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DEFINITION OF A FUNCTIONAL ARCHITECTURE FOR DERMS

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Definición de una Arquitectura Funcional para Sistemas de Gestión de Recursos Energéticos Distribuidos (DERMS)

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***Resumen*—La creciente penetración de los Recursos Energéticos Distribuidos (DERs, por sus siglas en inglés) está transformando la red eléctrica de un modelo centralizado a una red de distribución descentralizada, activa y dinámica. Este cambio presenta nuevos desafíos, como flujos de potencia inversos, sobrecargas en los alimentadores y fluctuaciones de voltaje, que las herramientas tradicionales no pueden gestionar de manera efectiva. Los Sistemas de Gestión de Recursos Energéticos Distribuidos (DERMS) han surgido como una solución prometedora para la supervisión, control y optimización de los DERs, aunque el concepto sigue siendo novedoso y aún carece de una definición universalmente aceptada y funcionalidades estandarizadas. Los enfoques actuales hacia los DERMS suelen dividirse en sistemas centralizados (Utility) para los recursos front-of-the-meter (FTM) y sistemas descentralizados (Aggregator) para las carteras de DERs behind-the-meter (BTM). Existe un consenso creciente sobre la necesidad de una solución integrada que unifique estos niveles. Este trabajo desarrolla una arquitectura funcional unificada y completa para los DERMS, diseñada para ser modular y adaptable, acomodándose a las necesidades de diversos actores, en una variedad de casos de uso, diferentes marcos regulatorios y estructuras de mercado. Validada a través de varios casos de estudio y una evaluación de los intereses de la industria, la arquitectura propuesta demuestra el potencial de una solución DERMS completa, modular y versátil, capaz de gestionar eficazmente tanto los recursos FTM como BTM, adaptándose a múltiples requisitos operativos e integrándose con los sistemas de gestión existentes.**

Índice de Términos*—Recurso Energético Distribuido (DER), Sistema de Gestión de DERs (DERMS), front-of-the-meter/ behind-the-meter (FTM/BTM), DERMS Utility/ Aggregator, declinaciones DERMS.

I. INTRODUCCIÓN

El rápido aumento de la participación de los DERs en la red de distribución—incluyendo la energía solar fotovoltaica, aerogeneradores, sistemas de almacenamiento de energía en baterías o vehículos eléctricos—está impulsando una transformación fundamental en la red eléctrica, pasando de un modelo centralizado basado en la generación a una red de distribución descentralizada, activa y dinámica [1]-[4]. Este cambio introduce complejidades técnicas significativas, como flujos de potencia inversos, sobrecargas en los alimentadores y desafíos en la regulación del voltaje, que las herramientas tradicionales de gestión de la red son inadecuadas para manejar [1], [2]. Además, la distinción entre los DERs Front-of-the-Meter (FTM)—típicamente recursos a escala de utility conectados a la red de distribución de media tensión (MT)—y los DERs Behind-the-Meter (BTM)—recursos más pequeños ubicados en el lado del consumidor—se vuelve cada vez más difusa, complicando su gestión y requiriendo el desarrollo de sistemas más sofisticados que puedan integrar y optimizar estos diversos recursos energéticos [1]-[6].

En este contexto, los DERMS han emergido como una solución prometedora para la monitorización, control y optimización en tiempo real de los DERs [1]-[3], [5], [7]. Sin embargo, el concepto de DERMS sigue siendo novedoso, sin una definición universalmente aceptada ni un conjunto estandarizado de funcionalidades y servicios principales [1]. La literatura y las prácticas de la industria revelan un panorama fragmentado, con soluciones DERMS a menudo divididas en DERMS centralizados (Utility)—típicamente el enfoque principal de la industria eléctrica hoy en día—que gestionan DERs FTM de escala media a grande y grupos de DERs BTM agregados, y DERMS descentralizados (Aggregator), destinados a manejar carteras de DERs BTM, como paneles solares residenciales y sistemas de baterías. Sin embargo, parece haber un consenso creciente sobre la necesidad de integrar estos niveles en una solución de gestión unificada y completa para garantizar la integración óptima y fiable de los DERs [1]-[3], [5], [7], [8].

Este trabajo busca cerrar estas brechas proporcionando una definición unificada para los DERMS, aclarando su ámbito de aplicación y desarrollando una arquitectura funcional unificada y completa para las soluciones DERMS que pueda acomodar tanto las necesidades de gestión centralizada como descentralizada. La arquitectura está diseñada para asegurar una amplia adaptabilidad, ofreciendo siete declinaciones distintas adaptadas a varias partes interesadas y casos de uso, marcos regulatorios y estructuras de mercado, y proponiendo una estrategia de modularización que permita su integración con las plataformas de software existentes y los requisitos operativos de diferentes tipologías de clientes, ya sea que requieran una solución integral o mejoras selectivas a la infraestructura existente.

La arquitectura propuesta se valida a través de varios casos de estudio en la industria y una evaluación de la preparación del mercado. Este proceso de validación demuestra (i) el interés por una solución DERMS integral que pueda ayudar tanto a las utilities como a los operadores de la red de distribución (DSOs), así como a los agregadores de terceros a gestionar tanto los recursos FTM como BTM, y (ii) la necesidad de que esta solución sea modular y adaptable a las particularidades de diversos clientes y casos de uso, así como la viabilidad técnica y la aplicabilidad en el mundo real de este enfoque. Por lo tanto, el resultado del trabajo es una solución unificada para la integración de DERs, que consiste en un conjunto de funcionalidades centrales comunes a todos los actores, complementadas por servicios específicos para casos de uso particulares, y que tiene como objetivo proporcionar una base sólida para una mayor comprensión, desarrollo e implementación de los DERMS, sentando las bases para una gestión más eficiente y efectiva de los DERs.

II. Marco Teórico

A. *Recursos Energéticos Distribuidos (DERs)*

Es necesario comprender con precisión el término DER para poder analizar las soluciones de gestión para estas tecnologías. Dentro del sector eléctrico se han ofrecido múltiples definiciones para los Recursos Energéticos Distribuidos (DER). Por lo tanto, aunque algunas tecnologías son fáciles de clasificar dentro o fuera de esta descripción—como la solar fotovoltaica en tejados o el almacenamiento de energía a pequeña escala—para otras no resulta tan sencillo determinarlo [9]. Para ofrecer una muestra de esta amplia variedad de definiciones, a continuación, se incluyen algunas de las propuestas en la industria.

El Departamento de Energía (DOE) describe los DER como “dispositivos modulares y de menor escala diseñados para proporcionar electricidad, y en ocasiones también energía térmica, en ubicaciones cercanas a los consumidores” [10]. El Laboratorio Nacional Lawrence Berkeley considera que los DER “incluyen sistemas de generación distribuida limpia y renovable (como los sistemas de cogeneración de alta eficiencia y los sistemas solares fotovoltaicos), almacenamiento distribuido, respuesta en demanda y eficiencia energética”, y considera a los vehículos eléctricos enchufables como parte del almacenamiento distribuido. Para el Departamento de Servicios Públicos de Massachusetts, "un DER es un dispositivo o medida que produce electricidad o reduce el consumo de electricidad y está conectado al sistema eléctrico, ya sea 'detrás del contador' en las instalaciones del cliente, o en el sistema de distribución primario de la utility”, y también incluye a las microrredes y los sistemas de gestión de energía como DER [12]. Finalmente, el Instituto de Investigación de Energía Eléctrica (EPRI) simplemente considera que los DER son “fuentes de energía más pequeñas que pueden agregarse para proporcionar la energía necesaria para satisfacer la demanda regular” [13].

Esta variedad de descripciones de un DER ha sido utilizada por la Asociación Nacional de Comisionados Reguladores de Servicios Públicos (NARUC) para establecer una definición unificada de los DER: "un DER es un recurso ubicado cerca de los clientes que puede proporcionar toda o parte de sus necesidades inmediatas de energía y también puede ser utilizado por el sistema para reducir la demanda (como la eficiencia energética) o aumentar la oferta para satisfacer las necesidades de energía o servicios auxiliares de la red de distribución. Los recursos, si proporcionan electricidad o energía térmica, son de pequeña escala, están conectados al sistema de distribución y se encuentran cerca de la carga” [9]. La definición de NARUC reúne, bajo el paraguas de los DER, la energía solar fotovoltaica, eólica, y la cogeneración, almacenamiento de energía, respuesta en demanda, vehículos eléctricos, microrredes y eficiencia energética", mientras que el Estándar IEEE 1547-2018—para la Interconexión e Interoperabilidad de los DER con Sistemas Eléctricos Asociados ([14])—y otras fuentes ([3]-[5]) enfatizan la inclusión de pequeñas centrales hidroeléctricas y generadores diesel de respaldo.

La definición de NARUC ha sido ligeramente adaptada aquí para intentar acomodar todas las perspectivas presentadas previamente e incluidas en [9]-[14], así como los conceptos y tecnologías mencionados en [3]-[5] y otras fuentes consultadas: los DER pueden ser tanto activos FTM como BTM de pequeña y mediana escala—si proporcionan electricidad o energía térmica—típicamente de propiedad privada, conectados a alimentadores de baja o media tensión del sistema de distribución, y ubicados cerca de la carga. Los DER pueden ser utilizados para reducir la demanda o aumentar la oferta para satisfacer las necesidades de energía o servicios auxiliares de la red de distribución, siendo así capaces de modificar los requerimientos de carga y optimizar la demanda energética.

Aunque los DER BTM de pequeña escala se están convirtiendo en componentes cada vez más predominantes en comparación con los FTM—como la generación distribuida a mayor escala—se ha puesto énfasis en ambos como componentes fundamentales del concepto de DER. Esta es la definición de DER a la que se hará referencia en adelante y que se utilizará para comprender mejor sus soluciones de gestión. Las siguientes tecnologías estarán, por lo tanto, abarcadas bajo esta perspectiva de los DER: sistemas solares fotovoltaicos (PV) y de energía eólica, pequeñas centrales hidroeléctricas, sistemas de cogeneración (CHP), generadores diesel distribuidos, sistemas de almacenamiento de energía (ESS), vehículos eléctricos (VE) y sus estaciones de carga, microrredes, respuesta en demanda (DR), cargas controlables y programas de eficiencia energética (EE) [3], [14].

B. *Soluciones Precedentes para la Integración de DERs*

Si bien la aparición de los DERs presenta desafíos significativos, los beneficios potenciales que ofrecen—si se gestionan adecuadamente—en términos de modernización de la red, eficiencia económica, mejoras operativas y sostenibilidad ambiental, podrían convertirlos en una adición muy valiosa a la red eléctrica. Esta sección explorará algunas de las soluciones existentes, ya bien establecidas en la industria eléctrica y anteriores a la aparición de los DERMS, para la integración y gestión de estos recursos dentro de la red de distribución.

1) Smart Inverters (SIs): aunque no son una solución de gestión integral para los DERs, los SIs apoyan la integración de recursos distribuidos renovables en la red eléctrica. Un SI es un dispositivo avanzado de electrónica de potencia diseñado para convertir la corriente continua a la salida de algunos recursos energéticos distribuidos—como la energía solar fotovoltaica (PV) y los sistemas de almacenamiento de energía en baterías (BESS)—en corriente alterna compatible con la red eléctrica. A diferencia de los inversores tradicionales, los SIs están equipados con software adicional que proporciona funcionalidades mejoradas y facilita la integración general de fuentes de energía renovable en el sistema eléctrico [15]. Algunas de estas capacidades adicionales incluyen la regulación de voltaje y potencia de salida, adaptabilidad a las condiciones cambiantes de la red y requisitos operativos, gestión autónoma, autodiagnóstico del estado y la salud del dispositivo, funcionalidad plug-and-play para una integración sin problemas en sistemas existentes, y registro de los servicios prestados para compensación económica [9], [15].

2) Advanced Metering Infrastructure (AMI): AMI se refiere al marco tecnológico que incluye medidores avanzados capaces de medir el consumo de electricidad en incrementos de tiempo granulares—por ejemplo, cada 15 minutos a una hora. Integra tecnologías de información digital, combinando sistemas de hardware y software para facilitar la comunicación remota entre usuarios finales, proveedores de servicios (SPs) y utilities. A diferencia de los medidores tradicionales, AMI puede proporcionar hasta 8,760 puntos de datos por año si se mide por hora, lo que mejora significativamente la disponibilidad de datos tanto para las utilities como para los clientes [9], [16]. AMI incluye medidores inteligentes, un Sistema de Gestión de Datos de Medición (MDMS) y una red de comunicaciones, que trabajan juntos para permitir a las utilities recopilar datos detallados en tiempo real sobre la demanda y generación para mejorar la gestión de la energía, precios en tiempo real y diseño avanzado de tarifas, y una compensación más precisa de los DERs [16], [17].

3) Microgrids Controllers (MCs): una microrred es definida por el Grupo de Intercambio de Microrredes del Departamento de Energía de EE.UU. como "un grupo de cargas interconectadas y recursos energéticos distribuidos (DERs) dentro de límites eléctricos claramente definidos que actúan como una entidad controlable única con respecto a la red." Las microrredes pueden operar en modo conectado a la red o independientemente en modo isla, mejorando la resiliencia y la sostenibilidad al integrar varios DERs, como la energía solar PV, aerogeneradores, BESS y generadores de respaldo [18]. Un Controlador de Microrredes (MC) es responsable de gestionar la operación de una microrred, permitiendo la integración, coordinación y control de los DERs, y permitiendo la participación en varios servicios de red. Los MCs utilizan algoritmos de despacho óptimo y basado en reglas para maximizar el uso de energía renovable y la rentabilidad económica, mejorando la resiliencia en el borde de la red, asegurando el suministro continuo de energía durante perturbaciones en la red y permitiendo beneficios económicos y un sistema más sostenible [7], [18], [19].

4) Virtual Power Plants (VPPs): una VPP es una agregación de varios recursos distribuidos, que funcionan colectivamente como una única entidad despachable en las operaciones del sistema eléctrico y en los mercados mayoristas. El objetivo principal de una VPP es aprovechar diversas unidades de generación distribuida, sistemas de almacenamiento y cargas flexibles y controlables para proporcionar capacidad adicional y servicios auxiliares a la red mientras se optimiza la producción y el consumo de electricidad. Esto permite cumplir diferentes objetivos, como la minimización de costos, la mejora de la fiabilidad o la reducción de emisiones de gases de efecto invernadero (GHG) [20]-[22]. Idealmente, las VPPs aprovechan una cartera diversificada de recursos que incluyen respuesta a la demanda, fuentes de energía renovable, sistemas de almacenamiento de energía e incluso fuentes de energía tradicionales para crear un recurso virtual agregado que puede operarse como una única entidad, pero que está compuesto por potencialmente miles de DERs individuales. Cuanto más diversa sea la cartera de dispositivos, más flexible y resiliente será la VPP agregada y mayor será su utilidad para la red [21].

5) Demand-Side Management (DSM) and Demand Respone Management System (DRMS): DSM se refiere a iniciativas y tecnologías destinadas a optimizar los patrones de consumo de energía para reducir costos, mejorar la fiabilidad y minimizar el impacto ambiental, entre otros objetivos. Involucra varias estrategias—tarifas energéticas inteligentes con incentivos para patrones de consumo específicos, control en tiempo real de recursos energéticos distribuidos, etc.—implementadas por las utilities para alentar a los consumidores a ajustar su uso de electricidad para reducir el consumo total de energía, gestionar la demanda pico y mejorar la eficiencia energética en general [23], [24]. DSM incluye medidas y tecnologías destinadas a modificar o desplazar el consumo de energía según los requerimientos del sistema, como la eficiencia energética, el crecimiento estratégico de la carga o las reservas giratorias, y la respuesta en demanda [23], [25].

La respuesta en demanda implica ajustes en tiempo real o casi en tiempo real en el consumo de electricidad por parte de los usuarios finales en respuesta a señales de precios o pagos de incentivos para reducir el consumo durante períodos pico o desplazarlo a momentos de menor demanda. DR tiene como objetivo mejorar la fiabilidad y eficiencia de la red al equilibrar dinámicamente la oferta y la demanda. Las tecnologías que pueden participar en DR incluyen vehículos eléctricos y electrodomésticos inteligentes como termostatos y enchufes. Las iniciativas de respuesta en demanda pueden categorizarse en basadas en la fiabilidad, orientadas a asegurar la estabilidad de la red reduciendo la carga durante períodos críticos, y basadas en el mercado, centradas en la eficiencia económica respondiendo a señales de precios—por ejemplo, tarifas de tiempo de uso (ToU) o precios críticos de pico (CPP) [23], [25]. Los Sistemas de Gestión de Respuesta en Demanda (DRMS) surgieron para ayudar a los proveedores de energía y a las utilities a gestionar estrategias de DR, recopilando y analizando datos BTM para manejar la demanda de energía, reducir el consumo de energía y mejorar la eficiencia y fiabilidad del sistema. Proporcionan herramientas para analizar y optimizar el uso de energía, reduciendo la necesidad de nueva infraestructura de red, previniendo todo tipo de interrupciones en el servicio y minimizando los costos asociados [25].

6) Advanced Distribution Management System (ADMS): un DMS es una plataforma de software integral empleada por las utilities para controlar y optimizar la operación del sistema de distribución eléctrica. Los DMS convencionales controlan reguladores de voltaje, bancos de capacitores y seccionadores. Tienen acceso a medidores, modelos de sistemas eléctricos y modelos de carga, y realizan continuamente análisis de flujo de potencia para determinar los ajustes óptimos para estos dispositivos de control basados en las necesidades de la utility y las prioridades actuales [26]. Los Sistemas de Gestión Avanzada de la Distribución (ADMS) combinan las funcionalidades de los DMS tradicionales y los Sistemas de Gestión de Interrupciones (OMS) con los servicios proporcionados por los DERs para producir respuestas mejoradas del sistema en general—como un DMS mejorado y listo para DER que maneja las complejidades que surgen del despliegue generalizado de DERs que los DMS y OMS tradicionales luchan por gestionar [26], [27]. Los ADMS añaden niveles de comunicación, inteligencia y visibilidad a la red de distribución, permitiendo a las utilities comprender mejor las condiciones en tiempo real en todo su territorio de servicio [9]. Están diseñados para gestionar tanto activos de red tradicionales como DERs para realizar la optimización Volt/VAR, la reducción de voltaje por conservación (CVR), la localización automatizada de fallas, aislamiento y restauración del servicio (FLISR), o incluso funcionalidades de DR para garantizar la seguridad y fiabilidad de la red [7], [9], [26].

Los ADMS, DRMS, VPPs y MCs ofrecen soluciones valiosas para la gestión y operación de la red. Sin embargo, enfrentan desafíos e ineficiencias al adaptarse a la creciente presencia de DERs en la red de distribución, y a menudo quedan cortos frente a la naturaleza dinámica del sistema eléctrico moderno. Esto allana el camino para la aparición de los DERMS y para su posible integración con estas soluciones anteriores. La siguiente sección profundizará en una revisión exhaustiva de la literatura sobre el concepto de DERMS, examinando sus diferentes actores, la jerarquía de soluciones DERMS, la especificación funcional, los protocolos habilitantes para la integración de DER, las arquitecturas de control de DER, así como las últimas propuestas legislativas.

III. DERMS – Estado del Arte

Parece haber cierto consenso respecto a que los DERMS son soluciones de software diseñada para ayudar a los operadores de la red de distribución, utilities, planificadores de redes, ingenieros, clientes finales y prosumidores en la gestión y operación de la creciente penetración de recursos energéticos distribuidos en las redes de distribución. Estos sistemas proporcionan herramientas para la monitorización en tiempo real, control, coordinación de despacho y optimización de los DERs, asegurando que la red opere de manera confiable y eficiente dentro de los límites técnicos, mitigando los posibles impactos negativos de una alta penetración de DERs y ofreciendo beneficios económicos [1], [2]. Los DERMS facilitan la integración de diversos recursos distribuidos, incluyendo generación renovable y no renovable—como paneles solares en tejados, pequeños aerogeneradores, cogeneración o generadores diésel—, sistemas de almacenamiento de energía, estaciones de carga de vehículos eléctricos, respuesta en demanda, control de carga y programas de eficiencia energética, a menudo agregando sus capacidades para apoyar beneficios a nivel de todo el sistema (ver Fig. 1) [1]-[4], [9], [26].

