Definition of a Functional Architecture for Distributed Energy Resource Management Systems (DERMS)

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***Abstract*— The increasing penetration of Distributed Energy Resources (DERs) is transforming the electricity grid from a centralized model to a decentralized, active, and dynamic distribution network. This shift presents new challenges like reverse power flows, feeder overloads, and voltage fluctuations, which traditional tools cannot manage effectively. Distributed Energy Resource Management Systems (DERMS) have emerged as a promising solution for the monitoring, control, and optimization of DERs, although the concept remains novel and still lacks a universally accepted definition and standardized functionalities. Current approaches to DERMS are typically divided into centralized (Utility) systems for front-of-the-meter (FTM) resources and decentralized (Aggregator) systems for behind-the-meter (BTM) DER portfolios. There is a growing consensus on the need for an integrated solution that unifies these levels. This work develops a unified, comprehensive functional architecture for DERMS, designed to be modular and adaptable, accommodating the needs of various stakeholders, in variety of use cases, different regulatory frameworks, and market structures. Validated through several case studies and an assessment of industry interests, the proposed architecture demonstrates the potential for a comprehensive, modular, and versatile DERMS solution capable of effectively managing both FTM and BTM resources, adapting to multiple operational requirements, integrating with existing management systems.**

Keywords*— *Distributed Energy Resource (DER), DER Management System (DERMS), front-of-the-meter/behind-the-meter (FTM/BTM), Utility/Aggregator DERMS, DERMS declinations.

I. INTRODUCTION

The rapidly increasing share of DERs within the distribution grid—including solar photovoltaic, wind turbines, battery energy storage systems, or electric vehicles—is driving a fundamental transformation in the electricity grid, from a centralized generation-based model to a decentralized, active, and dynamic distribution network [1]-[4]. This shift introduces significant technical complexities, such as reverse power flows, feeder overloads, and voltage regulation challenges, which traditional grid management tools are inadequate to handle [1], [2]. Additionally, as DERs continue to proliferate the distinction between Front-of-the-Meter (FTM) DERs—typically utility-scale resources connected to the MV distribution grid—and Behind-the-Meter (BTM) DERs—smaller resources located on the consumer's side of the meter—is becoming increasingly blurred, complicating their management and necessitating the development of more sophisticated systems that can integrate and optimize these diverse energy resources [1]-[6].

In this context, DERMS have emerged as a promising solution for real-time monitoring, control, and optimization of DERs [1]-[3], [5], [7]. However, the concept of DERMS remains novel with no universally accepted definition or a standardized set of functionalities and core services [1]. The literature and industry practices reveal a fragmented landscape, with DERMS solutions often divided into centralized (Utility) DERMS—typically the main focus of the electricity industry nowadays—managing medium-to-large-scale FTM DERs and groups of aggregated BTM DERs, and decentralized (Aggregator) DERMS, intended to handle portfolios of BTM DERs such as residential solar panels and battery systems. However, there seems to be a growing consensus on the need to integrate these levels into a unified and comprehensive management solution to ensure the optimal and reliable integration of DERs [1]-[3], [5], [7], [8].

This work seeks to bridge these gaps by providing a unified definition for DERMS, clarifying its scope of application and developing a unified, comprehensive functional architecture for DERMS solutions that can that accommodate both centralized and decentralized management needs. The architecture is designed to ensure broad adaptability, offering seven distinct declinations tailored to various stakeholders and use cases, regulatory frameworks, and market structures, and proposing a modularization strategy to enable its integration with the existing software platforms and operational requirements of different client typologies, whether they require an end-to-end solution or selective enhancements to existing infrastructure.

The proposed architecture is validated through several industry case studies and an assessment of market readiness. This validation process demonstrates (i) the interest for a comprehensive DERMS solution that can help utilities and distribution system operators (DSOs), but also third-party aggregators to manage both FTM and BTM resources, and (ii) the need for this solution to be modular and adaptable to the particularities of various clients and use cases, as well as the technical feasibility and real-world applicability of this approach. Therefore, the outcome of the work is a unified solution for DER integration, consisting of a set of core functionalities common to all stakeholders, complemented by specific services for particular use cases, that aims at providing a solid foundation for further understanding, development, and implementation of DERMS, setting the stage for more efficient and effective management of DERs.

II. THEORETICAL FRAMEWORK

A. Distributed Energy Resources (DERs)

A precise understanding of the term DER is required to be able to analyze the management solutions for these technologies. Multiple definitions have been offered within the electric sector for Distributed Energy Resources. Therefore, while some technologies are easy to classify within or outside this description—such as rooftop solar or small-scale energy storage—others have yet to be determined whether they fit into this category [9]. To provide a sample of this wide variety of definitions, some of those offered from across the industry are included below.

The Department of Energy (DOE) describes DERs as "smaller-scale and modular devices designed to provide electricity, and sometimes also thermal energy, in locations close to consumers" [10]. The Lawrence Berkeley National Laboratory considers that DERs "include clean and renewable distributed generation systems (such as high efficiency combined heat and power and solar photovoltaic systems), distributed storage, demand response, and energy efficiency", and considers plug-in electric vehicles as part of distributed storage. For the Massachusetts Department of Public Utilities "a DER is a device or measure that produces electricity or reduces electricity consumption and is connected to the electrical system, either 'behind the meter' in the customer's premise, or on the utility's primary distribution system", and also includes microgrids and energy management systems as DERs [12]. And finally, the Electric Power Research Institute (EPRI) simply considers that DERs are "smaller power sources that can be aggregated to provide power necessary to meet regular demand" [13].

This variety of descriptions of a DER have been used by the National Association of Regulatory Utility Commissioners (NARUC) to establish a unified definition of DERs: "a DER is a resource sited close to customers that can provide all or some of their immediate power needs and can also be used by the system to either reduce demand (such as energy efficiency) or increase supply to satisfy the energy or ancillary service needs of the distribution grid. The resources, if providing electricity or thermal energy, are small in scale, connected to the distribution system, and close to load" [9]. NARUC's definition brings together, under the umbrella of DER, photovoltaic solar, wind, and combined heat and power, energy storage, demand response, electric vehicles, microgrids, and energy efficiency", while the IEEE Standard 1547-2018—for Interconnection and Interoperability of DERs with Associated Electric Power Systems Interfaces ([14])—and other sources ([3]-[5]) emphasize the inclusion of small hydro power plants and backup diesel generators.

NARUC's definition has been slightly adapted here to try to accommodate all the perspectives previously presented and included in [9]-[14], as well as the concepts and technologies mentioned in [3]-[5], and other consulted sources: DERs can be both FTM and BTM small- and medium-scale assets—if providing electricity or thermal energy—typically privately-owned, connected to low or medium voltage feeders of the distribution system, and located close to the load. DERs can be used to either reduce demand or increase supply to satisfy the energy or ancillary service needs of the distribution grid, thereby being capable of modifying load requirements and optimizing energy demand.

Although small BTM DERs are becoming increasingly predominant compared to FTM—such as larger-scale DG—emphasis has been placed on both as fundamental components of the DER concept. This is the definition of DERs that will be referred to in the remainder and that shall be used to better understand their management solutions. The following technologies shall be, therefore, encompassed under this perspective of DERs: solar photovoltaic (PV) and wind energy systems, small hydro power plants, Combined Heat and Power (CHP), distributed diesel generators, Energy Storage Systems (ESS), Electric Vehicles (EVs) and their charging stations, microgrids, Demand Response (DR), controllable loads, and Energy Efficiency (EE) programs [3], [14].

B. Precedent Solutions for DER Integration

While the appearance of DERs presents significant challenges, the potential benefits they offer—if properly managed—in terms of grid modernization, economic efficiency, operational enhancements, and environmental sustainability could make them a highly valuable addition to the electricity grid. This section will explore some of the existing solutions, already well established in the electric industry and prior to the emergence of DERMS, for the integration and management of these resources within the distribution network.

1) Smart Inverters (SIs): although not a comprehensive management solution for DERs, SIs support the integration of renewable distributed resources into the electricity grid. A SI is an advanced power electronics device designed to convert direct current at the output of some distributed energy resources—such as solar PV and BESS—into alternating current compatible with the electricity grid. Unlike traditional inverters, SIs are equipped with additional software that provides enhanced functionalities and facilitates the overall integration of renewable energy sources into the power system [15]. Some of these additional capabilities are output voltage and power regulation, adaptability to changing grid conditions and operational requirements, autonomous management, self-awareness of the device's health and operational status, plug-and-play functionality for seamless integration into existing systems, and registering of provided services for economic compensation [9], [15].

2) Advanced Metering Infrastructure (AMI): AMI refers to the technology framework that includes advanced meters capable of measuring electricity consumption in granular time increments—e.g., every 15 minutes to an hour. It integrates digital information technologies, combining hardware and software systems to facilitate remote communication among end-users, service providers (SPs), and utilities. Unlike traditional meters, AMI can provide up to 8,760 data points per year if measured hourly, significantly enhancing data availability for both utilities and customers [9], [16]. AMI encompasses smart meters, a Meter Data Management System (MDMS), and a communications network, which work together to enable utilities to collect detailed real-time demand and generation data for improved energy management, real-time pricing and advanced rate design, and more accurate DER compensation [16], [17].

3) Microgrids Controllers (MCs): a microgrid is defined by the U.S. Department of Energy's Microgrid Exchange Group as "a group of interconnected loads and distributed energy resources (DERs) within clearly defined electrical boundaries that act as a single controllable entity with respect to the grid." Microgrids can operate in grid-connected mode or independently in islanded mode, enhancing resilience and sustainability by integrating various DERs, such as solar PV, wind turbines, BESS, and backup generators [18]. A Microgrid Controller (MC) is responsible for managing the operation of a microgrid, enabling the integration, coordination, and control of DERs, and allowing participation in various grid services. MCs utilize rule-based and optimal dispatch algorithms to maximize renewable energy use and economic profitability, enhancing grid-edge resilience, ensuring continuous power supply during grid disturbances, and allowing for economic benefits and a more sustainable power system [7], [18], [19].

