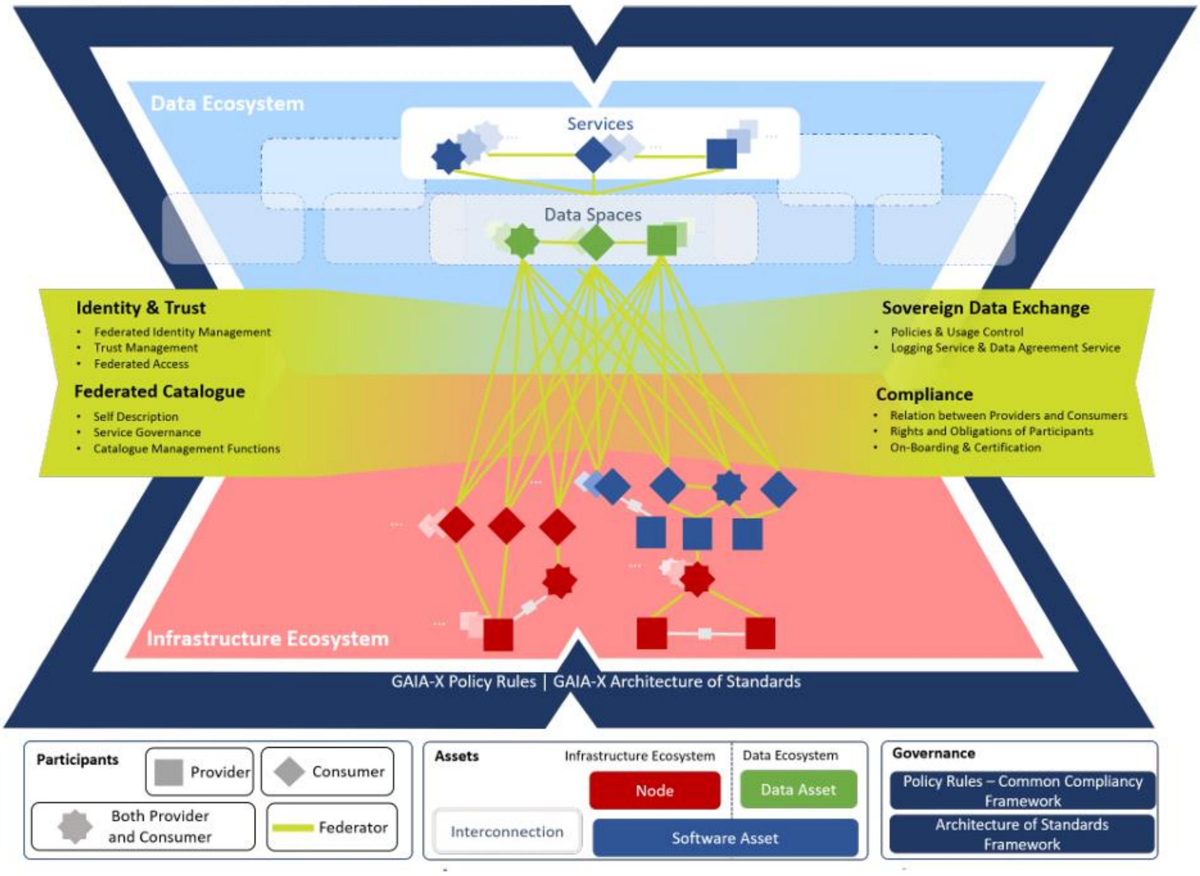

FIGURE 17: GAIA-X INFRASTRUCTURE AND DATA ECOSYSTEM VISUALISATION.

7.4 OPENDEI

The OPENDEI project is centred on creating a framework for Digital Transformation across various domains. What follows is a description of the architecture and principles behind the OPENDEI project [46].

- **Reference Architecture Framework:**

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The project has formulated a common Reference Architecture Framework aimed at fostering Cross Domain Digital Transformation. This was achieved through a case analysis of Reference Architectures and requirements derived from Innovation Actions under the CSA umbrella [47].

- **6C Architecture:**

  OPENDEI has adopted a 6C architecture, which is based on state-of-the-art architectures from domains like Industry 4.0. The 6C architecture encompasses the following pillars:

  - Connection: Incorporating sensors and networks.
  - Cyber: Focusing on model & memory.
  - Computing: Including edge/cloud computing and data on demand [48].

- **Pan-European Data Spaces:**

  The project has laid foundations for pan-European data spaces that are designed to be compatible and interoperable from inception. It generated a framework encompassing all necessary building blocks for this task, rooted in the broader European strategy to digitize the industry [49].

- **Unification and Standardisation:**

  OPENDEI aims at aligning Reference Architectures, Open Platforms, and Large-Scale Pilots in digitizing the European industry, with a priority on creating common data platforms based on a unified architecture and established standards [50].

- **Design Principles and Building Blocks:**

  Task Force 1 of OPENDEI has been crucial in designing data spaces. They have defined design principles for data spaces and identified implementations to harmonize the data spaces. They have also provided guidelines for the deployment of data spaces, assessed minimal viable data spaces, and common building blocks for implementation.

- **Design Principles for Data Spaces:**

  A position paper delineated the fundamental design principles for constructing data spaces. It discussed the high-level architecture of data spaces, common building blocks from technical, business, and organisational perspectives, sector-specific data spaces in manufacturing, health, energy, and agriculture, governance and business models for data spaces, and a roadmap for creating the underlying soft infrastructure for European data spaces [51].

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The project's primary focus revolves around the identification of cutting-edge, cross-domain content that is pertinent to four key sectors: manufacturing, agriculture, energy, and health & care. Within each sector, a designated ambassador takes on the responsibility of fostering connections with their respective sector or community. Each sector is characterized by several large-scale pilot initiatives, funded by the European Commission. Additionally, following a participatory and collaborative Open Innovation approach, Cross-domain Task Forces, initiated by OPEN DEI activities, aim to engage not only renowned experts from the four domains within the project's ecosystem but also external experts who serve as Facilitators. The Task Force, under the technical moderation of Antonio Kung (TRIALOG), is dedicated to involving a pool of experts in the domain of Digitising European Industry (DEI). Its core objective is to establish a framework that encourages creative thinking, facilitates discussions, and disseminates insights and innovative proposals related to defining and implementing reference architectures, interoperability frameworks, and standards that underpin the deployment of next-generation European digital platforms in the four foundational industrial domains: manufacturing, agriculture, energy, health & care.

The digital transformation of European industries introduces new challenges in terms of data, knowledge, and technology adoption, largely due to critical interoperability issues affecting the underlying digital platforms and their synergies. These challenges centre on identifying the most valuable data and information for exploitation.

The ongoing series of Innovation Actions, falling under the OPEN DEI umbrella, is addressing the impact on Digital Transformation pathways through the adoption of IoT, Big Data, Artificial Intelligence, and some preliminary exploration of Data Spaces. The overarching challenge is to harness the full potential of these technologies, as well as the most recent advancements that empower digital platforms to play a pivotal role in addressing competitive pressures and integrating new technologies, applications, and services.

The activities carried out by OPEN DEI in this realm are designed to reduce barriers for all stakeholders in the four target domains and their value chains. The objective is to enable the adoption and full utilisation of trusted technologies in the field of Digital Transformation, ultimately fostering end-to-end sustainability in the innovation market, with a particular focus on SMEs.

This effort involves an in-depth analysis of the State of the Art with respect to general-purpose architectures and standard architectures, which serve as the foundation for the OPEN DEI Reference Architecture Framework (RAF) specifications. The RAF is guided by six fundamental principles: interoperability, openness, reusability, avoidance of vendor lock-in, security and privacy, and support for a data-driven economy.

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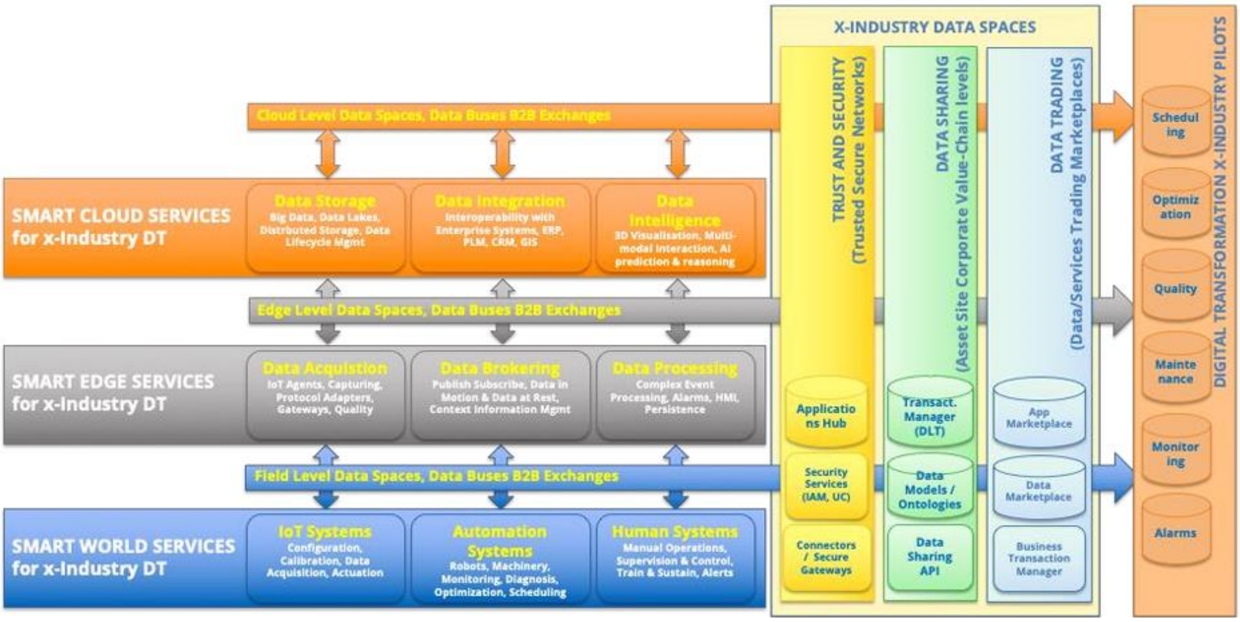

FIGURE 18: OPEN DEI REFERENCE ARCHITECTURE FRAMEWORK.

The OPEN DEI RAF therefore represents a very high-level abstraction of a platform supporting digital transformation of organisations/business/companies, but it does not represent a specific business case (or a set of) or technological approach.

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8 RELATED PROJECTS: REFERENCE ARCHITECTURES

8.1 INTERRFACE

The IEGSA platform is developed by the INTERRFACE project to perform as a common platform to connect multiple actors such as Market Operators, Systems Operators (i.e. TSOs and DSOs), Flexibility Service Provides (i.e. Balance Service Providers or Aggregators), Settlement Responsible Parties, along various energy markets focusing on providing support on the procurement of services (such as balancing, congestion management and ancillary services) from assets connected to the network both at transmission and at distribution level, in a coordinated way. This is achieved by implementing multiple coordination schemes between TSOs and DSOs. Therefore, IEGSA provides a channel that establishes the seamless coordination between system operators towards their efficient communication on procuring network services by enabling flexibility from all levels. The increasing participation of energy stakeholders (i.e., providing or trading available flexibility), implies the need for a channel to allow the secure information and data exchange, a fact which is well addressed by the IEGSA platform.

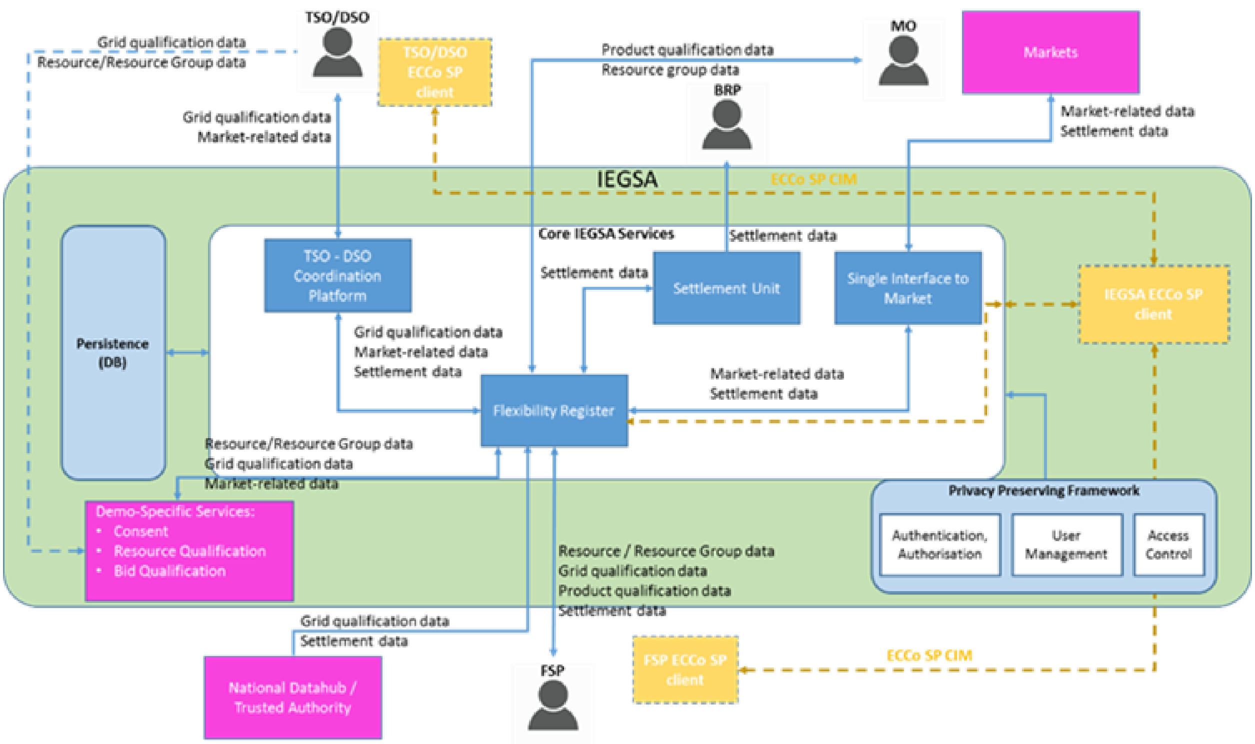

FIGURE 19: IEGSA LOGICAL ARCHITECTURE.

IEGSA proposes a modular architecture platform which enables the data exchange with existing hubs in Europe, facilitating the interconnection of different actors such as TSOs, DSOs and other market participants or customers connected to the system. The conceptual and logical architecture design of the IEGSA platform essentially allows the interactions

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among system operators as well as flexibility providers. Therefore, IEGSA comprises a data exchange platform enabling the digitalisation of the energy value chain ensuring data security and privacy requirements by-design. Particular effort is given to engage flexibility services from multiple types of Balancing Service Providers (BSPs), and facilitating access and interconnection with various market platforms, covering different timeframes, enhancing also the coordination among TSOs and DSOs with the introduction of standardized services and market designs. IEGSA platform encompasses advanced tools and technologies as a matter of integrating multiple actors and systems to serve various business requirements focusing mainly on the flexibility procurement in a coordinated way among TSOs and DSOs. The logical and conceptual technical composition of IEGSA platform is demonstrated in Figure 19.

IEGSA's design follows the SGAM (Smart Grid Architecture Model, see Figure 20) Framework and has been implemented in its different layers so called: **business, function, information, communication and components layer** respectively.

The combination of the communication, information and function layers from a technical standpoint acts as the middleware between the Business Layer with the needs of users and their BUCs; and the Component Layer where the demo specific implementation meets the business layer requirements.

There are four main functional blocks that lie in the architecture which follow a modular approach to integrate complementary services and functionalities within the IEGSA framework.

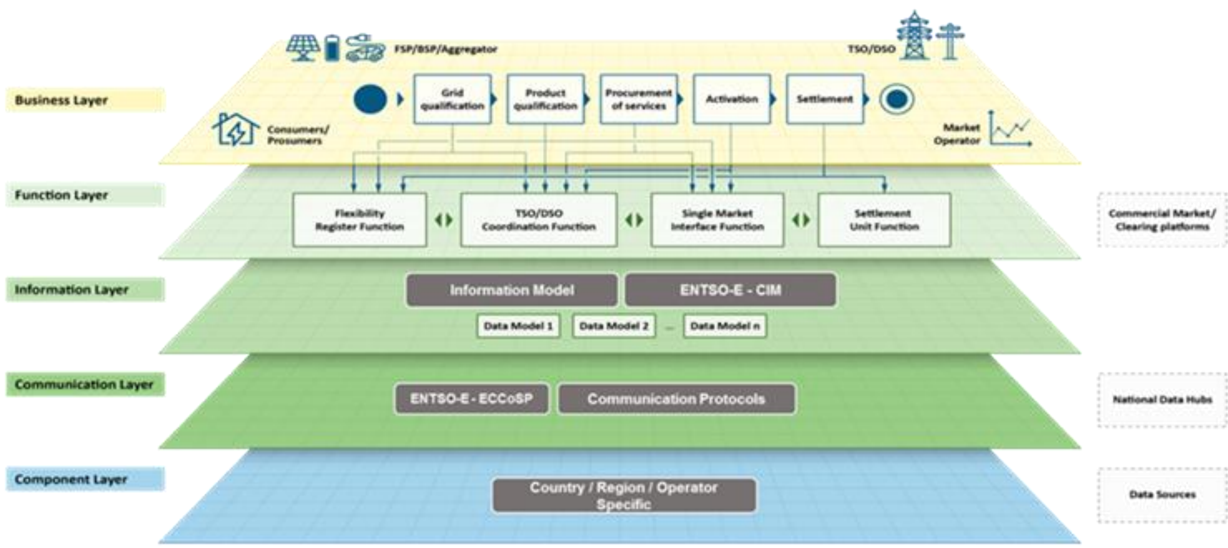

FIGURE 20: SGAM-BASED IEGSA ARCHITECTURAL REPRESENTATION.