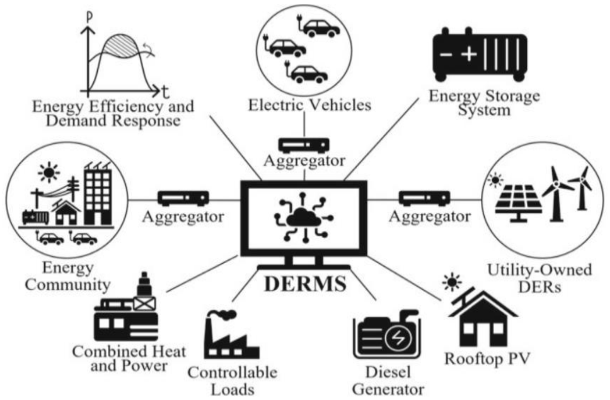

Fig. 1. Activos DER potencialmente gestionados por un DERMS [3].

A. *Jerarquía de Soluciones DERMS y Partes Interesadas*

Se ha observado cierta tendencia en la literatura a distinguir dos niveles diferentes de soluciones DERMS existentes. Esta estructura jerárquica en los DERMS es necesaria para gestionar las complejas interacciones entre los diversos DERs, con los diferentes niveles jerárquicos cumpliendo propósitos distintos y adaptándose a necesidades operativas específicas dentro de la red. Sin embargo, un desafío significativo en la implementación de los DERMS ha sido y sigue siendo la falta de definiciones claras para las diferentes soluciones de gestión. El hecho de que todas estas soluciones se denominen simplemente DERMS puede llevar a malentendidos entre las utilities, los reguladores, los operadores de mercado o los proveedores de tecnología respecto a cuál es la más adecuada para sus intereses. Por lo tanto, definir y distinguir estos niveles de jerarquía entre los DERMS es crucial para evitar confusiones entre los diferentes actores, de manera que puedan comprender mejor los roles y responsabilidades asociados a cada solución [1], [2], [6].

1) *DERMS Centralizados*

Los DERMS centralizados surgieron de los sistemas tradicionales de gestión de la red, enfocados en operaciones a gran escala controladas por utilities, razón por la cual a menudo se les refiere en la literatura como DERMS de Utility [1]-[3], [5]-[8]. Los DERMS de Utility se despliegan típicamente en los centros de control de los operadores de la red de distribución y tienen acceso completo al modelo de red preciso. Utilizan recursos tradicionales (cambiadores de tomas de carga, bancos de capacitores o interruptores) en combinación con DERs individuales de mediana a gran escala (BESS a escala de utility, grandes parques solares y aerogeneradores) y grupos de DERs a pequeña escala agregados para operar de manera óptima la red de distribución sin incurrir en violaciones de restricciones. Los DERMS centralizados se centran en la optimización y control a nivel de toda la red, la fiabilidad y la integración de DERs de mayor tamaño, con el objetivo de proporcionar beneficios técnicos, operativos y monetarios al DSO/TSO/ISO [1]-[3], [5], [6], [8].

2) *DERMS Descentralizados*

También llamados DERMS de Agregador [33], fueron desarrollados a partir de aplicaciones centradas en el cliente, permitiendo una mayor colaboración de los consumidores finales en la gestión energética. Las soluciones de software DERMS descentralizadas se centran en la agregación de múltiples recursos BTM a pequeña escala conectados a la red de baja tensión (BT)—por ejemplo, sistemas de aire acondicionado o calefacción, paneles solares en tejados, pequeños sistemas de baterías residenciales, VE y sus estaciones de carga, y electrodomésticos inteligentes—con el objetivo de proporcionar sus servicios de manera agregada, optimizada, más simple y útil para los operadores del sistema eléctrico—por ejemplo, participando en el mercado eléctrico o a través de iniciativas de respuesta en demanda [1]-[3], [6]-[8]. Los sistemas descentralizados suelen ser gestionados por entidades privadas, industrias o comunidades energéticas, y tienen como objetivo mejorar la participación del cliente, la eficiencia energética y la gestión local de generación y consumo. Proporcionan mayor visibilidad y controlabilidad de los DERs BTM [1]-[3], [8], pero generalmente no tienen acceso a un modelo de red preciso—y esto se considerará precisamente como la frontera entre los DERMS de Utility (Centralizados) y los DERMS de Agregador (Descentralizados) [1], [3], [5], [6], [8].

Las soluciones DERMS descentralizadas se suelen categorizar en la literatura en (i) Agregadores de DER, responsables de gestionar grupos de DERs BTM y cargas despachables conectados a la red LV—por ejemplo, Sistemas de Gestión Energética de Edificios/Hogares, comunidades energéticas, VPPs, y proveedores de respuesta en demanda [1]-[8]; (ii) Operadores de Mercados Eléctricos Locales (LEMOs), encargados de organizar y operar mercados locales donde los DERs agregados pueden comerciar energía y proporcionar servicios auxiliares, asegurando el cumplimiento de las restricciones de la red local y los requisitos regulatorios—por ejemplo, potencia mínima para ingresar al mercado [1]; y (iii) Controladores de Microrredes (MCs), que gestionan la operación de microrredes, asegurando que puedan funcionar tanto como parte de la red principal como en modo isla. En el modo conectado a la red, los MCs gestionan el compromiso de unidades, despacho económico y otros servicios que ofrecen flexibilidad a la red principal. Cuando están aislados, los MCs realizan operaciones de formación de red, gestionan la frecuencia y el voltaje, y aseguran el balance de carga [1], [7], [18]. La Tabla 1 recopila estos diferentes niveles de jerarquía entre los DERMS, junto con los actores clave interesados en implementar estas soluciones y los principales objetivos que cada una de estas entidades busca cumplir con su implementación.

TABLA 1. SOLUCIONES DE GESTIÓN DE DERS, SUS OBJETIVOS, PARTES INTERESADAS Y ESTRUCTURA JERÁRQUICA [1], [2].

Stakeholder	*Objetivos*	*Solución DERMS*
Operador de la red de transporte (TSO/ISO)	Balance de oferta/demanda, servicios auxiliares de red, capacidad flexible, gestionar la demanda y la variabilidad de la generación renovable	Centralizada (con conocimiento de red)
DSOs; departamentos de planificación en utilities de distribución	Aliviar congestiones y violaciones de voltaje, posponer refuerzos de la red, aumentar la capacidad de alojamiento de DER, estabilidad y optimización en el borde de la red	Centralizada (con conocimiento de red)
Participantes del mercado y operadores de mercados locales	Mayorista: optimizar la mezcla de generación, minimizar los costos ENS. Minorista: promover la competitividad y la eficiencia, nuevas tarifas minoristas	Descentralizada (sin conocimiento de red)
Agregadores, operadores de microrredes, prosumidores	Agregar DERs para la gestión energética local, optimizar costos (cargos por energía y demanda), integrar generación distribuida renovable, mejorar la resiliencia	Descentralizada (sin conocimiento de red)

B. *Soluciones DERMS Híbridas*

Las soluciones centralizadas y descentralizadas son frecuentemente llamadas simplemente DERMS, a pesar de que difieren ampliamente en su naturaleza, roles y las posibilidades que ofrecen para las diferentes partes interesadas dentro del sistema eléctrico [1], [2], [5], [6]. Los sistemas puramente centralizados o descentralizados pueden implementarse de manera independiente (aunque los DERMS de Agregador típicamente requieren colaboración con un sistema de gestión centralizado para coordinar la flexibilidad que proporcionan, como se ha desarrollado anteriormente), pero presentan varias limitaciones—es decir, la falta de conocimiento de la red por parte de los agregadores, la necesidad de validación centralizada de los horarios de los DER, problemas de coordinación y escalabilidad, o estándares y protocolos inconsistentes—que podrían mitigarse si se integran adecuadamente [1], [2], [5], [6].

Integrar soluciones centralizadas y descentralizadas plantea, no obstante, varios desafíos, ya que aumenta la complejidad general de los DERMS. Asegurar una comunicación fluida e interoperabilidad entre diversas soluciones requiere la estandarización de protocolos e interfaces [1]-[4], [6], [26], que en muchos casos aún están sin desarrollar o en desarrollo por diferentes proveedores, proyectos de organizaciones internacionales (Proyecto Platone [29]) o asociaciones de estándares (como el IEEE Std 2030.5 para la comunicación con dispositivos DER [30]). Además, gestionar datos en tiempo real a través de múltiples capas de control—con diferentes niveles de centralización—es técnicamente exigente, lo que requiere una infraestructura de red mejorada y robusta que podría necesitar la actualización de los sistemas existentes [1], [2], [5], [6]. La ciberseguridad también se vuelve crítica debido al aumento de la conectividad y el intercambio de datos, introduciendo posibles vulnerabilidades [3], [4], [28]. Finalmente, la regulación debe evolucionar en gran medida para apoyar enfoques híbridos [1], [2], [5], [31], [32]. Iniciativas como la Orden No. 2222 de la FERC en los EE.UU., que apoya la participación de los DER en los mercados mayoristas [1], [3], [7], [31], o la Propuesta de la Entidad DSO de la UE y ENTSO-E para un Código de Red sobre Respuesta en Demanda [33], contribuyen a definir un marco regulatorio que favorezca el desarrollo de soluciones integrales de gestión de DER.

A través del intercambio de datos casi en tiempo real con un DERMS de utility, los agregadores de DER mejoran la visibilidad de los DER BTM y su impacto en las condiciones de la red local, particularmente en operaciones relacionadas con los consumidores, como la participación en mercados eléctricos e iniciativas de DR o EE. Los agregadores gestionan la variabilidad e intermitencia de la producción de los DERs para que las utilities puedan disponer de una mayor capacidad flexible para una variedad de servicios de la red [1], [2]. Además, la integración de los DERMS de utility con los LEMOs es esencial para validar los horarios y garantizar el cumplimiento de las restricciones técnicas mientras se aprovecha la flexibilidad de los DER para una gestión de la red más eficiente y rentable [1], [6]. Finalmente, los sistemas híbridos mejoran la escalabilidad de las soluciones de software DERMS al descentralizar parte de las funciones de control y optimización, de modo que se pueda integrar eficientemente un mayor número de DERs [1].

Estas ideas sobre la integración de los DERMS de Utility y Agregador están perfectamente resumidas en [1], [2], y [6], hasta el punto de que el autor de este trabajo ha considerado apropiado transcribir literalmente aquí un pasaje de [2], que también se utiliza en [6]: "[…] los DERMS de utility y los agregadores de DER deben entenderse como diferentes niveles en una jerarquía: los agregadores de DER se comunican principalmente con unidades behind-the-meter y las utilizan de manera agregada para proporcionar varios servicios relacionados con la participación de los consumidores y las operaciones, mientras que los DERMS de utility utilizan agregadores de DER—entre otros recursos, como DERs individuales de mediana a gran escala, varios tipos de grupos de DER, VPPs, microrredes y recursos tradicionales como interruptores, capacitores, etc.—para proporcionar a los operadores de la red de distribución (DSOs) una visibilidad completa, una gestión sin esfuerzo en tiempo real y anticipada de las restricciones, una coordinación y gestión óptima de los DERs y grupos de DER, y otras operaciones a nivel de todo el sistema. Por lo tanto, si se integran adecuadamente, los agregadores de DER y los DERMS de utility se complementan perfectamente entre sí y pueden proporcionar un espectro completo de servicios DER tanto para operaciones relacionadas con los consumidores como con la red, independientemente del tamaño y la ubicación de los DERs".

C. *Especificación Funcional DERMS*

Las funcionalidades y servicios de los DERMS se han estructurado de diversas maneras en la literatura en los últimos años. Esta sección proporciona una revisión exhaustiva de estas perspectivas, integrando los conocimientos de 12 utilities y 11 proveedores tal como los proporciona SEPA en [34], las especificaciones funcionales propuestas por el IEEE Std 2030.11-2021 ([28]), así como otros conocimientos recopilados principalmente de [1]-[3]. En general, la literatura no distingue entre las funciones asignadas a los DERMS Centralizados (Utility) y Descentralizados (Agregador). Sin embargo—y a pesar de que el propósito de este documento es proyectar una solución DERMS integral—, este trabajo intentará hacer una distinción entre las funcionalidades específicas de cada solución para enfatizar la última, en un contexto donde la industria tiende a ver los DERMS como un producto exclusivo para utilities.

1) *DERMS Centralizados (Utility)*

a) Enrollment: permite que todos los DERs sean correctamente identificados, categorizados y gestionados para apoyar los demás servicios de los DERMS. Esto incluye la gestión de información detallada sobre cada dispositivo DER y grupos de DERs (gestionados por un agregador) en lo que respecta a registro, agrupamiento y capacidades y limitaciones operativas, para que puedan visualizarse topográficamente dentro del modelo de red de la utility. Esto es de particular interés para determinar el impacto general y la flexibilidad que ofrecen los activos en el borde de la red y los BTM para los servicios de la red. Incluye [28], [34]:

- *Registro*: identificación y validación de los dispositivos DER inscritos en la plataforma DERMS para garantizar que solo los dispositivos conformes y validados se integren en el sistema de gestión [28]. El objetivo es capturar información relevante del activo (placa de identificación), información de comunicación y programática, fechas de entrada/salida de servicio, ubicación eléctrica y detalles de conectividad de la red sobre los DERs propiedad de la utility y los agregadores de terceros para proporcionar una mayor visibilidad a la utility o al operador de la red de distribución (DSO) [34].
- *Agrupamiento*: tiene como objetivo organizar los dispositivos DER en grupos lógicos, agregando datos en tiempo real, energía y salidas de potencia para facilitar una gestión y control más eficiente. El agrupamiento puede atender a consideraciones jerárquicas (basadas en la topología del sistema), dinámicas, programáticas (basadas en la participación de los DERs en programas de la utility) o de capacidad (tiempos de respuesta, determinismo, etc.).
- *Configuración y Modelado de Activos*: implica que los dispositivos DER (de forma individual o agregada) notifiquen al DSO sobre su estado actual y proyectado, capacidades operativas y limitaciones (con una periodicidad acordada), para permitir que las utilities incorporen datos DER precisos en tiempo real a sus modelos digitales de la red de distribución.

b) Planificación: estas funciones facilitan la planificación estratégica a largo plazo para la integración de DERs en la red. Este módulo tiene como objetivo garantizar que la red pueda manejar niveles crecientes de DERs sin comprometer la estabilidad y la resiliencia. Ofrece estudios y evaluaciones exhaustivos, guiando a las utilities y creando planes detallados para inversiones en infraestructura y estrategias de integración de DERs. Esto incluye varias funcionalidades como el *Análisis de Hosting Capacity* para evaluar el impacto de nuevas conexiones de DERs, la *Ubicación Óptima de DER* para identificar el punto de conexión óptimo para una capacidad específica de DER, la creación de *Hosting Capacity Heat Maps (HCHMs)* para permitir a las partes interesadas visualizar la capacidad disponible en diferentes secciones de la red, y los *Estudios NWA* para explorar alternativas para posponer inversiones en infraestructura de la red—contratos flexibles, soluciones de almacenamiento de energía o capacidades de DR [28], [34].

c) Operación en Tiempo Real: este módulo se centra en la monitorización en tiempo real y el control operativo de los DERs y activos de la red para mantener la estabilidad y eficiencia de la red [1]. Aprovecha la información del módulo de Enrollment para entender el estado actual y la capacidad de la red, permitiendo una gestión activa de la red y la optimización de activos [34]. Incluye las siguientes funciones:

- *Monitorización y Visualización*: los DERMS deben ser capaces de monitorear, detectar y visualizar no solo parámetros generales de la red, sino también valores operativos críticos de los DERs, a menudo aprovechando datos en tiempo real de los sistemas SCADA y AMI para proporcionar continuamente información actualizada a los operadores y planificadores de la utility [2], [3], [28], [34]. Según el IEEE Std 1547-2018, la información recopilada debe incluir: salida de potencia activa y reactiva del DER, voltaje RMS instantáneo de una o tres fases y corriente RMS, frecuencia, estado operativo, estado de conexión, estado de alarma y estado de carga operativo (SoC) [28].
- *Optimización y Despacho Económico de DERs*: implica la prestación eficiente de los servicios solicitados por la red utilizando la mejor combinación de activos DER, lo que reduce los costos, minimiza el desgaste y maximiza el valor de los activos. Los DERMS permiten a las utilities realizar el despacho económico dinámico de los DERs en su cartera considerando los costos de generación, tarifas del mercado, restricciones de la red, límites operativos de los DERs, períodos contratados y participación en programas de la utility, y consideraciones ambientales [28].
- *Gestión y Control de la Red*: esto implica controlar las salidas de los DERs para alcanzar objetivos de energía, capacidad y servicios auxiliares. Los DERMS pueden utilizar la capacidad flexible de los DERs para ayudar a equilibrar la oferta y la demanda, gestionar restricciones de la red, mantener la frecuencia y el voltaje dentro de los límites, evitar sobrecargas en los alimentadores y mejorar la calidad de la energía de la manera más eficiente. Esto también incluye la ejecución de comandos de control para los DERs en tiempo real, asegurando que proporcionen las capacidades programadas [1], [28], [34].
- *Optimización Volt/VAR (VVO):* la VVO tiene como objetivo reducir las pérdidas de energía—mejorando la eficiencia general de la red—al disminuir los flujos de potencia reactiva a través de la red de distribución. En particular, la Reducción de Voltaje por Conservación (CVR) pretende gestionar el sistema de transmisión y distribución (T&D) para que los voltajes de los clientes se mantengan cerca del extremo inferior del rango aceptable y la demanda total se reduzca [28], [34].
- *Fault Location, Isolation, and Service Restoration (FLISR):* un DERMS puede monitorear la red y manejar interruptores y activos tradicionales de la red para localizar y aislar fallas—a veces a través de la colaboración con un OMS o un ADMS. Durante la fase de restauración de energía, coordina los DERs para organizar su reinicio—por ejemplo, mediante el control de SIs o la gestión de estaciones de carga de VEs—y mitigar los efectos tradicionales del arranque en frío de la carga [5], [28].

d) Operación a Corto Plazo: este módulo está diseñado para proporcionar análisis predictivo y planificación para condiciones futuras cercanas de la red. Ayuda a las utilities a anticipar problemas potenciales y violaciones de restricciones al pronosticar perfiles de carga y generación, condiciones meteorológicas y operación programada de DERs [1], [2]. Los servicios de predicción a corto plazo (CP) también utilizan información del módulo de Enrollment para entender las condiciones operativas históricas y actuales de los DERs [34].

- *Forecasting y Estimación*: predice la demanda futura de energía, generación y estado de los DERs, parámetros de la red—como perfiles de voltaje y flujos de potencia a través de líneas críticas—e incluso condiciones del mercado. Esta funcionalidad utiliza datos en tiempo real e históricos, pronósticos meteorológicos e información de precios del mercado para implementar algoritmos de estimación de estado para una mayor conciencia situacional y visibilidad del sistema [1], [3], [28], [34].
- *Programación de DER a CP (Unit Commitment)*: esta función aprovecha los pronósticos de carga y generación, los precios proyectados del mercado eléctrico y las condiciones estimadas de la red para desarrollar horarios óptimos de los DERs. El objetivo es optimizar la secuencia y prioridad de las operaciones de los DERs y su entrega de energía durante intervalos de tiempo definidos—horas, días, semanas e incluso meses—mientras se cumplen con las restricciones de la red y los límites operativos de los DERs [28], [34].
- *Gestión de Red a CP*: integra pronósticos de carga y generación con modelos de red para anticipar y abordar posibles restricciones de la red—perfiles de voltaje, corrientes a través de la red de distribución, potencia en transformadores, etc.—antes de que ocurran. Estima la flexibilidad disponible de los DERs y se comunica con los DERs y agregadores para ajustar proactivamente las operaciones de los DERs y los horarios críticos de los DERs para prevenir violaciones de restricciones proyectadas de la manera óptima [1], [2], [28].

e) Análisis e Informes: tiene como objetivo evaluar y documentar el rendimiento técnico y económico de los DERMS en la prestación de servicios a la red y a los clientes, así como su cumplimiento con los requisitos regulatorios. Este análisis retrospectivo permite la compensación económica de los DERs propiedad de los clientes y de las utilities—incentivando la adopción de DERs—y puede servir como base para la planificación de carteras de DERs tanto a nivel de la utility como del agregador [34]. Se deben generar informes personalizados para las diferentes partes interesadas, como los operadores de la red de distribución (DSOs), los reguladores o los clientes.