4) Virtual Power Plants (VPPs): a VPP is an aggregation of various distributed resources, which function collectively as a single dispatchable entity in power system operations and wholesale markets. The main aim of a VPP is to leverage diverse distributed generating units, storage systems, and flexible and controllable loads to provide added capacity and ancillary services to the grid while optimizing electricity production and consumption. This allows for the fulfillment of different objectives like cost minimization, improved reliability, or GHG emissions reduction [20]-[22]. Ideally, VPPs leverage a diversified portfolio of resources including demand response, renewable energy sources, energy storage systems, and even traditional energy sources to create an aggregated virtual resource that can be operated like a single entity, but which is comprised of potentially thousands of individual DERs. The more diverse the portfolio of devices, the more flexible and resilient the aggregated VPP and greater its usefulness for the grid [21].

5) Demand-Side Management (DSM) and Demand Respone Management System (DRMS): DSM refers to initiatives and technologies aimed at optimizing energy consumption patterns to reduce costs, improve reliability, and minimize environmental impact among other objectives. It involves various strategies—smart energy tariffs with incentives for specific consumption patterns, real-time control of distributed energy resources, etc.—implemented by utilities to encourage consumers to adjust their electricity usage to reduce overall energy consumption, manage peak demand, and improve energy efficiency in general [23], [24]. DSM includes measures and technologies aimed at modifying or shifting energy consumption based on system requiremets, such as energy efficiency, strategic load growth, or spinning reserves, and demand response [23], [25].

DR it involves real-time or near-real-time adjustments in electricity consumption by end-users in response to price signals or incentive payments to reduce consumption during peak periods or to shift it to valley times. DR aims to enhance grid reliability and efficiency by balancing supply and demand dynamically. Technologies that can take part in DR include EVs and smart appliances like thermostats and plugs. Demand response initiatives can be categorized into reliability-based, aimed at ensuring grid stability by reducing load during critical periods, and market-based, focused on economic efficiency by responding to price signals—e.g., time-of-use rates (ToU) or critical peak pricing (CPP) [23], [25]. Demand Response Management Systems (DRMS) emerged to help energy providers and utilities manage DR strategies, collecting and analyzing BTM data to handle power demands, reduce energy consumption, and improve system efficiency and reliability. They provide tools for analyzing and optimizing energy use, reducing the need for new network infrastructure, preventing all kind of service interruptions, and minimizing associated costs [25].

6) Advanced Distribution Management System (ADMS): a DMS is a comprehensive software platform employed by utilities to control and optimize the operation of the electrical distribution system. Conventional DMS controls voltage regulators, capacitor banks, and sectionalizing switches. It has access to meters, power system models, and load models, and continuously performs power-flow analysis to determine the optimal settings for these control devices based on the utility's needs and current priorities [26]. Advanced Distribution Management Systems (ADMS) combine the functionalities of traditional DMS and Outage Management Systems (OMS) with the services provided by DERs to produce overall improved system responses—as an enhanced DER-ready DMS and handle the complexities arising from the widespread deployment of DERs that traditional DMS and OMS struggle to manage [26], [27]. ADMS add levels of communication, intelligence, and visibility into the distribution grid, allowing utilities to better understand real-time conditions across their service territory [9]. They are designed to manage both traditional grid assets and DERs to perform Volt/VAR optimization, Conservation Voltage Reduction (CVR), Automated Fault Location, Isolation, and Service Restoration (FLISR), or even DR functionalities to ensure grid safety and reliability [7], [9], [26].

ADMS, DRMS, VPPs and MCs all offer valuable solutions for grid management and operation. However, they encounter challenges and inefficiencies when adapting to the increasing presence of DERs in the distribution grid, and often fell short in facing the dynamic nature of the modern power system. This paves the way for the emergence DERMS, and for their potential integration with these previous solutions. The following section will delve into a thorough literature review of the DERMS concept, examining their different stakeholders, hierarchy of DERMS solutions, functional specification, enabling protocols for DER integration, DER control architectures, as well as the latest legislative proposals.

III. DERMS – State of the Art

There appears to be consensus regarding the notion that a DERMS is a software solution designed to aid distribution system operators, utilities, grid planners, engineers, end-customers, and prosumers in managing and operating the increasing penetration of distributed energy resources in distribution grids. These systems provide tools for real-time monitoring, control, dispatch coordination, and optimization of DERs, ensuring that the grid operates reliably and efficiently within technical limits, mitigating potential negative impacts of high DER penetration, and offering economic benefits [1], [2]. DERMS facilitate the integration of various distributed resources, including renewable and non-renewable generation—such as rooftop solar panels, small wind turbines, combined heat and power, or diesel generators—, energy storage systems, electric vehicle charging stations, DR, load control, and energy efficiency programs, often aggregating their capabilities to support system-wide benefits (see Fig. 1) [1]-[4], [9], [26].

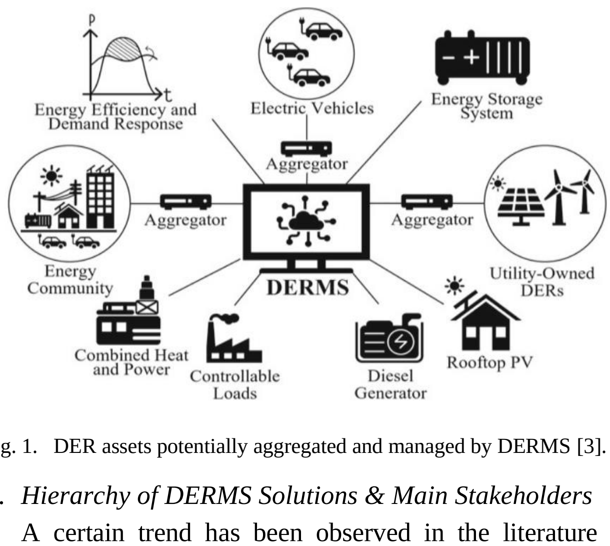

Fig. 1. DER assets potentially aggregated and managed by DERMS [3].

A. Hierarchy of DERMS Solutions & Main Stakeholders

A certain trend has been observed in the literature to distinguish two different levels of existing DERMS solutions. This hierarchical structure in DERMS is necessary to manage the complex interactions between various DERs, with the different hierarchical levels serving distinct purposes and being tailored to specific operational needs within the grid. However, a significant challenge in DERMS deployment has been and still is the lack of clear definitions for different management solutions. The fact that all these solutions are simply called DERMS can lead to misunderstanding among utilities, regulators, market operators, or technology providers regarding which is the most suitable for their interests. Thus, defining and distinguishing these levels of hierarchy among DERMS is critical to avoid confusion among the different stakeholders, so that they can better understand the roles and responsibilities associated with each solution [1], [2], [6].

1) Centralized DERMS

Centralized DERMS emerged from traditional grid management systems, focusing on large-scale, utility-controlled operations—reason why they are often referred to in the literature as Utility DERMS [1]-[3], [5]-[8]. Utility DERMS are typically deployed at the control centers of distribution system operators and have complete access to the accurate network model. They use traditional resources (load tap changers, capacitors, or switches) in combination with individual medium-to-large-scale DERs (utility-scale BESS, large solar farms, and wind turbines) and groups of aggregated small-scale DERs to optimally run the distribution grid without incurring in constraint violations. Centralized DERMS focus on grid-wide optimization and control, reliability, and integration of larger DERs, with the aim of providing technical, operational, and monetary benefits to the DSO/TSO/ISO [1]-[3], [5], [6], [8].

2) Decentralized DERMS

Also Aggregator DERMS [33], third-party DERMS [5], [8], [28], or simply non-utility DERMS [3], [28], developed from customer-centric applications, enabling greater collaboration of end-users in energy management. Decentralized DERMS software solutions focus on the aggregation of multiple small-scale, BTM resources connected to the low voltage *(*LV*)* network (e.g., air-conditioning*/*heating systems, rooftop solar panels, small residential battery systems, EVs and their charging stations, and smart home appliances) with the objective of providing their services in an aggregated, optimized, simpler, and more useful manner for power system operators—for instance, participating in the electricity market or through demand response initiatives [1]-[3], [6]-[8]. Decentralized systems are usually managed by private parties, industries, or energy communities, and aim to enhance customer engagement, energy efficiency, and local generation and consumption management. They provide greater visibility and controllability of BTM DERs [1]-[3], [8], but typically do not have access to an accurate network model and are not aware of technical constraints—and this will be precisely considered as the boundary between Utility (Centralized) and Aggregator (Decentralized) DERMS [1], [3], [5], [6], [8].

Decentralized DERMS solutions are often categorized in the literature into (i) *DER Aggregators*, responsible for managing groups of BTM DERs and dispatchable loads connected to the LV grid—e.g., Building/Home Energy Management Systems, energy communities, VPP, and DR providers [1]-[8]; (ii) *Local Electricity Market Operators (LEMOs)*, in charge of organizing and operating local markets where aggregated DERs can trade energy and provide ancillary services, ensuring compliance with local grid constraints and regulatory requirements—e.g., minimum power to enter the market [1]; and (iii) *Microgrid Controllers (MCs)*, managing the operation of microgrids, ensuring they can function both as part of the main grid and in an islanded mode. In grid-connected mode, MCs manage unit commitment, economic dispatch, and other services offer flexibility to the main grid. When isolated, MCs perform grid-forming operations, manage frequency and voltage, and ensure load balancing [1], [7], [18]. Table 1 compiles these different levels of hierarchy among DERMS, along with the key stakeholders interested in deploying these solutions and the main goals that each of these entities aims to fulfill with their implementation.

TABLE 1. DER MANAGEMENT SOLUTIONS, THEIR GOALS, STAKEHOLDERS, AND HIERARCHICAL STRUCTURE [1], [2].

Stakeholder	*Goal*	*DERMS Solution*
Transmission/ Independent System Operator (TSO/ISO)	Supply/demand balancing, ancillary grid-wide services, provide flexible capacity, manage demand and renewable generation variability	Centralized (aware of network model)
DSOs; planning departments in distribution utilities	Relieve congestions and voltage violations, defer network reinforcements, increase DER hosting capability, grid-edge stability and optimization	Centralized (aware of distribution network model)
Market participants and local market operators	Wholesale: optimize generation mix, minimize ENS costs. Retail: promote competitiveness and efficiency, new retail tariffs	Decentralized (not aware of network model)
DER aggregators, microgrid operators, prosumers	Aggregate DERs for local energy management, optimize costs (energy and demand charges), integrate renewable DG, improve resiliency	Decentralized (not aware of network model)

B. *Hybrid DERMS Solutions*

Centralized and decentralized solutions are both frequently simply called DERMS, even though they widely differ in nature, roles, and the possibilities they offer for the different stakeholders within the power system [1], [2], [5], [6]. Purely centralized or decentralized systems may be independently implemented (although Aggregator DERMS typically require collaboration with a centralized management system to coordinate their provided flexibility as developed above), buy they present several limitations—i.e., aggregators' lack of grid awareness, need for centralized validation of DER schedules, coordination and scalability issues, or inconsistent standards and protocols—that could be mitigated if properly integrated [1], [2], [5], [6].