Those functional modules are the following:

- **Flexibility Register (FR),** acting as the core component; processes that are performed within this module include: user management, resource/resource group registration, interaction with consent manager, product definition, trigger of product, grid and bid qualification. The FR module can be accessed by all users of IEGSA such as Flexibility Service Provider (FSP), Market Operator (MO) and the System Operators (SOs). Each of

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them has different rights when accessing it. Several UI functionalities reside in FR to ease resource registration (i.e., view and update existing, add new), resource groups definition (i.e., view and update existing, add new), qualification status tab (preview resources and resource groups qualifications status), product definitions and product qualification requests.

- **TSO-DSO Coordination platform** which essentially is the module that enables the coordination among SOs. Therefore, this module interacts with the bid and grid qualification services and market-related processes (e.g., merit-order list documents) via the flexibility register. Subsequent User Interface (UI) functionalities are implemented to support SOs to view resources and resource groups. Regarding Resources the SOs may proceed with changes on the qualification status. A dashboard for the merit order lists of all IEGSA integrated markets is also available for SOs which also may allow the activation of certain bids directly from IEGSA. Activated bids can be previewed on the "Trades" environment of the TSO-DSO Coordination platform.
- **Single Interface to Market** is essentially a backend component that acts as the gateway to connect energy markets with IEGSA, essentially allowing the exchange of market related data. The Single Interface to Market is actually a set of standardized REST APIs, which handle the communication of IEGSA with the various markets that it is connected with. This component lies on the back-end and there is no dedicated UI. The APIs that comprise the Single Interface to Market are responsible for the transfer of data that facilitate all the processes in IEGSA that surround the market integration. The scalable and standardized design of the APIs allows the agnostic connection to different market platforms and the seamless data exchange. Thus, IEGSA can exchange bids, Merit Order Lists and Activation Orders with all interconnected markets. The connection to different markets gives a more holistic overview of the available offers and bids to the System Operators, allowing the more efficient and secure grid management.
- **Settlement Unit** which performs the energy settlement of all trades. The FSP may upload documents related to metered and/or sub-meter readings along with activated volumes for all the metering points affiliated with the particular resource object for all metering points.

8.2 ONENET

One of the purposes of OneNet is to provide an open and flexible architecture for transforming the European electricity system, which is often managed at country-level, into a pan-European smarter and subsequently more efficient one. Its Reference Architecture (Figure 23) consists of three logical layers:

- the **OneNet Participants Layer** which makes available and accessible data from different Data Sources to the Energy Stakeholders in a secure and trusted way, ensuring data ownership and privacy,
- the **OneNet Network of Platforms Layer** which facilitates the platforms integration and cooperation for cross-platform market and network operation services. It includes any

demo platform (e.g., DSO platforms, Market platforms, Data Exchange platforms) able to connect with the OneNet Middleware using the OneNet Connector, and

- the **OneNet Framework Layer** which could be described as a scalable and pluggable solution for facilitating the platform cooperation and integration. It is able to create a unique ecosystem in which any energy stakeholder can participate.

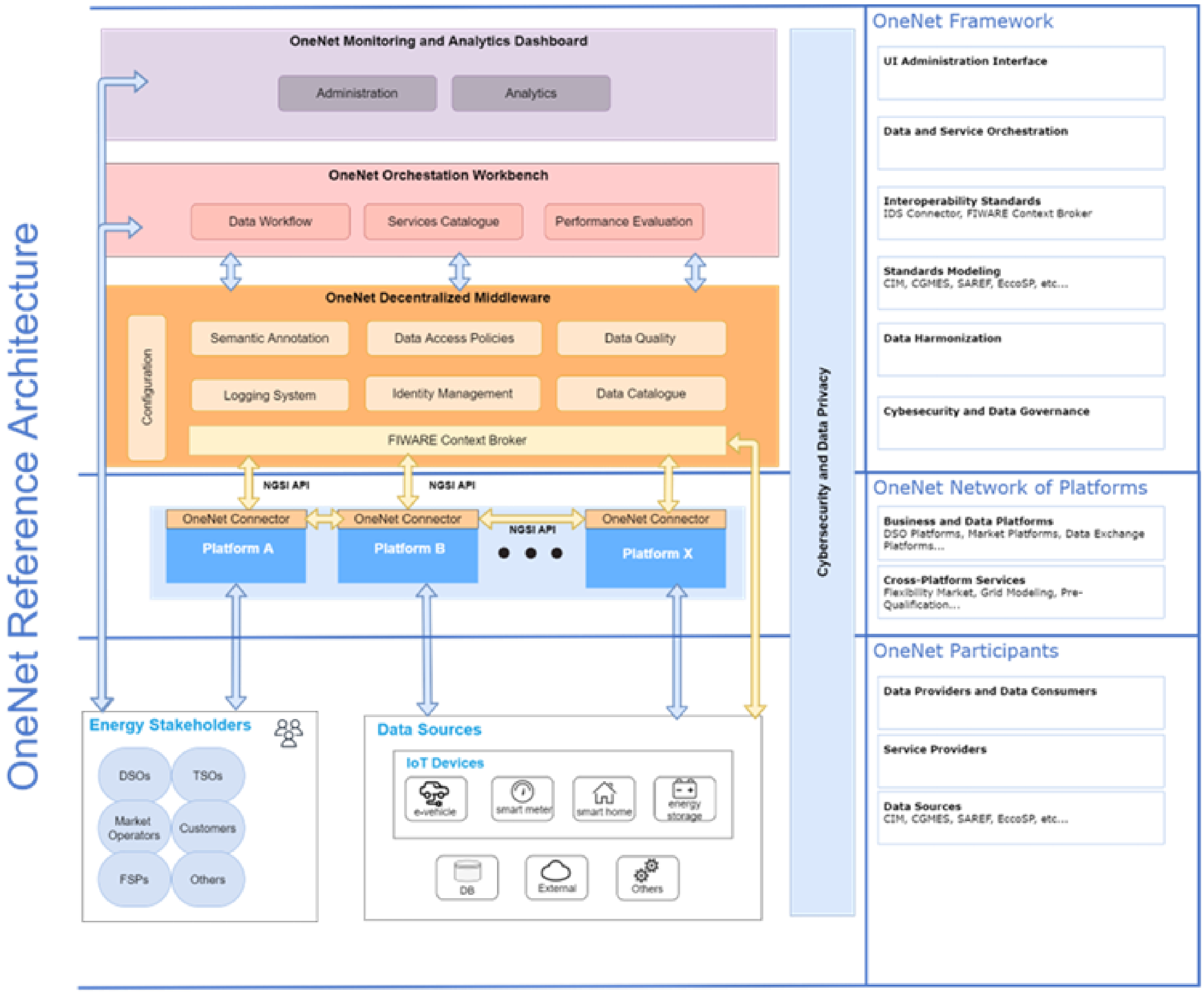

FIGURE 21: THE ONENET REFERENCE ARCHITECTURE.

The **OneNet Participants layer** is composed of ***Data Sources*** and ***Energy Stakeholders***.

- ***Data Sources*** component refers to all the assets that produce or process data. Indeed, data can come from different energy sectors, such as electric mobility, energy storage, residential energy monitoring, and it can be generated by sensors, actuators, gateways, edge computing nodes, etc.
- ***Energy Stakeholders*** component refers to the stakeholders identified in the OneNet market. The actors are named according to their business role, such as DSO, TSO, Market operator, Customer and so on. Due to the focus of the architecture on the data exchange,

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the stakeholders can be gathered in Service Providers, Data Consumers and Data Providers.

This layer is connected with the OneNet Network of Platforms layer since it represents the source of data for the business and data platforms as well as the integrable services or applications. As a data source, the layer is directly connected to the OneNet Framework, using the OneNet Middleware and its interoperability mechanisms based on the FIWARE Architecture and on the FIWARE Orion Context Broker. Moreover, the energy stakeholders have the opportunity to access the Orchestration Workbench for evaluating and testing apps, tools and services and they can exploit the analytic features accessing the OneNet Monitoring Dashboard offered by the OneNet Framework.

The OneNet Network of Platforms layer focuses on the integration of external platforms, such as DSO platforms, market platforms and other data exchange platforms into the OneNet system using an approach fully decentralized. In this infrastructure, indeed, two systems (OneNet Participants) can interact directly with each other, without intermediation by a third party. From the OneNet perspective, the most important component included in this layer is the **OneNet Connector** since it is responsible for the execution of the complete data exchange process. The OneNet Connector is a specific instance of the OneNet Decentralized Middleware which is placed inside each platform and allows easy integration and cooperation among the platforms. This component follows the IDS specifications, and the Context Broker is based on the FIWARE Orion Context Broker and NGSI-API. As shown in Figure 22, the Connector includes a configuration tool, a set of interoperable APIs for the connection with already existing platforms, applications and services as well as the Data Harmonisation services.

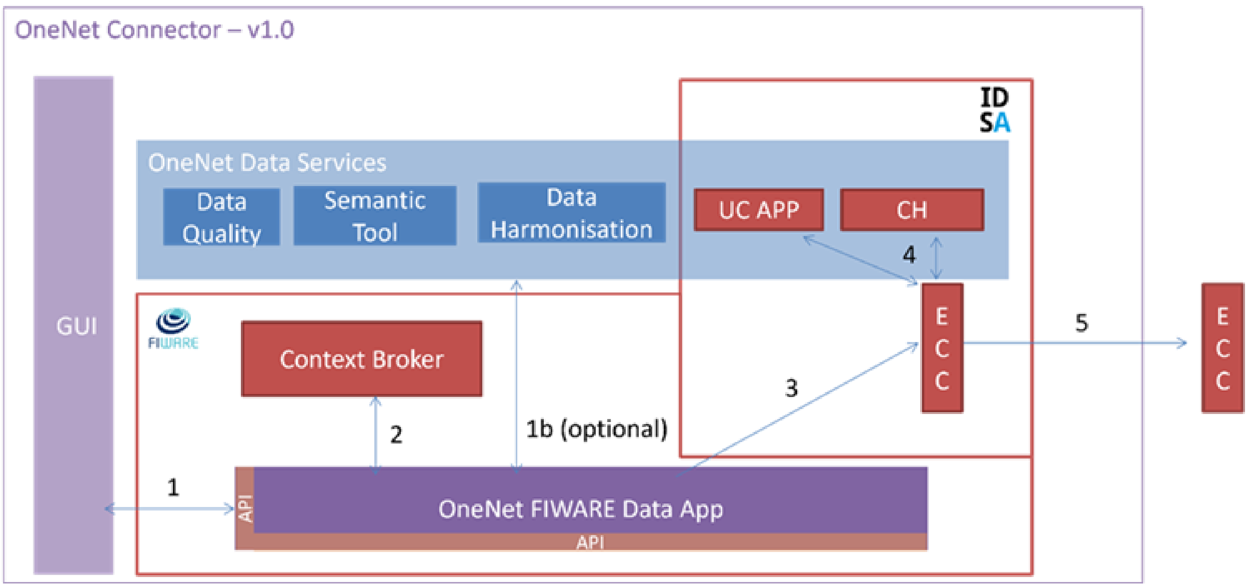

FIGURE 22: THE ONENET CONNECTOR ARCHITECTURE.

The **OneNet Framework layer** is the core of the OneNet Architecture. It is composed of: the Decentralized Middleware, the Orchestration Workbench, and the Monitoring and Analytics Dashboard.

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- ***OneNet Middleware*** enables a secure and reliable end-to-end data exchange between all the assets and components integrated in the OneNet Network. The Middleware also provides central features to all the actors like identity management, sources discovery, semantic annotation, vocabularies and ontologies.
- ***OneNet Orchestration Workbench*** aims to support data orchestration for evaluating performance and scalability of the AI, IoT and Big Data cross-platform services for market and grid operations. The workbench allows to integrate data coming from the OneNet Middleware and to implement a data pipeline orchestration.
- ***OneNet Monitoring and Analytics Dashboard*** can be considered an administrative and configuration tool. In addition to having an easy integration with the OneNet Orchestration Workbench and OneNet Middleware, this tool provides the data-analytics dashboard, the monitoring and alerting dashboard for data processes and platform integrations, the user-friendly selection of data sources and services from the catalogues.

8.3 PLATOON

During the design process of the PLATOON architecture, the goal was to achieve the compliant architecture with other public initiatives such as COSMAG reference architecture, FIWARE, SGAM and IDS. The PLATOON architecture (Figure 23) is layered with logical components and interaction [52]. This approach makes the system more modular and maintainable. Each layer has a specific responsibility, from data collection to intelligence and security.

PLATOON layers:

- **Physical infrastructure and data sources:** This layer is crucial for any system dealing with energy data as it needs to collect data from various sources, including sensors, historical records, and external data sources like weather forecasts.
- **Interoperability layer** plays a pivotal role in handling heterogeneous data sources. It is responsible for data collection, semantic adaptation, and data curation. This layer ensures that data from diverse sources can be harmonized and used effectively.
- **Data Management layer** focuses on storing and providing access to data through standard APIs. Managing vast amounts of data is essential in energy-related projects, and this layer typically involves big data technologies to handle the data efficiently.
- **The intelligence layer** is where data analysis and artificial intelligence come into play. It is the layer where the value-added services are generated from the data collected. In the context of i-STENTORE, this layer could be crucial for creating real-time or batching processing for planning or making data-driven decisions.
- **The marketplace layer** components provide a means for sharing data, services, and applications within the ecosystem. This is valuable for collaborative projects like i-STENTORE, where different stakeholders can contribute and access resources such as datasets, services and analytic tools.

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- **The security, privacy and sovereignty layer** is a transversal layer. Especially in the energy sector, security, privacy, and data sovereignty are critical concerns. This layer ensures that data is protected and access is controlled appropriately.

Standard APIs are emphasized throughout the architecture. Standardisation helps in ensuring that different components and systems can communicate effectively. This is greatly valuable for i-STENTORE to interface with existing infrastructure and technologies. Furthermore, using common semantic models for data integration plays a vital role so that data from different sources can be understood and processed cohesively. The architecture promotes collaboration by enabling the sharing and monetisation of assets. This can facilitate cooperation among different stakeholders in projects like i-STENTORE.

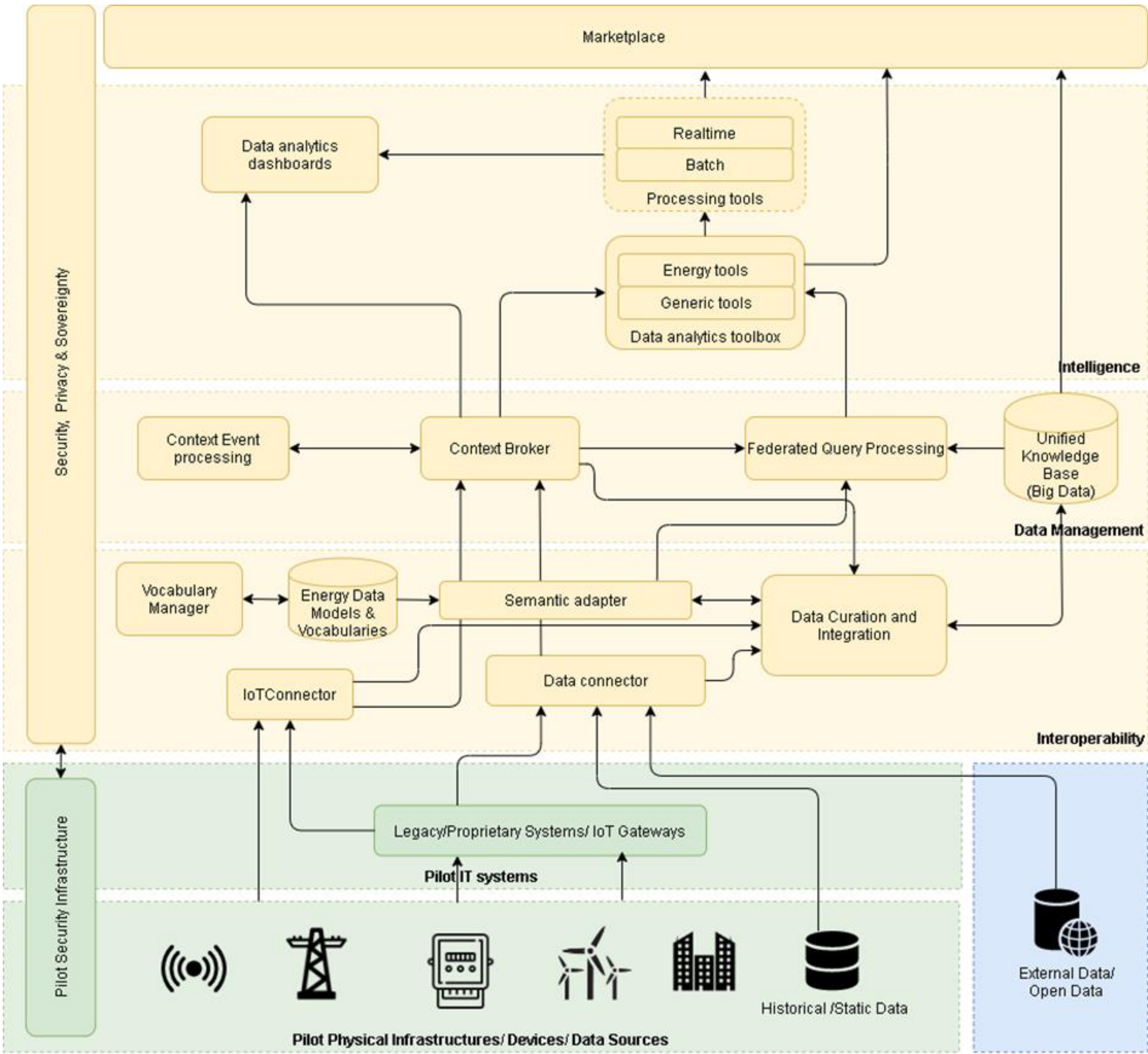

FIGURE 23: PLATOON REFERENCE ARCHITECTURE.