2) *DERMS Descentralizados (Aggregator)*

a) Enrollment: permite que todos los DERs sean correctamente identificados, categorizados y modelados para apoyar las funciones agregadas. Debe incluir información detallada sobre cada dispositivo DER dentro de la cartera del agregador en términos de identificación, agregación y detalles y parámetros técnicos, para que puedan ser visualizados y controlados adecuadamente por el agregador con el fin de proporcionar una variedad de servicios para la red [28], [34]. Incluye funcionalidades equivalentes a las descritas anteriormente, es decir, *Registro*, *Agregación* (crucial para que los operadores del sistema solo tengan que monitorear la energía total inyectada en la red por un agregador en lugar de las salidas individuales de cada DER BTM), y *Configuración y Modelado de Activos*, adaptadas al nivel del agregador.

b) Servicios Agregados de Red: los Aggregator DERMS aprovechan la agrupación de múltiples DERs a pequeña escala, a menudo BTM, para mejorar su visibilidad, facilitar su gestión, optimizar su operación y proporcionar varios servicios para la red que mejoran la fiabilidad, la resiliencia y la eficiencia de la red, beneficiando tanto a los consumidores como a los operadores del sistema. Las siguientes funcionalidades deben incluirse aquí:

- *Monitorización y Control de DERs*: Los agregadores de DER deben ser capaces de monitorear, detectar y medir parámetros críticos de la red de distribución local y, especialmente, de los DERs bajo su gestión. Los datos recopilados deben incluir: salida de potencia activa y reactiva de los DERs, voltaje y corriente RMS, frecuencia, estado operativo, estado de conexión, estado de alarma y estado de carga (SoC) [28]. El control de los DERs implica utilizar estos datos monitoreados para garantizar que los DERs estén proporcionando las capacidades requeridas en los momentos adecuados.
- *Optimización de DERs y de Carteras*: implica garantizar la prestación de los servicios solicitados por la red optimizando el uso de energía y capacidad de los DERs dentro de la cartera del agregador. Esto incluye optimizar los horarios de operación de cada DER individual (compromiso de unidades) y realizar un despacho económico que maximice el valor total de los DERs y minimice los costos totales de generación mientras se cumplen los requisitos técnicos impuestos por los DERMS de Utility [28], [34].
- *Respuesta en Demanda*: gestión de programas de DR, incluyendo la inscripción de clientes, programación de eventos, previsión de impactos meteorológicos y capacidad disponible de los DERs, comunicación de puntos de consigna a los diferentes recursos y medición y verificación de los resultados de los eventos [2], [34].
- *Virtual Power Plant*: las VPPs combinan varios DERs en una única entidad despachable que puede proporcionar capacidad flexible para una variedad de servicios de red—por ejemplo, DR, equilibrio de carga, recorte de picos, regulación de frecuencia, participación agregada en mercados eléctricos, etc. Los DERMS de Agregador permiten la integración de VPPs con sistemas empresariales conscientes de la red para ofrecer servicios localizados de manera confiable y eficiente [1], [34].
- *Gestión de Microrredes*: esta funcionalidad requiere interacción con sistemas conscientes de la red, de modo que los MCs puedan tener acceso a información de la red sobre las restricciones locales de la red. Implica la operación segura y eficiente de una microrred, gestionando los DERs y las cargas tanto en modos conectados a la red como en modo isla y permitiendo transiciones suaves para mejorar la resiliencia de la red local, manteniendo la estabilidad de la frecuencia y el voltaje y asegurando el suministro de energía frente a grandes cortes [1], [5], [22], [28], [34].

c) Operaciones de Mercado: este módulo consiste en una serie de funcionalidades económicas diseñadas para facilitar la interacción de los DERs con los mercados eléctricos, permitiendo transacciones de energía locales a nivel de distribución, y proporcionando una plataforma para servicios de red basados en el mercado. Los DERMS deben estar equipados para monitorear, prever y proporcionar información sobre las condiciones del mercado para optimizar el uso de recursos, compras y ventas de energía, y coordinarse con entidades de terceros que gestionen DERs BTM [1], [2], [34].

- *Intercambio de Datos del Agregador*: esencial para permitir que las utilities interactúen e intercambien datos con DERs BTM a pequeña escala, gestionados por agregadores de terceros, y permitir su participación en los mercados eléctricos.
- *Ofertas*: permite que tanto los DERs de propiedad de la utility como los agregadores de terceros que gestionan DERs a pequeña escala—que no podrían participar en los mercados eléctricos de manera independiente—puedan presentar activamente ofertas para comprar o vender energía en mercados de servicio locales o mayoristas.
- *Liquidación*: implica comparar las operaciones reales con las operaciones planificadas o previstas y realizar los cargos requeridos. La liquidación se lleva a cabo tanto a nivel mayorista como minorista, por ejemplo, entre la utility y los usuarios que participan en programas de DR a través de un agregador.
- *Energía Transactiva*: esta funcionalidad consiste en coordinar a productores y consumidores para comunicar y intercambiar energía automáticamente, de manera virtual, dinámica y en tiempo real, basándose en señales de valor y restricciones de fiabilidad.

d) Análisis de Ingresos y de Cartera: similar al servicio de Análisis e Informes de un DERMS de Utility, el objetivo es revisar y documentar el desempeño técnico y económico de un DERMS de Agregador en la prestación de servicios a la red y a los clientes bajo su gestión. Esto debería permitir la compensación económica de los DERs y servir como base para el análisis y la planificación de la cartera de DERs del agregador [34]. Se pueden generar diferentes informes para las diferentes partes interesadas, como operadores de utilities, reguladores y clientes. Este módulo debe cubrir:

- *Análisis de Rendimiento:* evalúa el desempeño técnico y económico de los DERs bajo la gestión del agregador en la prestación de servicios para la red—por ejemplo, participando en programas de la utility como DR—comparando el uso de energía antes y durante los eventos [34]. Los informes deben rastrear métricas críticas—como producción de energía, calidad de la energía, eficiencia de los DERs y estado operativo—y analizar el impacto más amplio de los DERs en la red de distribución, incluidas las contribuciones a la estabilidad de la red y la gestión de la congestión [3], [28].
- *Análisis y Planificación de la Cartera:* responsable de evaluar continuamente y tratar de optimizar la cartera de DERs gestionada por el agregador. Esta funcionalidad se basa en los conocimientos adquiridos del análisis de desempeño para mejorar el desempeño técnico y económico de la cartera del agregador, asegurando que sea capaz de satisfacer de manera efectiva las necesidades futuras de la red y de los clientes.

D. *Comparativa de Proveedores de Servicios DERMS*

Considerando la especificación funcional anterior de los DERMS, se ha llevado a cabo un análisis preliminar—no exhaustivo—del posicionamiento estratégico en el mercado de varios proveedores que ofrecen soluciones DERMS, en colaboración con Minsait, empresa con la que el autor tuvo la oportunidad de colaborar durante el desarrollo de este trabajo. La clasificación resultante se muestra a continuación y se basa en dos parámetros clave: (i) el nivel de centralización de la solución DERMS de cada competidor (eje x), lo que significa si ofrecen soluciones para la utility, para el agregador, o para ambos; y (ii) el grado de madurez de estas soluciones (eje y).

Fig. 2. Comparativa de proveedores de servicios DERMS. Fuente: Minsait.

Minsait, junto con otros proveedores de servicios como Autogrid (recientemente adquirida por Schneider Electric) y Smarter Grid Solutions, se posiciona en el centro del gráfico. Esto indica que sus ofertas incluyen tanto soluciones DERMS centralizadas (para utilities) como descentralizadas (para agregadores y la gestión de DERs BTM). También debe señalarse que, a pesar de la presencia de muchos proveedores en el lado negativo del eje x (soluciones descentralizadas), muchos de sus productos no serían clasificados como DERMS según los términos que se detallarán a continuación, sino más bien como aplicaciones especializadas o casos de uso particulares de una solución DERMS—como VPPs, gestión de estaciones de carga de VEs o inversores solares. De hecho, como se mencionó anteriormente, la industria a menudo tiende a ver los DERMS como exclusivos para utilities.

E. *Protocolos Habilitantes para el Despliegue de DERMS*

Como se introdujo en secciones anteriores, un desafío importante para el aumento de la penetración de DERs es la falta de protocolos y estándares universalmente aceptados para la comunicación entre dispositivos DER, utilities y agregadores, y entre agregadores y DERs individuales [1]-[4], [6], [26]. Este trabajo sostiene que los DERMS serán esenciales para la gestión e integración de los DERs dentro de los sistemas eléctricos modernos y las redes inteligentes (SGs), y que los estándares robustos se vuelven fundamentales para un despliegue exitoso de los DERMS, especialmente en un contexto donde existen y existirán múltiples sistemas y empresas involucradas. Esta sección discutirá algunos de los protocolos de comunicación habilitantes y modelos de información para la implementación escalable de los DERMS, enfocándose primero en la interfaz a nivel de utility y después a nivel de dispositivo, como se propone en [3], [4], y [26], y se muestra en la Fig. 3:

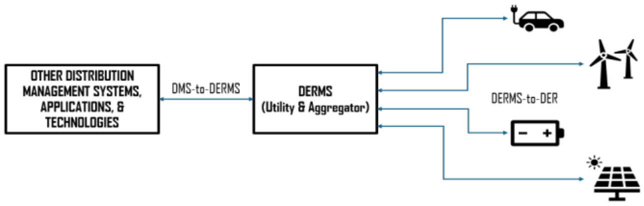

Fig. 3. Visión general de los niveles de interfaz de los protocolos DERMS.

1) Nivel DMS-a-DERMS

La integración efectiva de datos es esencial para optimizar la gestión de los DER, evitar costos indirectos y garantizar operaciones fluidas dentro del ecosistema de la utility. Sin una interoperabilidad adecuada, pueden surgir problemas como la duplicidad e inconsistencia de datos, lo que impacta negativamente en las operaciones de la utility. La integración empresarial de utilities es un concepto vital en este contexto, ya que implica la capacidad de desplegar y expandir varios sistemas y tecnologías dentro de las utilities de distribución. En este sentido, el Modelo de Información Común (CIM) ha ganado el apoyo de la industria y entre las utilities y proveedores como un estándar clave que apoya la integración entre diferentes sistemas y aplicaciones de utilities [3], [35].

CIM es una familia de estándares diseñados para abordar los desafíos de interoperabilidad y estandarización de datos entre diferentes sistemas empresariales de utilities. Proporciona un marco para modelar el sistema eléctrico, reduciendo la necesidad de mantener múltiples bases de datos en varios formatos. El modelo CIM consta de tres grupos de trabajo (WGs): el WG13, que se centra en el modelado eléctrico desde la perspectiva de los operadores de la red de transporte (TSO); el WG14, que amplía los conceptos del WG13 para abordar las utilities de distribución, el modelado de DER y las redes de baja/media tensión; y el WG16, que apoya la interoperabilidad de datos entre los participantes del mercado. El WG14 ha llevado al desarrollo de la serie de estándares 61968 de la Comisión Electrotécnica Internacional (IEC), que extiende los conceptos de CIM específicamente para la gestión de la distribución, proporcionando pautas para la integración de varias aplicaciones y sistemas dentro de una utility [3], [4], [35].

En particular, el IEC 61968-5 es de particular importancia para el despliegue de soluciones DERMS y su interacción con otros sistemas de utilities. Proporciona pautas detalladas para que las utilities aseguren que sus implementaciones de DERMS sean robustas, escalables y capaces de interactuar eficientemente con otros sistemas de gestión como los ADMS [3], [35]. El estándar aborda varias áreas relacionadas con la gestión óptima de grupos de DER, estableciendo un conjunto de reglas para la creación, mantenimiento y eliminación de agregaciones de DER, monitoreo de estado y eventos, pronóstico, despacho, control de la tasa de rampa de voltaje y (des)conexión de DERs individuales [36].

2) Nivel DMS-a-DERMS

Este nivel involucra protocolos de comunicación que permiten la interacción entre DERMS y DERs individuales, asegurando un intercambio de datos confiable, monitoreo en tiempo real y control de los activos DER. La información intercambiada típicamente incluye mediciones de AMI de los DERs, producción pronosticada y horarios de operación [1], [6]. El protocolo a emplear, así como los requisitos de rendimiento para la comunicación con los dispositivos DER, serán a menudo determinados por el operador del sistema competente en una determinada área. La Tabla 6 de la sección 7.3 del IEEE Std 2030.11-2021 ([28]) incluye una lista de protocolos de comunicación comunes identificados como alternativas viables para los DERs, algunos de los cuales se presentan brevemente a continuación:

a) IEEE Std 1815-2012 (DNP3): uno de los estándares de comunicación más utilizados en las utilities norteamericanas para monitoreo y control. Está diseñado para facilitar la interoperabilidad entre equipos de diferentes proveedores, asegurando una transmisión de datos consistente y precisa dentro de la misma red. DNP3 presenta informes impulsados por eventos, verificación de errores, verificación de secuencia y sincronización de tiempo para un registro y análisis de datos precisos. Inicialmente, DNP3 carecía de funciones de seguridad, pero estas se incorporaron más tarde a través de la Autenticación Segura DNP3, que mejora la protección contra amenazas cibernéticas [3], [37].

b) IEEE Std 2030.5-2018: también conocido como el Protocolo de Aplicación de Perfil de Energía Inteligente, está diseñado para la gestión sin problemas de recursos energéticos por parte de las utilities. Este estándar integra elementos de otros estándares y proporciona un amplio soporte para servicios de red como la respuesta en demanda y el control de carga. Incluye medidas de seguridad robustas, como HTTPS y cifrado AES-CCM, lo que lo convierte en una opción preferida para la implementación de DERMS debido a su alta interoperabilidad y soporte para una amplia gama de dispositivos de red [3], [37].

c) OpenADR (Respuesta Automatizada en Demanda Abierta): es un protocolo estandarizado y no propietario diseñado para soportar precios dinámicos y DR. Implementado en la capa de aplicación del Modelo OSI, OpenADR facilita la comunicación bidireccional entre proveedores de electricidad y clientes. El protocolo incluye servicios como el Servicio de Opt para horarios de disponibilidad, el Servicio de Registro para el intercambio de datos, y el Servicio de Sondeo para solicitudes de datos en tiempo real. OpenADR asegura una comunicación segura utilizando Seguridad TLS y Firmas Digitales, lo que lo hace esencial para habilitar la comunicación en tiempo real e interoperabilidad entre proveedores de servicios y cargas agregadas que participan en programas de respuesta en demanda [3], [38].

d) SunSpec Modbus: este es un estándar de comunicación abierto diseñado para mejorar la interoperabilidad entre sistemas DER. Se basa en el protocolo Modbus original y cumple con los requisitos de interoperabilidad del estándar IEEE 1547-2018. SunSpec Modbus define parámetros comunes para monitorear y controlar los DERs, simplificando la implementación del sistema y mejorando las posibilidades de despliegue. La interfaz física de Modbus es ampliamente utilizada, estando incorporada en aproximadamente el 80 por ciento de los dispositivos DER instalados, lo que la convierte en una interfaz de comunicación estandarizada, rentable y fácil de integrar [3], [39].

F. *Arquitecturas de Control de DERs*

La creciente integración de los DERs en el borde de la red requiere arquitecturas de control avanzadas para agrupar y utilizar eficazmente su flexibilidad. Los DERs en el borde de la red, que incluyen diversas fuentes de generación renovables y no renovables, soluciones de almacenamiento, cargas controlables y programas de respuesta en demanda ubicados en los sistemas de distribución de media a baja tensión, tienen el potencial de ofrecer múltiples posibilidades a la red eléctrica, pero requieren coordinación para maximizar su potencial. Por lo tanto, las estrategias de control para los DERs son esenciales para optimizar la flexibilidad en el borde de la red. Estas pueden clasificarse en cinco tipos principales: *centralizado* (involucra un controlador central que recopila datos de todos los DERs y realiza una optimización global), *jerárquico* (múltiples capas de controladores con cierta autonomía pero coordinados entre sí), *descentralizado* (controladores locales independientes para grupos de DERs), *distribuido* (control descentralizado con comunicación y coordinación mejoradas entre los controladores locales), e *híbrido* (que proporciona flexibilidad para adaptarse a diversas estructuras de propiedad de los DERs) [5]. Se han desarrollado diversas arquitecturas para la integración de los DERs en el borde de la red, basadas en una o más de estas estrategias de control, en el marco de diferentes proyectos. Dos de estas, consideradas las más desarrolladas y analizadas en la literatura, se discuten brevemente a continuación.

1) *Arquitectura Jerárquica*

Este es un enfoque multinivel diseñado para gestionar cargas BTM y DERs en el borde de la red, como sistemas fotovoltaicos (PV), sistemas de almacenamiento de energía (ESS) y cargas flexibles. Esta arquitectura se ilustra en la Fig. 4 y puede estructurarse en tres componentes clave [5], [40]:

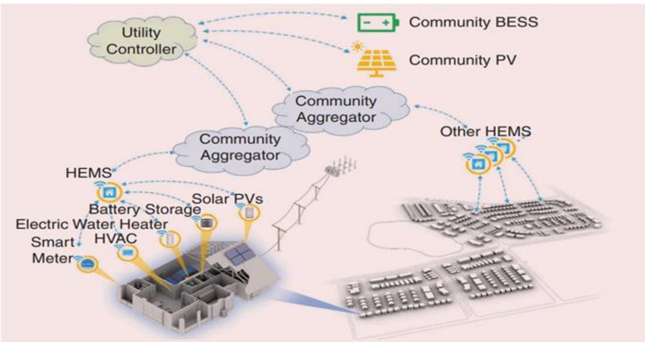

Fig. 4. Arquitectura Jerárquica para el control de DERs BTM [5].

- *Sistema de Gestión Energética del Hogar (HEMS):* en la capa base, el HEMS gestiona el consumo y la generación de energía dentro de los hogares individuales. Optimiza el uso de los DERs considerando las preferencias del cliente, los límites técnicos de los DERs y las tarifas eléctricas, y calcula la flexibilidad agregada de DERs.
- *Agregadores Comunitarios*: operando a un nivel intermedio, coordinan las operaciones de múltiples HEMS dentro de una comunidad. Realizan un despacho económico con restricciones de seguridad de la flexibilidad agregada, equilibrando las preferencias individuales de los hogares con los objetivos y las restricciones técnicas a nivel comunitario.
- *Controlador de la Utility*: en la capa superior, supervisa la red de distribución más amplia, aprovechando la flexibilidad agregada proporcionada por los Agregadores Comunitarios para resolver problemas a nivel de sistema. También gestiona los DERs de mayor escala conectados a la red de distribución de media tensión (MT), facilitando su participación en los servicios de la red.

Esta arquitectura se caracteriza por un flujo continuo de información de flexibilidad desde el HEMS a los Agregadores Comunitarios y finalmente al Controlador de la Utility, y un flujo opuesto de puntos de consigna y señales de control que se envían desde el Controlador de la Utility hacia el HEMS y, en última instancia, a los DERs individuales. La efectividad de esta arquitectura jerárquica se demostró en el Estudio Piloto de Campo de Basalt Vista en Colorado, donde permitió reducir significativamente las sobretensiones, mejorar la resiliencia de la red durante las perturbaciones y desplazar cargas fuera de los períodos de máxima demanda. En esta ocasión, el análisis a nivel de sistema y la optimización de los DERs se realizaron con la ayuda de un ADMS [5], [40].

2) *Arquitectura Federada*

La Arquitectura Federada para Soluciones de Gestión de Recursos Energéticos Distribuidos Seguros y Transactivos (FAST-DERMS) es un marco de control integral desarrollado bajo el programa del Consorcio de Laboratorios de Modernización de la Red (GMLC) del Departamento de Energía de los EE. UU. Esta arquitectura tiene como objetivo proporcionar servicios confiables de transmisión y distribución (T&D) mediante la agregación escalable y la gestión en tiempo casi real de diversos DERs en el borde de la red. Integra estructuras de control centralizadas, jerárquicas y distribuidas para coordinar de manera eficiente tanto los DERs individuales como los grupos locales de DERs, como edificios (B) o microrredes (MG) [5], [6], [41]. La arquitectura se muestra en la Fig. 5 e incluye los siguientes componentes [41]:

- *Planificador de Recursos Flexibles (FRS):* es responsable de realizar un despacho económico con restricciones de fiabilidad a nivel de subestación. Agrega y optimiza los DERs dentro de su área de servicio, coordinando su flexibilidad para generar ofertas firmes para los mercados mayoristas. El FRS también desagrega las señales de control de la red, asegurando que el voltaje y la carga del equipo se mantengan dentro de límites seguros.
- *Coordinador FRS*: supervisa y coordina las operaciones de los FRS individuales en diferentes subestaciones, alineando sus actividades con los precios del mercado mayorista y los objetivos generales de red. Interactúa con sistemas de gestión de la distribución y con el TSO para negociar servicios de red y retransmitir señales de control.
- *Agregadores*: consolidan y controlan múltiples DERs para actuar como participantes únicos en las operaciones de la red y en los mercados, proporcionando flexibilidad agregada al FRS.
- *Gestor de Mercado Transactivo (TMM):* actúa como agregador y creador de mercado, facilitando las negociaciones de precios y gestionando recursos transaccionales. Soporta esquemas de comunicación unidireccionales, donde los DERs responden a señales de precios, y bidireccionales, donde estos presentan ofertas que influyen directamente en la formación de precios.