Integrating centralized and decentralized solutions poses, nevertheless, several challenges, as it increases the overall complexity of DERMS. Ensuring seamless communication and interoperability between diverse solutions requires standardizing protocols and interfaces [1]-[4], [6], [26], in many cases still undeveloped or under development by different vendors, projects from international organizations (Platone Project [29]) or standards associations (such as the IEEE Std 2030.5 for communication with DERs devices [30]). Moreover, managing real-time data across multiple control layers—with different centralization levels—is technically demanding, necessitating an improved and robust network infrastructure which could require upgrading existing systems [1], [2], [5], [6]. Cybersecurity becomes also critical due to increased connectivity and data exchange introducing potential vulnerabilities [3], [4], [28]. Finally, regulation must evolve to a large extent to support hybrid approaches [1], [2], [5], [31], [32]. Initiatives like the FERC Order No. 2222 in the US supporting DER participation in wholesale markets [1], [3], [7], [31], or the EU DSO Entity and ENTSO-E's Proposal for a Network Code on Demand Response [33] contribute to define a regulatory framework that favour the development of comprehensive DER management solutions.

Through near real-time data exchange with a utility DERMS, DER aggregators enhance the awareness of BTM DERs and their impact on local network conditions, particularly in customer-related operations such as participation in electricity markets and DR or EE initiatives. Aggregators manage the variability and intermittency of DER outputs so that utilities can dispose of increased flexible capacity for a variety of grid services [1], [2]. Moreover, the integration of Utility DERMS with LEMOs is essential for validating schedules and ensuring compliance with technical constraints while leveraging DER flexibility for a more efficient and cost-effective grid management [1], [6]. Finally, hybrid systems enhance the scalability of DERMS software solutions by decentralizing part of the control and optimization functions, so that a larger number of DERs can be efficiently integrated [1].

These ideas for Utility and Aggregator DERMS integration are perfectly summarized in [1], [2], and [6], to the extent that the author of this work has deemed it appropriate to literally transcribe here a passage from [2], is also used in [6]: "[…] utility DERMSs and DER aggregators should be understood as different levels in a hierarchy: DER aggregators mainly communicate with behind-the-meter units and use them in an aggregated fashion to provide various services regarding customer engagement and operations, whereas utility DERMSs use DER aggregators—among other resources, such as individual medium-to-large-scale DERs, various types of DER groups, virtual power plants (VPPs), microgrids, and traditional resources such as switches, capacitors, etc.—to provide DSOs with complete awareness, effortless real-time and look-ahead constraint management, optimal coordination and management of DERs and DER groups, and other system-wide operations. Therefore, if properly integrated, DER aggregators and utility DERMS perfectly complement one another, and can provide a full spectrum of DER services regarding both customer- and grid-related operations, regardless of DERs' sizes and locations".

C. DERMS Functional Specification

DERMS functionalities and services have been structured in various ways in the literature over recent years. This section provides a comprehensive review of these perspectives by integrating the insights from 12 utilities and 11 vendors as provided by SEPA in [34], the functional specifications proposed by IEEE Std 2030.11-2021 ([28]), as well as other insights primarily gathered from [1]-[3]. In general, the literature does not distinguish between functions assigned to Centralized (Utility) and Decentralized (Aggregator) DERMS. However—and despite the purpose of this document to project a comprehensive DERMS solution—, this work will attempt to draw a distinction between the specific functionalities of each solution in order to emphasize the latter—in a context where the industry tends to view DERMS as a utility-exclusive product.

1) Centralized/Utility DERMS

a) Enrollment: the enrollment service enables that all DERs are properly identified, categorized, and managed to support further DERMS services. This includes managing detailed information about each DER device and groups of DERs (managed by an aggregator) regarding registration, grouping, and operational capabilities and limitations, so that they can be visualized topographically within the utility's network model. This is of particular interest for determining the overall impact and the flexibility offered by grid-edge and BTM assets for grid services. It encompasses [28], [34]:

- *Registration*: identification and validation of the DER devices enrolled to the DERMS platform to ensuring that only compliant and validated devices are integrated into the management system [28]. The aim is to capture relevant asset (nameplate) information, communication, and programmatic information, in/out service dates, electrical location and network connectivity details about utility-owned DERs and third-party aggregators to provide greater visibility to the utility or DSO [34].
- *Grouping*: aims at organizing DER devices into logical groups, aggregating real-time data, energy, and power outputs for easier and more efficient management and control. Grouping can attend to hierarchical (based on system topology), dynamic, programmatic (based on DER participation in utility programs), or capacity (response times, determinism, etc.) considerations.
- *Asset Configuration & Modeling*: it involves DER devices (on an individual or aggregated basis) notifying the DSO of their current and projected status, operational capabilities, and limitations (with an agreed periodicity), to allow utilities for incorporating accurate real-time DER data to their digital models of the distribution network.

b) Planning: planning functions facilitate long-term strategic planning for integrating DERs into the grid. This module aims at ensuring the grid can handle increasing DER levels without compromising stability and resilience. It offers comprehensive studies and assessments, guiding utilities and creating detailed plans for infrastructure investments and DER integration strategies. This includes various functionalities such as *DER Connection (Hosting Capacity) Analysis* for assessesing the impact of new DER connections, *Optimal DER Placement* for identifying the optimal connection point for a specific DER capacity, the creation of *Hosting Capacity Heat Maps (HCHMs)* to enable stakeholders to visualize the available capacity in different grid sections, and *NWA Studies* to explore alternatives to defer investments in grid infrastructure—flexible contracts, energy storage solutions, or DR capabilities [28], [34].

c) Real-Time Operation: this module focuses on real-time monitoring, and operational control of DERs and grid assets to maintain network stability and efficiency [1]. It leverages information from the Enrollment module to understand the current state and capacity of the network, enabling active grid management and asset optimization [34]. It includes the following functions:

- *Monitoring & Visualization*: DERMS must be capable of monitoring, sensing, and visualizing not only general grid parameters but also critical operating values of DERs, often leveraging real-time data from SCADA and AMI systems to continuously provide updated information to utility operators and planners [2], [3], [28], [34]. According to IEEE Std 1547-2018, collected information shall include: DER active and reactive power output, instantaneous single- or three-phase RMS voltage and current, frequency, operational status, connection status, alarm status, and operational state of charge (SoC) [28].
- *DER Optimization & Economic Dispatch*: it involves delivering the requested grid services efficiently by using the best combination of DER assets, which reduces costs,

minimizes wear, and maximizes asset value. DERMS enable utilities to perform dynamic economic dispatch of the DERs in its portfolio considering generation costs, market rates, grid constraints, DER operating limits, contracted periods and participation in utility programs, and environmental considerations [28].

- *Grid Management & Control*: this involves controlling DER outputs to achieve energy, capacity, and ancillary service goals. DERMS can use DERs' flexible capacity to help balance supply and demand, manage grid constraints, keep frequency and voltage within limits, avoid feeder overloads, and improve power quality in the most efficient fashion. This also includes the execution of control commands for DERs in real-time, ensuring they provide the scheduled capacities [1], [28], [34].
- *Volt/VAR Optimization (VVO):* VVO aims at reducing energy losses—improving the overall efficiency of the grid—by decreasing reactive power flows through the distribution network. In particular, Conservation Voltage Reduction (CVR) intends to manage the transmission and distribution (T&D) system so that customer voltages are kept close to the lower end of the acceptable range and overall demand is reduced [28], [34].
- *Fault Location, Isolation, and Service Restoration (FLISR):* a DERMS can monitor the network and handle switches and traditional grid assets to locate and isolate faults—sometimes through collaboration with an OMS or an ADMS. During the power restoration phase, it coordinates DERs to stage their restart—e.g., through SI control or managing EVs' charging stations—and mitigate traditional effects of cold load pickup [5], [28].

d) Short-Term/Look-Ahead Operation: this module is designed to provide predictive analysis and planning for near-future grid conditions. It helps utilities anticipate potential issues and constraint violations by forecasting load and generation profiles, weather conditions, and scheduled operation of DERs [1], [2]. Look-ahead (L-A) services also use information from the enrollment module to understand the historical and current operating conditions of DERs [34].

- *Forecasting & Estimation:* it predicts future energy demand, DER generation and status, grid parameters—such as voltage profiles and power flows through critical lines—and even market conditions. It uses real-time and historical data, weather forecasts, and market prices to implement state estimation algorithms for greater situational awareness and visibility [1], [3], [28], [34].
- *L-A DER Scheduling (Unit Commitment):* this function leverages forecasted load and generation forecasts, projected electricity market prices, and estimated network conditions to develop optimal DER schedules. The aim is to optimize the sequence and priority of DER operations and their energy delivery over defined time intervals—hours, days, weeks, and even months—while complying with grid constraints and DER operating limits [28], [34].
- *L-A Grid Management*: this functionality integrates load and generation forecasts with network models to anticipate and address potential grid constraints—voltage profiles, currents through the distribution network, power in transformers, etc.—before they occur. It estimates available DER flexibility and communicates with DERs and aggregators to proactively adjust DER operations and critical DER schedules to prevent projected constraint violations in an optimal fashion [1], [2], [28].

e) Analysis & Reporting: aims to assess and document the technical and economic performance of DERMS in providing services to the grid and to customers, as well as their compliance with regulatory requirements. This retrospective analysis allows for economic compensation of customer- and utility-owned DERs—incentivizing DER adoption—and can serve as a basis for DER portfolio planning at either the utility's or the aggregator's level [34]. Customized reports shall be generated for the different stakeholders, such as DSOs, regulators, or customers.