Building on the established framework of the PLATOON architecture, i-STENTORE can leverage the modularity and maintainability features for enhanced performance and easier

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system updates. The importance of a well-defined interoperability layer, as seen in PLATOON, cannot be overstated for i-STENTORE, given its role in ensuring seamless data integration from diverse sources, which is crucial for accurate analysis and intelligent decision-making. By adopting standardized APIs and common semantic models from PLATOON, i-STENTORE stands to benefit from improved communication between different systems and components, fostering a collaborative environment that is essential for the success of such complex energy-related projects.

8.4 BD4NRG

The Reference Architecture of BD4NRG is based on the BRIDGE DERA v2.[12] It broadly uses its structure, but is focused to fit the BD4NRG project goals and pilot use cases. It specifically adds nuance in spaces where specialization is possible according to the project's boundaries.

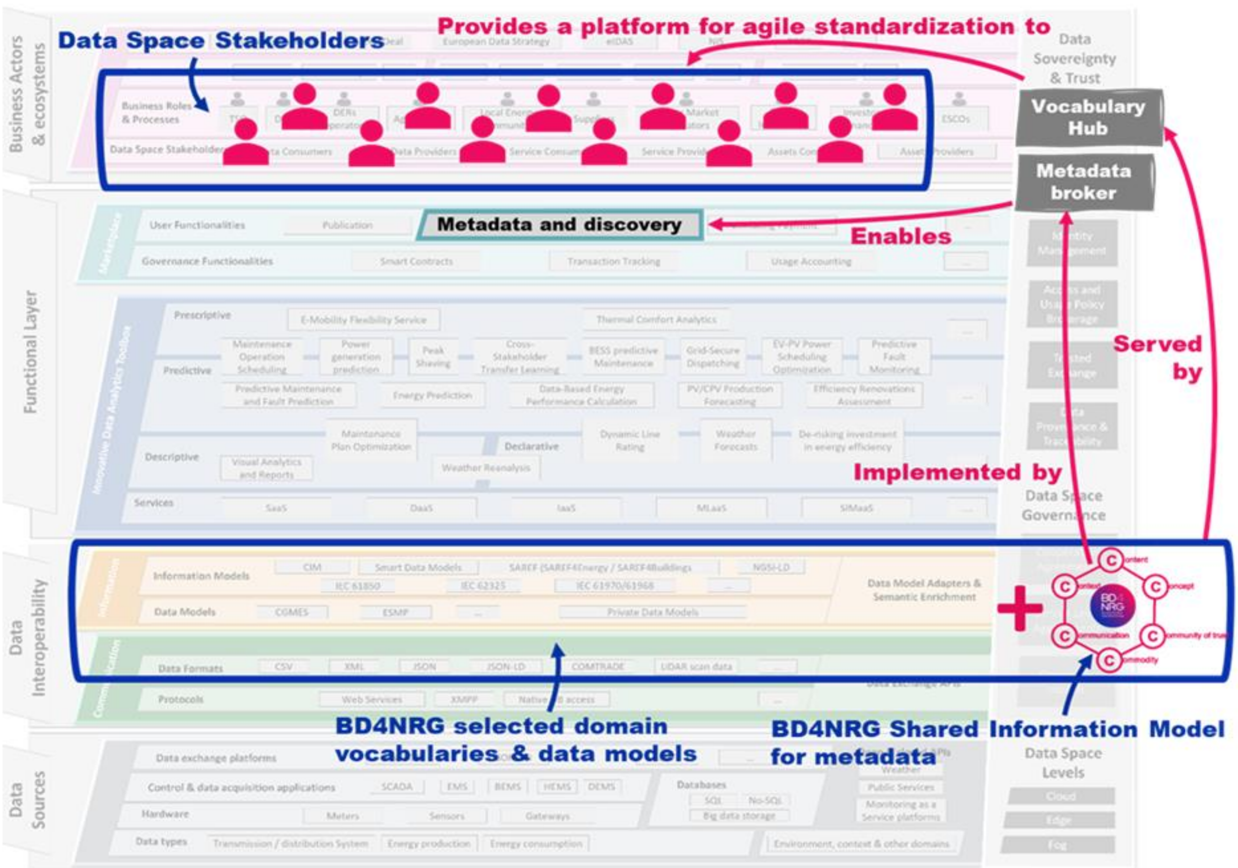

FIGURE 24: BD4NRG DATA SPACE MODULES (SRC. BD4NRG D2.6).

[12] https://op.europa.eu/o/opportal-service/download-handler?identifier=e1017a58-ac1e-11ed-b508-01aa75ed71a1&format=PDF&language=en&productionSystem=cellar

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The methodology for defining data exchange requirements in BD4NRG started from the project's pilots as a base. They were mapped to the BRIDGE DERA to form a common overview, before individual datasets they planned to use were listed and evaluated, together with the implemented protocols, data formats, etc.

Given this information, the interoperability layer of the BD4NRG RA was populated. The BD4NRG shared Information model was defined, along with two components necessary for data access and integration: the Vocabulary Hub and Metadata Broker (see Figure 24).

The BD4NRG-shared information model, itself a vocabulary hosted in the Vocabulary Hub, builds upon the IDS Information Model, the GAIA-X Taxonomy and the ETSI NGSI-LD standard, therefore connecting alignment with IDSA, GAIA-X and FIWARE at once.

The metadata broker enables data discovery and exchange by storing and retrieving metadata in an internal repository, and is not involved in the exchange of payload data. The BD4NRG system specifically uses IDS Metadata Broker, which enables publishing and searching of metadata of IDS Connectors between IDS Data Providers and Data Consumers.

The BD4NRG Vocabulary Hub, likewise aligned with IDSA, provides "vocabularies", including reference data models, ontologies, etc. It enables a user to access and edit these vocabularies and aims at a collaborative approach in line with agile standardization.

In addition to existing standard vocabularies and data models, agile standardization is employed to expand interoperability with IDSA and FIWARE as well as the GAIA-X concept. In contrast to classic standardization, it does not require a stable and fully dedicated standardization body, and the involved standardization groups can be put together from interested experts instead of having to be specifically balanced. The prestige of standards is defined by users' application of results instead of by a source entity, and accordingly, consensus is not necessarily found through global participant reviews, but instead can depend on contributions, a community of users, or even a single deciding entity.

With this combination of classic and agile standardization, BD4NRG aims to find a balance between the reliability and completeness of classically standardized vocabularies and data models, and the need for flexibility arising from the individual needs of the project's pilots [21].

The aforementioned alignment of standards, combined with the needs of the BD4NRG pilots, informs the choice of supported information models; this includes CIM, NGSI-LD, as well as IEC-61850. The core of the communication platform is formed by an Orion-LD Context Broker, which provides an NGSI Interface and enables clients to query and update context information, receive notifications in the case of such updates, and register context provider applications.

Identity management is handled by FIWARE Keyrock as the main component combined with other security components such as PEP Proxy and Authzforce, making it possible to add Oauth2-based authentication and authorization security to services and applications [22].

8.5 ATTEST

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The EU-funded H2020 project Advanced Tools Towards cost-efficient decarbonisation of future reliable Energy SysTems (ATTEST) aimed to develop a secure ICT platform that integrates an innovative open-source toolbox. The toolbox comprises innovative tools to help TSOs and DSOs to run, maintain and plan future energy systems (for 2030 and beyond) in an optimised and coordinated manner by improving and coordinating their systems from a technical, economic and environmental standpoint.

At distribution level, a tool was developed in ATTEST to enable DSOs to optimally procure ancillary services, specifically for voltage control and congestion management, resorting to the flexibility of emerging sources such as RES, flexible loads (e.g., EVs) and BESS. It is based on a tractable Stochastic Multi-Period Optimal Power Flow (S-MP-OPF) tool that models every aspect of these grids (e.g., energy time coupling of flexible resources, uncertainty aspects of renewable DERs) and is computationally efficient.

The objective of this tool is to determine the optimal flexibility scheduling of available DER to support the procurement of ancillary services (congestion management and voltage control) by the DSO on a 24-hour basis.

The tool optimises the use of flexibility by mitigating RES units' uncertainties and ensuring that network capacity is never exceeded during the real-time operation stage of distribution networks.

The developed tool takes-into-account:

- the uncertainty modelling of RES units,
- modern flexible DER such as EES and flexible loads (FL),
- aggregated flexibility of low-voltage systems at medium-voltage/low-voltage interface, and
- actions of network management controllers (e.g., on-load tap changer transformer) of medium-voltage grid.

The output data of this tool are:

- the expected cost of the procurement of ancillary services,
- optimal set-points of each DER/optimal re-adjustment of flexible assets corresponding to various ancillary services during each uncertainty scenario and time-period, and
- the total number of nodes voltage and branch current violation as well as the magnitude of maximum violation.

Moreover, at transmission level, another tool was developed in the project to enable TSOs to optimally procure ancillary services resorting to the flexibility of emerging sources such as EV and BESS, specifically for voltage control and congestion management, to mitigate renewables uncertainty and ensure that the network N-1 security criterion is satisfied in a multi-period day-ahead scheduling. Such tool is based on a Stochastic Multi-Period AC Security Constrained Optimal Power Flow (S-MP-AC-SCOPF), a tractable and scalable day-ahead SCOPF model to procure ancillary services that is both uncertainty-aware and flexibility-driven.

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As previously described, the tools that were developed deal directly with flexibility estimation (from storage and other flexible resources) for transmission and distribution systems with high amounts of DER as well as optimal utilisation for services provision via a secure ICT platform integrating a set of optimisation tools for operating, planning and managing power systems assets. These tools will be adapted in i-STENTORE to optimise the management of hybrid energy storage systems.

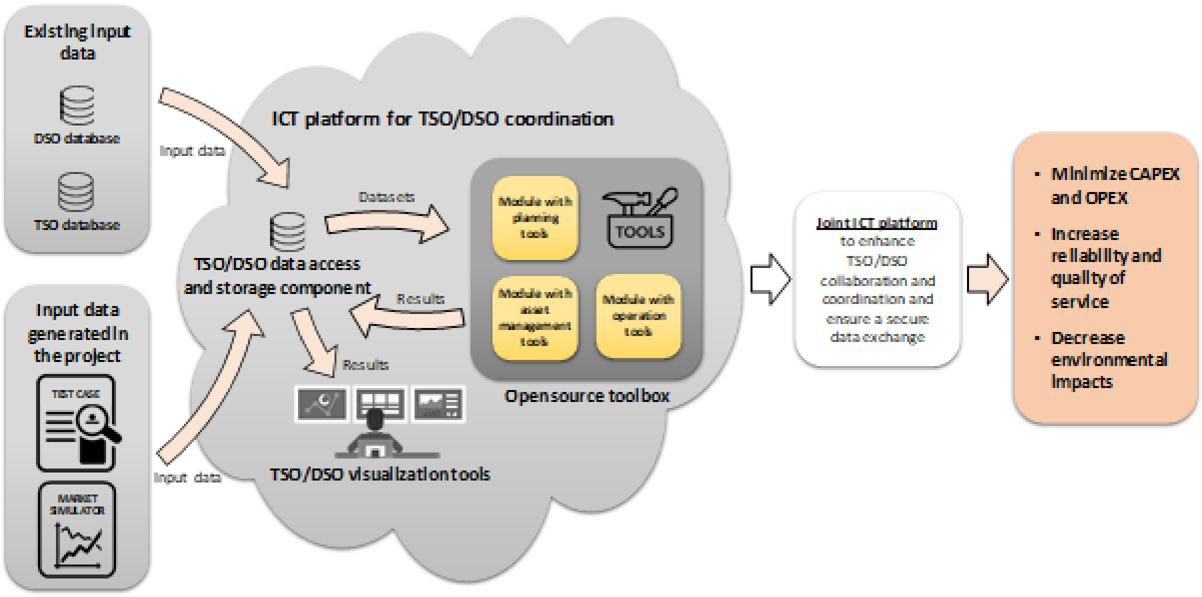

FIGURE 25: ATTEST CONCEPTUAL ARCHITECTURE.

8.6 IMPORTANT ASPECTS FOR CONSIDERATION

A key technology enabler to steer and substantiate such multi-lateral cross-domain relationships ecosystems are the analysis of other Interoperable Cross-sector Open Energy-centred Architectures and solutions which leads to more efficient, interoperable, integrated, resilient, and sustainable energy systems. To define the i-STENTORE Reference Architecture, models such as SGAM and BRIDGE Data Management are considered. In parallel, H2020 projects like BD4NRG, OneNet, INTERRFACE, InterConnect, and PLATOON will be leveraged to extend and hybridise the SGAM model with a view to incorporate cross-sector domain-agnostic data value chain roles and underlying governance models. Standardizable and open interoperable interfaces among electricity sectors will be evolved and enabled through Reference Architecture by leveraging on Open Standards and/or Standardizable Interfaces and formal languages/ontologies.

When it comes to the energy sector, Data Spaces domain-agnostic perspective, introduces a cross-sector perspective (data value chain), across and beyond energy, while SGAM layered model is a widely used framework in the energy sector and is centred on functions and business processes. Thus, i-STENTORE will use the SGAM architecture and hybridise it by adding and incorporating the Data Value Chain IDS business perspective, where new data-

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driven roles are included as required by the Business Use-cases and Demo requirements, such as:

- Data Provider,
- Data Service Provider,
- Data Consumers,
- Data Marketplace Operator,
- Data Broker,
- Data Cooperatives, among the others

New different roles will interact within the Energy Data Value Chain and at the interplay of Data vs Energy Value Chain (i.e., with energy stakeholders). The emergence of these new roles will give rise to a new wave of business stakeholders, participating in a secure and trusted energy data sharing, such as:

- Energy Data Aggregators,
- Data Quality Enhancement Managers,
- Data Onboarding Service providers

The interplay among Data and Energy Value Chain boosts the development of new Energy-Data-driven SMEs ecosystems, which will offer their services to energy value chain stakeholders.

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9 I-STENTORE BUILDING BLOCKS

9.1 VIRTUAL POWER PLANT

Implementation of the i-STENTORE Virtual Power Plant Tool will be focused on enhancing the Flexibility Register within the context of the IEGSA platform, which was originally developed as part of the H2020 INTERRFACE project. The aim is to build upon the Flexibility Register and develop a complete Energy Storage System Virtual Power Plant (ESS-VPP) for supervisory control over various energy storage technologies. The upgraded Flexibility Register will incorporate detailed ontologies for various energy storage systems and renewable assets. This enhanced register will not only allow the registration of these assets but also provide real-time operational data insights, enabling better operational planning for interconnected assets.

The ESS-VPP, once established, will significantly improve portfolio management efficiency. Its primary purpose will be to enable more efficient provisioning of grid-supporting services. The VPP itself will operate as a model-based supervisory and automated decision-making platform. It will be designed with replicability in mind, making it adaptable to a wide range of stationary integrated applications incorporating renewable energy sources (RES) and energy storage solutions. To connect with existing data acquisition systems, the modular supervisory system will integrate with the i-STENTORE Data Governance Middleware from Task 3.4, adhering to industrial-grade standards. Additionally, a cost-effective solution for health management and lifetime monitoring of these integrated applications will be provided. Furthermore, the VPP will deliver an automated approach covering the entire process from the design phase to the commissioning phase of the online supervisory system, encompassing the visualisation of information and data services. In summary, the VPP will be a robust, flexible, and efficient software tool that will play a pivotal role in managing and optimizing the operation of energy storage systems, renewable assets and loads.

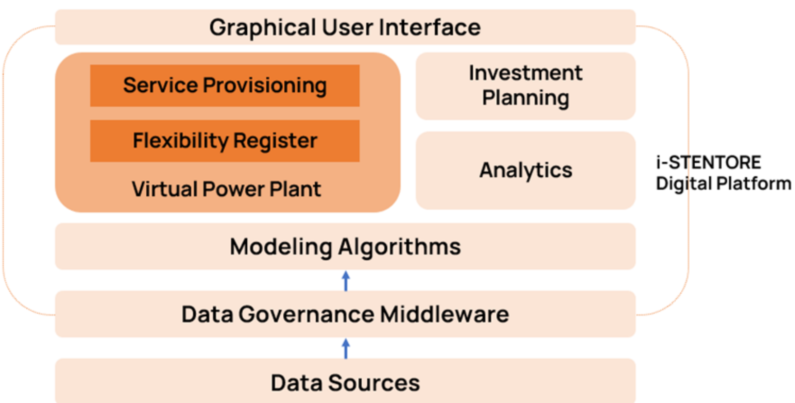

FIGURE 26: ESS-VPP COMPONENT STATIC VIEW.

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9.2 INVESTMENT PLANNING TOOL

This section describes the main features of the Investment Planning Tool (IPT) that is going to be developed in the context of Task 3.6 "Implementation of an investment planning tool" and will enable the comparison among different options for energy storage technologies. The tool gathers, under a common conceptual umbrella, several advanced Multi-Criteria Decision Analysis (MCDA) methods that will be performed taking into consideration a group of cross-sectoral criteria covering various dimensions of economic, technology, social, and environmental nature.

IPT will constitute a suite of distance-based MCDA methods. In particular, VIKOR methodology [56], [57] will be the basis of the MCDA framework, on which various recent extensions will be integrated in order to enable solving complex decision-making problems in the presence of imprecise and/or uncertain input data.