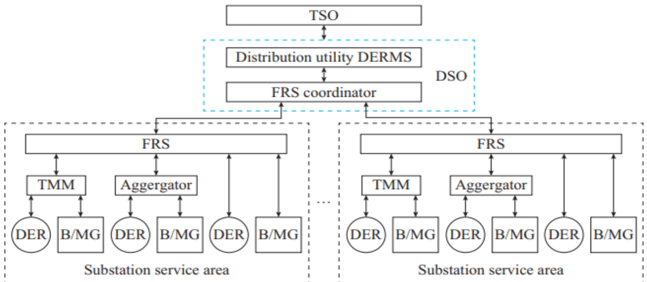

Fig. 5. Esquema conceptual de FAST-DERMS [6].

FAST-DERMS proporciona una solución escalable para la integración de DERs gestionados por los operadores de la red de distribución (DSO) en los mercados mayoristas de electricidad y en las operaciones del sistema de transmisión. Hace hincapié en un modelo total-DSO, donde todos los recursos dentro de una red de distribución se agregan a través de la utility de distribución. Este modelo garantiza un control integral sobre la red, equilibrando los objetivos locales y a nivel de sistema en términos de fiabilidad y económicos. Los DERMS facilitan la implementación escalable de estas arquitecturas de control proporcionando una plataforma para la agregación, monitoreo y coordinación de las operaciones de los DERs.

G. *Marco Regulatorio Europeo*

Como se desarrolló en secciones anteriores, la falta de un marco regulatorio común y bien definido sobre la gestión de DERs constituye un gran obstáculo para lograr una plataforma DERMS integral. En este sentido, la Propuesta de la Entidad DSO de la UE y ENTSO-E para un Código de Red sobre Respuesta en Demanda, aún en desarrollo, ha surgido como el marco regulatorio más completo y significativo sobre la integración de DERs a nivel europeo. A continuación, se enumeran algunos de sus objetivos principales y asuntos de interés para la implementación de DERMS [33]:

- *Desarrollo de términos y condiciones nacionales*: el código de red tiene como objetivo establecer principios objetivos para la creación de normas nacionales en relación con varios aspectos de la gestión de DERs. Esto incluye modelos de agregación, respuesta en demanda, almacenamiento de energía, generación distribuida y reducción de la demanda. Está destinado a guiar a los Estados Miembros en el desarrollo de regulaciones coherentes y efectivas que apoyen la integración de los DERs en la red.
- *Integración en el mercado y competencia*: se pretende asegurar que todos los recursos disponibles y proveedores de servicios puedan participar en los mercados eléctricos, definiendo medidas para promover la no discriminación y la competencia efectiva, asegurando que los mercados operen de manera eficiente.
- *Modelos de agregación y participación en el mercado*: se incluyen directrices para que los Estados Miembros definan modelos de agregación de DERs, que son cruciales para permitir que los DERs a pequeña escala participen en los mercados eléctricos. Estos modelos determinarán cómo se agrupan los DERs y cómo se miden y compensan los servicios que proporcionan. También incluye requisitos generales para los términos nacionales sobre el cálculo de la línea base, que se utilizará para cuantificar los servicios prestados por los DERs y garantizar una tarificación y liquidación precisas.
- *Requisitos de precalificación para el acceso al mercado*: se detallan las condiciones para que los proveedores de servicios (SPs) participen en la prestación de servicios locales o de balance, junto con los requisitos de precalificación y verificación para los productos de flexibilidad ofrecidos en los mercados de servicios locales.
- *Diseño de mercado*: establece directrices para el diseño de mercados locales que faciliten la adquisición eficiente y la tarificación de los servicios proporcionados por los DERs. Se enfatiza la prioridad de los mecanismos de adquisición basados en el mercado e incluye directivas sobre acuerdos de conexión flexibles, los roles principales de los operadores de mercados locales y sobre cómo los mercados locales deben integrarse con los mercados de día anterior, intradía y de balance en diferentes plazos.
- *Coordinación entre los TSOs y DSOs*: la Regulación destaca la necesidad de una propuesta común para términos y condiciones nacionales para la coordinación entre los TSO-DSO y DSO-DSO, con especial consideración a la definición del área de observabilidad de los DSOs, las responsabilidades en relación con los problemas de congestión y voltaje, y los requisitos de intercambio de datos DSOs-DSOs y DSOs-TSOs.
- *Gestión de Datos de Flexibilidad*: la propuesta describe la necesidad de un registro centralizado de flexibilidad en cada Estado Miembro, donde los SPs y otros actores autorizados puedan leer, registrar o actualizar la información sobre la flexibilidad de los DERs y los servicios que proporcionan.

Sin embargo, la regulación a nivel europeo sigue siendo ambigua y poco definida en muchos de los términos mencionados anteriormente, y a menudo se limita a establecer que los Estados Miembros deben desarrollar sus propios términos y condiciones nacionales para cada uno de estos aspectos—es decir, modelos de agregación, métodos para cuantificar los servicios, precalificación y verificación de productos, diseño de mercado para servicios locales y coordinación entre los operadores del sistema (SOs).

IV. Nueva Arquitectura Funcional Integrada DERMS

El gráfico de comparación de proveedores incluido anteriormente muestra que Minsait se considera que tiene una visión significativamente más global y holística de las soluciones DERMS en comparación con muchos competidores en este sector, que se enfocan en soluciones puramente centralizadas para utilities/DSOs (por ejemplo, ADMS con capacidades de DER) o herramientas solo para agregadores (VPP o DR). Por lo tanto, la arquitectura funcional descrita a continuación se inspira en su solución DERMS y se complementa con la especificación funcional incluida en la revisión anterior del estado del arte, basada en la información presentada en [1]-[3], la norma IEEE Std 2030.11-2021 como en [28], y la colección de servicios y casos de uso de SEPA en [34]. Se ha prestado especial atención para asegurar que esta arquitectura pueda cubrir la más amplia gama posible de aplicaciones y casos de uso para todas las partes interesadas potenciales—DSOs, agregadores, utilities verticalmente integradas, etc.—en diferentes países, al menos a nivel europeo. Además, ha sido diseñada para ser implementable en las plataformas de todos los posibles clientes y capaz de integrarse con sus soluciones existentes.

A. *Metodología*

Los siguientes aspectos serán cubiertos en relación con la arquitectura funcional DERMS propuesta:

- *Consideraciones preliminares*: estructura general de la arquitectura y la lógica detrás de su desarrollo.
- *Descripción general de la arquitectura*: descripción de funcionalidades y servicios, junto con las razones de su posicionamiento en la arquitectura, y la posible interacción entre las diferentes capas y módulos.
- *‘Declinaciones’ DERMS*: particularización de la arquitectura DERMS para diferentes clientes potenciales,

a saber, agregadores, plataformas verticales de nicho, microrredes, DSOs en un contexto de separación que buscan integrar su ADMS con el DERMS y aquellos que no buscan preservarlo, y utilities verticalmente integradas con y sin ADMS.
- *Estrategia de modularización*: basada en las declinaciones anteriores, diseño de cómo las diferentes funciones y servicios pueden ser modularizados y desacoplados para que la solución DERMS pueda ser implementada en cada cliente, integrándose o reemplazando su propio software.

B. Consideraciones Preliminares

La arquitectura funcional del DERMS se presenta en la Fig. 6 a continuación, con las funcionalidades y servicios exclusivos para la utility/DSO resaltados en verde, aquellos exclusivos para los agregadores en rojo, y los aplicables a ambos compartiendo ambos colores. Esta misma caracterización también se ha aplicado a los dispositivos de campo, sistemas de medición, sistemas de gestión de redes de distribución, mercados, centros de control y operadores del sistema con los que el DERMS debe ser capaz de interactuar. Para comprender la lógica detrás del diseño de la arquitectura, deben tenerse en cuenta varios puntos:

- Dado que el objetivo es desarrollar una solución DERMS única e integral, muchas de las funcionalidades y servicios que anteriormente estaban duplicados en el estado del arte—o tenían versiones muy similares—para los DERMS Centralizados (Utility) y los DERMS Descentralizados (Agregador), ahora se unificarán tanto para los DERs BTM como para los DERs propiedad de la utility—por ejemplo, funciones de inscripción. De manera similar, algunas funcionalidades que eran exclusivas de los DERMS de Utility o de Agregador han ampliado su alcance, mientras que otras permanecen separadas para adaptarse a las diferentes necesidades de los clientes. Ejemplos son las funciones de optimización de DERs, aplicadas ya sea a la cartera de un agregador, o a los DERs gestionados por agregadores y la utility.
- La distribución de funcionalidades y servicios se ha modificado parcialmente con respecto a lo que se presentó en la especificación funcional anterior, con algunas funciones adicionales incorporadas y otras que ya no se consideran. Esto responde a (i) integrar conocimientos de la experiencia de Minsait en el despliegue de soluciones de gestión de DERs, y (ii) intentar limitar las funcionalidades incluidas al nivel de servicio y no a los casos de uso. Esto implica, por ejemplo, que la Gestión de VPP o Microrredes no aparezcan en el diagrama, ya que son más bien un caso de uso potencial para una solución DERMS. Es decir, un agregador puede usar un DERMS para crear y gestionar un VPP o para controlar una microrred combinando algunas de sus funcionalidades y servicios específicos: registro y agregación de DERs, optimización de la cartera, etc.
- La arquitectura se ha estructurado de abajo hacia arriba, siguiendo el flujo de información y el orden de los procesos desde los dispositivos de campo—DERs y sistemas SCADA—hasta los mercados eléctricos o el TSO. De esta manera, aquellas funcionalidades que solo requieren información de campo y no la finalización de procesos previos se encuentran en la parte inferior, mientras que los servicios más complejos que necesitan la ejecución de otras funciones de nivel inferior se sitúan hacia la parte superior de la arquitectura.
- La solución DERMS en sí está delineada por el rectángulo grueso que abarca ambos Multi-Protocol Brokers. Alrededor de ella se encuentran todos los dispositivos de campo (DERs y dispositivos de medición), sistemas de medición y control (SCADA), sistemas de Gestión de Datos de Medición (MDM), soluciones para la gestión de redes (ADMS, OMS, gestión del rendimiento de activos), Sistemas de Información Geográfica (GIS), proveedores de datos meteorológicos, operadores del sistema competentes y mercados eléctricos con los que el DERMS ha de poder interactuar. Los Centros de Control y las Plataformas de Intercambio de Datos Operativos—SIORD en España, GOPACS en los Países Bajos para la comunicación entre DSOs y proveedores de servicios, o EQUIGY en varios países europeos para la interacción DSO-TSO—se han incorporado como posibles intermediarios potenciales.

C. Descripción General de la Arquitectura

Teniendo en cuenta todo lo anterior, en esta sección se presentará el desarrollo conceptual de la arquitectura funcional del DERMS. Las lecturas de la red y las unidades DER son recopiladas por dispositivos de medición de campo, traducidas a través del *Multi-Protocol Broker (MPB)* en protocolos y modelos de información con los que el DERMS puede trabajar, y colocadas en la cola de mensajería de la *Communication Interface (CI)* para ser procesadas y utilizadas por otros módulos. Lo mismo ocurre en la dirección opuesta con los comandos enviados desde el DERMS a los dispositivos de campo: en este caso, el MPB los traduce en los protocolos correspondientes utilizados por cada dispositivo.

Una capa de *Connectivity* se posiciona inmediatamente por encima de la CI, ya que es responsable de la interacción con DERs y con la red. Esto incluye *DER* y *Grid*—refiriéndose a elementos tradicionales de la red, como cambiadores de tomas, interruptores, capacitores, etc.—*Monitoring* (adquisición de mediciones de manera periódica), *Status* (seguimiento de parámetros como modo operativo, estado de carga, etc.) y *Control* (envío de comandos, verificación de que los DERs estén operando según lo programado, etc.), *DER Alarms & Events Logging* (para activar notificaciones—alarms—o activar procesos asociados—events—cuando un parámetro monitoreado supera un cierto umbral) y *Edge Management* (qué dispositivos edge existen, dónde están ubicados, autenticación para garantizar que solo dispositivos verificados puedan enviar datos al DERMS, etc.). Un *CIM Converter* se incluye en paralelo a la CI y al módulo de Connectivity para hacer que el DERMS sea compatible con GIS externos u otros sistemas que exporten archivos de topología de red en formato CIM.

El módulo de *Data Storage & Task Management* se coloca directamente por encima de la capa de Connectivity. Incluye (i) el *Task Manager*, responsable del inventario y la ejecución de procesos programados de todo tipo: pronósticos, optimización, recálculo de mediciones, generación de informes, etc., (ii) un *Real-Time Communication Bus* que permite el intercambio de datos en tiempo real a través de varios mecanismos—asignado solo a las utilities ya que los agregadores no suelen tener requisitos en tiempo real (milisegundos) para la operación de DERs—y (iii) el almacenamiento de datos recopilados en varios formatos para diferentes usos: *Time-Series* (para información registrada periódicamente a intervalos regulares), *Relational* (para bases de datos relacionales tradicionales en formato de tabla), *File Storage* (repositorio en la nube de archivos) e *In-Memory* (almacenamiento temporal de datos, para ser utilizados y después descartados).

La primera capa que ofrece servicios para el cliente consiste en el módulo de *DER Enrollment & Flexibility Management*, que cubre *Registration* tanto de DERs individuales como de grupos de DERs en la plataforma DERMS, *Aggregation* de estos DERs, *Configuration y Modeling*, *Contracting* (gestión de tarifas de suministro, tarifas de flexibilidad hacia arriba y/o hacia abajo, etc.), y un *Service Catalogue* para productos de flexibilidad (gestión de conegstiones, control de tensión, control de isla, moldeo de la curva de carga, optimización ToU, etc.), indicando capacidad mínima/máxima y tiempo de activación, tiempo mínimo de preparación para la entrega de estos servicios, etc.

Después de esto, hay un módulo de funcionalidades centrales necesarias para proporcionar otros servicios: el *Calculation Engine*. Esto abarca funciones capaces de realizar *State Estimation, (Optimal) Distribution Power Flow*, y procesar topologías de red en tiempo real (*Topology Processor*) basadas en el estado de los dispositivos de conmutación de la red. También se incluyen en este módulo *Grid Fore*casting y *DER Forecasting*, junto con la capacidad de configurar escenarios de red para análisis adicionales y cálculos de flujo de cargas y estimación de estado (*Scenario Configurator*), y *Flexibility Calculation* para cada tipo de activo, basado en datos históricos y/o en la parametrización de restricciones (por ejemplo, el estado de carga no puede caer por debajo del 20% o superar el 90%). La mayoría de estas funcionalidades son exclusivas para utilities y operadores del sistema, ya que los agregadores carecen de un modelo de red para realizar cálculos de análisis de red.

La siguiente capa abarca todas las funciones de *Grid Planning* y *Grid Operation*, así como *Aggregation Services* como la optimización tanto de DERs individuales como de carteras de DERs, y la creación y gestión de programas de *DR* y *Energy Communities*. A diferencia de VPPs y microgrids, que podrían reducirse a casos de uso de un DERMS, DR implica funcionalidades específicas como la capacidad de transmitir un comando—por ejemplo, apagar todos los termostatos o poner todas las baterías a descargar—en lugar de simples puntos de consigna deterministas entregados a los DERs dentro de la cartera del agregador. Lo mismo se aplica a las Energy Communities, con sus propios servicios de planificación y operación. Las funcionalidades equivalentes a las incluidas en Grid Planning y Grid Operation ya se discutieron en el estado del arte, por lo que no se describirán aquí nuevamente. Se ha incluido una función de I*sland Control* para cubrir la gestión de regiones de la red que pueden aislarse debido a cortes mayores o por razones de eficiencia energética, así como la transición entre modos conectados a la red y de isla.

Por encima de ellas en la arquitectura, encontramos tres grupos paralelos de servicios. El primero es *Market Operations*, que abarca *Market Registration*—registro en mercados eléctricos, intercambio de datos estructurales de DER y cartera, y otros procedimientos administrativos—, *Bidding*, *Market Settlement* y *Billing*, todos ellos aplicables tanto a DERs que participan en el mercado a través de un aggregator como a DERs individuales propiedad de la utility. En segundo lugar, *Performance Analysis* incluye dos funcionalidades, exclusivas del nivel de agregador: (i) *Portfolio Analysis*, responsable de evaluar continuamente y tratar de optimizar la cartera de DERs del agregador, y (ii) *Audit* para cubrir aquellos procesos relacionados con la auditoría de un servicio de flexibilidad, es decir, lo que se comprometió frente a lo que finalmente se logró. Además, se incorpora un módulo de *Settlement* con los servicios de *Internal Settlement* y *Billing*, aplicables tanto dentro de una cartera de agregador, como en el caso de DERs gestionados por la utility que no participan en el mercado—por ejemplo, proporcionando servicios a través de contratos flexibles.

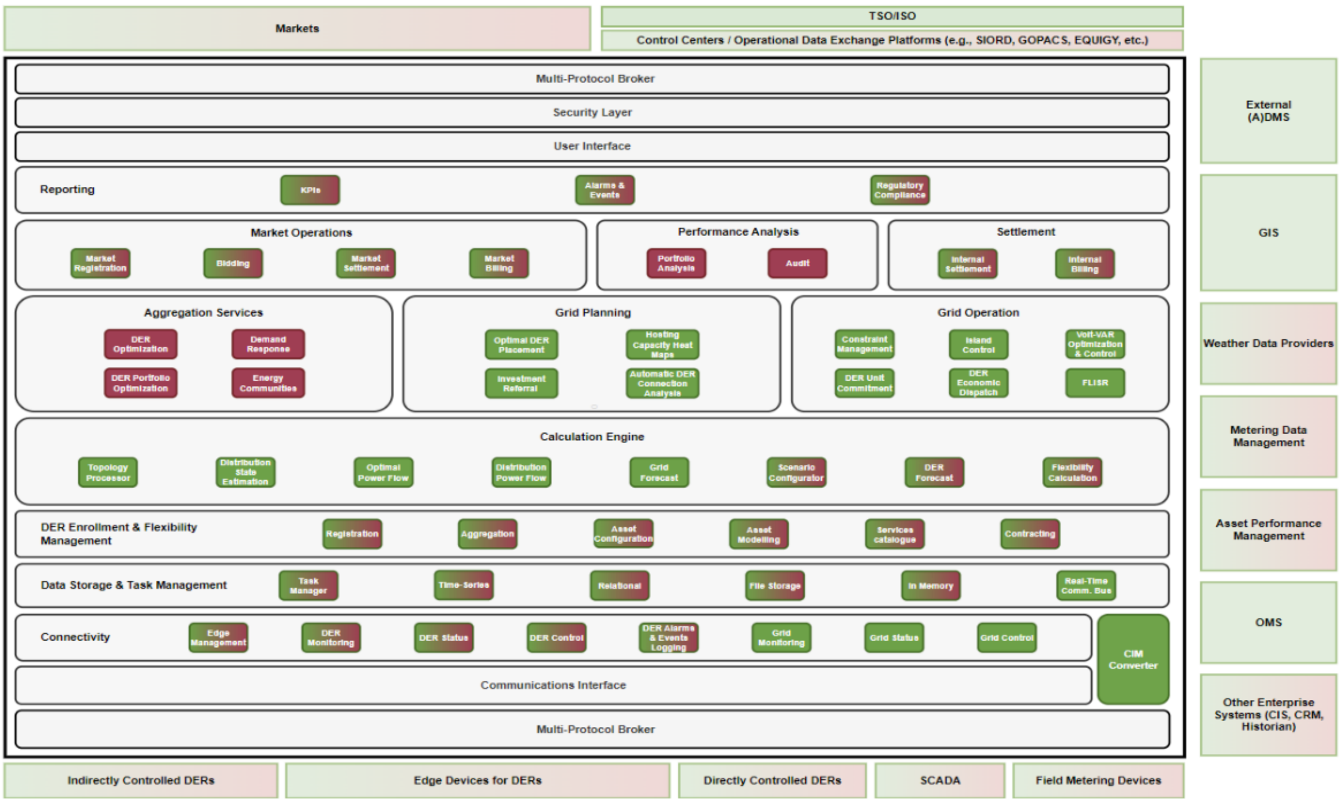

Fig. 6. DERMS Functional Architecture – General Schematic.