2) Decentralized/Aggregator DERMS

a) Enrollment: the enrollment service of an Aggregator DERMS enables that all DERs are properly identified, categorized, and modelled to support further aggregated functions. It should include detailed information about each DER device within the aggregator portfolio in terms of identification, aggregation, and technical details and parameters, so that they can be properly visualized and controlled by the aggregator to provide a variety of grid services [28], [34]. It encompasses equivalent functionalities to the ones described above—i.e, *Registration*, *Aggregation* (crucial so that system operators only have to monitor the total energy injected into the grid from an aggregator instead of the individual outputs of each BTM DERs), and *Asset Configuration & Modeling*—adapted to the aggreator level.

b) Aggregated Grid Services: Aggregator DERMS leverage the aggregation of multiple small-scale, often BTM DERs to improve their visibility, facilitate their management, optimize their operation, and provide various grid services to enhance the reliability, resilience, and efficiency of the network, favoring both consumers and system operators. The following functionalities shall be included here:

- *DER Monitoring & Control*: DER aggregators must be capable of monitoring, sensing, and measuring critical parameters of the local distribution grid and, specially, of the DERs under its management. Collected data shall include: DER active and reactive power output, RMS voltage and current, frequency, operational, connection, and alarm status, and SoC [28]. DER control involves utilizing this monitored data to ensure DERs are providing the required capacities at the times.
- *DER & DER Portfolio Optimization*: it involves ensuring the delivery of requested grid services by optimizing the energy and capacity usage of the DERs within the aggregator's portfolio. This includes optimizing the operation schedules of each individual DERs (unit commitment) and performing an economic dispatch that maximizes overall DER value and minimizes total generation costs while meeting the technical requirements imposed by Utility DERMS [28], [34].
- *Demand Response*: management of DR programs, including customer enrollment, event scheduling, forecasting weather impacts and DER available capacity, communication of setpoints to the different resources, and measuring and verifying event outcomes [2], [34].
- *Virtual Power Plant*: VPPs combine various DERs into a single, dispatchable entity that can provide flexible capacity for a variety of grid services—e.g., DR, load balancing, peak shaving, frequency regulation, aggregated participation in electricity markets, etc. Aggregator DERMS allow for integrating VPPs with grid-aware enterprise systems to offer localized services in a reliable and efficient fashion [1], [34].

- *Microgrid Management*: this functionality requires interaction with grid-aware systems, so that MCs can enjoy access to network information about local grid constraints. It involves the secure and efficient operation of a microgrid, managing DERs and loads both in grid-connected and island modes and enabling smooth transitions to enhance local grid resilience, maintaining frequency and voltage stability and ensuring power supply against major outages [1], [5], [22], [28], [34].

c) Market Operations: it consist of a series of economic functionalities designed to facilitate DER interaction with electricity markets, enabling local energy transactions at the distribution level, and providing a platform for market-based grid services. DERMS shall be equipped to monitor, forecast, and provide information about market conditions to optimize resource usage, energy purchases and sales, and coordination with third-party entities managing BTM DERs [1], [2], [34].

- *Aggregator Data Exchange*: essential for enabling utilities to interact and exchange data with small-scale, BTM DERs, managed by third party- aggregators, and enable their participation in electricity markets.
- *Bidding*: it enables both individual utility-owned DERs and third-party aggregators managing small-scale DERs—which could not take part in electricity markets independently—to actively submit bids for buying or selling energy in local service or wholesale markets.
- *Settlement*: it involves comparing actual operations with planned or forecasted operations and making the required charges. Settlement takes place at both wholesale and retail levels, e.g., between utility and users participating in DR programs through an aggregator.
- *Transactive Energy*: this functionality consists of coordinating producers and consumers' to automatically communicate and exchange energy, virtually, dynamically, and in real-time, based on value signals and reliability constraints.

d) Revenue & Portfolio Analysis: similar to the Analysis & Reporting service of a Utility DERMS, the objective is to review and document the technical and economic performance of an Aggregator DERMS in providing services to the grid and to the customers under its management. This should allow for the economic compensation of DERs and serve as a basis for the analysis and planning of the aggregator's DER portfolio [34]. Different reports may be generated for different stakeholders, such as utility operators, regulators, and customers. This module should cover:

- *Performance Analysis*: it assesses the performance of DERs under the aggregator management in providing grid services—e.g., participating in utility programs like DR—by comparing pre-event and during-event energy usage [34]. Reports should track critical metrics—such as energy production, power quality, DER efficiency, and operational status—, and analyze the broader impact of DERs on the distribution grid, including contributions to grid stability and congestion management [3], [28].
- *Portfolio Analysis & Planning*: responsible for continuously evaluating and trying to optimize the DER portfolio managed by the aggregator. This functionality builds on the insights gained from performance analysis to improve the technical and economic performance of the aggregator's portfolio, ensuring it is capable of meeting grid and customers' future needs effectively.

D. DERMS Vendors Comparison – Market Review

Considering the previous DERMS functional specification, a preliminary—not exhaustive—analysis of the strategic positioning in the market of various vendors offering DERMS solutions has been conducted in cooperation with Minsait, company with which the author had the opportunity to collaborate during the development of this work. The resulting classification is displayed below, and it is based on two key parameters: (i) the level of centralization of each competitor's DERMS solution (x-axis), meaning whether they offer solutions for the utility, for the aggregator, or for both; and (ii) the degree of maturity of these solutions (y-axis).

Fig. 2. DERMS Vendors' Comparison. Source: Minsait.

Minsait, along with other service providers such as Autogrid (recently acquired by Schneider Electric) and Smarter Grid Solutions, is positioned at the center of the graph. This indicates that their offerings include both centralized DERMS solutions (for utilities) and decentralized ones (for aggregators and BTM DERs' management). It must be also noted that, despite the presence of many vendors on the negative side of the x-axis (decentralized solutions), many of their products would not be classified as DERMS according to the terms that will be detailed below, but rather as specialized applications or particular use cases of a DERMS solution—such as VPPs, management of EV charging stations, or solar inverters, etc. In fact, as mentioned above, the industry often tends to view DERMS as utility-exclusive.

E. Enabling Protocols for DERMS Deployment

As introduced in previous sections, a major challenge for the increasing DER penetration is the lack of universally accepted protocols and standards for communication between DER devices, utilities and aggregators, and aggregators and individual DERs [1]-[4], [6], [26]. Is the view of this work that DERMS will be essential for managing and integrating DERs within modern power systems and smart grids (SGs), and robust standards become fundamental for successful DERMS deployment, especially in a context where there are and will be multiple systems and companies involved. This section will discuss some of the enabling communication protocols and information models for the scalable implementation of DERMS, first focusing on the DER-group level interface and then at the device level as proposed in [3], [4], and [26], and displayed in Fig. 3:

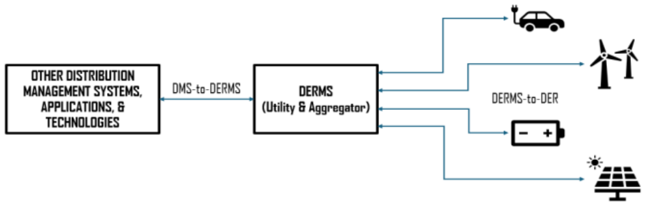

Fig. 3. Overview of interface levels of enabling protocols for DERMS.

1) DMS-to-DERMS Level

Effective data integration is essential for optimizing DER management, avoiding indirect costs, and ensuring smooth operations within the utility ecosystem. Without proper interoperability, issues such as data duplicity and inconsistency may arise, negatively impacting utility operations. Utility enterprise integration is a vital concept in this context, as it involves the capability to deploy and expand various systems and technologies within distribution utilities. In this regard, The Common Information Model (CIM) has gained the support of the industry and among utilities and vendors as a key standard supporting the integration between different utility systems and applications [3], [35].

CIM is a family of standards designed to address data interoperability and standardization challenges among different enterprise utility systems. It provides a framework for modeling the power system, reducing the need for maintaining multiple databases in various formats. The CIM model consists of three working groups (WGs): WG13, which focuses on electrical modeling from a TSO perspective; WG14, expanding on WG13 concepts to address distribution utilities, DER modeling, and low/medium voltage networks; and WG16, supporting data interoperability among market participants. WG14 has led to the development of the International Electrotechnical Commission (IEC) series of standards 61968, which extends CIM concepts specifically for distribution management, providing guidelines for integrating various applications and systems within a utility [3], [4], [35].

In particular, IEC 61968-5 is of particular importance for the deployment of DERMS solutions and their interaction with other utility systems. It provides detailed guidelines for utilities to ensure that their DERMS implementations are robust, scalable, and capable of interacting efficiently with other management systems like ADMS [3], [35]. The standard addresses several areas concerning the optimal management of DER groups, establishing a set of rules for the creation, maintenance, and deletion of DER aggregations, status & event monitoring, forecasting, dispatch, voltage ramp rate control, and (dis)connection of individual DERs [36].

2) DMS-to-DERMS Level

This level involves communication protocols that enable interaction between DERMS and individual DERs, ensuring reliable data exchange, real-time monitoring, and control of DER assets. The exchanged information typically includes AMI measurements from DERs, forecasted production, and operation schedules [1], [6]. The protocol to be employed, as well as performance requirements for communication with DER devices will be often determined by the competent system operator of a particular area. Table 6 of section 7.3 of IEEE Std 2030.11-2021 ([28]) includes a list of common communication protocols identified as viable alternatives for DERs, some of which are briefly presented below:

a) IEEE Std 1815-2012 (DNP3): one of the most widely used communication standards in North American utilities for monitoring and control. It is designed to facilitate interoperability between equipment from different vendors, ensuring consistent and accurate data transmission within the same network. DNP3 features event-driven reporting, error checking, sequence verification, and time synchronization for precise data logging and analysis. Initially, DNP3 lacked security features, but these were later incorporated through DNP3 Secure Authentication, which enhances protection against cyber threats [3], [37].

b) IEEE Std 2030.5-2018: also known as the Smart Energy Profile Application Protocol, it is designed for seamless utility management of energy resources. This standard integrates elements from other standards and provides extensive support for grid services like demand response and load control. It includes robust security measures, such as HTTPS and AES-CCM encryption, making it a preferred choice for DERMS implementation due to its high interoperability and support for a wide range of grid devices [3], [37].

c) OpenADR (Open Automated Demand Response): it is a non-proprietary, standardized protocol designed to support dynamic pricing and DR. Implemented at the application layer of the OSI Model, OpenADR facilitates two-way communication between electricity providers and customers. The protocol includes services like the Opt Service for availability schedules, the Registration Service for payload exchange, and the Poll Service for real-time data requests. OpenADR ensures secure communication using TLS Security and Digital Signatures, making it essential for enabling real-time communication and interoperability between service providers and aggregated loads participating in demand response programs [3], [38].

d) SunSpec Modbus: this is an open communication standard designed to enhance interoperability among DER systems. It builds on the original Modbus protocol and is compliant with the interoperability requirements of the IEEE 1547-2018 standard. SunSpec Modbus defines common parameters for monitoring and controlling DERs, simplifying system implementation, and enhancing deployment possibilities. The physical Modbus interface is widely used, being built into approximately 80 percent of installed DER devices, making it a standardized, cost-effective, and easy-to-integrate communication interface [3], [39].