In particular, the tool will integrate both the interval [58], as well as the incomplete information [59] extension of the core MCDA method, thus covering both the cases of interval data in the payoff table, and non-crisp importance weights adopted by the user. In this sense, the tool under development will provide solutions to decision making problems that are closer to reality (augmented reification), while also allowing the users to express their preferences in terms of criteria weighting, in a way that extends beyond strictly defining numerical values to determining relative order. The tool's mechanics are presented in Figure 27, while the underlying solution methods are based on the principles of convex optimisation. More details of the calculation process of the tool are included in Appendix A.

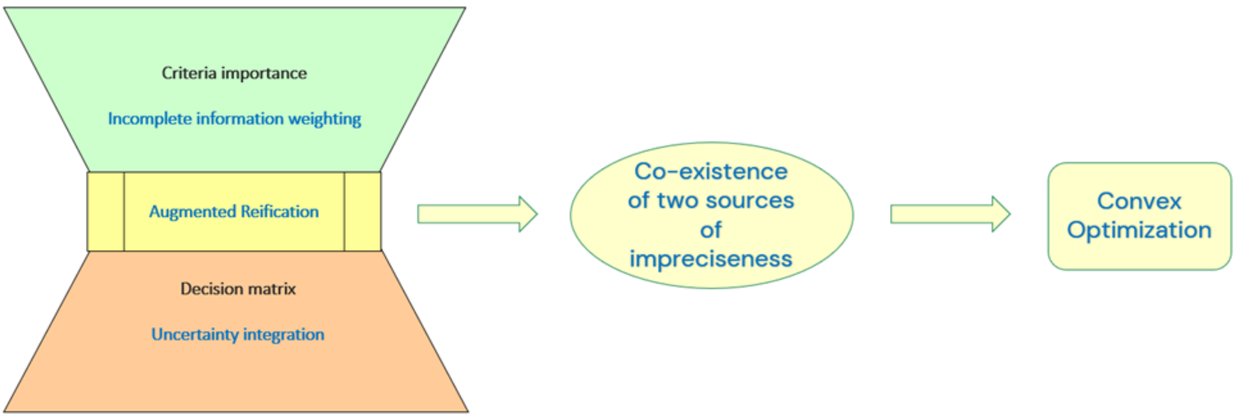

FIGURE 27: MECHANICS OF THE INVESTMENT PLANNING TOOL.

The system will be built on a foundation of cross-platform technologies, like Python and .NET Core, easily deployable on any sort of system through the use of containerisation. It will comprise a dynamic web-based front-end application, for the user interface and presentation layer, and a versatile backend API designed to serve multiple systems. The backend API will operate independently of the front-end, making it adaptable to various user interfaces and applications.

The front-end component, developed using a modern application development framework, incorporates the principles of Material Design and responsive UI elements (Figure 28). The

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backend component, implemented as a micro-service, will be responsible for executing the MCDA methods on the provided data. It will expose a stateless API that is designed to be agnostic, serving any client, be it the front-end application or another micro-service or system. This architectural approach allows for scalability, reusability, and ease of integration, making it an ideal choice for a versatile and modular system.

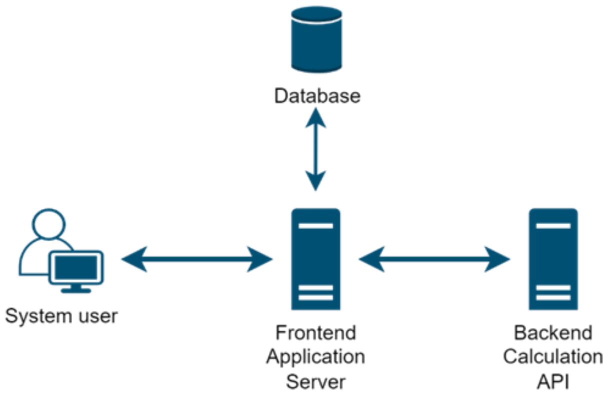

FIGURE 28: MATERIAL DESIGN.

As a side note, it should be mentioned that the development of an additional module (on top of the MCDA-based one that is described above) is currently being explored, oriented to Mathematical Programming, which assembles under a unified framework several constraints of economic, social, environmental, etc., aspects, in the scope of optimizing a set of predefined objectives (e.g., cost minimisation, risk minimisation, maximisation of RES penetration, etc.). On that reflection, users will be offered the chance to draw useful insights regarding the optimal sizing (e.g., storage capacity, etc.) of the energy storage technologies under examination and proceed with targeted and tailor-made investment solutions.

9.3 DATA GOVERNANCE MIDDLEWARE

The i-STENTORE Data Governance Middleware (iDGM), as its name suggests, is forming a layer between the underlying ESS and other interconnected assets and the i-STENTORE intelligent business layer (VPP, Investment Planning Tool, Asset Register, etc.). The primary and principal objective of the iDGM is the procurement of semantic interoperability across data providers and data consumers not only within the same i-STENTORE installation but to the whole energy and smart grid domain.

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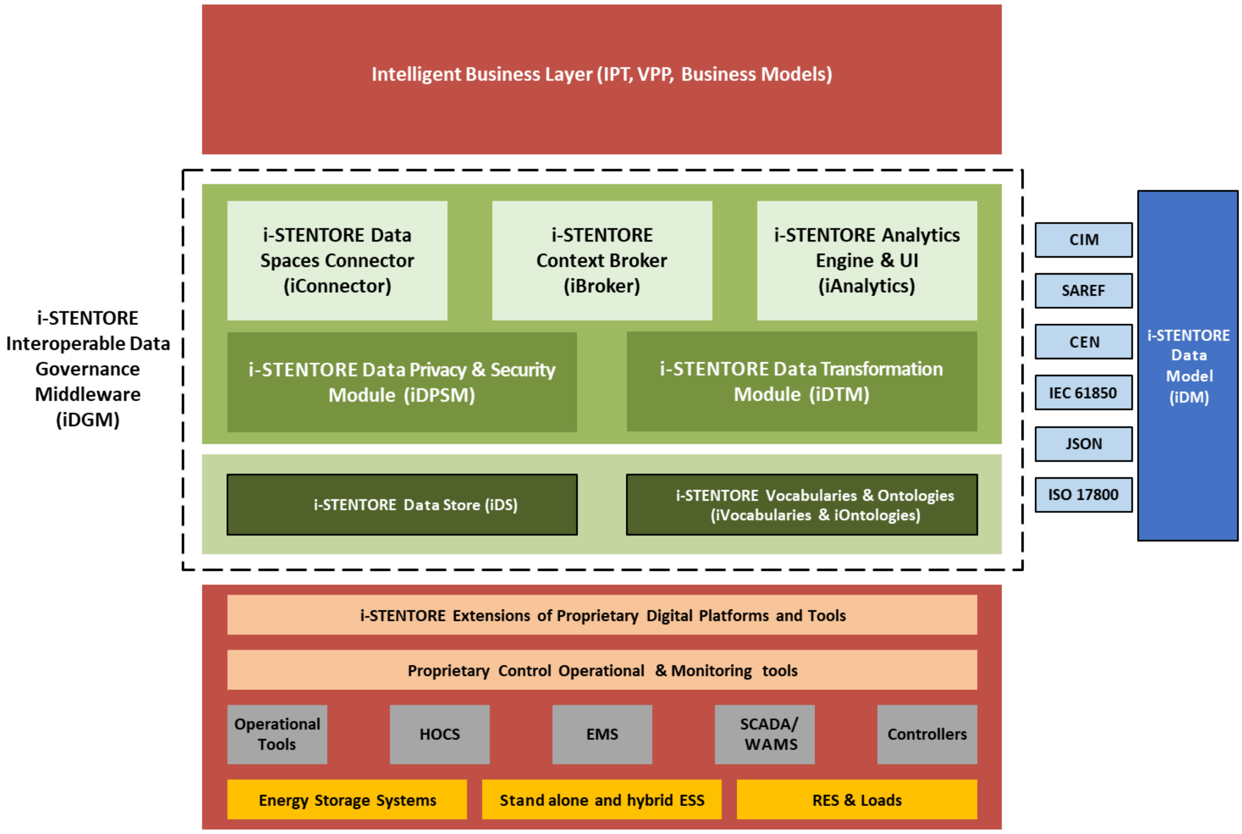

FIGURE 29: I-STENTORE DATA GOVERNANCE MIDDLEWARE DECOMPOSITION DIAGRAM (V1)

Semantic interoperability, in our case in the smart grid domain, refers to the ability of different systems to exchange and understand data in a meaningful way. Semantic interoperability is essential for the successful deployment and operation of the smart grid as the smart grid involves a wide range of heterogeneous devices and systems, all of which need to be able to communicate with each other to operate effectively.

To reach the envisioned interoperability objectives and achieve the desired functionality the iDGM will include the following internal modules and building blocks:

- i-STENTORE Set of Vocabularies & Ontologies (iVocabularies, iOntologies)
- i-STENTORE Data Store (iDS)
- i-STENTORE Context Broker (iBroker)
- i-STENTORE Data Privacy& Security Module (iDPSM)
- i-STENTORE Data Transformation Module (iDTM)
- i-STENTORE Analytics Engine & UI (iAnalytics)
- i-STENTORE Data Spaces Connector (iConnector)

Figure 29 presents the i-STENTORE Data Governance Middleware decomposition diagram (blocks in green background) with the abovementioned modules as well the related layers (in dark red background) in the i-STENTORE architecture. This is the first version of iDGM and is subject to changes or updates pending the second version of the i-STENTORE architecture.

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The final result is a data governance middleware providing functional and data interoperability between all the underlying proprietary local digital tools and systems and the functionality and capabilities implemented at the i-STENTORE intelligent business layer. This compatibility is ensured by adhering to the guidelines and recommendations of European initiatives like the European Data Space (EDS) , domain-wide established related architectures, such as IEGSA [60] and FIWARE [61] and of prominent Smart Grid Data Models (IDSA [62], family of IEC CIM standards [63]), and ontologies (SAREF4ENER [64], SAREF4Buildings [65]) as well as the potential extensions of them to fully cover the i-STENTORE user requirements. To this end, specific design decisions have been incorporated into the iDGM's modules and are analysed in the following subsections.

9.3.1 i-STENTORE Set of Vocabularies & Ontologies (iVocabularies, iOntologies)

Semantic models (conceptual data models including semantic information) are the cornerstone ingredient and perform a crucial role in achieving semantic interoperability by providing a formal representation of the concepts, relationships, and rules that govern the data being exchanged. More specifically, semantic models are the foundation for achieving semantic interoperability. They provide a shared understanding of data, enable consistent interpretation, facilitate machine-understandable processing, capture contextual information, and promote cross-domain compatibility.

i-STENTORE and the iDGM adopts semantic modelling to enable effective communication, collaboration, and leveraging of data across the different i-STENTORE tools and components as well external systems or applications in the energy domain or even different but relevant domains. The semantic modelling is achieved through the development and use of ontologies and vocabularies. Based on standard ontologies and vocabularies available for the smart grid domain, such as the Common Information Model (CIM) and SAREF4ENER the i-STENTORE Set of Vocabularies & Ontologies (iVocabularies & iOntologies) will be developed to support and facilitate internal information exchange and compliance with external standards and initiatives. The iVocabularies & iOntologies exact form and features will be extracted by the description of the detailed i-STENTORE use cases and the involved actors, roles, business entities and data requirements.

The iVocabularies will be developed to ensure consistent data description within the i-STENTORE platform boundaries. Since a vocabulary is a list of terms that can be used to describe data within a domain but does not define the relationships between the terms or their properties, it cannot be used to reason about data. On the other hand, an ontology is a formal representation of a set of concepts within a domain. It defines the concepts, their relationships to each other, and their properties. An ontology can be used not only to reason about data but also to ensure that it is consistent and complete. In general, ontologies are more powerful than vocabularies, but they are also more complex to develop and maintain. In case, specific reasoning requirements emerge or formal and transparent cross-platform or cross-domain data exchange is expected by the iDGM, the iOntologies will be developed to support the i-STENTORE seamless interaction with and participation with external established industry standardised ecosystems.

9.3.2 i-STENTORE Data Store (iDS)

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The iDGM requires a data storage module for the persistent storage of historical data related to the underlying energy assets and potentially to the actions performed on the data within the i-STENTORE platform. This role will be covered by the i-STENTORE Data Store (iDS) which will allow utilisation of data stored by the rest of IGM's modules for or a variety of purposes, such as analysis, reporting, and machine learning.

Besides persistence storage, the following functions are envisioned to be covered by the iDS:

- **Efficient data retrieval:** iDGM modules should be able to access historical data quickly and easily.
- **Data scalability:** iDS will need to be able to scale storage and manage large amounts of data consistently as more data are generated and persisted in the data store.
- **Data consistency:** iDS will need to ensure that the data in the data store is consistent and accurate, especially since this is an important feature for applications that rely on the data for decision-making.
- **Data security:** iDS will need to support data protection from unauthorized access as private data will be stored in the data store.
- **Data recovery:** iDS will need to be able to backup data to external storage spaces and recover them to the data store in the event of a disaster.

The main design decision for the iDS is the selecting a specific database engine to utilise. This decision should be compatible with the i-STENTORE Context Broker (iBroker) as the iBroker is the main module for data input and output to and from the iDS.

The review of database systems fulfilling the above requirements has produced the following candidates:

- HDFS [66], the Hadoop distributed file system,
- MySQL [67], a well-known opensource relational database manager,
- PostgreSQL [68], another well-known opensource relational database manager,
- MongoDB [69], the NoSQL document-oriented database,
- Kafka [70], a publish-subscribe messaging broker,
- Elasticsearch [71], a distributed full-text search engine with JSON documents.

The exact datastore selected will be described in the next version of the i-STENTORE architecture.

9.3.3 i-STENTORE Context Broker (iBroker)

The i-STENTORE Context Broker (iBroker) is the core component of the iDGM enabling the semantic interoperability of the i-STENTORE platform with the energy storage domain and the coherent real-time interaction between a diverse set of stakeholders in the energy value chain.

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The iBroker is compatible with the FIWARE Context Broker [72] paradigm by implementing a NGSIv2 REST API [73] to manage the entire lifecycle of both data and context information in i-STENTORE including acquisitions, updates, queries, registrations and subscriptions.

The NGSIv2 REST API is a standardized API for managing and providing access to real-time context information. Using the NGSIv2 REST API provides several advantages, including:

- **Standardization:** The NGSIv2 REST API is a standardized API, which means that it is defined and understood by a wide range of software vendors and developers. This makes it easy to integrate Context Brokers with other systems and applications.
- **Ease of use:** The NGSIv2 REST API is a simple and easy-to-use API. It uses a consistent set of HTTP methods and JSON-based data representation, which makes it easy to learn and use.
- **Flexibility:** The NGSIv2 REST API is a flexible API that can be used to CRUD (create, read, update, delete) context information. It can also be used to query context information and to subscribe to context updates.
- **Language independence:** The NGSIv2 REST API is a language-independent API. This means that it can be used with any programming language that has an HTTP client library.
- **Platform independence:** The NGSIv2 REST API is a platform-independent API. This means that it can be used with any operating system or hardware platform.
- **Widespread adoption:** The NGSIv2 REST API is a widely adopted API. It is used by a wide range of Context Brokers and applications.
- **Future-proof:** The NGSIv2 REST API is a future-proof API. It is designed to be extensible and to support new features in the future.

The iBroker functionality, based on a NGSIv2-compatible REST API will include the following features:

- **Managing context information:** to create, read, update, and delete context entities and attributes.
- **Querying context information:** query context information using a variety of filters and operators.
- **Subscribing to context updates:** subscribe to context updates so subscribers (i-STENTORE applications and components) can be notified whenever the context information changes.
- **Integrating with other systems:** integration of the iBroker with underlying digital platforms as IoT platforms, data analytics platforms, visualization tools as well as external systems. To be noted that the integration with the data spaces ecosystem is not handled by the iBroker but by the i-STENTORE Data Spaces Connector (iConnector).

The proposed approach is to base iBroker on Cygnus [74] a lightweight and easy-to-use NGSIv2 REST API context broker implemented in Python. Cygnus, besides being a powerful, flexible, and scalable context broker, it is a mature and well-tested platform that is used by a large number of organizations around the world. Moreover, Cygnus is an open-source context broker, freely available to use and modify. This will enable i-STENTORE to avoid

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vendor lock-in and customise iBroker to meet the specific needs of the i-STENTORE stakeholders. Moreover, iBroker is intended to be used by all internal and external to the iDGM components and modules to minimise need for development of data transformation logic (see iDTM).

9.3.4 i-STENTORE Data Privacy & Security Module (iDPSM)

The i-STENTORE Data Privacy & Security Module (iDPSM) is responsible for implementing the full extent of privacy and security measures on the data persisted in the iDS, including authentication, authorisation, encryption and anonymisation schemas to protect data, specifically sensitive one, during transactions and at rest.

The Cygnus Context Broker does not have native authentication and authorisation mechanisms so it relies on an external authentication and authorisation server to authenticate and authorise users and applications. In this context, the iDPSM works in collaboration with the iBroker as every iBroker action is filtered through the iDPSM to ensure data access is provided only to the intended actors emerging from the respective user requirements.

The most common way to implement data security within an FIWARE-compatible Context Broker is to use the FIWARE Keyrock Identity Management system [75]. Keyrock is an open-source identity management system that provides OAuth2 authentication and authorization services.