Finalmente, se incluye un módulo de *Reporting* para crear informes sobre varios aspectos, tanto a nivel de utility como de aggregator, como *KPIs* sobre el rendimiento técnico y económico del DERMS, la resolución de *Events & Alarms* específicos (siguiendo los resultados de la funcionalidad de DER Alarms & Events Logging), o sobre *Regulatory Compliance* con respecto a la prestación de servicios locales. En la parte superior del esquema, la *User Interface* ofrece un portal web front-end donde los usuarios pueden navegar, gestionar sus dispositivos, programar períodos de indisponibilidad, revisar la resolución de eventos, etc.; y la *Security Layer* maneja la protección contra malware, la autenticación (user login: usuario, contraseña, JSON Web Tokens, etc.) y la autorización (gestión de roles y permisos). Por último, otra capa de traducción de protocolos permite la interacción con mercados eléctricos y/o TSOs

D. Declinaciones DERMS

Es esencial que la arquitectura anterior pueda ser implementada en las plataformas de tantos clientes y partes interesadas potenciales como sea posible—es decir, DSOs, utilities verticalmente integradas, agregadores, verticales de nicho o gestores de microrredes—integrándose con sus soluciones de software existentes y cubriendo la más amplia gama de aplicaciones y casos de uso en múltiples países y varios marcos regulatorios. En este sentido, se han considerado siete adaptaciones diferentes de la arquitectura anterior. Para evitar redundancias, estas se presentarán a continuación especificando qué funcionalidades y servicios de los mencionados anteriormente se excluirán de cada declinación y las razones para ello. Sin embargo, cabe destacar que todas las funcionalidades incluidas en estas variaciones cumplen con los requisitos potenciales para un caso de uso particular, lo que no implica que todas las funciones sean necesarias en todas las instancias.

1) DERMS Agregadores

Los agregadores de DERs combinan DERs pequeños, generalmente BTM, en grupos más grandes y controlables para proporcionar capacidad flexible y servicios auxiliares a los DSOs y participar en mercados eléctricos, programas de DR o EE. Como resultado, esta declinación de la solución DERMS excluye todas las funcionalidades puramente de red, es decir, la monitorización, estado y control de la red, los servicios de operación y planificación de la red, y las funciones de cálculo exclusivas de la red del motor de cálculo (grid forecasting, topology processor, state estimation y power flow analysis), por no estar dentro del alcance del agregador. En cuanto a la "periferia" de la solución DERMS, no se contempla la interacción directa con TSOs para los agregadores (en cualquier caso, sería a través de los centros de control o plataformas de intercambio de datos operativos), ni tampoco con DMS, GIS o OMS, ya que estos sistemas contribuyen a una gestión de red de la cual un agregador independiente no es responsable—ni siquiera tiene acceso a modelos de la red. Por esta razón, el CIM Converter también se ha considerado innecesario para los agregadores.

2) DERMS Verticales de Nicho

Los verticales de nicho describen un grupo de empresas que se enfocan en un nicho específico o un mercado especializado que abarca múltiples industrias. Cubren las necesidades particulares de ese mercado y, en general, no se expanden a mercados más amplios. Ejemplos de verticales de nicho dentro del sector eléctrico incluyen proveedores y gestores de estaciones de carga de VE, BESS, inversores fotovoltaicos (PV) o termostatos inteligentes [42]. En consecuencia, esta adaptación de la arquitectura DERMS sería muy similar a la de los agregadores de DERs, con la particularidad de que, en este caso, el vertical de nicho es propietario de los DERs en su cartera (estos no pertenecen a terceros o a individuos) y, por lo tanto, también se excluirán las funcionalidades de internal settlement y billing—la empresa liquidaría y facturaría sus propios productos.

3) DERMS Microrredes

Las microrredes deben ser capaces de operar tanto en modo conectado a la red, realizando optimización local y asegurando un uso eficiente de los recursos para proporcionar servicios a la red, como en modo isla, gestionando operaciones de formación de red, equilibrio de carga y regulación de frecuencia y voltaje para garantizar la operación estable y confiable de la microrred. En consecuencia, esta declinación de DERMS debe incorporar casi todas sus funcionalidades, excepto los servicios de planificación de red que están reservados para los DSOs. Esto implica las ya incluidas para agregadores, pero también todos los servicios puros de red y las funcionalidades de cálculo de la red—para poder operar en modo isla. De manera similar, los gestores de microrredes deben ser capaces de interactuar con todo tipo de dispositivos de campo—DERs y dispositivos de medición—, sistemas de gestión de redes empresariales, GIS—también se incorpora el CIM Converter—, mercados eléctricos, DSOs y TSOs, ya sea directamente o a través de centros de control.

4) DERMS DSOs

Los DSOs son responsables de gestionar las redes de distribución de BT y MT locales y regionales. Esto implica la planificación de la red, el monitoreo y control en tiempo real de las condiciones de la red, la coordinación de activos locales y la optimización de DERs para servicios de red a nivel de distribución—como equilibrio de carga, recorte de picos o control de voltaje—, la previsión de carga y generación para anticipar posibles problemas en la red, la programación y despacho de recursos, aprovechando el valor de los DER en los mercados eléctricos, determinando la compensación para los propietarios de recursos y agregadores, así como interactuando con TSOs para requisitos más amplios de la red [43]. Esto implica que las funcionalidades de análisis de rendimiento y servicios de agregación son las únicas que no se consideran inicialmente para la solución estándar de DERMS de un DSO, ya que estas funciones son exclusivas para agregadores. Se han contemplado cuatro declinaciones diferentes de DERMS para DSOs, dependiendo de (i) si ya tiene un software DMS o ADMS que desea mantener DERMS, y (ii) si estamos dirigiéndonos a un DSO que opera en un contexto de unbundling—i.e., separación de los negocios que pueden ser realizados de manera competitiva (generación y venta) de los monopolios naturales (transmisión y distribución)—o si es una utility verticalmente integrada.

a) DERMS DSOs w/ ADMS – Unbundling: en este primer escenario, todos los servicios de planificación y operación de la red, las funcionalidades centrales de la red del motor de cálculo, el monitoreo y control de la red, el bus de comunicación en tiempo real y la conversión CIM serán cubiertos por el propio software ADMS del DSO. Cabe destacar que el componente *External (A)DMS* en el lado derecho del esquema será ahora el propio ADMS de la utility, parte de cuyas capacidades se integrarán con el DERMS.

b) DERMS DSOs w/o ADMS – Unbundling: lo mismo se aplica en el caso de que el DSO no tenga o no desee integrar su ADMS con el software DERMS, con la diferencia de que todas las funcionalidades pertenecen al DERMS y el ADMS se considera nuevamente como un elemento externo.

c) DERMS DSOs w/ ADMS – Vertically Integrated: todo lo anterior también es aplicable a utilities verticalmente integradas que buscan integrar la solución DERMS con un ADMS existente, con la particularidad de que las funcionalidades exclusivas de agregadores—es decir, los módulos de análisis de rendimiento y servicios de agregación—se incorporarán aquí, ya que el DSO ahora puede realizar funciones de agregación y venta. Las operaciones de mercado permanecen incluidas para permitir que el DSO tanto adquiera productos de flexibilidad de aggregators de terceros—por ejemplo, plataformas verticales de nicho para baterías o VEs—en mercados locales, como para participar en mercados mayoristas junto con otras utilities integradas. Además, los centros de control para la interacción con TSOs/ISOs podrían integrarse dentro de la misma utility vertical—al igual que el propio TSO—pero aún se consideran en la arquitectura en caso de que la utility gestione exclusivamente la distribución y la venta.

d) DERMS DSOs w/o ADMS – Vertically Integrated: la solución DERMS completa debe implementarse en el caso de una utility verticalmente integrada que no desea integrarla con su propio software ADMS. Esto constituiría, posiblemente, la tipología de cliente ideal para el despliegue de la arquitectura funcional DERMS aquí propuesta.

E. Estrategia de Modularización

Es fundamental que esta arquitectura pueda fragmentarse en múltiples módulos, de manera que pueda implementarse en las plataformas de todos los posibles clientes y ser capaz de integrarse con sus soluciones de software existentes si es necesario. En este sentido, esta sección presentará una estrategia de modularización que utiliza los patrones comunes y las conclusiones extraídas de las declinaciones de DERMS descritas anteriormente para desacoplar sus diferentes funcionalidades y servicios. Esto se muestra en la Fig. 7 a continuación, y los siguientes aspectos requieren una mayor aclaración:

- Las funciones de conectividad están divididas en dos módulos: *DER Connectivity* y *Grid Connectivity*. Esta separación permite que DER Connectivity se despliegue de manera independiente para aplicaciones específicas como DERMS para agregadores o DSOs que mantengan su software ADMS. Cabe destacar que el CIM Converter siempre está incluido con Grid Connectivity, y que tanto la CI como el MPB están integrados en ambos módulos, pero solo se implementan una vez cuando se necesitan ambos módulos.
- *Data Storage & Task Management* permanece como un único módulo, a pesar de incluir elementos que no son necesarios en todos los casos. Sus funcionalidades pueden usarse de manera independiente según lo requiera cada aplicación específica. Lo mismo es válido para los módulos de *DER Enrollment & Flexibility Management* y *Reporting*, los cuales se desplegarán para todos los clientes y casos de uso considerados anteriormente.
- El Calculation Engine se divide en módulos de red y de DER. El *DER Engine* puede incluirse solo para aplicaciones específicas, mientras que el *Grid Engine* también es necesario para microrredes y DSOs que no integran con ADMS. El Scenario Configurator está incluido en ambos módulos, asegurando que pueda incorporarse en cualquiera de ellos—nunca duplicado—o incluso omitido en caso de que un ADMS proporcione esta funcionalidad.

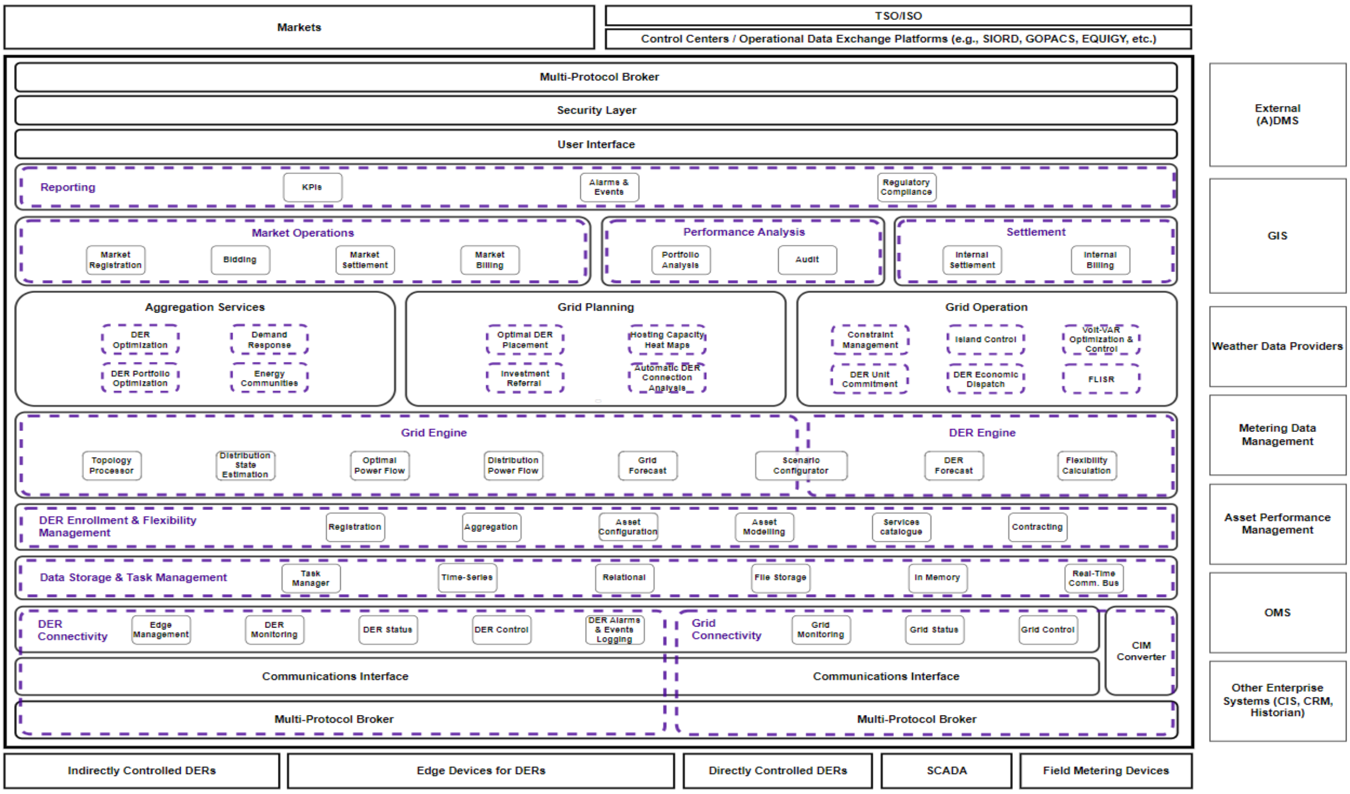

Fig. 7. Arquitectura Funcional DERMS – Estrategia de Modularización.

- Todos los servicios de planificación, operación de la red y agregación: se consideran módulos independientes, lo que permite a los clientes elegir qué funciones incorporar a su solución. Estos servicios dependen de funcionalidades de nivel inferior y podrán ser excluidos en caso de no ser necesarios para ciertos stakeholders.
- *Market Operations*, *Performance Analysis* y *Settlement*: también son módulos separados. Performance Analysis se excluye de las soluciones de DSO con separación (no realizan tareas de agregación), y Settlement no se aplica a los verticales de nicho (ellos liquidarían y facturarían sus propios productos), por lo que deben poder desacoplarse fácilmente del resto de la solución.

Estos módulos deben ser unidades de software independientes capaces de desacoplarse del resto de la solución, interactuar entre sí e integrarse con otros sistemas de software. Esto permitiría una solución DERMS integral basada en funciones comunes a todas las aplicaciones posibles, pero que al mismo tiempo puede adaptarse a los roles de los diferentes stakeholders, casos de uso y estructuras del sector eléctrico en diferentes países y regulaciones.

V. Validación de la Arquitectura

Este capítulo abordará la validación de la arquitectura funcional DERMS propuesta, las siete declinaciones que se han considerado y su estrategia de modularización. Primero, se presentará una evaluación IDC MarketScape de los proveedores de servicios DERMS para mostrar la relevancia de Minsait en el panorama internacional de DERMS. Luego, se ofrecerá una visión general de varios proyectos realizados por Minsait, implementando con éxito algunas partes de la arquitectura propuesta. Finalmente, un cuestionario distribuido entre miembros de TSO/DSOs, agregadores y la comunidad académica servirá para justificar el interés de la industria eléctrica en lo que se ha discutido aquí.

A. *IDC MarketScape – Proveedores de Servicios DERMS*

El IDC MarketScape evaluó a los SPs con una perspectiva global sobre DERMS, trabajando activamente con clientes y/o colaborando con utilities para actividades de monitoreo, control, operación, planificación e interacción con el cliente relacionadas con DERs. Cada proveedor fue evaluado tanto cuantitativa como cualitativamente según la variedad y madurez de las capacidades y servicios que podían ofrecer, considerando en particular áreas como la gestión de redes eléctricas y la experiencia en DERMS, la estrategia tecnológica e innovación, y la experiencia con protocolos de comunicación y control.

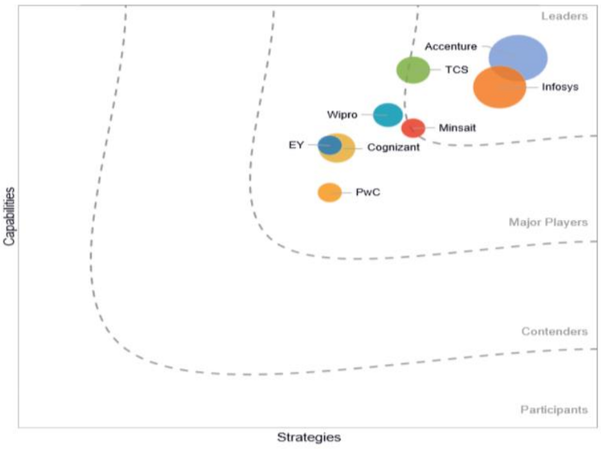

Fig. 8. IDC MarketScape – Evaluación de proveedores DERMS [44].

Los resultados del IDC MarketScape se presentan en la Fig. 8, con el eje Y representando las capacidades actuales y la alineación con las necesidades del cliente, el eje X evaluando las estrategias futuras de los proveedores para los próximos tres a cinco años, y el tamaño de los indicadores siendo una estimación de la cuota de mercado del proveedor [44]. Minsait se ubica en la categoría de Líderes, destacando su importancia como proveedor de DERMS y la relevancia de su solución DERMS.

B. *Referencias de Proyectos*

Esta sección presentará brevemente una serie de proyectos en los que Minsait ha sido capaz de cumplir con los requisitos de clientes muy diversos utilizando el mismo conjunto de módulos de software, combinados de diferentes maneras según el caso de uso específico. Cinco proyectos diferentes servirán para ilustrar cinco de las declinaciones de DERMS consideradas anteriormente, demostrando la viabilidad técnica del enfoque modular propuesto.

- *DERMS Agregadores*: en asociación con Ferrovial, Minsait desarrolló una solución DERMS destinada a optimizar la integración de sistemas PV y BESS dentro de edificios comerciales e industriales. El proyecto utiliza AI para mejorar la operación de las baterías y maximizar el ahorro energético mediante estrategias de arbitraje de precios. El DERMS integra la monitorización de medidores de energía, sistemas PV, baterías, y equipos HVAC bajo una plataforma unificada, empleando modelos de optimización económica basados en la demanda histórica, datos meteorológicos y tarifas ToU para determinar los horarios óptimos de operación [45].
- *DERMS Verticales de Nicho*: Minsait colaboró con Galp para implementar una solución DERMS para la agregación de estaciones de carga de VE. Este proyecto probó un modelo de negocio en el que Galp agrega la flexibilidad de la demanda de múltiples estaciones de VE para participar en mercados locales de energía. La integración con Etenic (una plataforma para gestionar sesiones de recarga) y OMIE (operador del mercado) permitió el intercambio de sesiones de recarga y horarios de mercado [46].
- *DERMS Microrredes*: Minsait apoyó la Iniciativa de Cero Emisiones Netas de la Universidad de Monash integrando varios DERs y soluciones de EE en una microrred en su campus de Clayton en Australia. El proyecto implicó la gestión distribuida de dispositivos de borde y una gestión activa de la red, proporcionando monitorización y control centralizados de los recursos en todo el campus [47].
- *DSO con ADMS – Unbundling*: Minsait se asoció con Enel, un DSO global líder, para integrar su DERMS con el ADMS de Enel. La solución DERMS, que destacó la efectividad del enfoque modular de Minsait, fue diseñada para gestionar funciones críticas fuera de las tareas principales del ADMS, incluyendo la detección de criticidades en la red a través de análisis OPF, previsión de carga, estimación de necesidades de flexibilidad y la asignación óptima de flexibilidad basada en las reglas del mercado. El sistema también se integra con mercados locales de flexibilidad para contratar servicios de flexibilidad a través de procesos competitivos [48].
- *DSO sin ADMS – Utility Verticalmente Integrada*: Minsait entregará una solución integral DERMS para Saudi Electricity Company (SEC) para gestionar sus operaciones de distribución en dos de sus centros de

control. El proyecto implica la entrega de todas las funcionalidades de ADMS para la planificación y operaciones en tiempo real, junto con herramientas para gestionar agregadores y activos FTM y BTM gestionados por terceros.

Estos proyectos, en conjunto, demuestran la versatilidad y viabilidad técnica de la solución DERMS integral y modular propuesta, confirmando su aplicabilidad en una amplia gama de perfiles de clientes y casos de uso.