F. DER Control Architectures

The increasing integration of grid-edge DERs necessitates of advanced control architectures to effectively aggregate and utilize their flexibility. Grid-edge DERs, which include various renewable and non-renewable generation sources, storage solutions, controllable loads, and demand response programs located at the medium-to-low-voltage distribution systems, have the potential to offer multiple possibilities to the electricity grid, but require coordination to maximize their potential. Control strategies for DERs are, therefore, essential for optimizing grid-edge flexibility. They can be broadly classified into five types, namely, *centralized* (involving a central controller gathering data from all DERs and performing global optimization), *hierarchical* (multiple layers of controllers with certain autonomy but coordinated among them), *decentralized* (independent local controllers for groups of DERs), *distributed* (decentralized control with enhanced communication and coordination among local controllers), and *hybrid* (providing flexibility to adapt to various DER ownership structures) [5]. Various architectures for the integration of grid-edge DER, built upon one or more than one of these control strategies, have been developed under different projects. Two of these, deemed the most developed and analyzed in the literature, are briefly discussed below.

1) Hierarchical Architecture

This is a multi-layered approach designed to manage BTM loads and grid-edge DERs, such as PV systems, ESS, and flexible loads. This architecture is illustrated in Fig. 4, and can be structured into three key components [5], [40]:

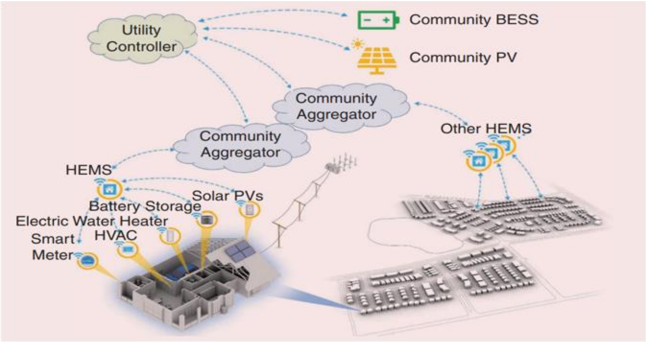

Fig. 4. Hierarchical Architecture for BTM DERs' control [5].

- *Home Energy Management System (HEMS):* at the base layer, the HEMS manages energy consumption and generation within individual households. It optimizes the use of DERs by considering customer preferences, DER technical limits, and electricity tariffs, and calculates the aggregated flexibility of all controllable DERs.
- *Community Aggregators*: operating at an intermediate level, they coordinate the operations of multiple HEMS within a community. They perform security-constrained economic dispatch of the aggregated flexibility, balancing individual household preferences with community-level objectives and technical constraints.
- *Utility Controller*: at the top layer, it oversees the larger distribution grid, leveraging the aggregated flexibility provided by Community Aggregators to solve system-wide problems. It also manages larger-scale DERs connected to the MV distribution network, facilitating their participation in grid services.

This architecture is characterized by a continuous flow of flexibility information from the HEMS to the Community Aggregators and finally to the Utility Controller, and an opposite flow of setpoints and control signals are sent from the Utility Controller down to the HEMS and ultimately to the individual DERs. The effectiveness of this hierarchical architecture was demonstrated in the Basalt Vista Field Pilot Study in Colorado, where it allowed for significantly reducing overvoltages, enhancing grid resilience during disturbances, and shifting loads away from peak periods. In this occasion, system-wide analysis and DER optimization were performed with the help of an ADMS [5], [40].

2) *Federated Architecture*

The Federated Architecture for Secure and Transactive Distributed Energy Resource Management Solutions (FAST-DERMS) is a comprehensive control framework developed under the U.S. Department of Energy's Grid Modernization Laboratory Consortium (GMLC) program. This architecture aims to provide reliable T&D services through the scalable aggregation and near real-time management of diverse grid-edge DERs. It integrates centralized, hierarchical, and distributed control structures to efficiently coordinate both individual and local groups of DERs like buildings (B) or microgrids (MG) [5], [6], [41]. The architecture is displayed in Fig. 5, and it includes the following components [41]:

- *Flexible Resource Scheduler (FRS):* it is responsible for performing a reliability-constrained economic dispatch at the substation level. It aggregates and optimizes DERs within its service area, coordinating their flexibility to generate firm offers for wholesale markets. The FRS also disaggregates grid control signals, ensuring that voltage and equipment loading remain within safe limits.
- *FRS Coordinator*: it supervises and coordinates the operations of individual FRSs across different substations, aligning their activities with wholesale market pricing and broader grid objectives. It interfaces with distribution management systems and with the TSO to negotiate grid services and relay control signals.
- *Aggregators*: they consolidate and control multiple DERs to act as single participants in grid operations and markets, providing aggregated flexibility to the FRS.
- *Transactive Market Manager (TMM):* it serves as both an aggregator and a market maker, facilitating price negotiations and managing transactive resources. It supports one-way communication schemes, where DERs respond to price signals, and two-way schemes, where DERs submit bids that directly influence price formation.

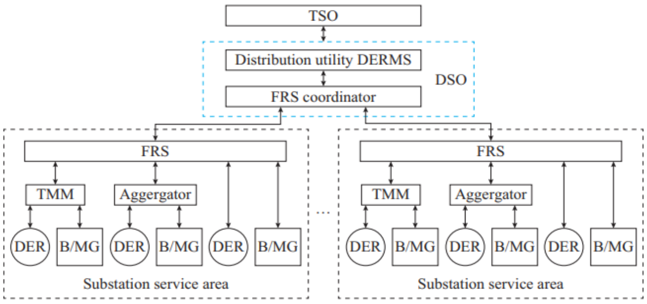

Fig. 5. Conceptual Schematic of FAST-DERMS [6].

FAST-DERMS provides a scalable solution for integrating DSO-managed DERs into wholesale electricity markets and transmission system operations. It emphasizes a total-DSO model, where all resources within a distribution grid are aggregated through the distribution utility. This model ensures comprehensive control over the network, balancing local and system-wide reliability and economic objectives. DERMS facilitate the scalable implementation of these control architectures by providing a platform for the aggregation, monitoring, and coordination of DER operations.

G. *European Regulatory Framework*

As developed in previous sections, the lack of a common, well-defined regulatory framework on DER management constitutes a great obstacle to achieving a comprehensive DERMS platform. In this regard, the EU DSO Entity and ENTSO-E's Proposal for a Network Code on Demand Response, still under development, has emerged as arguably the most complete and significant regulatory framework on DER integration at the European level. Thus, some of its primary goals and matters of interest for DERMS deployment are listed below [33]:

- *Development of national terms and conditions*: the network code aims to establish objective principles for creating national rules concerning various aspects of DER management. This includes aggregation models, demand response, energy storage, distributed generation, and demand curtailment. It is intended to guide Member States in developing consistent and effective regulations that support the integration of DERs into the grid.
- *Market integration and competition*: it intends to ensure that all available resources and service providers can participate in electricity markets, defining measures to promote non-discrimination and effective competition, ensuring that the markets operate efficiently.

- *Aggregation models and market participation*: guidelines are included for Member States to define DER aggregation models, which are crucial for enabling small-scale DERs to participate in electricity markets. These models will determine how DERs are aggregated and how their provided services are measured and compensated. It also includes general requirements for national terms concerning baseline calculation, which shall be used to quantify the services provided by DERs and ensure accurate pricing and settlement.
- *Prequalification requirements for market access*: conditions for SPs to participate in providing local or balancing services are detailed, along with prequalification and verification requirements for the provided flexibility products in local service markets.
- *Market design*: it establishes guidelines for the design of local markets that facilitate the efficient procurement and pricing of services provided by DERs. It emphasizes the priority of market-based procurement mechanisms, and includes directives on flexible connection agreements, the main roles of local market operators, and on how local markets should be integrated with day-ahead, intraday, and balancing markets across different timeframes.
- *Coordination between TSOs and DSOs*: the Regulation highlights the need for a common proposal for national terms and conditions for TSO-DSO and DSO-DSO coordination, with special consideration to defining the DSO observability area, responsibilities regarding congestion and voltage issues, and data exchange requirements between DSOs-DSOs and DSOs-TSOs.
- *Flexibility Data Management*: the proposal outlines the need for a centralized flexibility register in each Member State, where SPs and other authorized actors can read, register, or update information DER flexibility and their provided services.

However, European-level regulation is still ambiguous and poorly defined in many of the terms included above, and it often limits to establish that Member States shall develop their own national terms and conditions for each of these aspects—namely, aggregation models, methods for quantifying services, prequalification and verification of products, market design for local services, and coordination between SOs.

IV. End-to-End Functional Architecture for DERMS

The vendors comparison graph included above showcases that Minsait is considered to have a significantly more global and holistic view of DERMS solutions with respect to many competitors in this sector, focused on either purely centralized solutions for utilities/DSOs (e.g., ADMS with DER capabilities) or tool only for aggregators (VPP or DR). Thus, the functional architecture described below draws inspiration from its DERMS solution, and is complemented with the functional specification included in the previous review of the state of the art—based on the information presented in [1]-[3], the IEEE Std 2030.11-2021 as in [28], and the collection of services and use cases from SEPA in [34]. Special attention has been given to ensuring that this architecture can cover the widest possible range of applications and use cases for all potential stakeholders—DSOs, aggregators, vertically integrated utilities, etc.—across different countries, at least at the European level. Additionally, it has been designed to be implementable onto the platforms of all possible clients and capable of integrating with their existing solutions if needed.