The proposed approach is to base iDPSM by extending Keyrock to implement role-based access control (RBAC) for the iBroker. RBAC will allow administrators to define roles for users and applications, and to grant permissions to those roles. Besides controlling who has access to what data through the iBroker, iDPSM will implement appropriate data privacy measures including:

- **Data anonymisation:** This involves removing or modifying personal data so that it can no longer be identified with an individual. This can be done by removing identifying information such as names, addresses, and phone numbers.
- **Data pseudonymisation:** This involves replacing identifying information with pseudonyms or other non-identifying data. This can be done by replacing names with numbers or assigning pseudonyms to individuals.
- **Data minimization:** This involves only collecting the data that is necessary for a specific purpose. This can be done by only collecting data that is directly relevant to the purpose for which it is being collected and by deleting data that is no longer needed.
- **Data encryption:** This involves encrypting data so that it can only be read by authorized persons. This can be done using encryption algorithms such as AES or RSA.
- **Data disposal:** This involves securely disposing of data when it is no longer needed.

9.3.5 i-STENTORE Data Transformation Module (iDTM)

The i-STENTORE Data Transformation Module (iDTM) is responsible for all the essential data transformation procedures for preparing i-STENTORE ecosystem data to be acquired and

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consumed in a variety of internal processes, such as forecasts, grid analytics, and demand response programs. By transforming data into a clean, consistent, and meaningful format, the i-STENTORE platform can gain maximum value from the data produced at the demo sites.

The planned approach intends to minimize data transformation procedures by rolling the burden to the iBroker. This entails making a best effort attempt to enforce all data related operations through the iBroker and achieve the exclusive exchange of semantic information. The development of data transformation logic will probably be required to transform data between the i-STENTORE Data Spaces Connector (iConnector) and the iBroker. These operations may involve data mapping, translation, and adaptation to ensure compatibility between the two modules.

Moreover, the need for the iDTM to handle data synchronization and implement error handling operations will be examined. Data synchronization may be required for real-time or batch data synchronisation between the iConnector and the iBroker to ensure that changes in one module are reflected in the other. To render this mechanism redundant, the design of the iDGM will explore the possibility to make the iDS a common data store for both the iBroker and the iConnector (See iConnector). The implementation of error handling mechanisms may be required to monitor data acquisition procedures and address any issues that may be reported by data consumers.

Therefore, depending on the need for specific data requirements the following functionality could be implemented in the context of the iDTM:

- **Data cleaning and pre-processing:** This involves identifying and correcting errors, inconsistencies, and missing values in the raw data. It also involves normalising data formats and units to ensure consistency.
- **Data aggregation and summarisation:** This involves reducing the volume of data by summarising or aggregating it into smaller units. This can be done by averaging, min-maxing, or using other aggregation methods.
- **Data imputation:** This involves filling in missing values in the data. This can be done using statistical methods, machine learning algorithms, or other imputation techniques.
- **Data enrichment:** This involves adding additional information to the data to make it more useful. This can be done by linking data to other sources, such as weather data or geographical information systems (GIS) data.
- **Feature engineering:** This involves creating new features from existing data. This can be done by transforming data into new formats, extracting new information from data, or combining data from different sources.
- **Data normalisation:** This involves scaling data to a consistent range. This can be done using techniques such as min-max normalisation, z-score normalisation, or decimal scaling.
- **Data validation:** This involves verifying the accuracy and completeness of the data. This can be done using statistical methods, data quality checks, or other validation techniques.

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- **Data formatting:** This involves converting data into a format that can be easily processed by other applications or modules. This can involve converting data into a structured format, such as CSV or JSON, or into a format that is optimised for storage or transmission.

9.3.6 i-STENTORE Analytics Engine & UI (iAnalytics)

The purpose of the i-STENTORE Analytics Engine & UI (iAnalytics) is to provide mechanisms of data collection and analysis to extract meaningful insights and attempt to understand trends, identify patterns, and make better decisions beyond the functionality already implemented in the digital platforms of the demo sites. From a system capability viewpoint, the iAnalytics engine will perform the heavy lifting of data analysing, aggregation and summarisation. From a user experience viewpoint, the objective is to design the iAnalytics' UI to be easy to use, navigate, visualise and interact with the results.

9.3.7 i-STENTORE Data Spaces Connector (iConnector)

In the coming months of the project the team will examine, based on the Functional Requirements, whether there is an actual need to integrate the i-STENTORE digital platform with the IDSA framework. In the case that such an integration proves useful will design and implement the i-STENTORE Data Spaces Connector (iConnector).

The i-STENTORE Data Spaces Connector (iConnector) connects the iDGM to the IDS dataspace. iConnector is an IDS connector [76] compatible software module adhering to IDS specifications to enable interoperability of an i-STENTORE platform installation to the International Data Spaces (IDS) ecosystem. More specifically, it enables the exchange of data and metadata between i-STENTORE and the IDS ecosystem, in accordance with the IDS principles and standards, and particularly the IDS Reference Architecture Model [77].

The iConnector's role is enabling secure, controlled, and interoperable data sharing within the IDS ecosystem, facilitating the exchange of data and metadata, promote trust between organizations, enable application integration, and foster interoperability in the energy domain. By connecting i-STENTORE installations to the IDS ecosystem, the iConnector module can leverage the power of data sharing and collaboration between actors and stakeholders in the energy domain and assist them to drive innovation and create value in both the data and the services layers.

The most important advantages intended to be delivered through the iConnector by the participation of i-STENTORE-enabled organisations to the IDS ecosystem include:

- **Establishment of trust:** The utilisation of secure communication protocols, authentication mechanisms, and authorisation policies adopted by the IDS Reference Architecture Model will enable secure and collaborative data sharing of i-STENTORE installations participating in the IDS ecosystem.
- **Application integration:** The iConnector will enable the integration of i-STENTORE installations with IDS applications and services to leverage the capabilities of the IDS ecosystem regarding the process, analysis, and utilisation of the produced data in new and innovative paradigms.

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- **Interoperability:** The iConnector will promote interoperability between different systems and technologies in the IDS ecosystem. The use of open standards and protocols, such as NGSI-LD [78], will enable seamless communication and data exchange.

9.4 PROPRIETARY COMPONENTS & PLATFORMS

9.4.1 PILOT 1 – Slovenia

Figure 30 illustrates the Pilot architecture along with its components. Some of the components are proprietary thus direct access to them is not enabled due to security and safety reasons. Specifically, the furnace can only be indirectly controlled using OPC server tags.

Breakdown of components of Demo 1:

- **OPC Server:** The furnace, a critical component in the glass manufacturing process, is equipped with a proprietary control system. Direct access to this system is restricted for security and safety reasons. Instead, control and monitoring are facilitated through OPC server tags, ensuring a level of separation and safety.
- **Furnace monitoring system (FMS):** is a proprietary component essential for monitoring the furnace's operation. It has the capability to overdrive requests, which is essential to ensure glass batch quality and safety. However, it is not directly controllable by external systems, including the flexibility service.

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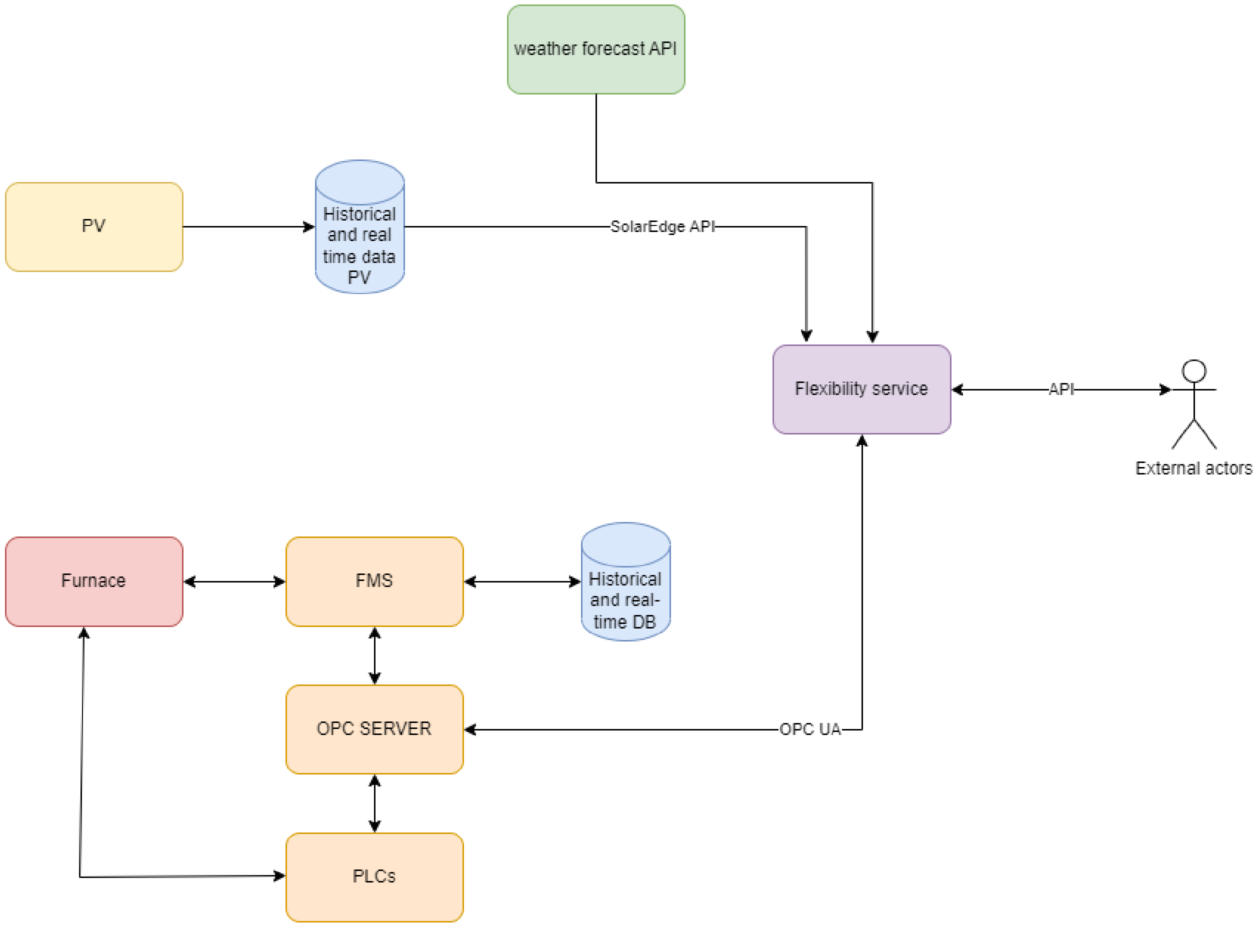

FIGURE 30: PILOT 1 ARCHITECTURE.

- **Programmable Logic Controller (PLC):** The PLC is a critical component of the glass manufacturing process. Like the FMS, it is not directly controllable by external systems but is essential for managing the furnace's operations.
- **Historical and Real-Time PV DB (DataBase):** Another proprietary component is the connection to historical and real-time PV data. This connection is established through the SolarEdge monitoring server API, which requires a unique API key for access. This data is crucial for optimizing the use of solar power in conjunction with the glass melting process.
- **External Flexibility Service:** This analytic component under development by partner COMS is an intermediary between the external systems and the proprietary furnace components. Its main goal is to optimise the day ahead usage of the PV energy and provide auxiliary service to external actors related to the flexibility energy available in the molten glass thermal energy storage. Service needs to be designed to be aware of the limitations and capabilities of the furnace, PLC, and FMS by reading predefined tags from the OPC server. This awareness allows the flexibility service to adjust its algorithms to align with the available electric power boost and maintain the safety and quality of the glass manufacturing process.

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- **VPN:** Components related to the control of the furnace, including the furnace control system, PLC, and FMS, are located within the Hrastnik VPN. This VPN ensures secure communication and access control for these critical systems.

9.4.2 PILOT 2 - Portugal

Demo 2 has installed essential proprietary components, including a Li-ion battery and hydropower system with a reservoir. To further enhance the Hybrid Energy Storage System (HESS), Demo 2 leader and its partners are in the process of purchasing and installing a Vanadium Redox Flow Battery (VRFB) and synchronous condenser. The VRFB to be installed in Madeira Island is a 50 kW/50kWh battery that will be assembled and tested in Porto. After validation and verification processes being concluded in Porto, the battery will be transported by sea to Madeira.

As displayed in Figure 31 and Figure 32, the VRFB system is going to be installed in a 20 ft customised ship container. The container will have thermal insulation and HVAC to ensure suitable operating temperature as well as protection against saline environments (to prevent corrosion of materials). The electrolyte tanks will not be transported to Madeira inside the container, given it is considered a dangerous substance and therefore must be transported in accordance to a specific protocol.

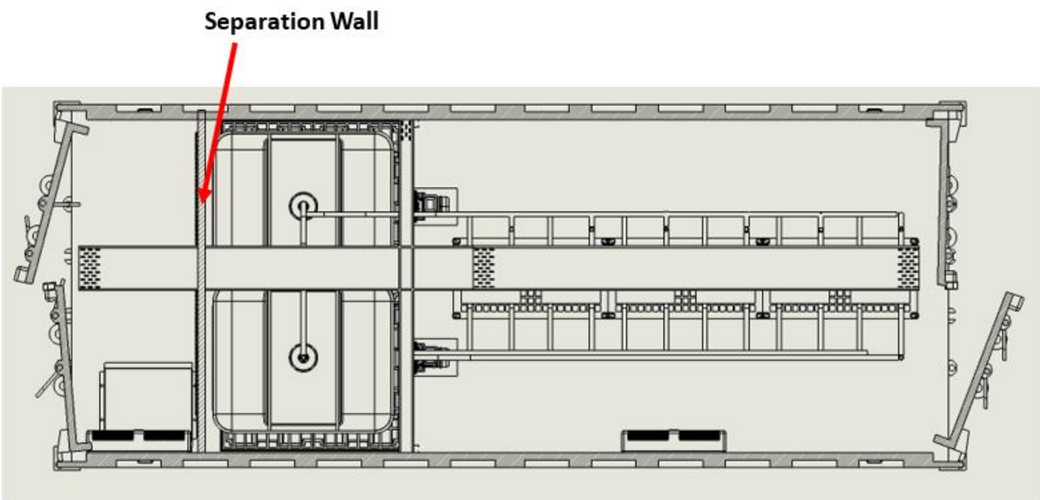

FIGURE 31: VRFB INSTALLATION LAYOUT.

The battery is composed of 12 stacks, 4 kW each, that can be overcharged up to 10 % thus totalling 50 kW, one pair of tanks of electrolyte, one pair of centrifugal pumps, DC-DC converters, DC-AC converter and grid isolation interface. The stacks will be hydraulically connected in parallel. To attain the 50 kWh, the battery will need 2127 L of electrolyte. The stack's output voltage varies between 40 V to 63 V. The power converters will ensure the interface between the battery and the grid (400 V AC three-phase).

Within the container, the power electronics and the electrochemical battery parts are separated by a separation wall to prevent damaging the electronics part in case of an electrolyte leakage.

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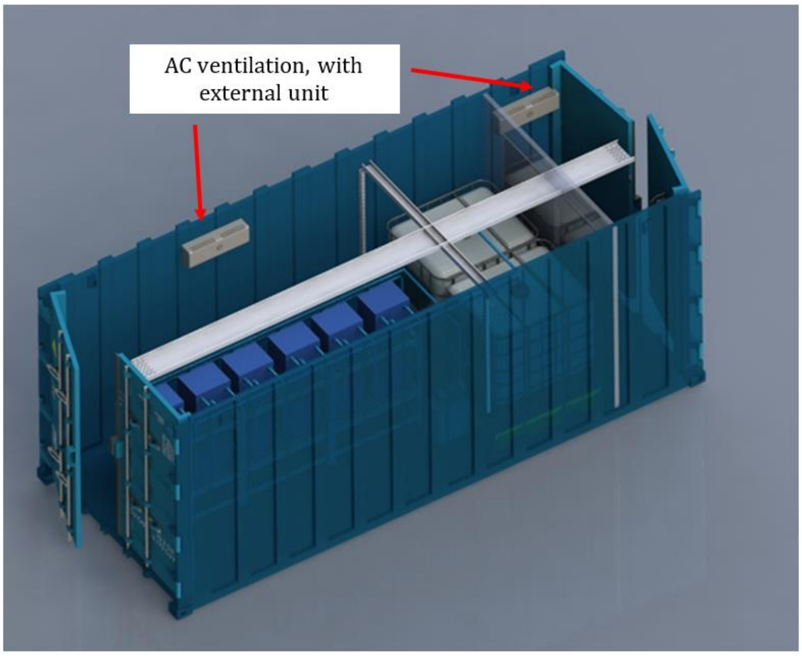

FIGURE 32: 3D VIEW OF THE VRFB CONTAINER LAYOUT.

This HESS is used to address common problems in isolated micro-grids with renewable energy production, from smoothing out photovoltaic (PV) ramps to regulating grid frequency and mitigating renewable energy curtailment. The HESS represents a significant step toward optimising our energy resources on Madeira Island.

To integrate all the technologies present in the HESS, EEM, the System Operator (SO) needs to manage and monitor this system. EEM relies on its Supervisory Control and Data Acquisition (SCADA) platform.

9.4.3 PILOT 3 - Spain

In Demo 3, the integration of energy storage plays a pivotal role in optimizing Granada's energy system. A Vanadium Redox Flow Battery (VRFB) strategically resides at a wind plant substation in Padul, while a Lithium-ion Battery (LIB) is located at the "Parque Metropolitano Solar" PV power plant in Escúzar. These components significantly enhance grid stability and streamline the incorporation of renewable energy. Furthermore, the collaboration of a small hydropower plant with the VRFB and LIB contributes to storage technology utilisation, further improving grid stability and renewable energy integration.

The renewable power plants interact dynamically with the VRFB and LIB through a Hierarchical Operation and Control System (HOCS). This system enables real-time coordination, allowing these diverse energy assets to provide various services and seamlessly participate in the current and future market infrastructure. The HOCS ensures these components work together to offer grid support services while managing battery degradation.