C. Cuestionario de Evaluación del Interés de la Industria

Finalmente, se distribuyó un cuestionario para evaluar el interés del sector eléctrico en algunos de los aspectos principales destacados a lo largo de este trabajo entre miembros de TSO/DSOs, agregadores y la comunidad académica. Las principales conclusiones extraídas de sus respuestas se enumeran a continuación:

- *Amplio apoyo para los DERMS*: alrededor del 80% de los encuestados cree que los DERMS son esenciales para todas las partes interesadas que gestionan DERs, independientemente de sus roles específicos.
- *Enfoque en prosumidores y agregadores*: se considera que los DERMS benefician principalmente a los prosumidores y agregadores al optimizar los recursos BTM, en lugar de simplemente ayudar a los operadores del sistema a gestionar la red de distribución. Esto resalta la aplicabilidad más amplia de los DERMS más allá de las utilities.
- *Funcionalidades específicas para stakeholders concretos*: aproximadamente el 90% apoya la necesidad de que los DERMS incluyan funciones específicas adaptadas a las necesidades de cada parte interesada, mientras que el 70% cree en la existencia de funciones básicas comunes para todas las partes interesadas, aunque esta idea es más discutida.
- *Consenso sobre la necesidad de mecanismos de mercado*: existe un fuerte acuerdo sobre la necesidad de nuevos mecanismos de mercado, como los mercados de servicios de flexibilidad locales, para maximizar el valor de los DERs, en lugar de depender únicamente de contratos bilaterales o flexibles.
- *Regulación vs. especialización*: la mayoría de los encuestados piensa que las funciones básicas de DERMS no deberían estar reguladas y compartidas entre las partes interesadas. En su lugar, apoyan la especialización competitiva en el mercado.
- *Necesidad de una nueva solución DERMS*: hay consenso en que los DERMS deben desarrollarse como una nueva solución, en lugar de una extensión de sistemas existentes como ADMS.
- *Especialización de proveedores vs. flexibilidad*: si bien muchos creen que los proveedores deberían centrarse en soluciones especializadas para partes interesadas específicas, también existe un apoyo significativo (70%) a la modularización y flexibilidad para adaptarse a diferentes contextos regulatorios y casos de uso.

Por lo tanto, esta evaluación del interés de la industria sirve para justificar el enfoque seguido para desarrollar la arquitectura funcional DERMS propuesta, la necesidad de sus siete declinaciones para diferentes clientes y casos de uso, así como para la modularización y flexibilidad. Sin embargo, también muestra que el sector eléctrico aún mantiene muchas convicciones contrarias a la visión defendida en este trabajo.

VI. CONCLUSIONES

El sistema eléctrico está experimentando una transformación significativa con la creciente penetración de los recursos energéticos distribuidos, lo que desafía el modelo tradicional de generación centralizada y ha llevado a una red de distribución más compleja, activa y dinámica. La integración de DERs, tanto FTM como BTM, ofrece múltiples oportunidades para la optimización técnica y económica de la red, pero también introduce desafíos significativos que requieren nuevas herramientas de gestión. En respuesta, han surgido los Distributed Energy Resource Management Systems (DERMS) para proporcionar una solución integral para la monitorización, el control y la optimización de la integración de DERs en la red eléctrica [1]-[6].

Este trabajo ha desarrollado y validado una arquitectura DERMS unificada y completa, que es tanto modular como versátil, adaptable a las particularidades de diversas tipologías de clientes y casos de uso. Se ha enfatizado que las soluciones DERMS no deben ser exclusivas para utilities y DSOs, sino que también deben dirigirse a agregadores de DERs BTM de terceros, gestores de microrredes y plataformas verticales de nicho, entre otros, subrayando la importancia de una solución unificada con funcionalidades básicas comunes para todas las partes interesadas, complementadas con funcionalidades y servicios específicos para casos de uso particulares. Se espera que los resultados de este trabajo proporcionen una base sólida para un mayor entendimiento, desarrollo e implementación de soluciones DERMS, estableciendo las bases para una gestión más eficiente y efectiva de los recursos energéticos distribuidos.

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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].

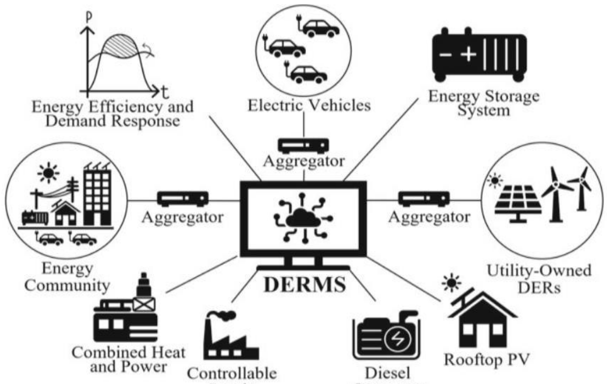

Fig. 1. DER assets potentially aggregated and managed by DERMS [3].

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:

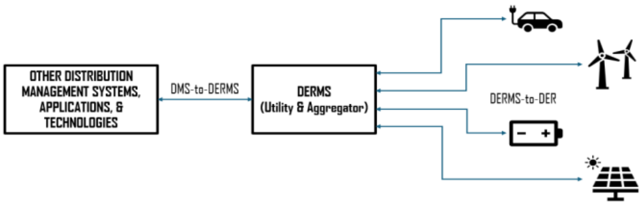

Fig. 3. Overview of interface levels of enabling protocols for DERMS.

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]:

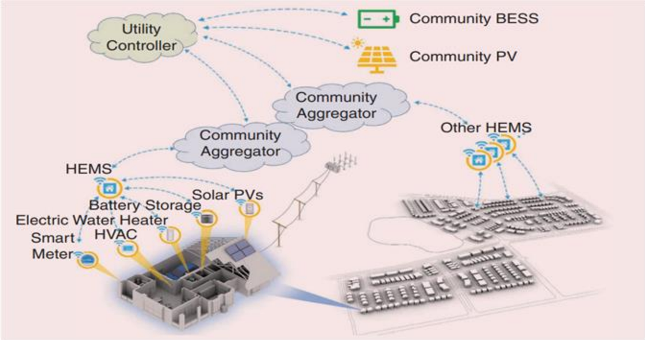

Fig. 4. Hierarchical Architecture for BTM DERs' control [5].

- *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.

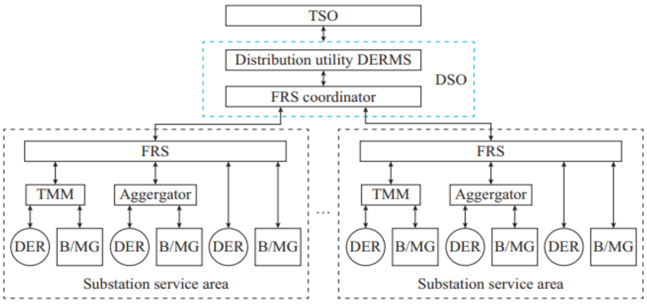

Fig. 5. Conceptual Schematic of FAST-DERMS [6].

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

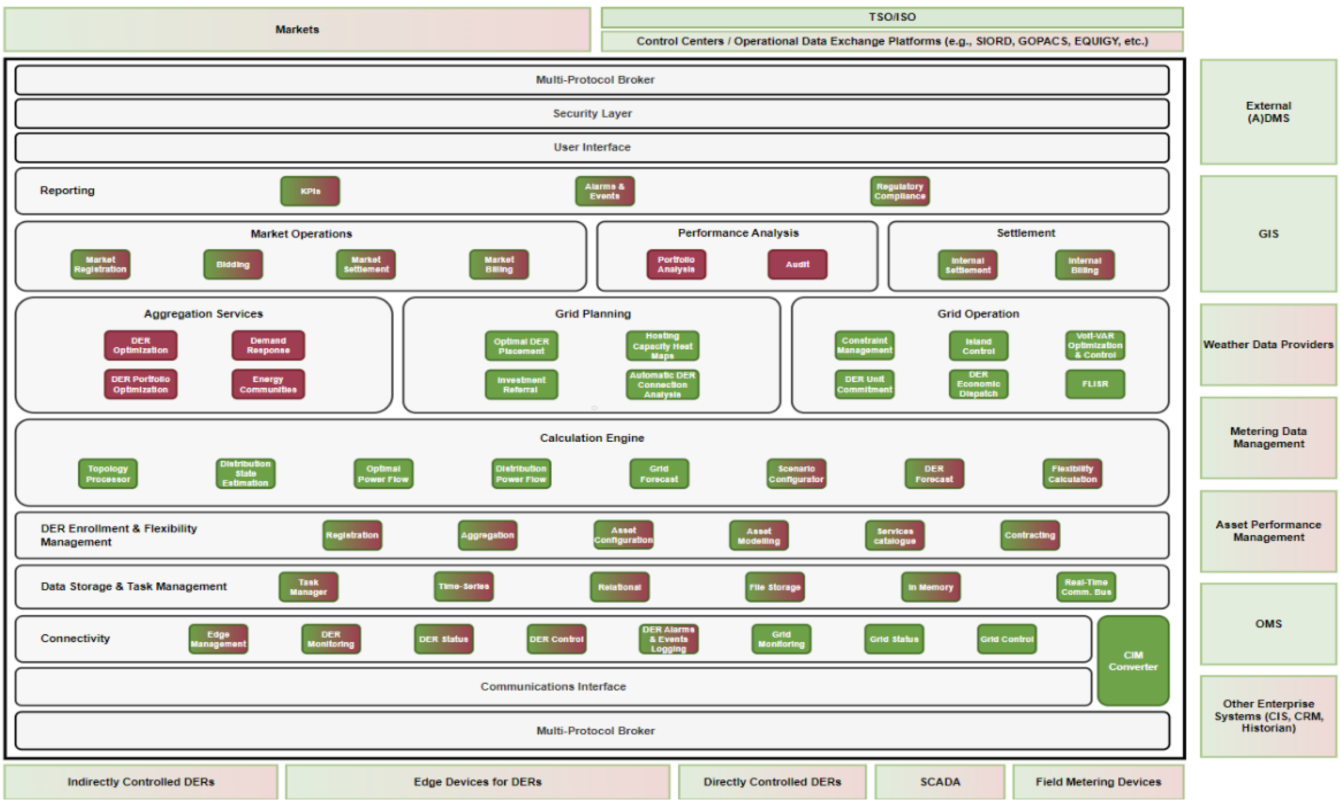

Fig. 6. DERMS Functional Architecture – General Schematic.

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.

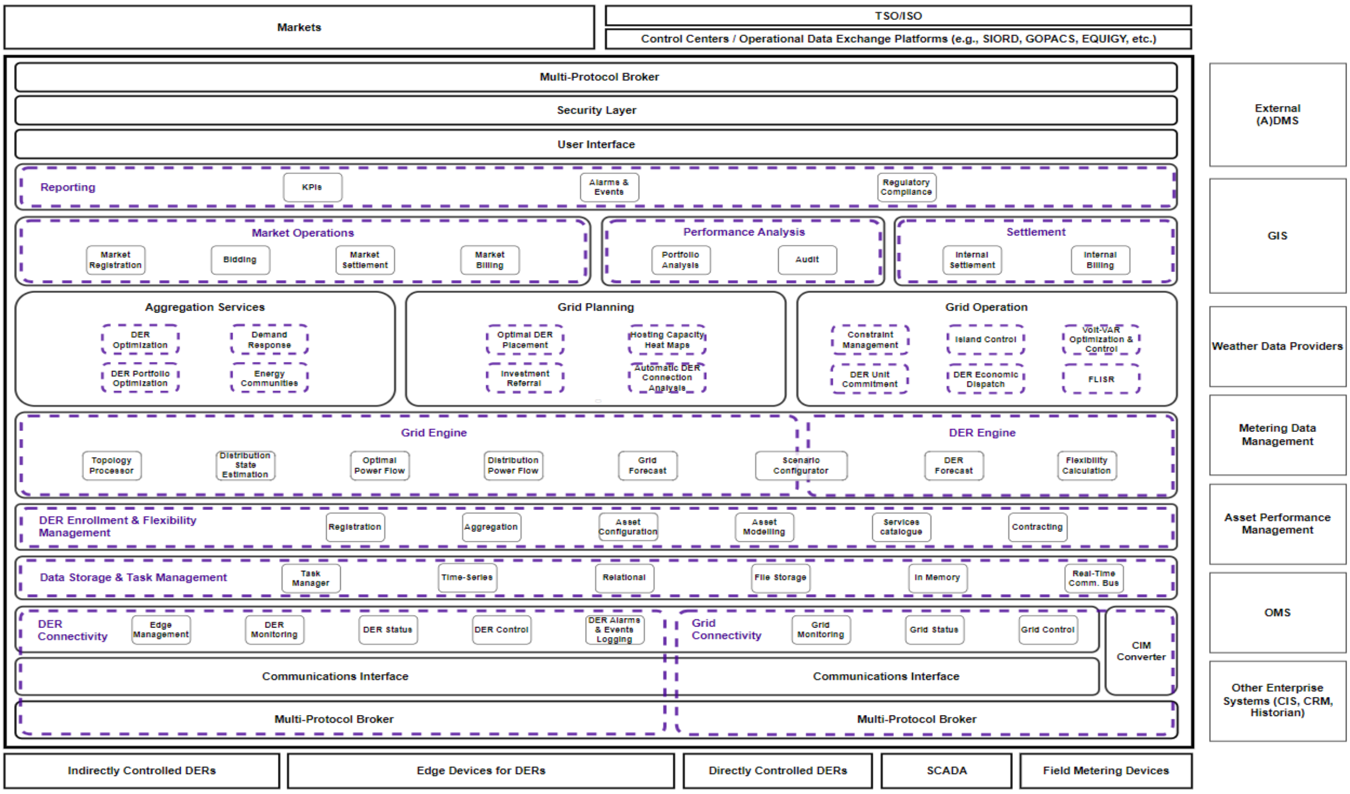

Fig. 7. DERMS Functional Architecture - Modularization Strategy.

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.

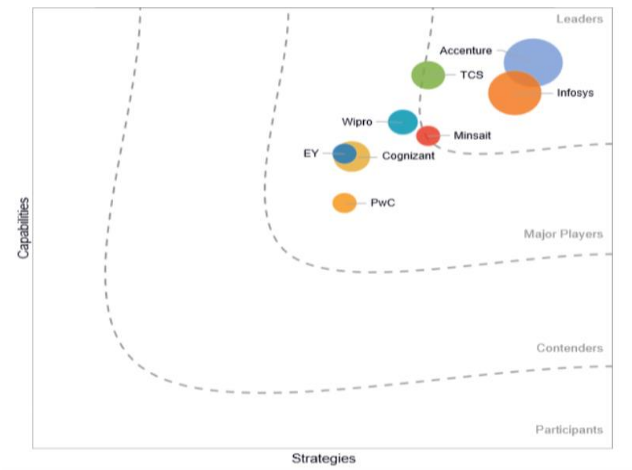

Fig. 8. IDC MarketScape DERMS SPs Vendor Assessment [44].

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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Table of Contents

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List of Abbreviations

ADMS – Advanced Distribution Management System

AMI – Advanced Metering Infrastructure

BRP – Balance Responsible Party

BTM – Behind the Meter

BEMS – Building Energy Management Systems

BESS – Battery Energy Storage System

CIM – Common Information Model

CPP – Critical Peak Pricing

CU – Control Unit

DER – Distributed Energy Resource

DERMS – Distributed Energy Resource Management System

DG – Distributed Generation

DMD – Dedicated Measurement Device

DMS – Distribution Management System

DNP3 – Distributed Network Protocol

DOE – Department of Energy

DRMS – Demand Response Management System

DSM – Demand-Side Management

DSO – Distribution System Operator

EE – Energy Efficiency

EMS – Energy Management System

ENTSO-E – European Network of Transmission System Operators for Electricity

EV – Electric Vehicle

FAST-DERMS – Federated Architecture for Secure and Transactive DERMS

FERC – Federal Energy Regulatory Commission

FRS – Flexible Resource Scheduler

FTM – Front of the Meter

HEMS – Home Energy Management Systems

HV – High Voltage

IEC – International Electrotechnical Commission

IEEE – Institute of Electrical and Electronics Engineers

ISO – Independent System Operator

LV – Low Voltage

MC – Microgrid Controller

MV – Medium Voltage

PPP – Product Prequalifying Party

PV – Photovoltaic

RMS – Root Mean Square

SCADA – Supervisory Control and Data Acquisition

SDG – Sustainable Development Goals

SG – Smart Grid

SoC – State of Charge

SPU – Service Providing Unit

SPG – Service Providing Group

TMM – Transactive Market Manager

ToU – Time of Use

TSO – Transmission System Operator

VPP – Virtual Power Plant

Chapter 1. INTRODUCTION

The electric power grid is undergoing a deep transformation driven by the increasing penetration of Distributed Energy Resources (DERs). DERs are a broad category of electricity generation, storage systems, and controllable loads within distribution networks, as opposed to the traditional, centralized power generation plants located upstream and connected to the transmission grid. DERs include a variety of technologies such as solar photovoltaic (PV) panels, wind turbines, energy storage systems (ESSs) like batteries, electric vehicles (EVs) and their charging infrastructure, Combined Heat and Power (CHP), diesel generators, as well as other renewable and non-renewable distributed generation sources, which can be connected either at the customer's or the utility's side of the power meters [1]-[4].

1.1 TOWARDS AN ACTIVE & DYNAMIC DISTRIBUTION GRID

DERs have become increasingly prevalent due to advances in technology, growing environmental concerns, and supportive regulatory frameworks to carbon emissions. They have introduced new technical challenges that traditional tools cannot effectively manage, involving a transition from a passive network to an active and dynamic distribution grid and requiring improved management solutions to ensure grid reliability, efficiency, and sustainability [1], [2]. The integration of DERs into the power grid represents a significant shift from the traditional centralized generation paradigm. Historically, electricity generation was dominated by large, centralized power plants injecting electricity into the grid to be transmitted over long distances through high-voltage lines to distribution networks and, ultimately, to end consumers. This model is evolving with the proliferation of DERs, which are typically smaller in scale and are located closer to the point of consumption. The electrical network is becoming more complex, often involving bidirectional power flows, and posing new technical problems such as voltage regulation, management of overloads, protection coordination, and a general need for redefined control strategies [1], [2].

The expansion of DERs, initiated by rooftop solar installations and accelerated by the decreasing costs of renewable generation and the growing demand and policy incentives for low-carbon energy, now encompasses a variety of technologies such as intelligent thermostats, heat pump water heaters, battery storage, and electric vehicle charging. This diversification enhances grid flexibility and potentially allows for optimized operation, greater control over energy use, significant cost savings, and, of course, environmental benefits [1]-[3], [5]. However, it also increases the complexity of managing multiple and diverse devices, which in addition can be utility-owned or customer-owned, and their interactions within the grid [3], [5]. On the one hand, these resources, connected to medium-to-low-voltage distribution systems, reshape traditional electricity generation by introducing controllable assets behind-the-meter, providing demand elasticity and flexible generation to enable, e.g., grid balancing functionalities [6]. On the other hand, the integration of the diverse DER technologies into existing grid infrastructures necessitates sophisticated management tools to cope with their intermittent nature and unpredictability, particularly in the case of solar PV and wind, and ensure reliable grid operation against poor observability, reverse power flows, voltage variations, and sudden overloads [3].

The rapid proliferation of DERs has transformed the Utility business, forcing it to evolve and incorporate new functions to its scope. Utilities now face the challenge of managing both utility-owned and third party-owned DERs, but also to meet regulatory mandates concerning renewable minimum requirements [7]. Utilities and distribution system operators (DSOs) need to evolve into more active roles, implementing advanced DER management systems to efficiently integrate their growing portfolio of DERs, to manage grid services, and support market operations, while ensuring grid stability and efficient operation [4], [8]. Consequently, utilities have been deploying various software solutions to interact with these grid-edge technologies (both utility- and customer-owned). Some of them, which will be discussed below, are already relatively mature, such as Virtual Power Plants (VPPs), Demand Response Management Systems (DRMS) services, or even Advanced Distribution Management Systems (ADMS). However, a nascent end-to-end solution has been forged over the last years under the name of Distributed Energy Resource Management Systems

(DERMS), which seeks to offer a comprehensive solution for monitoring, controlling, and optimizing the integration of DERs into the power grid [1]-[3], [5], [6]. Nonetheless, even the term DERMS itself is novel, and there is not yet a unique definition, nor a fixed template or a concrete and defined list of DERMS functionalities in the literature [1]. This work aims, therefore, to review these different DERMS conceptualizations, and to then provide a unified and comprehensive view of the concept of DERMS, contributing to lay the foundations for a unique solution for DER integration in the electrical industry.

1.2 IN FRONT VS. BEHIND THE METER: A BLURRED BOUNDARY

Initially, DERs were introduced to the power grid primarily to enhance grid reliability, provide ancillary services, and crucially defer investments in transmission and distribution infrastructure. Then, the early adoption and rapid increase of DER integration have been driven by technological innovations and policy incentives aimed at promoting renewable energy sources and reducing carbon emissions [1]-[3]. Over time, the role of DERs has expanded beyond these initial applications. They now play a critical role in enhancing grid capacity, providing flexibility in grid operations, and supporting the integration of intermittent renewable energy sources [1], [6].