A. Methodology

The following aspects will be covered regarding the proposed DERMS functional architecture:

- *Preliminary considerations*: general structure of the architecture and the rationale behind its development.
- *Architecture overview*: description of functionalities and services, along with the reasons for their positioning in the architecture, and the potential interaction between the different layers and modules.
- *DERMS 'Declinations'*: particularization of the DERMS architecture for different potential clients, namely, aggregators, niche vertical platforms, microgrids, DSOs in a context of unbundling aiming to integrate its ADMS with the DERMS and those not aiming to preserve it, and vertically integrated utilities with and without ADMS.
- *Modularization strategy*: based on the previous declinations, design of how the different functions and services can be modularized and decoupled so the DERMS solution can be implemented onto every client, integrating with or replacing its own software.

B. Preliminary Considerations

The DERMS functional architecture is presented in Fig. 6 below, with those functionalities and services exclusive to the utility/DSO highlighted in green, those exclusive to aggregators in red, and those applicable to both sharing both colors. This same characterization has also been applied to the field devices, measurement systems, distribution network management systems, markets, control centers, and system operators with which the DERMS must be able to interact. To understand the reasoning behind the architecture design, several points should be noted:

- Since the goal is to develop a unique and comprehensive DERMS solution, many of the functionalities and services that were previously duplicated in the state of the art—or had very similar versions—for Centralized (Utility) DERMS and Decentralized (Aggregator) DERMS, will now be unified both for BTM and utility-owned DERs—e.g., enrollment functions. Similarly, some functionalities that were exclusive to Utility or Aggregator DERMS have had their scope expanded, while others remain separate to adapt to different client needs. Examples are DER optimization functions, applied either for a single aggregator's portfolio, or to aggregators and utility-managed DERs.
- The distribution of functionalities and services has been partly modified with respect to what was presented in the functional specification above, with some additional functions incorporated and others no longer considered. This attends to (i) integrating insights from Minsait's experience in the deployment of DER management solutions, and (ii) attempting to limit the included functionalities to the service level and not to use cases. This implies, for example, that VPP or Microgrid Management do not appear in the diagram as they are more of a potential use case for a DERMS solution. That is, an aggregator can use a DERMS to create and manage a VPP or to control a microgrid by combining some of its specific functionalities and services: DER registration and aggregation, portfolio optimization, etc.
- The architecture has been structured from the bottom up, following the information flow and the order of processes from field devices—DERs and SCADA systems—to

electricity markets or the TSO. In this manner, those functionalities that only require field information and not the completion of previous processes are located at the bottom, while the more complex services necessitating the execution of other lower-level functions are positioned towards the top of the architecture.

- The DERMS solution itself is delineated by the thick rectangle encompassing both Multi-Protocol Brokers. Surrounding it are all the field devices (DERs and metering devices), measurement and control systems (SCADA), Metering Data Management (MDM) systems, solutions for network management (ADMS, OMS, asset performance management), Geographic Information Systems (GIS), weather data providers, competent system operators, and electricity markets which the DERMS must be capable of interacting with. Control Centers and Operational Data Exchange Platforms, like SIORD in Spain, GOPACS in the Netherlands for communication between DSOs and service providers, or EQUIGY in multiple European countries for DSO-TSO interaction, have been incorporated as potential intermediaries.

C. *Architecture Overview*

Taking all of the above into consideration, the conceptual development of the DERMS functional architecture will be presented in this section. The readings from the network and DER units are collected by field measurement devices, translated through the *Multi-Protocol Broker (MPB)* into protocols and information models that the DERMS can work with, and placed in the messaging queue of the *Communication Interface (CI)* to be processed and utilized by other modules. The same also works in the opposite direction with commands sent from the DERMS to the field devices: in this case, the MPB translates them into the corresponding protocols used by each device.

A *Connectivity* layer is positioned immediately above the CI, as it is responsible for the interaction with DERs and with the grid. This encompasses *DER* and *Grid*—referring to traditional grid elements, such as tap changers, switches, capacitors, etc.—*Monitoring* (measurements acquisition on a periodic basis), *Status* (tracking of parameters such as operational mode, state of charge, etc.), and *Control* (sending of commands, checking DERs are operating as scheduled, etc.), *DER Alarms & Events Logging* (for triggering notifications—alarms—or activating associated processes—events—when a monitored parameter exceeds a certain threshold), and *Edge Management* (for handling edge devices for DERs: which devices there are, where they are located, authentication to ensure only verified devices can send data to the DERMS, etc.). A *CIM Converter* is included in parallel to the CI and the Connectivity module to make the DERMS compatible with external GIS or other systems exporting network topology files in CIM format.

The *Data Storage & Task Management* module is placed directly above the connectivity layer. It includes (i) the *Task Manager*, responsible for the inventory and the execution of scheduled processes of all kinds: forecasts, optimization, recalculation of measurements, generation of reports, etc., (ii) a *Real-Time Communication Bus* allowing for real-time data exchange through various mechanisms—assigned only to utilities as aggregators do not typically have real-time (milliseconds) requirements for DER operation—and (iii) the storage of collected data in various formats for different uses: *Time-Series* (for information recorded periodically at regular intervals), *Relational* (for traditional relational databases in table format), *File Storage* (cloud repository of files), and *In-Memory* (temporary storage of data, to be used and discarded).

The first layer offering services for the client consists of the *DER Enrollment & Flexibility Management* module, covering the *Registration* of both individual DERs and DER

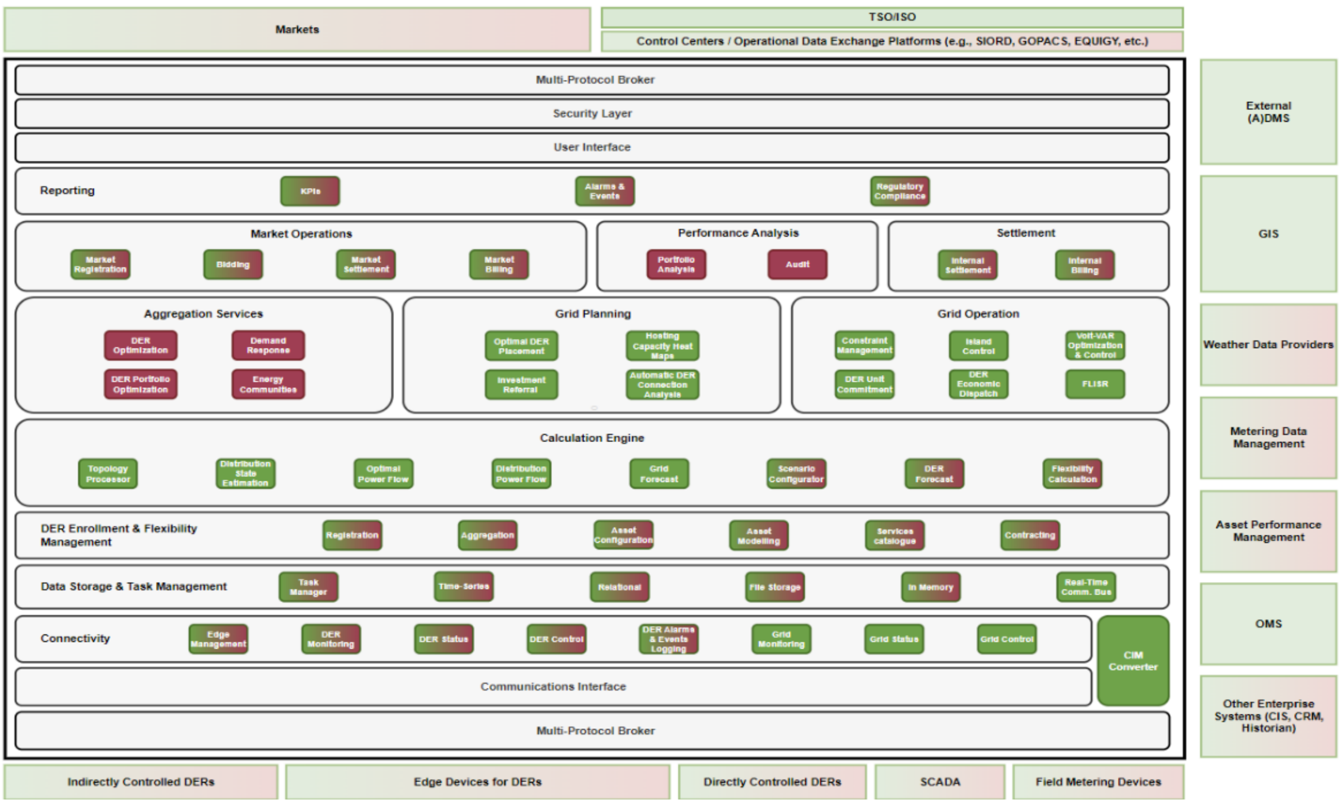

Fig. 6. DERMS Functional Architecture – General Schematic.

groups in the DERMS platform, the *Aggregation* of these DERs, their *Configuration* and digital *Modeling*, *Contracting* (management of supply rates, upward and/or downward flexibility tariffs, etc.), and a *Service Catalogue* for flexibility products (congestion management, voltage control, island control, load shaping, ToU optimization, etc.), indicating min/max capacity and activation time, minimum preparation time for the delivery of these services, etc.

Following this, there is a module of core functionalities required in order to provide further services: the *Calculation Engine*. This encompasses functions capable of performing *State Estimation*, *(Optimal) Distribution Power Flow*, and processing real-time grid topologies (*Topology Processor*) based on the status of the switching devices of the network. *Grid Forecasting* and *DER Forecasting* are also included in this module, along with the ability to configure network scenarios for further analysis and power flow/state estimation calculations (*Scenario Configurator*), and to conduct *Flexibility Calculation* for each type of asset, based on historical data and/or the parameterization of restrictions (e.g., SoC cannot fall below 20% or exceed 90%). Most of these functionalities are exclusive for utilities and system operators, since aggregators lack a network model to perform grid analysis calculations.

The next layer encompasses all *Grid Planning* and *Grid Operation* functions, as well as *Aggregation Services* such as the *Optimization* of both individual DERs and DER portfolios, and the creation and management of *DR* programs and *Energy Communities*. Unlike VPPs and microgrids, which could be reduced to use cases of a DERMS, DR involves specific functionalities such as the ability to broadcast a command—e.g., to turn off all thermostats or to set all batteries to discharge—instead of simple deterministic setpoints delivered to the DERs within the aggregator portfolio. The same applies to Energy Communities, with their own planning and operation services. Equivalent functionalities to those included in Grid Planning and Grid Operation were already discussed in the state of the art, so they will not be described here again. An *Island Control* function has been included to cover the management of regions of the network that may become isolated due to major outages or for energy efficiency reasons, as well as the transition between grid-connected and island modes.