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Demo 3's HOCS employs advanced technology tools for real-time interactions among the assets in the distribution area, including renewable power plants, VRFB, and LIB. The HOCS features a hierarchical structure with three control layers for effective energy asset management. The lower layers handle local control and operation, each asset having its dedicated local management system instance. Above them, the middle layer coordinates data exchange among local operation instances and the i-STENTORE Reference Architecture. The upper layer, focused on market operations, oversees VESS energy and services trading, as shown in Figure 33.

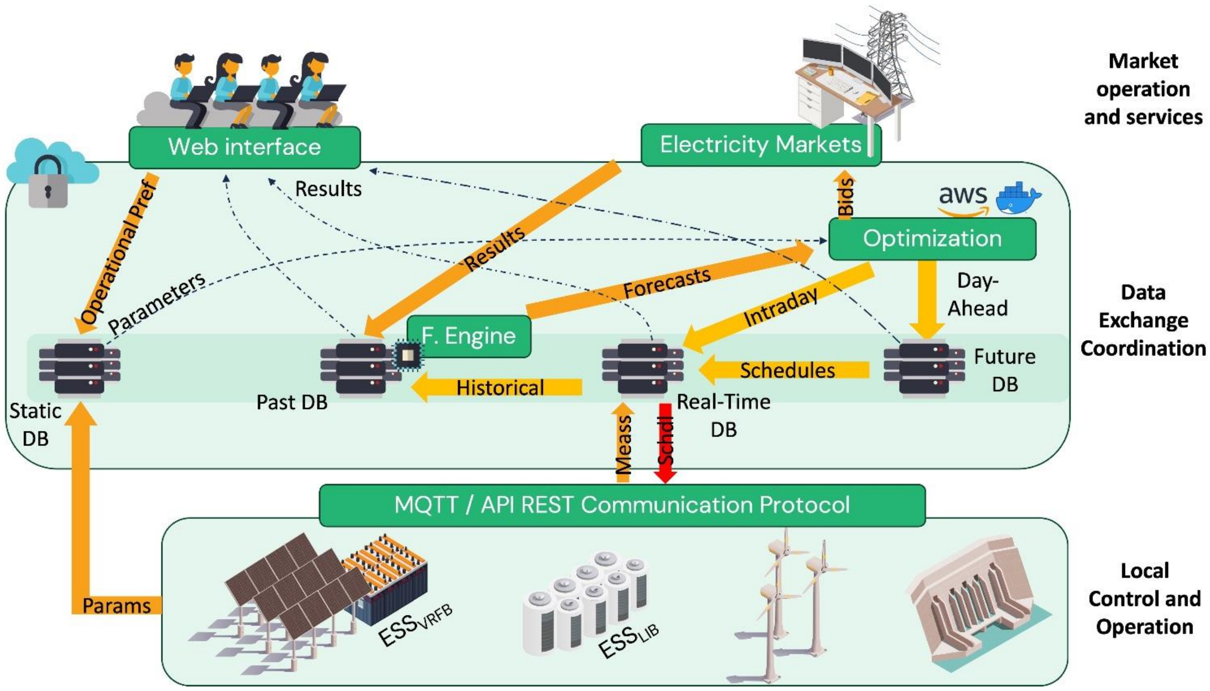

FIGURE 33: HOCS CONTROL LAYERS AND INTERACTIONS WITHIN THE CONTROL SYSTEM.

Figure 33 presents the conceptual platform architecture of Demo 3, consisting of four distinct databases tailored for specific temporal data characteristics. The 'static DB' stores component definitions and user account details, crucial for access control. In contrast, the 'real-time DB' captures streaming data from component metering devices, alongside specifications and parameters.

VESS components continually measure variables such as voltage, current, and power in real-time. They transmit this data to the real-time database, which also includes operational state information, alarms, and warnings. This data temporarily resides in buffer tables, following a Last-In-First-Out (LIFO) approach before moving to the 'past DB.' Historical data in the past DB becomes a valuable resource for the forecast engine, generating vital forecasts, including energy production and market prices.

These forecasts, coupled with operational parameters, guide the optimisation engine in forming BESS schedules and bids. The 'day-ahead' service first stores schedules in the 'future DB' before transitioning them to the 'real-time DB'. Subsequently, the schedules are relayed to VESS units and the market. Forecasts and optimisation results are archived in the 'past DB' for analysis.

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To efficiently manage these databases, Demo 3 combines SQL, NoSQL, and time-series database technologies. Inter-component communication relies on HTTP requests, while interactions between the platform and VESS assets are facilitated through the MQTT protocol.

The core of Demo 3's operation hinges on mathematical optimisation processes integrated into a cloud-based structure hosted on Amazon Web Services (AWS). Figure 33 illustrates the strategic placement of this optimisation container within AWS, facilitating interactions among diverse cloud components and databases. The platform acts as the central hub for VESS management, offering real-time analysis and continuous data collection from VESS components.

Furthermore, the platform excels in optimizing energy trading by evaluating and forecasting data related to energy demand, renewable generation, and market prices. This process identifies trading opportunities, enhancing economic efficiency. Utilizing Docker containers within AWS ensures operational efficiency. A web interface provides essential user interaction, offering real-time data, schedules, and graphical representations for informed decision-making.

Demo 3's components and platforms bridge traditionally isolated energy systems, fostering interoperable interfaces across diverse energy sectors. The Hierarchical Operation and Control System (HOCS), cloud-based platform, and energy storage components enhance data trust, ensuring secure information flow while respecting data sovereignty. These solutions promote interoperability, data trust, and grid flexibility, creating a sustainable, responsive, and consumer-centric European energy system, which is aligned with the Reference Architecture principles of the i-STENTORE Project.

In overall, Demo 3 represents a significant stride towards an integrated, efficient, and consumer-centric European energy system. Its strategic deployment of energy storage components, innovative control systems, and cloud-based digital platforms aligns seamlessly with the i-STENTORE Reference Architecture. This integration not only promotes interoperability but also instils trust in data management and enhances grid flexibility, ushering in a sustainable and responsive energy landscape for all stakeholders.

9.4.4 PILOT 4 - Italy

The objective of **DEMO 4** is to demonstrate different ESS applications to improve Electric Vehicle (EV) charging services and to provide energy to the grid when it is needed (see Figure 34). The main applications are:

- to use stationary **hybrid energy storage system (HESS)** for the improvement of EV **Ultra-Fast Charging** performance in terms of charging time, lifetime of battery-based charger and impact on the grid distribution,
- to promote the concept of "**We bring energy to your vehicle right, where and when it is needed",**
- to use a **portable swappable battery charger** to reduce range anxiety,
- to promote the application of V2G to highlight the benefit to the grid, and

- to promote PV grid penetration and sharing of extra-stored energy from stationary hybrid storage plants and **Mobile Chargers** for EV mobility service.

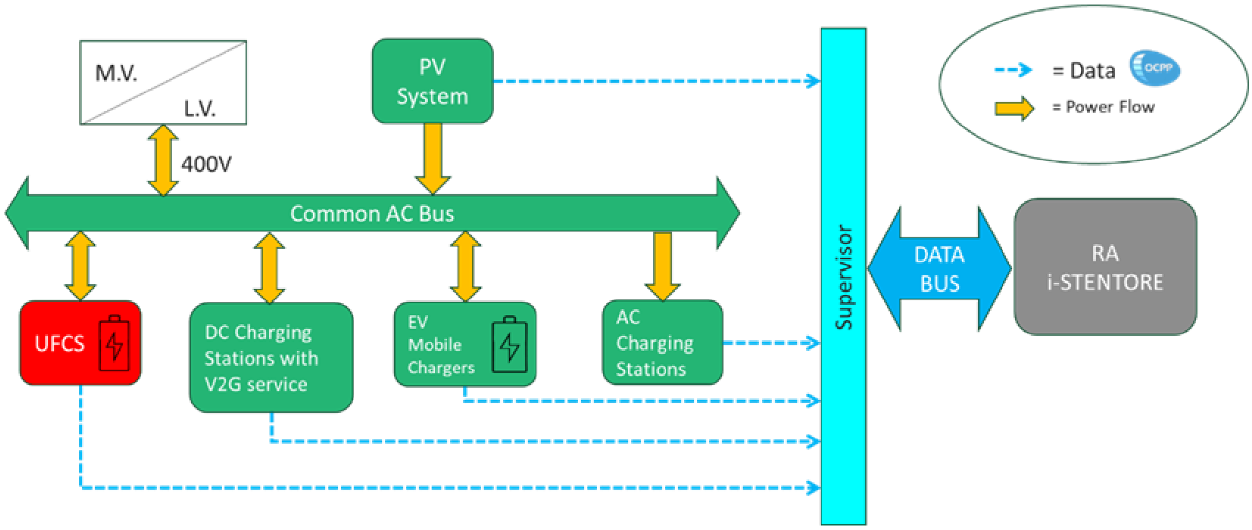

FIGURE 34: GLOBAL DEMO 4 PLANT SCHEME.

The charging infrastructure will be installed in a strategic position in the south of Italy to offer sustainable tourism through the sharing of electric mobility with the creation of "destination chargers" in the main tourist centres.

The Ultra-Fast Charging Station will be upgraded with an HESS composed of a lithium NMC battery storage system (the actual BESS installed) and a LTO battery storage system controlled by a DC/DC converter. The potential innovation of this upgrade could be cost savings related to the extended batteries lifetime. The new modules will be interfaced with the actual charging point with the same communication protocol (modbus TCP/IP) used for the current installed modules and then the UFCS will be capable of communicating to the smart charge infrastructure through Open Charge Point Protocol (OCPP) (see Figure 35).

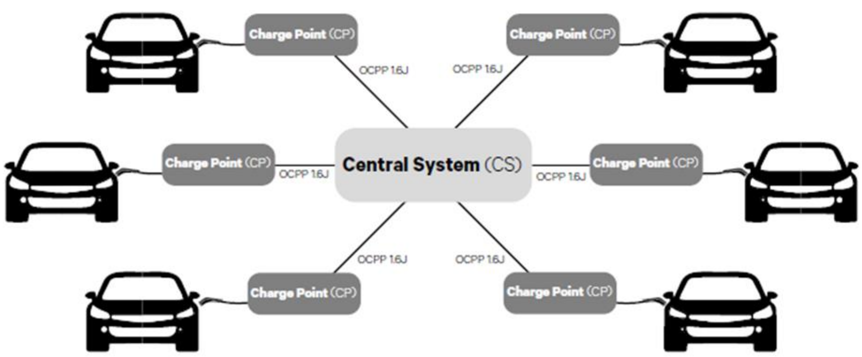

FIGURE 35: OCPP APPLICATION IN A GENERIC CHARGE INFRASTRUCTURE.

The OCPP is a standard and open protocol for communication between generic charging points (CP) and the central system (CS), where the operator mainly can monitor the status

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of charging points, the electrical measurements and authorize who can perform charging or perform tasks remotely, such as interrupting a transaction in progress.

Infrastructures will be managed by SCADA system that monitors the PV implants, batteries and micro-grid present in the charging hub and to collect and record data relating to their activities.

SCADA system will record the data from PV plant production and calculate the power exchanged with micro-grid (battery, SuperCap and charging stations).

Additionally, we'll record the energy provided from the Hybrid Storage to the Ultra-Fast Charging Station to calculate the energy saving provided by storage.

Charging stations will be monitored and managed by back-end software provided by Go Electric Stations, it allows us to monitor number of charging session, kWh supplied, revenues, logs. Moreover, we can manage the stations from remote in case of troubleshooting, remote diagnostics and re-boot in case of troubles.

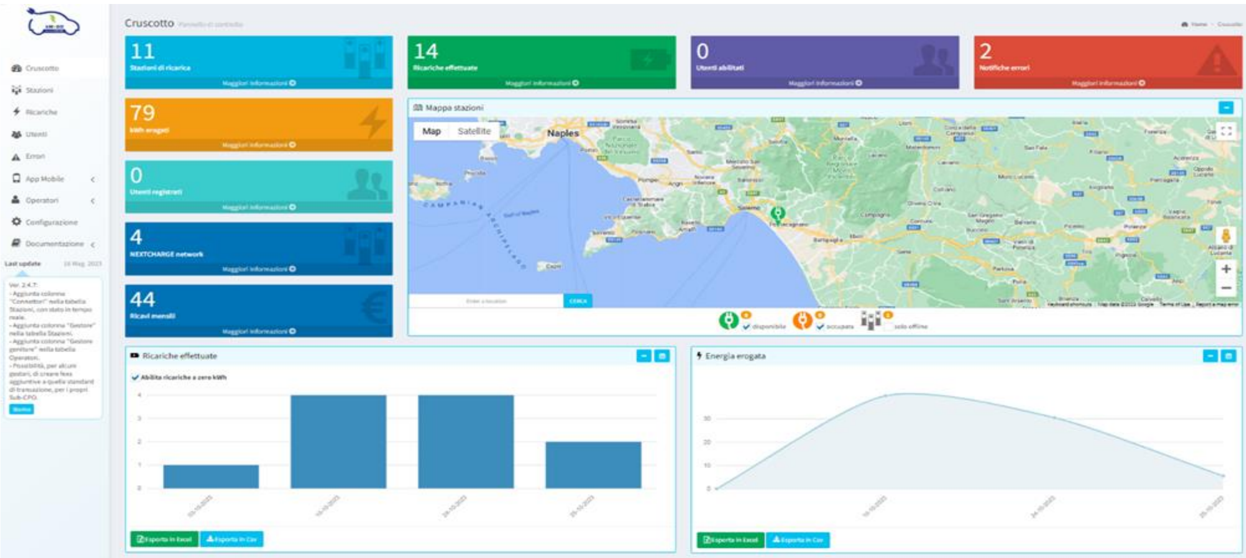

FIGURE 36: BACK-END SOFTWARE.

Database is stored on Go Electric Stations servers and we can retrieve the data in real time from our account for each charging station.

App is already in place and it is powered by Go Electric stations, in this App we can gather all the information related to number of charging session, kWh charged, users management, errors.

This app allows the EV drivers to find our charging stations and start charging through wallet or credit card accounts.

9.4.5 PILOT 5 – Luxembourg

The pilot integrates a hybrid energy storage system consisting of two different technologies, a large-scale electrolyser for green hydrogen production and a utility-scale BESS with an

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agri-photovoltaic (APV) plant and wind power generation. The hydrogen produced by the electrolyser will be stored in trailers and transported over short distances to industrial users. The energy management of the farm's assets will be ensured by the optimal operation of the BESS. The high-capacity, grid-forming BESS will provide new flexibility functionalities to the APV system and will be designed to potentially provide ancillary and flexibility services to the distribution grid. A proprietary high-precision HOCS to dynamically control the different operation scenarios of all energy processes at the different levels. The HOCS operation planning will be continuously optimised accordingly **with real-time multi-objective numerical models** taking into account the potential degrees of the energy storage systems and the forecasts of the APV generation, local energy demand and wholesale market prices.

The conceptual diagram of the platform that will host the different databases, services and relevant processes is shown in the Figure 37**.** The platform consists of four databases grouping the data according to their temporal characteristics with respect to the services. These databases are called, ***management***, ***operation***, ***planning*** and ***historical***.

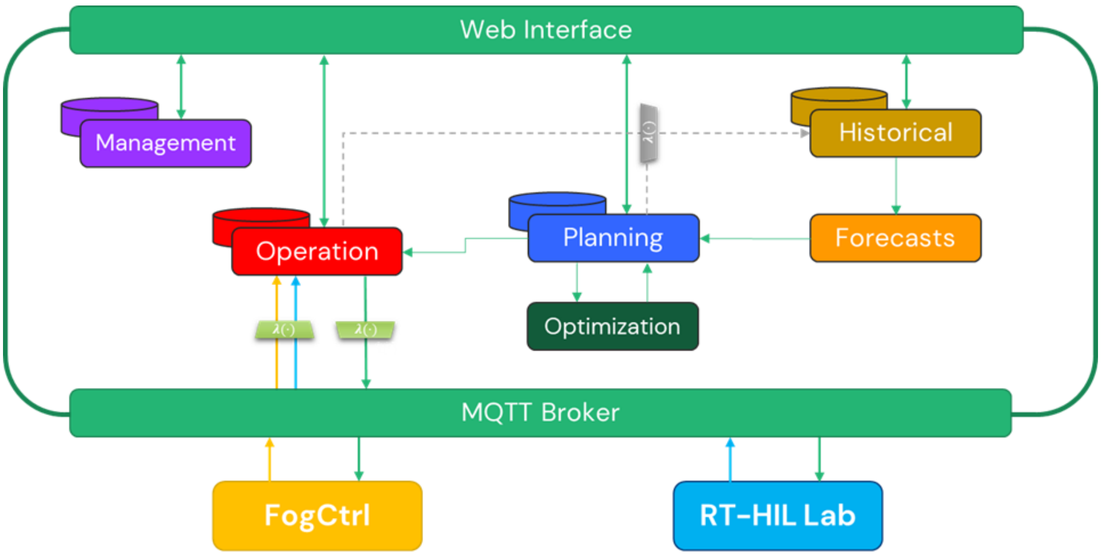

FIGURE 37: CONCEPTUAL FLOW DIAGRAM OF THE CONTROL PLATFORM OF DEMO 5.

- ***Management DB:*** Stores information about user accounts (credentials and basic details), the characteristics and specifications of the energy components of this demo, i.e., the BESS, Electrolyser, Hydrogen tank, etc.
- ***Operation DB:*** Stores streaming data from sensors and metering devices from the different components in real-time. Also, it includes information about the active services.
- ***Planning DB:*** Stores information related to short term planning i.e., from 24 to 72 hours ahead. The planning of the demo is based on certain inputs, like forecasts of generation and wholesale market prices. This information is also stored in this database.
- ***Historical DB:*** Essentially keeps a record of all data from the operation and planning DBS for later analysis and evaluation. These data are used also from the forecast engine for fitting new more accurate models and provide the actual forecasts.