Traditionally, DERs and their management solutions have been divided into two main categories or hierarchies: centralized or Front-of-the-Meter (FTM) DERs; and decentralized or Behind-the-Meter (BTM) [1]-[4], [6], [8]. The latter are located on the consumer's side of the power meter and were born to reduce the consumer's energy costs, obtain electrical self-sufficiency, and enhance energy security. Examples of BTM DERs include rooftop solar panels, home battery energy storage systems (BESSs), heat pump water heaters, and EVs. In contrast, FTM DERs are situated on the utility's side of the meters and are integrated into the broader distribution grid infrastructure to provide capacity, and ancillary services to the grid as a whole. Among the FTM DERs, one could include medium-to-large-scale solar farms, wind parks, grid-scale storage systems, or diesel generators, i.e., the so-called Distributed Generation (DG) [1]-[4], [6], [8].

However, the distinction between BTM and FTM DERs is becoming increasingly blurred due to several factors, namely, advances in DER management technologies, evolving regulatory frameworks, and the growing capabilities of DERs to provide multiple services to both consumers and the grid. Through aggregation, and with the necessary regulatory measures, small-scale BTM resources like residential solar and battery systems can now participate in Demand Response (DR) programs, provide grid services such as frequency regulation and voltage support through a VPP, and even participate in wholesale or local electricity markets. Similarly, FTM resources are increasingly being designed with capabilities to support localized energy needs and provide services directly to consumers [1]-[3], [6].

The emergence of Distributed Energy Resource Management Systems (DERMS) has been—and will be—crucial in closing the gap between BTM and FTM DERs to an even greater extend. DERMS software solutions enable real-time monitoring, control, and optimization of DERs across the grid. They facilitate the aggregation of BTM resources so that can be operated similarly to and together with FTM resources, providing grid balancing services and participating in energy markets—for example, a DERMS could manage the collective net output of residential solar panels and the state-of-charge (SoC) of batteries and EVs (BTM), and coordinate their operation with larger, grid-scale solar and wind farms (FTM) to reduce peak demand, optimize energy production and maintain grid stability. Therefore, this integration would allow for a more seamless and efficient operation of the grid, leveraging the full potential of both BTM and FTM resources and maximizing the economic and environmental benefits of DERs [1]-[2], [4], [6], [8].

Due to the nascency of DERMS, the different vendors and competitors that are offering this type of services are still establishing themselves in the market [5]. However, there seems to be a common understanding—to be discussed in following sections—of dividing DER management systems into centralized (for FTM DERs) and decentralized or aggregator DERMS (intended to collectively manage BTM DERs) [1]-[4], [6]-[8]. Despite this, there seems to be a tactful agreement in the literature to suggest the need—or at least the desirability for optimal grid operation—of integrating both levels of DERMS into a single solution providing a comprehensive tool for DER integration—from small-scale residential DERs to larger ones connected to the utility side of the distribution network. As this boundary continues to fade, the power grid will keep becoming more resilient (i.e., with greater capacity), flexible, and capable of integrating higher levels of renewable energy and distributed resources [1]-[3], [6], [8]-[11].

1.3 DEFINITION OF THE WORK

This section will seek to justify and explore the basis and structure of this work. It will outline the primary objectives to be achieved, as well as the methodology to be followed for conducting the research on the state of the art of DER management systems and developing the proposed DERMS functional architecture.

1.3.1 JUSTIFICATION & OBJECTIVES

The increasing penetration of Distributed Energy Resources (DERs) is driving a fundamental transformation in the electricity grid, necessitating the development of new management software solutions to ensure reliability, efficient operation, and sustainability of the network. Traditional centralized generation and passive distribution networks have been displaced by the diverse and dispersed nature of modern DERs. The proliferation of DERs such as solar PV, wind turbines, battery energy storage systems (BESSs), EVs, diesel generators, and other renewable and non-renewable sources, introduces complexities in grid management that traditional tools cannot handle effectively [1]-[4].

The emergence of Distributed Energy Resource Management Systems (DERMS) represents a promising solution to these challenges. DERMS enable advance network planning, real-time monitoring, control, and optimal DER integration in the power grid [1]-[3], [5], [6]. However, despite the unquestionable potential of DERMS, there is a lack of agreement on the definition and scope of application, standardized functionalities and use cases, and comprehensive architectures for these systems; instead, an extensive and very diverse list of tools, with various objectives, targeting very different stakeholders, can be seen in the literature and even offered in the marketplace [1], [2].

This work, therefore, aims to address this gap by conducting a thorough review of DERs and their management solutions. Particularly concerning Distributed Energy Resource Management Systems, the different definitions traditionally given to a DERMS will be explored, together with the various levels within the hierarchy of DERMS solutions, potential stakeholders identified in the literature, functional specification and most common applications in the electrical industry, relevant standards, information models and communication protocols between devices, DER control architectures, as well as most significant European regulators and legislative proposals.

Once this analysis of the state of the art is conducted, the aim is to propose a unique definition and clarify the scope of DERMS solutions, as well as to describe a comprehensive functional architecture—covering DERMS functionalities, applications, and interfacing with other systems—offering a unified and efficient solution for the integration of DERs into the distribution grid. Finally, another key point will be to specify how this DERMS architecture can be modularized and adapted to allow for its deployment onto different clients' platforms, as well as to validate it with references from the industry and with proofs of successful partial implementations in various projects.

1.3.2 METHODOLOGY

As mentioned, the overall purpose of the project is to achieve a comprehensive view of how DERMS are understood in the literature and by the different vendors seeking to offer DERMS solutions, to then propose a unified definition and a functional architecture capable of serving as an end-to-end solution for DER integration in the power grid. To achieve this, first, a theoretical framework will be drawn in Chapter 2 about DERs and the preceding solutions for their optimal management and integration into the electricity grid—ADMS, DRMS, VPPs, etc.—and how they compare and how they can fit with DERMS. Then, an extensive literature review among academic publications, reports from the industry, relevant standards, and regulatory documents, will be conducted in Chapter 3 in order to clarify the issues below:

1) *Definition and Scope of DERMS*: the intention will be to provide a clear and concrete definition of DERMS, exploring the various conceptualizations and terminologies used in the literature and narrowing the scope of this emerging solution.
2) *DERMS Hierarchy*: the different levels of hierarchy among DERMS solutions will be investigated, together with some of its main real-world applications that illustrate their benefits to grid management.
3) *Stakeholders*: a crucial aspect will be to identify the main stakeholders and interested parties that could play a part in the development and adoption of DERMS solutions—TSOs and DSOs, utilities, market participants and electricity market operators, microgrid operators, DER owners and aggregators, prosumers, etc.
4) *Functional Specification*: the essential functions and services that a DERMS should encompass will be described—planning, monitoring, control, optimization, DER aggregation, participation in electricity markets, etc.—together with the different approaches identified in the literature to organize these functionalities.
5) *Standard Communication Protocols and Information Models*: analyze the communication protocols and information models, both at DER-group level interface and at the device level, typically employed in DERMS solutions.
6) *DER Control Strategies and Architectures*: control strategies—such as centralized, decentralized, distributed, etc.—most commonly used to manage DERs, as well as two comprehensive architectures—federated (FAST-DERMS) and hierarchical—for DER control already tested in real-world applications.
7) *European Regulatory Organizations and Legislative Proposals*: the main competent European regulatory bodies in this field will be review, to then analyze the main applicable regulatory framework at European level. The aim is to understand the policy landscape and compliance requirements for DERMS implementation.

Once this compilation of the state of the art has been completed, Chapter 4 will narrow down the concept of DERMS and its scope of application and develop a comprehensive functional architecture for DERMS that can address the needs of all stakeholders and ensure optimal end-to-end DER integration. The following aspects will be covered:

1) *Unified Definition and Scope of Application*: the different definitions, terminologies, and DERMS applications identified in the literature will be merged to achieve a clear and unified concept of what shall be understood as a DERMS.
2) *Functional Design*: the findings from the literature review will be synthesized to describe an end-to-end functional architecture that can then be adapted to the majority of use cases and stakeholders.
3) *DERMS 'Declinations'*: this section will delve into the particularization of the above general architecture to the different clients—aggregators, DSOs in contexts of unbundling, vertically integrated utilities, etc.—and use cases.
4) *Modularization Strategy*: the previous analysis will be utilized to find the opening points of the proposed DERMS solution, and to determine how the different functions and services can be modularized and decoupled so that the DERMS solution can be implemented onto every client, integrating with or replacing its own software.

Chapter 5 will finally address the validation of the proposed architecture, along with its different declinations, and its modularization strategy. First, a vendor assessment of DERMS service providers will be presented to justify Minsait's relevance in the international DERMS landscape, company with which the author of this work has had the opportunity to collaborate during the development of this proposal of DERMS solution. Then, it will provide an overview of several projects conducted by Minsait that intend to illustrate the feasibility of a single, modular and adaptable DERMS solution targeting the needs of multiple stakeholders in a variety of applications.

Finally, a questionnaire assessing the interest of the electricity industry in some of the main issues discussed here will be distributed among members of TSO/DSOs, aggregators, and the academic community. Their responses will serve to justify the approach followed to develop the DERMS architecture and validate the conclusions of the project—presented in Chapter 6 along with some suggestions leading to future works. This methodology will reinforce the final product of this work, which aims at contributing significantly to the understanding and theoretical development of DERMS solutions within the electricity industry, providing a solid foundation for future research and real-world implementations.

Chapter 2. THEORETICAL FRAMEWORK

This chapter aims to provide a comprehensive definition of Distributed Energy Resources (DERs), and examine the main challenges and opportunities associated with their increasing penetration into the electricity grid. Additionally, it will explore some of the most relevant existing solutions for DER optimal integration and management and compare them and discuss how they can integrate or coexist with Distributed Energy Resource Management Systems (DERMS).

2.1 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 [12]. To provide a sample of this wide variety of definitions, some of those offered from across the industry are included below, together with some of the main challenges and opportunities brought by the increasing penetration of DERs into the electricity grid.

2.1.1 DEFINING DERS

The Department of Energy (DOE) of the United States of America describes DER as "a range of smaller-scale and modular devices designed to provide electricity, and sometimes also thermal energy, in locations close to consumers" [13]. 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 includes plug-in electric vehicles as part of distributed storage [14]. The California Public Utilities Code understands that the term DER should encompass "distributed renewable generation resources, energy efficiency, energy storage, electric vehicles, and demand response technologies" [15]; whilst the New York Public Service Commission agrees to include Energy Efficiency (EE), Demand Response (DR), and Distributed Generation (DG) [16].

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. A DER can include, but is not limited to, energy efficiency, distributed generation, demand response, microgrids, energy storage, energy management systems, and electric vehicles" [17]. 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”, and states that “as the electricity grid continues to modernize, DER such as storage and advanced renewable technologies can help facilitate the transition to a smarter grid" [18]. This variety of descriptions of a DER have been used by the National Association of Regulatory Utility Commissioners (NARUC) to establish the basic characteristics that a certain technology must comply with to be defined as a DER [12]:

1) It is connected to the distribution grid and not the bulk transmission system.
2) It must be relatively small, certainly under 10MW.
3) Generally, it will not be individually scheduled by, nor reported to an RTO and/or ISO. This would be done on an aggregated manner by a 3rd-party or the utility itself.
4) Responsiveness and dispatchability, among other services, could be also associated to a DER, but are mainly related to the specific technology.

Therefore, and taking all the above into consideration, a unified definition of DER is provided by NARUC: "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” [12].

This is coherent with the description included in the IEEE Standard 1547-2018 (IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with

Associated Electric Power Systems Interfaces) and presented in [19], in which a DER is "a source of electric power that is not directly connected to bulk power systems, including distributed generation (DG), behind-the-meter (BTM) generation, energy storage facilities, DER aggregation, microgrids, co-generation and backup generation". NARUC's definition brings together, under the umbrella of DER, photovoltaic solar, wind, and combined heat and power (CHP), energy storage, demand response, electric vehicles, microgrids, and energy efficiency", while IEEE ([19]) and other sources ([3], [4], [6]) emphasize the inclusion of other renewable and non-renewable distributed generation, such as 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 [12]-[19], as well as the concepts and technologies mentioned in [3], [4], [6], and other consulted sources: *DERs can be both front-of-the-meter (FTM) and behind-the-meter (BTM) small- and medium-scale assets*[1]*—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 distributed generation—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 of this work and shall be used to better understand their management solutions. The following technologies are encompassed under this perspective of DER [3], [12]:

[1] In the remainder, 'large-scale DERs' is occasionally used to refer to those FTM resources connected to the MV network at the utility-side of the meter, only in order to differentiate them from small-scale DERs connected BTM. However, this shall not be interpreted as contradictory to this definition or to the fact that DERs should be smaller in scale than traditional power generation plants.

1) *Solar Photovoltaic (PV) Systems*: small-scale solar PV systems installed on rooftops of homes or commercial and industrial buildings (residential PV) or ground mounted. These systems can be intended for self-consumption with the possibility of feeding their surplus into the grid, or they can be exclusively aimed at energy generation for sale in the electricity market. Recent technological advancements and the decreasing costs of this technology have made PV systems the fastest-growing DER.
2) *Wind Energy Systems & Small Hydro Power Plants*: distributed Wind Energy Conversion Systems (WECS) and small-scale hydro plants designed for localized electricity production. Typically installed on residential, agricultural, commercial, and industrial sites, these systems can vary in size and are typically connected directly to the distribution grid (although, particularly wind, could be also linked to the customer's side of the meter), and contribute to increasing the share of renewables in the energy mix.
3) *Combined Heat and Power (CHP)*: CHP systems provide both electric power and useful thermal energy from a single fuel source. They recover waste heat from electricity generation and use it for heating, cooling, as domestic hot water, or for industrial processes. These systems can use various fuels, including natural gas (most common nowadays), biomass, coal, and process wastes, achieving efficiencies over 80%.
4) *Diesel Generators*: conventional fuel-based, typically small-scale, generators used to provide backup power in the event of grid outages, as well as to ensure power supply in remote locations where the distribution network is weaker. They fall, therefore, within the category of non-renewable distributed generation together with CHP systems.
5) *Energy Storage Systems (ESS)*: ESS add stability, control, and reliability to the electric grid. They can store energy generated from intermittent sources like wind and solar, supplying power during low-generation periods and reducing curtailment during off-peak times when energy production is high. Technological improvements and cost reductions are starting to make storage systems competitive. Among these systems, pumped hydro energy storage, spinning reserves, compressed air storage, flywheel, superconducting magnetic energy storage, battery energy storage systems, supercapacitors, and hydrogen fuel cells may be included.

6) *Electric Vehicles (EVs) & Charging Stations*: EVs can respond to price or demand response signals, adjusting their charging times and even supplying power back to the grid. In this manner, they can act as mobile storage devices. This bidirectional flow capability provides additional grid services and backup power during outages.
7) *Microgrids*: the DOE defines a microgrid as a group of interconnected loads and distributed energy resources (DERs) that can act as a single controllable entity to provide services to the grid—which is why it is included under this designation of DER. Microgrids can operate both in grid-connected mode and island mode, allowing them to disconnect from the main grid and function independently. Microgrids optimize and control loads and DERs at specific sites, providing resilience, facilitating faster system response and recovery, and ensuring continuous power supply during outages [5].
8) *Demand Response (DR)*: DR involves various technologies—such as EVs and smart appliances—that allow utilities and grid operators to balance supply and demand in real time or near real time by incentivizing consumers—with price signals or incentive payments—to reduce or shift their energy usage during peak periods. DR can lower electricity costs and reduce retail rates while enhancing grid reliability and efficiency.
9) *Controllable Loads & Energy Efficiency (EE) Programs*: controllable loads are mainly smart appliances—such as smart thermostats and smart plugs—that can be controlled remotely to actively manage electricity consumption and adjust to grid needs and electricity prices. They can be lowered or completely switched on/off without significant discomfort to users. EE refers to initiatives aimed at reducing energy consumption through efficient technologies and practices, normally instantiated from the utility side.

2.1.2 CHALLENGES OF DER PENETRATION

Once the definition of Distributed Energy Resources, as well as the technologies that fall within this terminology, is clarified, it is crucial to understand the main challenges posed by the increasing integration of these resources into the distribution grid. The complexities caused by DERs span economic, technological, regulatory, and operational domains, and must be addressed to be able to acknowledge the need of a comprehensive management solution for DER integration.

1) *Technological and Physical Issues*

The integration of non-dispatchable, variable, and intermittent DERs, especially customer-sited renewable generation, presents substantial technological and physical challenges. The effect of these resources is often localized at the feeder level where the monitoring and communication network is less robust, complicating grid management due to the lack of control and visibility [12]. Moreover, the unpredictability of renewable DERs—mainly wind and PV systems—complicates generation and net demand forecasting as the power supplied by these resources can fluctuate dramatically [12]. This circumstance challenges traditional network configuration, service restoration, and phase balancing [19].

The increasing DER penetration can alter the traditional voltage profiles of distribution grids and involve grid stability issues. Sudden changes in generation output from DERs can lead to bidirectional power flows, potentially causing great voltage fluctuations and affecting power quality [3], [12]. High volumes of Behind-the-Meter (BTM) DERs can trigger ohmic losses and result in operational constraint violations—such as feeder congestion (power bottlenecks) and overvoltages—due to their uncoordinated injection of power [19].

2) *Operational Planning*

The operational planning and management of the grid become increasingly complex with high DER penetration. The variable and intermittent nature of many DERs, particularly wind and solar, makes accurate operational planning difficult, potentially leading to mismatches between supply and demand [2], [6]. Additionally, this unpredictability in system planning and operation, driven by the volatility of renewable generation, impacts day-ahead load forecasts, ramping capacity needs, and system unit commitment [4].

3) *Protection and Control Systems*

Traditional protection systems, designed for unidirectional power flow, may malfunction or be unable to coordinate correctly due to the new dynamics introduced by DERs in the distribution grid [2], [3], [6]. There is also a need for faster protection schemes to clear faults before voltage fluctuations cause the disconnection of resources, and for more flexible control systems capable of managing bidirectional flows without triggering inappropriately [4]. Additionally, connecting DERs can increase short circuit levels and fault severity, posing risks to grid stability [3].

4) Monitoring and Data Management

The rise of BTM DERs complicates data collection from the distribution grid, challenging traditional monitoring systems which are designed for single-way power flow—likewise protection devices. The complexity is exacerbated when BTM DERs compensate entirely for local consumption, leading to potential misinterpretations in the monitoring systems such as misreporting nodal outages or meter tampering. Conventional methods of data collection and monitoring are becoming obsolete in the context of DER management [19].

5) Regulatory and Policy Issues

Traditional regulatory frameworks and business models may not be well-suited to accommodate the unique characteristics and requirements of DERs—for example, many DERs are promoted by third parties and not utilities, leading to visibility and control issues, and complex business model alignment between utilities and third-party DER providers [1]. The integration of DERs into the grid necessitates the development of new strategies for grid management and planning. In this regard, recent initiatives like FERC Order No. 2222 in the US supporting DER participation in wholesale markets [1], [3], [5], [10], or the EU DSO Entity and ENTSO-E's Proposal for a Network Code on Demand Response ([20]) try to define a regulatory framework for DER integration into the electricity grid.

6) Economic Complexities

One of the primary economic challenges is the potential for revenue erosion and cost shifting. As DER penetration increases, utilities may struggle to recover sunk costs necessary for providing adequate service in the long term. Additionally, increased DER adoption can lead to cross-subsidies where non-DER customers subsidize DER customers, causing inequities and inefficiencies in the rate structure [12].

7) Investment Requirements

Significant investments are needed to enhance grid infrastructure and implement advanced monitoring and control systems to manage the increased complexity and ensure the reliable and efficient operation of a network with high DER penetration [2], [6]. Utilities must invest in new equipment and capital-intensive solutions to improve the controllability of the grid, especially downstream of distribution feeders, enabling proactive responses to outages through network topology reconfigurations and coordination with BTM DERs [19].

2.1.3 OPPORTUNITIES & POTENTIAL BENEFITS FOR THE ELECTRICITY GRID

As presented above, the increasing penetration of DERs into the distribution grid presents a multifaceted set of challenges including technological and operational complexities, new planning and monitoring requirements, regulatory issues, and economic impacts. However, when correctly managed, the growing adoption of DERs offers interesting opportunities for optimizing the electricity grid and obtaining significant economic savings for both operators and users, generators and consumers. The following are some of the potential benefits derived from an adequate integration of DERs.

1) Operational Benefits – Enhanced Grid Capacity and Flexibility

Grid operation and control could be greatly enhanced by DERs. These resources, with their fast dynamic response capabilities—e.g., through DR instances using BTM DERs, or employing larger-scale BESS or diesel generators connected to the distribution grid—can actively participate in frequency regulation, ensuring that the grid remains stable in the event of load imbalances causing frequency or voltage excursions [19]. In this regard, DERs can provide generation reserve capacity and ramping support to mitigate net load variability and severe ramping events, which is crucial for maintaining grid stability when dealing with the unpredictability of intermittent renewable sources like wind and solar [19].