Above them in the architecture, we can find three parallel groups of services. The first is *Market Operations*, encompassing *Market Registration*—enrollment in electricity markets, exchange of DER and portfolio structural data, and further administrative procedures—, *Bidding*, *Market Settlement* and *Billing*, all of them applicable both to DERs participating in the market through an aggregator and to individual utility-owned DERs. Secondly, the *Performance Analysis* includes two functionalities, exclusive to the aggregator level: (i) *Portfolio Analysis*, responsible for continuously evaluating and trying to optimize the aggregator's DER portfolio, and (ii) *Audit* to cover those processes related to the audit of a flexibility service, i.e., what was committed vs. what was ultimately achieved. Moreover, a *Settlement* module is also incorporated with the *Internal Settlement* and *Billing* services, applicable both within an aggregator portfolio, or in the case of utility-managed DERs that are not participating in the market—e.g., providing services through flexible contracts.

Finally, a *Reporting* module is included to create reports on various aspects, both at utility and aggregator levels, such as *KPIs* on the technical and economic performance of the DERMS, the resolution of specific *Events & Alarms* (following the outputs of the DER Alarms & Events Logging functionality), or on *Regulatory Compliance* regarding the provision of local services. At the top of the schematic, the *User Interface* offers a front-end web portal where users can navigate, manage their devices, schedule periods of unavailability, review the resolution of events, etc.; and the *Security Layer* handles malware protection, authentication (user login: user, password, JSON Web Tokens, etc.) and authorization (role and permission management). Lastly, another layer of inter-protocol translation enables the interaction with electricity markets and/or TSOs.

D. DERMS Declinations

It is essential that the previous architecture can be implemented onto the platforms of as many different potential clients and stakeholders as possible—i.e., DSOs, vertically integrated utilities, aggregators, niche verticals, or microgrid controllers—integrating with their existing software solutions and covering the widest range of applications and use cases across multiple countries and various regulatory frameworks. In this sense, seven different adaptations of the previous architecture have been considered. To avoid redundancy, these will be presented below by specifying which of the above functionalities and services shall be excluded from each declination and the reasons for it. However, it must be noted that all the functionalities included in these variations meet potential requirements for a particular use case, which does not imply that every function will be required in all instances.

1) DERMS Aggregators

DER aggregators combine small, usually BTM DERs, into larger, controllable groups to provide flexible capacity and ancillary services to the DSOs and participate in electricity markets, DR, or EE programs. As a result, this declination of the DERMS solution excludes all pure network functionalities, i.e., grid monitoring, status, and control, grid operation and planning services, and the grid-exclusive functions of the calculation engine (grid forecasting, topology processor, state estimation, and power flow analysis), for not being within the scope of the aggregator. Regarding the 'periphery' of the DERMS solution, direct interaction with TSOs is not contemplated for aggregators (it would be through the control centers or operational data exchange platforms in any case), nor is it with DMS, GIS, or OMS, as these systems contribute to a network management for which an independent aggregator is not responsible—it does not even have access to network information or models. For this reason, the CIM Converter has also been deemed unnecessary for aggregators.

2) DERMS Niche Verticals

Niche verticals describe a group of companies that focus on a specific niche or specialized market spanning multiple industries. They cover that market's particular needs and generally do not expand to broader markets. Examples of niche verticals within the electricity sector include providers and managers of EV charging stations, BESS, PV inverters, or smart thermostats [42]. Consequently, this adaptation of the DERMS architecture would be very similar to that of DER aggregators, with the particularity that this time the niche vertical is owner of the DERs in its portfolio (these do not belong to third parties or individuals) and, therefore, internal settlement and billing functionalities shall be excluded too—the company would be settling and billing its own products.

3) DERMS Microgrids

Microgrids must be capable of operating both in grid-connected mode, performing local optimization and ensuring efficient resource usage to provide grid services, and islanded, managing grid-forming operations, load balancing, and frequency and voltage regulation to ensure the stable and reliable operation of the microgrid. Consequently, this DERMS declination must incorporate nearly all its functionalities, except for the network planning services that are reserved for DSOs. This involves those already included for aggregators, but also all pure grid services and network calculation functionalities—to be able to operate in island mode. Similarly, MCs must be capable of interacting with all types of field devices—DERs and measurement devices—, enterprise network management systems, GIS—CIM converter is also incorporated—, electricity markets, DSOs, and TSOs, either directly or through control centers.

4) DERMS DSOs

DSOs are responsible for managing the local and regional LV and MV distribution networks. This involves grid planning, real-time monitoring and controlling of grid conditions, coordinating local assets and optimizing DERs for distribution-level grid services—such as load balancing, peak shaving or voltage control—, forecasting load and generation to anticipate potential network issues, scheduling and dispatching resources, leveraging DER's value in the electricity markets, determining compensation for resource proprietors and aggregators, as well as interacting with TSOs for broader grid requirements [43]. This implies that performance analysis functionalities and aggregation services—local optimization, DR, and EC—are the only ones not initially considered for the standard DSO's DERMS solution, as these functions are exclusive for aggregators. Four different DERMS declinations have been contemplated for DSOs, depending on (i) whether it already has a DMS or ADMS software that it aims to maintain without overlapping with the DERMS, and (ii) whether we are targeting a DSO that operates in a market context of unbundling—i.e., separation between the electricity businesses that can be conducted competitively (generation and retail) from natural monopolies (T&D)—or it is a vertically integrated utility.

a) DERMS DSOs w/ ADMS – Unbundling: in this first scenario, all grid planning and operation services, core grid functionalities of the calculation engine, grid monitoring and control, real-time communication bus, and CIM conversion shall be covered by the DSO's own ADMS software. Note that the External (A)DMS component on the right-hand side of the schematic shall be now the utility's own ADMS, part of whose capabilities will be integrated with the DERMS.

b) DERMS DSOs w/o ADMS – Unbundling: the same applies in the case the DSO does not have or does not wish to integrate its ADMS with the DERMS software, with the difference that all functionalities belong to the DERMS and the ADMS is again considered as an external element.

c) DERMS DSOs w/ ADMS – Vertically Integrated: all of the above is also applicable to vertically integrated utilities aiming to integrate the DERMS solution with an existing ADMS, with the particularity that aggregator-exclusive functionalities—i.e., performance analysis and aggregation services modules—shall be incorporated here, as the DSO can now perform aggregation and retailing functions. Market operations remain included to allow the DSO both for the acquisition of flexibility products from third-party aggregators—e.g., niche vertical platforms for batteries or EVs—in local markets, and for the participation in wholesale markets alongside other integrated utilities. Additionally, control centers for interaction with TSOs/ISOs might be integrated within the same vertical utility—just like the TSO itself—but are still considered in the architecture in the case the utility exclusively manages distribution and retail.

d) DERMS DSOs w/o ADMS – Vertically Integrated: the complete DERMS solution must be implemented in the case of a vertically integrated utility that does not wish to integrate it with its own ADMS software. This would arguably constitute the ideal client typology for the deployment of the DERMS functional architecture proposed in this work.

E. Modularization Strategy

It is fundamental that this architecture can be fragmented into multiple modules, so that it can be implemented onto the platforms of all possible clients and capable of integrating with their existing software solutions if necessary. In this regard, this section will present a modularization strategy that uses the common patterns and conclusions drawn from the DERMS declinations described above to decouple its different functionalities and services. This is displayed in Fig. 7 below, the following aspects requiring further clarification:

- Connectivity functions are split into two modules: *DER Connectivity* and *Grid Connectivity*. This separation allows DER Connectivity to be deployed independently for specific applications like DERMS for aggregators or DSOs maintaining their ADMS software. Note that the CIM Converter is always included with Grid Connectivity, and that both the Communications Interface and the Multi-Protocol Broker are integrated into both modules, but they are only implemented once when both modules are needed.
- *Data Storage & Task Management* remains a single module, despite including elements not necessary in all cases. Its functionalities can be used independently as required by each specific application. The same is valid for *DER Enrollment & Flexibility Management* and *Reporting* modules, which shall be deployed for all clients and use cases considered above.
- The Calculation Engine is divided into grid and DER modules. The *DER Engine* can be included alone for specific applications, while the *Grid Engine* is also required for microgrids and DSOs not integrating with ADMS. The Scenario Configurator is included in both modules, ensuring it can be incorporated in either one—never duplicated—or even omitted in the case an ADMS provides this functionality.
- All planning, grid operation, and aggregation services are deemed independent modules, allowing clients to choose which functions to incorporate to their solution. These services rely on lower-level functionalities that can be excluded if unnecessary for certain stakeholders.
- *Market Operations*, *Performance Analysis*, and *Settlement* are also separate modules. Performance Analysis is excluded from DSO solutions with unbundling (do not perform any aggregation tasks), and Settlement does not apply to niche verticals (they would be settling and billing their own products), so these must be easily decoupled from the rest of the solution.