The '**Forecasts**' block hosts processes that are required for retrieving relevant data from the historical database, loading the appropriate model, and providing the forecasts that are

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necessary for the '**Optimisation**' block. The 'Optimisation' block hosts the optimisation models for the different services. This block will pull inputs and push outputs to the planning DB. The platform will interact with the demo components using the MQTT protocol through a message broker. During the design and development phase, these components will be simulated in the RT-HIL laboratory to enable message exchange between the platform and the real-time simulators. Later, communication with the real equipment will be established using the same structure as with the virtual equivalents. All the data resulting from the different processes will be accessible through dedicated dashboards hosted on a web-interface.

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10 TECHNICAL CONVERGENCE: I-STENTORE HIGH-LEVEL S/W ARCHITECTURE

Figure 38 attempts to visualise a high-level i-STENTORE concept based on the current information at the time of writing, regarding:

- Reference Architecture Models
- Business Use Cases as application scenarios
- Functional Requirements

The idea is to create a concept consisting of building blocks (software components) in an hierarchical manner, that present the information & data process flow, among the different building blocks. The concept also attempts to present the potential interfaces (interconnections between components) which upon finalisation will assist in the API design and implementation. This first conceptual version of the i-STENTORE software reference architecture will be refined as the project progresses and the ideas mature and in the second version of this deliverable we will zoom-in and examine what lies in the background of each one of these building blocks and how all interconnections and data exchanges will be implemented.

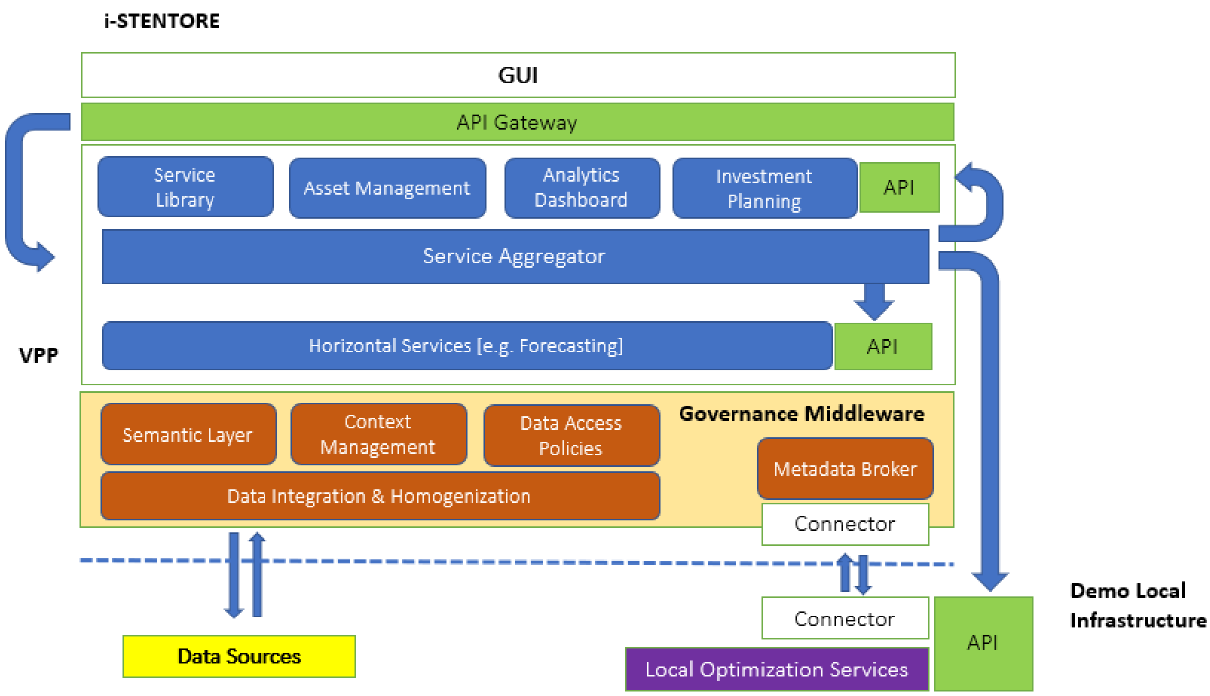

FIGURE 38: THE I-STENTORE HIGH-LEVEL S/W RA.

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11 INTEGRATION PROCESS AND GUIDELINES

Integrating software components and systems is a critical aspect of software development. A well-defined methodology and guidelines are essential to ensure that integration is smooth, efficient, and error-free. In i-STENTORE the integration process will be based on a stepwise approach which will smooth the framework development process. This Chapter describes the methodology that will be followed for the integration of the i-STENTORE components. The actual integration plan will be an outcome of Task 3.7, the activities of which will also implement the integration. The plan will be documented, refined and updated in Deliverables 3.4-3.6. The below list presents the basic integration process step from a methodological perspective:

Planning:

- **Define integration objectives:** Clearly specify what needs to be achieved through integration.
- **Identify integration points:** Determine which components or systems need to be integrated.
- **Create a timeline:** Establish a schedule for integration activities.

Integration Environment Setup:

- Set up a dedicated integration environment that mirrors the production environment as closely as possible.
- Configure version control systems and issue tracking tools for integration.

Integration Testing:

- Perform unit testing for individual components to ensure they work as expected.
- Execute integration tests to verify the interactions between different components.
- Use test cases and test data that cover various scenarios, including edge cases and common use cases.
- Automated testing tools can help streamline this process.

Continuous Integration (CI):

- Implement CI pipelines to automatically build, test, and integrate code changes from developers.
- CI tools like Jenkins, Travis CI, or GitLab CI can help automate these processes.

API Design and Documentation:

- Clearly define APIs for components/systems to communicate.
- Document API specifications, including input/output parameters, data formats, and authentication requirements.

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Version Control:

- Use a version control system like Git to manage code changes and track versions.
- Apply branching and merging strategies to coordinate changes between teams or developers.

Dependency Management:

- Keep track of third-party libraries, modules, or components used in the project.
- Ensure dependencies are up to date and compatible with each other.

Continuous Monitoring:

- Implement monitoring and logging systems to track the performance and behavior of integrated components in the production environment.
- Set up alerts for potential issues.

i-STENTORE integration process will consider also the following guidelines:

Small, Frequent Changes:

- Integrate small code changes frequently to minimize the risk of large, complex integrations.

Code Reviews:

- Conduct code reviews to ensure that the integrated code adheres to coding standards and best practices.

Automated Testing:

- Use automated testing tools and frameworks to validate integrated components quickly and consistently.

Rollback Plan:

- Develop a rollback plan in case integration fails, and have a strategy to revert to the previous state.

Documentation:

- Maintain comprehensive documentation for APIs, integration processes, and troubleshooting guides.

Communication:

- Ensure open and regular communication between teams and individuals involved in integration.

Security and Compliance:

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- Address security and compliance concerns during integration by implementing necessary measures like encryption and access control.

Performance Optimisation:

- Continuously monitor and optimise the performance of integrated components.

Regression Testing:

- Perform regression testing to ensure that new integrations do not break existing functionality.

Scalability:

- Consider scalability requirements and design integrations to accommodate future growth.

Backup and Disaster Recovery:

- Implement backup and disaster recovery strategies to safeguard data and maintain service continuity.

By following this methodology and adhering to these guidelines, i-STENTORE integration process will be reliable, stable, and effiient. Integration is a complex and ongoing task, and continuous improvement is crucial for a successful outcome.

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12 SECURITY, PRIVACY & LEGAL COMPLIANCE

This Chapter aims to specify the methodology for the development of a privacy and cyber-security framework which will guarantee security, fine-grained access control, anonymisation and encryption across every architectural component of the platform. For this reason, various security mechanisms will be employed during implementation indicatively considering ***decentralisation***, ***authentication***, ***authorisation***, ***auditing***, ***policy-based management***, and ***data encryption***. The end goal is to achieve a secured and functional platform resulting from the integration of all these elements and providing a prototype suitable for validation.

The Security, Privacy and Legal Compliance framework will be based on the analysis of:

- Use case scenarios, data types, involved actors.
- Well-proven technologies and standards to be applied to data (e.g., anonymisation, aggregation, minimisation), taking into account possible ethical issues as well.
- Data protection needs and the available standards, policies and methodologies about the data acquisition, data management and data access, in order to guarantee the user's data governance and ownership.
- Current EU and international legislative frameworks that concern information security (e.g., NISD), but also taking into consideration legislative requirements that affect the EPES sector (e.g., GDPR, Third Energy Package, and the Electricity Network Codes and Guidelines).
- Security and privacy of data guidelines and rationale behind them.

From a methodological perspective i-STENTORE will apply a three-step process, where the conceptual framework constitutes the foundation (see Figure 40).

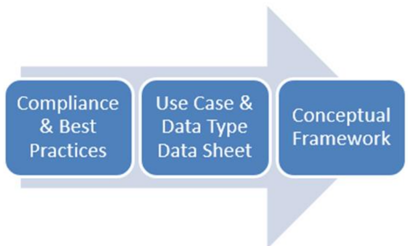

FIGURE 39: I-STENTORE LEGAL & SECURITY SPECIFICATION METHODOLOGY.

In overall, the final conceptual framework will provide

- an outlook on the legal regulations and security standards to be applied for the specific i-STENTORE objectives, use case scenarios and technology implementation and
- compliance rules and governance policies to be followed during the whole project lifecycle. For defining the conceptual framework, i-STENTORE will take into consideration references such as GDPR, Electricity Network Codes and Guidelines, and NISD.

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13 CONCLUSIONS

The objective of this Deliverable was to present the outcomes of Tasks 2.3, 2.5 and 2.6 that have been achieved by the time of writing leading to an initial version of the i-STENTORE Reference Architecture. The aim was to align it with the current components and requirements within the project.

Through the 'Novel Business Model Design for ESS Establishment' (Task 2.3), we explored innovative business models for Energy Storage Systems (ESS), which are crucial for integrating renewable energy into the power grid. This emphasized the importance of developing both single-use and multi-use ESS applications, highlighting their significance in driving Europe's climate neutrality and enhancing grid reliability.

The 'Functional Specifications for Standardised Data Access and Integration' (Task 2.5), are focusing on creating standardized frameworks for data access and integration in ESS. The Task offered insights into standardized data management practices and methodologies for the multi-use operation of ESS. It played a critical role in establishing harmonized data exchange protocols, facilitating efficient utilization of energy storage systems within the broader scope of the i-STENTORE project.

In Task 2.6, through employing the '4+1' View model approach, we will bring further together project-specific scenarios and requirements, creating a final RA which will be aligned with the project's development status. The first RA version incorporates several architecture models, one of which is the SGAM. Through this framework, we attempt to present the users' entry point into the system and design communication interfaces. Furthermore, we present a streamlined Governance layer as an aspect of the Reference Architecture harmonized with the Interoperability Specifications accompanying it.

These interoperability specifications are based on WP2 and provide depth to both the data interoperability layer and the Sovereignty and Trust layer within RA. Specifically, they elucidate how alignment with existing initiatives and concepts can be managed in these areas, combining the approaches of IDSA, GAIA-X, and FIWARE to serve the i-STENTORE objectives. The continuous outcome of this and future RA versions will be a 'development view' with a concrete perspective on i-STENTORE functional specifications mapped to unique components which will be developed according to these specifications. This information builds on the initial WP2 Tasks outcome, as it attempts to substantiate the concepts presented in this document and link them with the project's current status.

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REFERENCES

1. F. Baumgarte, G. Glenk, and A. Rieger, "Business Models and Profitability of Energy Storage,", iScience, early access. doi: 10.1016/j.isci.2020.101554.
2. X. Li et al., "Bringing innovation to market: business models for battery storage,", Energy Procedia, vol. 159, pp. 327–332, 2019. doi: 10.1016/j.egypro.2019.01.007. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1876610219300074
3. S. Englberger, Optimized energy management for battery energy storage via multi-use and multi-storage operation, 2022. [Online]. Available: http://mediatum.ub.tum.de/?id=1633126
4. S. Englberger, A. Jossen, and H. Hesse, "Unlocking the Potential of Battery Storage with the Dynamic Stacking of Multiple Applications,", Cell Reports Physical Science, vol. 1, no. 11, p. 100238, 2020, doi: 10.1016/j.xcrp.2020.100238.
5. L. Koltermann, K. Jacqué, J. Figgener, S. Zurmühlen, and D. U. Sauer, "Operational Validation of a Power Distribution Algorithm for a Modular Megawatt Battery Storage System,", Batteries & Supercaps, vol. 6, no. 3, 2023, doi: 10.1002/batt.202200414.
6. K. Jacqué, L. Koltermann, J. Figgener, S. Zurmühlen, and D. U. Sauer, "The Influence of Frequency Containment Reserve on the Operational Data and the State of Health of the Hybrid Stationary Large-Scale Storage System,", Energies, vol. 15, no. 4, p. 1342, 2022, doi: 10.3390/en15041342.
7. S. Zhang, H. Liu, F. Wang, T. Yan, and K. Wang, "Secondary frequency control strategy for BESS considering their degree of participation,", Energy Reports, vol. 6, pp. 594–602, 2020. doi: 10.1016/j.egyr.2020.11.183. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2352484720316085
8. M. Merten, Participation of battery storage systems in the automatic frequency restoration reserve market based on machine learning. RWTH Aachen University, 2020.
9. F. Zimmermann and A. Sauer, "Sizing electric storage systems for industrial peak shaving applications,", Procedia CIRP, vol. 90, pp. 666–671, 2020. doi: 10.1016/j.procir.2020.01.073. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2212827120301633
10. Y. Zhao et al., "Energy storage for black start services: A review,", Int J Miner Metall Mater, vol. 29, no. 4, pp. 691–704, 2022. doi: 10.1007/s12613-022-2445-0. [Online]. Available: https://link.springer.com/content/pdf/10.1007/s12613-022-2445-0.pdf
11. S. Rummeny and E. Waffenschmidt, "Options for an autarkic operation of a communal power grid using a battery and renewable energies,", Energy Procedia, vol. 155, pp. 329–335, 2018. doi: 10.1016/j.egypro.2018.11.045. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1876610218309925
12. J. Mitali, S. Dhinakaran, and A. A. Mohamad, "Energy storage systems: a review,", Energy Storage and Saving, vol. 1, no. 3, pp. 166–216, 2022. doi:

Co-funded by
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10.1016/j.enss.2022.07.002. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S277268352200022X

13. D. Mikkelson and K. Frick, "Analysis of controls for integrated energy storage system in energy arbitrage configuration with concrete thermal energy storage,", Applied Energy, vol. 313, p. 118800, 2022, doi: 10.1016/j.apenergy.2022.118800.
14. Kadri and K. Raahemifar, "Optimal Sizing and Scheduling of Battery Storage System Incorporated with PV for Energy Arbitrage in Three Different Electricity Markets," in 2019 IEEE Canadian Conference of Electrical and Computer Engineering (CCECE): 2019 IEEE Canadian Conference of Electrical and Computer Engineering (CCECE) took place 5-8 May 2019 in Edmonton, AB, Canada, Edmonton, AB, Canada, 2019, pp. 1–6, doi: 10.1109/CCECE.2019.8861776.
15. J. Engels, G. Deconinck, and B. Claessens, Integration of Flexibility from Battery Storage in the Electricity Market.
16. J. Engels, B. Claessens, and G. Deconinck, "Optimal Combination of Frequency Control and Peak Shaving With Battery Storage Systems,", IEEE Trans. Smart Grid, vol. 11, no. 4, pp. 3270–3279, 2020, doi: 10.1109/TSG.2019.2963098.
17. D. Pagnani, Ł. Kocewiak, J. Hjerrild, F. Blaabjerg, and C. L. Bak, "Integrating black start capabilities into offshore wind farms by grid-forming batteries,", IET Renewable Power Gen, 2023, Art. no. rpg2.12667, doi: 10.1049/rpg2.12667.
18. C. Brivio, S. Mandelli, and M. Merlo, "Battery energy storage system for primary control reserve and energy arbitrage,", Sustainable Energy, Grids and Networks, vol. 6, pp. 152–165, 2016, doi: 10.1016/j.segan.2016.03.004.
19. J. Engels, B. Claessens, and G. Deconinck, "Combined Stochastic Optimization of Frequency Control and Self-Consumption With a Battery,", IEEE Trans. Smart Grid, vol. 10, no. 2, pp. 1971–1981, 2019, doi: 10.1109/TSG.2017.2785040.
20. F. Braeuer, J. Rominger, R. McKenna, and W. Fichtner, "Battery storage systems: An economic model-based analysis of parallel revenue streams and general implications for industry,", Applied Energy, vol. 239, pp. 1424–1440, 2019, doi: 10.1016/j.apenergy.2019.01.050.
21. Source D2.6
22. Source D3.2
23. Source D6.3
24. Source D5.5
25. Source D5.7
26. Source D6.5
27. ISO/IEC/IEEE 42010. (n.d.). A Conceptual Model of Architecture Description. Retrieved from http://www.iso-architecture.org/ieee-1471/cm/
28. Architectural Blueprints — The "4+1" View Model of Software Architecture. https://www.cs.ubc.ca/~gregor/teaching/papers/4+1view-architecture.pdf
29. GridWise Architecture Council. (n.d.). GridWise Interoperability Context-Setting Framework v1.1. Retrieved from https://gridwiseac.org/pdfs/interopframework_v1_1.pdf