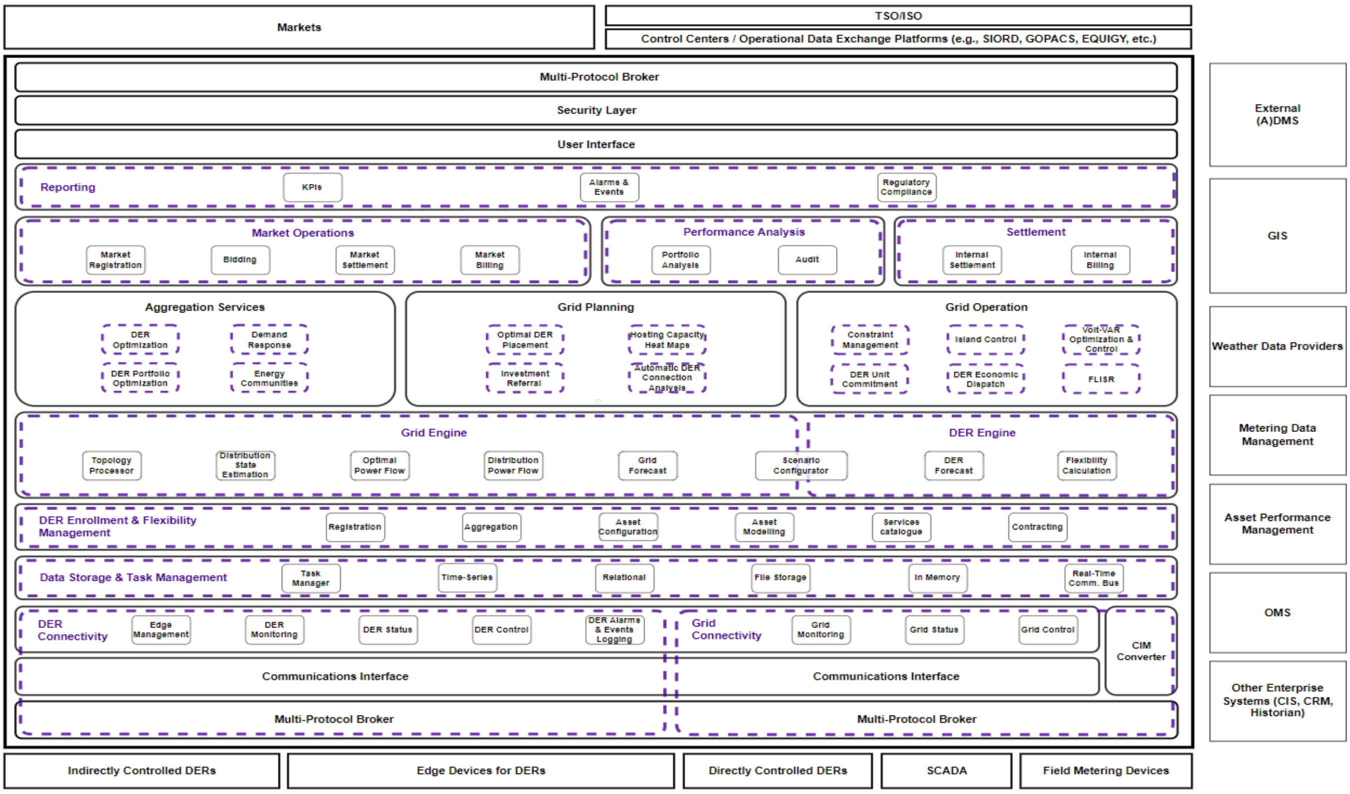

Fig. 7. DERMS Functional Architecture - Modularization Strategy.

These modules must be independent software units capable of decoupling from the rest of the solution, interacting with each other, and integrating with other software systems. This would allow for a comprehensive DERMS solution that is based on core functions which are common to all possible applications, but that at the same time can be adaptable to the roles of the different stakeholders, use cases, and structures of the electricity business in different countries and regulations.

V. Architecture Validation

This chapter will address the validation of the proposed DERMS functional architecture, the seven declinations that have been considered, and its modularization strategy. First, an IDC MarketScape assessment of DERMS service providers will be presented to show Minsait's relevance in the international DERMS landscape. Then, an overview will be provided of several projects conducted by Minsait, successfully implementing some parts of the proposed architecture. Finally, a questionnaire distributed among members of TSO/DSOs, aggregators, and the academic community will serve to justify the interest of the electricity industry in what has been discussed here.

A. IDC MarketScape – DERMS Service Providers

The IDC MarketScape evaluated SPs with a global perspective on DERMS actively working with clients and/or collaborating with utilities for monitoring, control, operation, planning, and customer engagement activities related to DERs. Each vendor was assessed both quantitative and qualitatively according to the variety and maturity of the capabilities and services they could offer, in particular considering areas such as power grid management and DERMS expertise, technology strategy and innovation, and experience with communication and control protocols. The results of the IDC MarketScape are presented in Fig. 8, with the Y-axis representing current capabilities and alignment with customer needs, the X-axis evaluating vendors' future strategies over the next three to five years, and the size of the indicators being an estimate of the vendor's market share [44]. Minsait falls into the *Leaders* category, highlighting its significance as a DERMS vendor and the relevance of its proprietary DERMS solution.

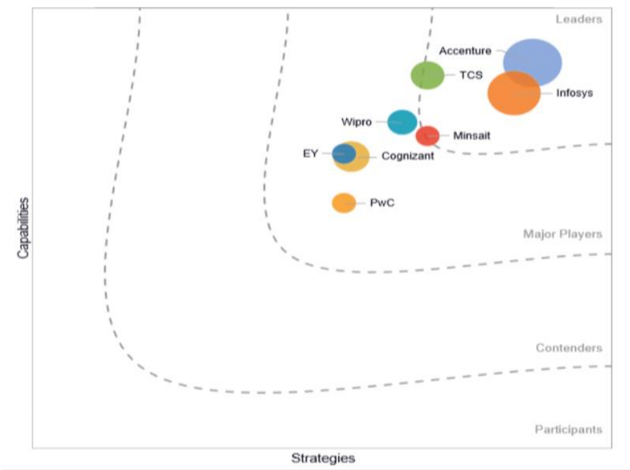

Fig. 8. IDC MarketScape DERMS SPs Vendor Assessment [44].

B. Project References

This section will briefly present a series of projects in which Minsait has been capable of meeting the requirements of very diverse clients using the same set of software modules, combined in different ways according to the specific use case. Five different projects will serve to illustrate five of the DERMS declinations considered above, demonstrating the technical feasibility of the proposed modular approach.

- *DERMS Aggregators*: in partnership with Ferrovial, Minsait developed a DERMS solution aimed at optimizing the integration of PV systems and BESS within commercial and industrial buildings. The project leverages AI to enhance battery operations and maximize energy savings through price arbitrage strategies. The DERMS integrates the monitoring of power meters, solar PV, batteries, and HVAC equipment under a unified platform, employing economic optimization models based on historical demand, weather data, and ToU tariffs to determine optimal operation schedules [45].

- *DERMS Niche Verticals*: Minsait collaborated with Galp to implement a DERMS solution for the aggregation of EV charging stations. This project tested a business model where Galp aggregates demand flexibility from multiple EV stations to participate in local energy markets. Integration with Etenic (a platform for managing recharge sessions), and OMIE (market operator) enabled exchange of recharge sessions and market schedules [46].
- *DERMS Microgrids*: Minsait supported Monash University's Net Zero Initiative by integrating various DERs and EE solutions into a microgrid on its Clayton Campus in Australia. The project involved the distributed management of edge devices and an active grid management, providing centralized monitoring and control of resources across the campus [47].
- *DSO with Proprietary ADMS – Unbundling*: Minsait partnered with Enel, a leading global DSO, to integrate its DERMS with Enel's ADMS. The DERMS solution, which highlighted the effectiveness of Minsait's modular approach, was designed to manage critical functions outside of the ADMS core tasks, including the detection of grid criticalities through OPF analysis, load forecasting, flexibility needs estimation, and the optimal allocation of flexibility based on market rules. The system also integrates with local flexibility markets to contract flexibility services through competitive processes [48].
- *DSO without Proprietary ADMS – Vert. Int. Utility*: Minsait will deliver a comprehensive DERMS solution for Saudi Electricity Company (SEC) to manage its distribution operations in two of its control centers. The project involves delivering full ADMS functionalities for planning and real-time operations, along with tools for managing aggregators and FTM and BTM assets managed by third parties.

These projects collectively demonstrate the versatility and technical feasibility of the proposed comprehensive and modular DERMS solution, confirming its applicability across a wide range of client profiles and use cases.

C. Industry Interest Assessment Questionnaire

Finally, a questionnaire assessing the interest of the electricity sector in some of the primary aspects emphasized throughout this work was distributed among members of TSO/DSOs, aggregators, and the academic community. The main conclusions drawn from their responses are listed below:

- *Broad support for DERMS*: around 80% of respondents believes that DERMS are essential for all stakeholders managing DERs, regardless of their specific roles.
- *Focus on prosumers and aggregators*: DERMS are deemed to primarily benefit prosumers and aggregators by optimizing BTM resources, rather than just helping SOs manage the distribution network. This highlights the broader applicability of DERMS beyond utilities.
- *Support for stakeholder-specific functions*: about 90% support the need for DERMS to include specific functions tailored to each stakeholder's needs, while 70% believe in having common core functions for all stakeholders, though this idea is more contested.
- *Consensus on market mechanisms*: there is strong agreement on the need for new market mechanisms, such as local flexibility services markets, to maximize the value of DERs, rather than relying solely on bilateral or flexible contracts.
- *Regulation vs. specialization*: most respondents think that core DERMS functions should not be regulated and shared among stakeholders. Instead, they support competitive specialization in the market.
- *Need for a new DERMS Solution*: there is consensus that DERMS should be developed as a new solution, rather than an extension of existing systems like ADMS.
- *Vendor specialization vs. flexibility*: while many believe vendors should focus on specialized solutions for specific stakeholders, there is also significant support (70%) for modularization and flexibility to adapt to different regulatory contexts and use cases.

Therefore, this assessment of the industry interest serves to justify the approach followed to develop the proposed DERMS functional architecture, the need for its seven declinations for different clients and use cases, as well as for modularization and flexibility. However, it also shows that the electricity sector still holds many convictions that are contrary to the vision advocated in this work.

VI. Conclusions

The electric power system is undergoing a significant transformation with the increasing penetration of distributed energy resources, which challenges the traditional centralized-generation model and has led to a more complex, active, and dynamic distribution grid. The integration of DERs, both FTM and BTM, offers multiple opportunities for the technical and economic optimization of the network, but also introduces significant challenges that require new management tools. In response, Distributed Energy Resource Management Systems have emerged to provide a comprehensive solution to monitoring, controlling, and optimizing the integration of DERs into the power grid [1]-[6].

This work has developed and validated a unified, comprehensive DERMS architecture that is both modular and versatile, adaptable to the particularities of various client typologies and use cases. It has been emphasized that DERMS solutions shall not be exclusively for utilities and DSOs, but also target third-party aggregators of BTM DERs, microgrid controllers, and vertical niche platforms, among others, and underscores the importance of a unified solution with core functionalities common to all stakeholders, complemented by specific functionalities and services for particular use cases. The outcomes of this work are expected to provide a solid foundation for further understanding, development, and implementation of DERMS solutions, setting the stage for more efficient and effective management of distributed energy resources.

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