Co-funded by the European Union

30. SyC Smart Energy. (n.d.). IEC SRD 63200 - SGAM basics. Retrieved from https://syc-se.iec.ch/deliveries/sgam-basics/
31. The GridWise Architecture Council. GridWise Interoperability Context-Setting Framework; Technical Report; NIST: Gaithersburg, MD, USA, 2008.
32. International Data Spaces Association. (n.d.). IDS Reference Architecture Model. Retrieved from https://internationaldataspaces.org/publications/ids-ram/
33. International Data Spaces Association. (n.d.). Purpose and Structure of the Reference Architecture. In IDS Knowledge Base. Retrieved from https://docs.internationaldataspaces.org/ids-knowledgebase/v/ids-ram-4/introduction/1_1_goals_of_the_international_data_spaces/1_2_purpose_and_structure_of_the_document
34. International Data Spaces Association. (n.d.). 3.5.2 IDS Connector. In IDS Knowledge Base. Retrieved from https://docs.internationaldataspaces.org/ids-knowledgebase/v/ids-ram-4/layers-of-the-reference-architecture-model/3-layers-of-the-reference-architecture-model/3_5_0_system_layer/3_5_2_ids_connector
35. International Data Spaces Association. (n.d.). IDS RAM. Retrieved from https://internationaldataspaces.org/publications/ids-ram/
36. FIWARE Foundation e.V. (n.d.). Smart Energy. Retrieved from https://www.fiware.org/about-us/smart-energy/
37. GAIA-X European Association for Data and Cloud AISBL. (n.d.). Home - Gaia-X: A Federated Secure Data Infrastructure. Retrieved from https://gaia-x.eu/
38. GAIA-X European Association for Data and Cloud AISBL. (n.d.). What is Gaia-X. Retrieved from https://gaia-x.eu/what-is-gaia-x/
39. Goujard, Clothilde; Cerulus, Laurens (26 October 2021). "Inside Gaia-X: How chaos and infighting are killing Europe's grand cloud project"
40. European Commission. (n.d.). Project GAIA-X. Retrieved from https://www.bmwk.de/Redaktion/EN/Publikationen/Digitale-Welt/das-projekt-gaia-x-executive-summary.pdf?__blob=publicationFile&v=1
41. Bundesministerium für Wirtschaft und Energie. "Gaia-X vollzieht wichtigen Schritt hin zu einer souveränen europäischen digitalen Infrastruktur" (PDF)
42. Federal Ministry for Economic Affairs and Energy (BMWi). (n.d.). GAIA-X: Technical Architecture. Retrieved from https://www.bmwk.de/Redaktion/EN/Publikationen/gaia-x-technical-architecture.pdf?__blob=publicationFile&v=1
43. BMWi - Federal Ministry for Economic Affairs and Energy - GAIA-X, bmwi.de.
44. GAIA-X Federation Services (GXFS). (n.d.). Gaia-X Overview. Retrieved from https://www.gxfs.eu/gaia-x/
45. GAIA-X European Association for Data and Cloud AISBL. (n.d.). Home - Gaia-X: A Federated Secure Data Infrastructure. Retrieved from https://gaia-x.eu/
46. Engineering Ingegneria Informatica SpA. (2020). D2.1 REFERENCE ARCHITECTURE FOR CROSS-DOMAIN DIGITAL TRANSFORMATION V1. OPEN DEI project.

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https://www.opendei.eu/wp-content/uploads/2020/10/D2.1-REF-ARCH-FOR-CROSS-DOMAIN-DT-V1_UPDATED.pdf

47. Open DEI. (n.d.). OPEN DEI Reference Architecture for cross-domain Digital Transformation. Retrieved from https://www.opendei.eu/open-dei-reference-architecture-for-cross-domain-digital-transformation/
48. VLOCA Kennishub. (n.d.). OpenDEI 6C. Retrieved from https://vloca-kennishub.vlaanderen.be/OpenDEI_6C
49. International Data Spaces. (n.d.). From Digitizing the European Industry (project OpenDEI) to the Data Spaces Support Centre: a clear path to the emergence of cross-sectoral European data spaces. Retrieved from https://internationaldataspaces.org/from-digitizing-the-european-industry-project-opendei-to-the-data-spaces-support-centre-a-clear-path-to-the-emergence-of-cross-sectoral-european-data-spaces/
50. Open DEI. (n.d.). Home. Retrieved from https://www.opendei.eu/
51. Nagel, L., & Lycklama, D. (2021). Design Principles for Data Spaces – Position Paper. OPEN DEI Task Force 1. Retrieved from https://design-principles-for-data-spaces.org/
52. PLATOON D2.1, «PLATOON Reference Architecture» 2020. Available: https://platoon-project.eu/wp-content/uploads/2023/02/D2.1-PLATOON-Reference-Architecture-v1.pdf
53. BD4NRG. (n.d.). Home. Retrieved from https://www.bd4nrg.eu/
54. K. A. Wehrmeister et al., "The BD4NRG Reference Architecture for Big Data Driven Energy Applications," 2022 13th International Conference on Information, Intelligence, Systems & Applications (IISA), Corfu, Greece, 2022, pp. 1-8, doi: 10.1109/IISA56318.2022.9904424.
55. BD4NRG (2021). Deliverable 2.5: BD4NRG Reference Architecture First Version. Available at: https://www.bd4nrg.eu/sites/default/files/2023-06/BD4NRG%20Reference%20Architecture%20First%20Version%201.0.pdf
56. Opricovic, S., Tzeng, G. H., & Engn, F. C. (2004). Emerging research fronts-2009. Eur. J. Oper. Res, 156(2), 445-455.
57. Opricovic, S., & Tzeng, G. H. (2007). Extended VIKOR method in comparison with outranking methods. European journal of operational research, 178(2), 514-529.
58. Sayadi, M. K., Heydari, M., & Shahanaghi, K. (2009). Extension of VIKOR method for decision making problem with interval numbers. Applied Mathematical Modelling, 33(5), 2257-2262.
59. Kim, J. H., & Ahn, B. S. (2019). Extended VIKOR method using incomplete criteria weights. Expert Systems with Applications, 126, 124-132.
60. IEGSA (Interoperable European Grid Services Architecture), European Dynamics, Online: https://www.eurodyn.com/rnd-product/iegsa/ , Date Accessed: 2023 November 06.
61. FIWARE - Open APIs for Open Minds, URL: https://www.fiware.org, Date Accessed: 2023 November 06.

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the European Union

62. IDSA, The Association - International Data Spaces, URL: https://internationaldataspaces.org/we/the-association/, Date Accessed: 2023 November 06.
63. IEC 61970-301:2020+AMD1:2022 CSV, Consolidated version, Energy management system application program interface (EMS-API) - Part 301: Common information model (CIM), URL: https://webstore.iec.ch/publication/74467, Date Accessed: 2023 November 06.
64. SAREF4ENER: an extension of SAREF for the energy domain created in collaboration with Energy@Home and EEBus associations, URL: https://saref.etsi.org/saref4ener/v1.1.2/, Date Accessed: 2023 November 06.
65. SAREF4BLDG: SAREF extension for building, URL: https://saref.etsi.org/saref4bldg/v1.1.2/, Date Accessed: 2023 November 06.
66. Apache Hadoop, URL: https://hadoop.apache.org/, Date Accessed: 2023 November 06.
67. MySQL, URL: https://www.mysql.com/, Date Accessed: 2023 November 06.
68. PostgreSQL: The world's most advanced open source database, URL: https://www.postgresql.org/, Date Accessed: 2023 November 06.
69. MongoDB: The Developer Data Platform, URL: https://www.mongodb.com/, Date Accessed: 2023 November 06.
70. Apache Kafka, URL: https://kafka.apache.org/, Date Accessed: 2023 November 06.
71. Elasticsearch Platform — Find real-time answers at scale, URL: https://www.elastic.co/, Date Accessed: 2023 November 06.
72. FIWARE Context Broker: The engine for future energy systems, URL: https://www.fiware.org/2020/12/11/fiware-context-broker-the-engine-for-future-energy-systems/, Date Accessed: 2023 November 06.
73. FIWARE-NGSI v2 Specification, URL : https://fiware.github.io/specifications/ngsiv2/stable/, Date Accessed: 2023 November 06.
74. FIWARE Cygnus, URL: https://fiware-cygnus.readthedocs.io/en/latest/, Date Accessed: 2023 November 06.
75. Identity Manager – Keyrock, URL: https://fiware-idm.readthedocs.io/en/latest/, Date Accessed: 2023 November 06.
76. International Data Spaces Association. (2021, June 21). IDS Connector Framework (Version 5.0.4). Retrieved from https://github.com/International-Data-Spaces-Association/IDS-Connector-Framework/releases.
77. International Data Spaces Association. (n.d.). IDS Reference Architecture Model (Version 4.0). Retrieved from https://github.com/International-Data-Spaces-Association/IDS-RAM_4_0/blob/main/documentation/FrontMatter.md
78. ETSI. (2022, September 1). NGSI-LD standard version 1.6.1. European Telecommunications Standards Institute. Retrieved from https://www.etsi.org/

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APPENDIX A: MATHEMATICAL FORMULATION OF THE IPT

A.1 The VIKOR method

The VIKOR method has been developed as a multi-attribute decision making method for solving discrete decision making problems with non-commensurable and conflicting criteria [1, 2]. Based on L^p–metric for the aggregation process, the method focuses on compromise ranking from a set of alternatives.

Let $(A_1, \dots, A_m)$ be a set of alternatives which are evaluated across a set of criteria $(C_1, \dots, C_n)$ with consequences $f_{ij}, i = 1, \dots, n, j = 1, \dots, n$, and criteria weights lying in the following set

$$W = \left\{ \boldsymbol{w} \in \mathbb{R}^n : \sum_{j=1}^{n} w_j = 1, w_j \geq 0, j = 1, \dots, n \right\}$$

The VIKOR decision model includes the following steps:

1. Determination of the positive and negative ideal solution as follows:

$$f_j^* = \max_i f_{ij}, \quad f_j^- = \min_i f_{ij}$$

if criterion C_j is of benefit type, and

$$f_j^* = \min_j f_{ij}, \quad f_j^- = \min_j f_{ij}$$

if it is of cost type.

2. Calculation of S and R metrics as follows:

$$S_i = \sum_{j=1}^{n} w_j \left| \frac{f_j^* - f_{ij}}{f_j^* - f_j^-} \right|$$

$$R_i = \max_j w_j \left| \frac{f_j^* - f_{ij}}{f_j^* - f_j^-} \right|$$

3. Calculation of Q metric as follows:

$$Q_i = \nu \frac{S_i - S^*}{S^- - S^*} + (1 - \nu) \frac{R_i - R^*}{R^- - R^*}$$

where

$$S^* = \min_i S_i, \quad S^- = \max_i S_i$$

$$R^* = \min_i R_i, \quad R^- = \max_i R_i$$

and $\nu \in [0, 1]$ stands for the strategy coefficient, weighting the “majority of criteria” perspective against the “individual regret” one.

4. Q ranking.

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A.2 The interval extension

In this case, consider that consequences of alternatives against criteria are of interval form, that is $f_{ij} \in [f_{ij}^L, f_{ij}^U]$. Let also I and J denote the set of indices associated with the benefit and cost type criteria. Then, the extended VIKOR decision model [3] consists of the following steps:

1. Determination of the positive and negative ideal solution as follows:

$$\boldsymbol{f}^* = (f_1^*, \dots, f_n^*) = \left\{\left(\max_i f_{ij}^U : j \in I\right) \text{ or } \left(\min_i f_{ij}^L : j \in J\right)\right\}$$

$$\boldsymbol{f}^- = (f_1^-, \dots, f_n^-) = \left\{\left(\min_i f_{ij}^L : j \in I\right) \text{ or } \left(\max_i f_{ij}^U : j \in J\right)\right\}$$

2. Calculation of $S_i = [S_i^L, S_i^U]$ and $R_i = [R_i^L, R_i^U]$ metrics as follows:

$$S_i^L = \sum_{j \in I} w_j \left|\frac{f_j^* - f_{ij}^U}{f_j^* - f_j^-}\right| + \sum_{j \in J} w_j \left|\frac{f_{ij}^L - f_j^*}{f_j^- - f_j^*}\right|$$

$$S_i^U = \sum_{j \in I} w_j \left|\frac{f_j^* - f_{ij}^L}{f_j^* - f_j^-}\right| + \sum_{j \in J} w_j \left|\frac{f_{ij}^U - f_j^*}{f_j^- - f_j^*}\right|$$

$$R_i^L = \max\left\{w_j \left|\frac{f_j^* - f_{ij}^U}{f_j^* - f_j^-}\right| : j \in I,\ \ w_j \left|\frac{f_{ij}^L - f_j^*}{f_j^- - f_j^*}\right| : j \in J\right\}$$

$$R_i^U = \max\left\{w_j \left|\frac{f_j^* - f_{ij}^L}{f_j^* - f_j^-}\right| : j \in I,\ \ w_j \left|\frac{f_{ij}^U - f_j^*}{f_j^- - f_j^*}\right| : j \in J\right\}$$

3. Calculation of $Q_i = [Q_i^L, Q_i^U]$ metric as follows:

$$Q_i^L = v \frac{S_i^L - S^*}{S^- - S^*} + (1 - v) \frac{S_i^L - S^*}{S^- - S^*}$$

$$Q_i^U = v \frac{S_i^U - S^*}{S^- - S^*} + (1 - v) \frac{S_i^U - S^*}{S^- - S^*}$$

where

$$S^* = \min_i S_i^L, \quad S^- = \max_i S_i^U$$

$$R^* = \min_i R_i^L, \quad R^- = \max_i R_i^L$$

4. Q ranking.

The final step includes the comparison and ordering of interval numbers. To cope with this difficulty, in the present framework we adopt the degree of possibility method presented in [4].

A.3 Degree of possibility method

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Consider two interval numbers $Q_i = [Q_i^L, Q_i^U], Q_j = [Q_j^L, Q_j^U]$ and let $l_i = Q_i^U - Q_i^L$ and $l_j = Q_j^U - Q_j^L$ for all $i, j = 1, \dots, m$. Then, the degree of possibility of Q_i over Q_j is defined as follows:

$$p_{ij} = \max\left\{1 - \max\left\{\frac{Q_j^U - Q_i^L}{l_i + l_j}, 0\right\}, 0\right\}$$

Similarly, the degree of possibility of Q_j over Q_i is defined as follows:

$$p_{ji} = \max\left\{1 - \max\left\{\frac{Q_i^U - Q_j^L}{l_i + l_j}, 0\right\}, 0\right\}$$

The degree of possibility of all intervals is expressed through a complementary matrix, defined as follows:

$$P = \begin{pmatrix} p_{11} & \cdots & p_{1m} \\ \vdots & \ddots & \vdots \\ p_{m1} & \cdots & p_{mm} \end{pmatrix}, p_{ij} \geq 0, p_{ij} + p_{ji} = 1, p_{ii} = \frac{1}{2}$$

Then, to rank the intervals, the aggregated degree of possibility is used, which is calculated as follows:

$$p_i = \sum_{j=1}^{m} p_{ij}, \quad i = 1, \dots, m$$

A.4 The incomplete information method

In this case, we consider that criteria weights are not precise, but the user is able to define them with some freedom. In particular, we consider incomplete information criteria weights [5] and, specifically, the “weak inequalities” case [6], thus, they are formulated as follows:

$$W = \left\{ \boldsymbol{w} \in \mathbb{R}^n : \sum_{j=1}^{n} w_j = 1, w_j \geq 0, j = 1, \dots, n \right\}$$

$$w_1 \geq w_2 \geq \cdots \geq w_n \geq 0$$

Then, the incomplete information VIKOR decision model is consists of the following steps:

1. Determination of the positive and negative ideal solution as follows:

$$\boldsymbol{f}^* = (f_1^*, \dots, f_n^*) = \left\{\left(\max_i f_{ij}^U : j \in I\right) \text{ or } \left(\min_i f_{ij}^L : j \in J\right)\right\}$$

$$\boldsymbol{f}^- = (f_1^-, \dots, f_n^-) = \left\{\left(\min_i f_{ij}^L : j \in I\right) \text{ or } \left(\max_i f_{ij}^U : j \in J\right)\right\}$$

2. Calculation of $S_i = [S_i^L, S_i^U]$ and $R_i = [R_i^L, R_i^U]$ metrics as follows:

$$S_i^L = \min\{\boldsymbol{d_i^L E}\}$$

$$S_i^U = \max\{\boldsymbol{d_i^U E}\}$$

$$R_i^L = \min_k \left\{\max_j \{d_{ij}^L \lambda_{kj}\}\right\}$$

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$$R_i^U = \max_k \left\{ \max_j \{ d_{ij}^U \lambda_{kj} \} \right\}$$

where

$$\boldsymbol{d_i^L} = \left(\frac{f_j^* - f_{ij}^U}{f_j^* - f_j^-} \middle| j \in I, \frac{f_{ij}^L - f_j^*}{f_j^- - f_j^*} \middle| j \in J \right)$$

$$\boldsymbol{d_i^U} = \left(\frac{f_j^* - f_{ij}^L}{f_j^* - f_j^-} \middle| j \in I, \frac{f_{ij}^U - f_j^*}{f_j^- - f_j^*} \middle| j \in J \right)$$

$$\boldsymbol{E} = (\lambda_1, \dots, \lambda_n) = \begin{pmatrix} 1 & \frac{1}{2} & \cdots & \frac{1}{n-1} & \frac{1}{n} \\ 0 & \frac{1}{2} & \cdots & \frac{1}{n-1} & \frac{1}{n} \\ 0 & 0 & \cdots & \frac{1}{n-1} & \frac{1}{n} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & \cdots & \frac{1}{n-1} & \frac{1}{n} \\ 0 & 0 & \cdots & 0 & \frac{1}{n} \end{pmatrix}$$

and λ_{kj} is the jth element of λ_k.

3. Similar to step 3 of section A.2.

4. Similar to step 4 of section A.2.

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