Local control schemes like Volt/VAR and Volt/WATT curves in smart inverters and coordinated control systems requiring a communication infrastructure, enable both BTM and FTM PV solar installations to offer voltage support, enhancing voltage stability in both low and medium voltage networks [12], [19]. Finally, consumers can participate in demand-side flexibility programs by responding to time-varying electricity prices, reducing non-essential loads and shifting consumption to off-peak times. Additionally, controllable loads & EE programs allow for an active management of electricity consumption from the utility, adjusting it to the system needs and to electricity prices. This controllability and flexibility allow for the provision of grid services, reduce peak demand, minimize system losses, and enhance overall grid efficiency [19].

2) Enhanced System Resilience and Three-Phase Load Balancing

High penetration of DERs has the potential to significantly enhance system resilience. By managing demand and grid-forming DERs, such as BESS and distributed (diesel) microgenerators, these resources can expedite restoration processes after faults, support local voltage stability, and enable autonomous microgrid reconfiguration, which are all critical for maintaining grid reliability against outages and other disruptions [2], [6], [12], [19]. Moreover, BTM DERs help achieve a balanced distribution system by ensuring loads and generations are evenly distributed among the three phases. This balancing reduces power quality issues, prevents equipment damage—extending its lifespan and, therefore, reducing overall system costs—and avoids the accidental tripping of protection devices [19].

3) Economic and Environmental Benefits

DERs contribute significantly to economic and environmental goals. One of the major enablers for cost savings is the reduction in peak demand, e.g., through demand-side flexibility programs and overall energy efficiency. Thus, DERs can be utilized as non-wire solutions to defer or even avoid the need for costly infrastructure upgrades in low and medium voltage distribution networks [12], [19]. To this adds the flexibility offered by DERs in power generation and consumption, which allows for the optimization of control decisions to eliminate energy waste and improve efficiency. This leads to lower energy bills for consumers and reduces carbon footprints by maximizing the use of renewable generation capabilities [6].

In this regard, the increased adoption of renewable DERs contributes to reduce green-house-gases emissions, supporting public policy objectives on renewable energy and sustainability—such as the Paris Agreement or the 2030 Agenda for Sustainable Development (see Appendix A. Sustainable Development Goals) [12].

4) Automation and Grid Modernization

Grid-edge DERs utilize advanced communication and control techniques to quickly adjust generation or consumption to meet customer-set targets. These advanced sensing and intelligent control capabilities enable DERs to adapt to environmental changes and self-adjust, which is essential for the automated operation of smart homes and buildings [6].

Furthermore, the increasing penetration of DERs has accelerated the development and implementation of Advanced Distribution Management Systems (ADMS) and DER Management Systems (DERMS), which play a crucial role in modernizing the grid [12]. These systems improve communication, intelligence, and visibility within the distribution network, allowing better management of real-time conditions and to integrate DERs more effectively. With the help of these brand-new solutions, utilities can optimally dispatch distributed resources, better forecast supply and demand, and more easily support islanding functionalities, which are essential for the resilience of modern distribution grids [12].

2.2 PRECEDENT SOLUTIONS FOR DER INTEGRATION

It can be inferred from previous sections that, 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 in the distribution network. Their main characteristics and functionalities will be analyzed, in order to specify their roles within the power system, clarify potential overlaps, and highlight their fundamental differences with respect to the DERMS solution.

2.2.1 SMART INVERTER (SI)

Although not a comprehensive management solution for DERs, smart inverters support the integration of renewable distributed resource into the electricity grid. A SI is an advanced power electronics device designed to convert direct current (DC) at the output of some distributed energy resources—such as solar PV and BESS—into alternating current (AC) compatible with the electricity grid. Unlike traditional inverters, smart inverters are equipped with additional software that provides enhanced functionalities and facilitates the overall integration of renewable energy sources into the power system [21]. Some of these additional capabilities are listed below:

1) *Voltage Regulation & Power Flow Balancing*: smart inverters can actively regulate the voltage output of solar PV systems—for example, they can address voltage drops caused by clouds before exporting electricity to the grid, thereby providing voltage support and helping maintain grid stability [12]. Additionally, SIs enable generation or storage resources to autonomously manage and balance electricity flow, enhancing the grid's ability to handle fluctuations and maintain stability. These services allow for lowering peak power flows and help defer or avoid additional distribution upgrades to increase the network capacity [12].
2) *Adaptability:* SIs can adjust to changing grid conditions and operational requirements. They are designed to be control-adaptive, frequency-adaptive, and impedance-adaptive, which means they can modify their control parameters in response to varying grid disturbances. They can also adapt their operation modes to maintain stability and performance, including fault tolerance to continue operating safely under outage conditions. This flexibility allows them to provide reliable service in a wide range of scenarios, from stable grid conditions to dynamic and uncertain environments [21].
3) *Autonomous Management:* smart inverters can operate independently without the need for constant external control. Autonomous SIs can make decisions about their operation modes, such as switching between grid-connected and islanded states and can perform functions like dynamic grid forming and load sharing. This capability is particularly valuable for applications like microgrids, where inverters must manage local energy

resources with limited or no communication infrastructure with the main grid, while ensuring reliable and continuous power supply [21].

4) *Self-Awareness:* it involves the device's ability to monitor its own health and operational status. This feature enhances the operational reliability of the inverter by continually assessing its internal state, which includes diagnostics for detecting faults, isolating issues, and predicting the remaining lifespan of critical components. Thus, a SI can take or instantiate preemptive actions to perform maintenance and avoid potential system failures [21].
5) *Enhanced Integration:* SIs' plug-and-play functionality allows for seamless integration into existing systems without the need for extensive configuration. This feature ensures that SIs can be added to a network and start operating immediately and in an automated fashion, which simplifies installation and accelerates scalability. By supporting standardized communication protocols and unified control interfaces, plug-and-play smart inverters enable interoperability between different devices and systems [21]. In this regard, SI can work collaboratively with other inverters and grid components, sharing information and coordinating actions to achieve common objectives, thus enhancing overall system stability and performance—e.g., cooperative control allows multiple inverters to manage voltage regulation, reactive power compensation, and fault recovery. This distributed approach reduces the burden on central control systems and improves the resilience and efficiency of the power network [21]. These capabilities are crucial for facilitating the widespread adoption of DERs and ensuring that they can interact with the broader electrical grid. Indeed, the integration of SIs in new solar PV installations and other distributed resources is increasingly becoming a standard practice, as recommended by multiple regulatory bodies such as the California Public Utilities Commission (PUC) [12].
6) *Economic Compensation:* the services provided by smart inverters and the cost savings achieved can be registered and valued through appropriate compensation methodologies, particularly in areas with high solar PV adoption. This ensures that the services provided by smart inverters are recognized and rewarded, encouraging further adoption [12].

2.2.2 ADVANCED METERING INFRASTRUCTURE (AMI)

Advanced Metering Infrastructure (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, distribution companies, and utilities [12], [22]. Unlike traditional meters, which provided only monthly data, advanced meters can provide up to 8,760 data points per year if measured hourly, significantly enhancing data availability for both utilities and customers [12]. AMI encompasses the following components:

1) Smart Meters

These advanced meters measure electrical parameters such as current, voltage, and frequency, providing detailed data beyond what traditional meters offer. Smart meters consist of various hardware components, including microprocessors, memory units, real-time clocks, and communication modules—such as ZigBee, Wi-Fi, or GPS/GPRS. They are typically installed at customer premises and can send real-time consumption data to the utility and receive commands or pricing signals [22], [23].

2) Meter Data Management System (MDMS)

The MDMS manages and utilizes the data collected from smart meters. Its functions include automating data collection from various technologies, evaluating data quality, generating estimates to fill data gaps, and delivering data to utility billing systems. The MDMS is typically located at the utility's control center and ensures accurate and reliable data handling, essential for utility operations and customer billing [22], [23].

3) Communication Network

This component ensures the bidirectional exchange of information between the utility and end-users. It involves a network that connects smart meters to local and backbone concentrators, which then communicate with the control center [22]. This communication network can be divided into three layers: (i) a Home Area Network (HAN) connecting smart meters to smart appliances, in-home displays, and other smart devices within a home, typically using wired or wireless protocols; (ii) a Neighborhood Area Network (NAN), which transfers real-time data between neighboring smart meters, often using ZigBee due to its high speed and low cost; and (iii) a Wide Area Network (WAN) supporting communication with remote servers and using technologies such as GSM, GPRS, 3G, and WiMAX [23]. Lower-layer networks (HAN and NAN), typically use a meshed topology to gather consumption data from customers and transmit it to the upper network directly or via local concentrators [22].

These three components work together to enable utilities to collect real-time consumption data, which helps in improving energy management, operational efficiency, and customer engagement in energy-saving activities. AMI is critical for DER integration and in modern power systems as it supports the implementation of smart grids by providing several key functionalities [23], some of which are listed below [12]:

1) *Granular Data Collection and Transmission:* smart meters collect detailed consumption and generation data, including voltage levels and BTM DER outputs like rooftop solar. This data helps utilities and regulators understand and manage the impact of DERs on the grid. Additionally, AMI supports two-way communication, allowing utilities to send and receive real-time information, such as pricing signals and DR instances.
2) *Enhanced Customer Engagement:* building on the previous, customers can access real-time usage data, helping them understand their energy consumption patterns and the financial impacts of DER investments or of shifting their energy usage to periods when electricity is cheaper. Furthermore, advanced meters often include a second radio for HANs, facilitating communication with other in-home smart appliances—e.g., thermostats, plugs, in-home displays, etc.
3) *Support for Advanced Rate Designs and Accurate DER Compensation:* the granular data from AMI makes it feasible to implement real-time pricing and advanced rate designs like Time-of-Use (ToU) or Critical Peak Pricing (CPP), encouraging customers to shift consumption to off-peak periods. In the same manner, by collecting detailed generation

data from BTM DERs, advanced meters enable accurate compensation for DER contributions, supporting fair and transparent DER compensation methodologies and, therefore, stimulating DER integration.

4) *Policy Development:* in the same regard, regulators can also use detailed data to better understand customer responses to different rate designs and optimize policies to promote efficient energy use, and to develop more accurate DER policies and compensation schemes, ensuring they are effective and sustainable, and promoting DER integration.
5) *Improved Grid Management:* real-time data helps utilities manage voltage levels and distribution loads more effectively, reducing the risk of overvoltages and feeder overloads, particularly during periods of low demand and high renewable production. This same data can also improve the detection, isolation, and fast resolution of faults in the grid, contributing to a more reliable grid and a greater continuity of supply.

In summary, although again not a management solution for DERs, AMI provides the essential data and communication infrastructure needed to facilitate and optimize the integration of DERs into the distribution grid. Proceeding with the first of the management solutions for DERs, it should be noted that this particular system is likely the least common and utilized within the industry, and that it does not typically serve as a standalone implementation.

2.2.3 MICROGRID CONTROLLER (MC)

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 [24].

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—while complying with grid codes. MCs utilize rule-based and optimal dispatch algorithms to maximize renewable energy use and economic profitability, thus enhancing grid-edge resilience, and allowing for economic benefits and a more sustainable power system. MCs can manage both islanded and grid-connected modes, providing critical load support when an outage forces the disconnection from the main grid, and optimizing energy use—generation and consumption—under normal operations [5], [24].

Although still an emerging field, microgrids are increasingly found in a wide range of applications, from commercial buildings and industrial facilities to military bases, enabling the coordination of different DERs and obtaining significant cost reductions and ensuring continuous operation during outages [24]. The following are some of the main services provided by MCs for the integration of DERs into the distribution network [24]:

1) *Resilience*: MCs enable microgrids to operate independently in the event of a fault isolating it from the main grid, ensuring a reliable continuity of supply power supply to critical loads. Moreover, they foster a distributed architecture for grid operation and control, without relying on a complex communication network and a central operator managing the primary, secondary and tertiary control functions [25].
2) *Economic Benefits*: MCs optimize the use of local DERs—prioritizing the least expensive resources—for power injection into the grid, and the provision of local and balancing services, minimizing overall energy costs.
3) *Interconnection Management*: they can handle interconnection agreements with the main grid and manage voltage at the point of common coupling (PCC), ensuring stable operation and compliance with power system requirements.
4) *Sustainability*: by promoting the integration of renewable sources and storage, MCs contribute to reducing carbon emissions and enhancing the sustainability of the system.

Therefore, the localized control provided by MCs focuses on optimizing and controlling loads and DERs at specific sites—or closely connected sites—ensuring resilience and continuous power supply during grid disturbances. In comparison, the Distributed Energy Resource Management Systems that constitute the scope of this work provide a centralized platform to coordinate and optimize DERs across a broader area [5].

While microgrid controllers emphasize local management and site-specific optimization, a DERMS coordinates these localized sites with the larger grid, ensuring cohesive—and coherent—operation and delivering system-wide benefits. A DERMS could integrate multiple microgrids, which would serve as DER aggregators providing services to the grid. DERMS leverages the resilience and localized control offered by microgrid controllers to enhance the overall performance of the distribution network, achieving a balance between the localized microgrid benefits and broader grid optimization [5].

2.2.4 VIRTUAL POWER PLANT (VPP)

A Virtual Power Plant (VPP) is an aggregation of various distributed energy resources, which function collectively as a single dispatchable entity in power system operations and electricity wholesale markets. The main aim of a VPP is to coordinate diverse distributed generating units, storage systems, and flexible 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 [26]-[28].

VPPs use artificial intelligence and machine learning to dynamically combine flexibility from a large array of distributed resources. 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 [27]. These resources can be categorized into:

1) *Energy Production Units*

This includes various distributed generation units such as Combined Heat and Power (CHP) plants, biomass and biogas units, small power plants or microgenerators (gas turbines, diesels), small hydro plants, wind turbines, and solar PV [26]. These technologies can be either (i) dispatchable—such as conventional power plants (gas turbines, diesel generators, and biogas-based generators)—if they can be turned on or off as required to meet demand, or (ii) intermittent generating units. These are typically renewable energy sources like wind and solar, which have variable outputs depending on weather conditions. Their intermittent nature requires backup from dispatchable units or ESS to ensure a stable power supply [27].

Additionally, power generation units can be further divided into (i) Domestic Distributed Generators (DDGs), when they consist of small units serving individual consumers, possibly with surplus power injected into the grid; and (ii) Public Distributed Generators (PDGs): larger units primarily intended for power injection [26].

2) Energy Storage Units

These systems help balance supply and demand by storing excess energy for later use. Types include pumped hydro energy storage, compressed air storage, flywheel, superconducting magnetic energy storage, battery energy storage systems, supercapacitors, and hydrogen fuel cells. Even electric vehicles' batteries can also act as mobile storage units within a VPP [26], [27].

3) Flexible and Controllable Loads

Consumer loads that can adjust their power consumption—via demand-side management or demand response programs—based on grid needs or price signals. They help in balancing supply and demand and ensuring grid stability by shifting energy usage patterns in response to incentives (DR) or by direct intervention of the utility without excessively affecting the end-user (DSM) [27].

4) Information Communication Technology (ICT)

Essential for the coordination and control of the VPP, ICT involves communication systems used in Energy Management Systems (EMS), Supervisory Control and Data Acquisition (SCADA), and Distribution Dispatching Centers (DCC) [26].

Furthermore, concerning their geographical boundaries and main objectives within the power system, two main types of VPPs can be distinguished. A Technical VPP (TVPP) focuses on the technical aspects of integrating DERs into the grid within a certain area. They consider real-time local network conditions and operating characteristics, managing the impact of DER outputs, ensuring uninterrupted monitoring, fault detection, and localization. TVPPs enhance visibility and control of DER units, optimizing their contribution to the local system and providing ancillary services to DSOs and/or TSOs [26], [27].

On the other hand, Commercial VPPs (CVPPs) aggregate DERs without necessarily being geographically constrained. A CVPP focuses on optimizing and scheduling the aggregated DERs to participate in electricity markets, enabling DER units within the VPP to balance their trading portfolios efficiently, and minimizing financial risks through aggregation. CVPPs do not account for local network conditions, instead aiming to maximize market value by predicting production and consumption, forming bids or offers, scheduling daily operations [26], [27]. Finally, with the intention of correctly understanding the term VPP, it has been deemed appropriate to offer a brief comparison with other somewhat similar systems in order to clearly distinguish it and avoid possible confusions in the remainder.

First, both VPPs and the previously described microgrids allow for the integration of renewable and non-renewable DG, energy storage, and controllable loads, but they differ in several key aspects. Crucially, microgrids are geographically limited and focus on self-management, with components connected through power lines; they ensure power quality and reliability within their local area. In contrast, VPPs focus on both the technical aspects and the participation of DERs in larger electricity markets. They facilitate DER aggregation and control over broader areas using technology and communication networks rather than physical proximity. VPPs are connected to the grid via an open protocol, allowing them to offer additional services like frequency regulation and peak shaving, whereas microgrids focus on local management and optimizing loads and DERs at specific sites [28].

Virtual Synchronous Machines (VSM) are based on control strategies designed to replicate the dynamic response of traditional synchronous machines, providing auxiliary services like reactive power control or emulation of rotating inertia. They focus on transient dynamics and maintaining the inertia of power electronic devices. On the contrary, VPPs concentrate on steady-state operations and business models, ensuring the coordinated operation and market participation of aggregated DERs. While VSMs emphasize control of single DG units with power electronic interfaces, VPPs focus on the efficient coordination of multiple and very diverse resources [28].

Finally, and returning to the main focus of this work, both VPPs and DERMS aim to manage and optimize DERs to provide grid services, but they differ in scope and application. VPPs provide system-wide benefits and are typically used for large-scale grid services such as demand response, frequency regulation, and peak demand management. On the other hand, DERMS can provide more localized grid services along specific feeders, sections of the grid, but also across the entire power system. DERMS can manage power flows and general network condition with greater precision, offering services such as voltage management, optimal power flow, and locational capacity relief at specific feeders and locations. This allows DERMS to address specific local grid issues while still delivering broader system-wide benefits in a similar manner to VPPs [5].

2.2.5 Demand-Side Management (DSM) & Demand Response Management Systems (DRMS)

Demand-Side Management (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 [29], [30]. DSM includes:

1) *Energy Efficiency (EE):* long-term measures aimed at reducing energy consumption through improved processes and technologies. It encompasses permanent changes to

equipment or systems—such as the replacement of fluorescent lights by LEDs—, thermal insulation of buildings, and the use of energy-efficient appliances [29], [31].

2) *Strategic Load Growth*: encourages the use of electricity during off-peak hours through technologies like thermal storage, dual fuel heating, and heat pumps [29], [31].
3) *Spinning Reserves (SRs)*: quick response measures where loads act as virtual SRs, reducing or increasing consumption based on grid frequency to maintain stability [31].
4) *Demand Response (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 [29], [31].

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 on the customer side, but also AMI, Home Energy Management Systems (HEMS), and load control devices [29]. Demand Response initiatives can be categorized into [29], [31]:

1) *Reliability-Based*: aimed at ensuring grid stability by reducing load during critical periods. Programs include:
    - Interruptible Load Programs: large consumers agree to temporarily reduce their load in exchange for lower rates or incentives.
    - Direct Load Control Programs: utilities directly manage specific appliances or equipment to reduce load during peak times without affecting the end-users.
    - Emergency Programs: consumers voluntarily reduce their usage during emergencies without the Utility incurring in penalties for non-compliance.
2) *Market-Based*: focuses on economic benefits by responding to price signals. Programs include:
    - Demand Bidding and Capacity Market Programs: consumers bid their willingness and commit to reduce load at certain times and prices, especially during peak demand periods.
    - Real-Time Pricing: consumers are incentivized to adjust their usage based on real-time electricity prices. Real-time pricing includes:

i. Time-of-Use Rates: different rates at different times of the day to incentivize off-peak usage.
ii. Critical Peak Pricing: higher rates are charged during periods of peak demand to discourage consumption.
iii. Real-Time Rate: prices vary continuously based on real-time market conditions.

Given the potential offered by demand response programs, there was a need for a management solution with which the system operator could manage all these initiatives. This is how the Demand Response Management Systems (DRMS) were born. A DRMS helps energy providers and utilities to manage DR strategies, collecting and analyzing BTM data to handle power demands, reduce energy consumption, and improve the overall system efficiency and reliability. Utilizing advanced metering and real-time monitoring technologies, DRMS allows for responsive energy management, particularly during peak demand times. It provides tools and data for analyzing and optimizing energy use, reducing the need for new network infrastructure, preventing all kind of service interruptions, and minimizing costs and environmental impact [31].

DRMS was initially created to handle a utility's day-ahead and bulk system requirements using behind-the-meter applications. However, with the transition of utilities towards real-time control and management of distributed energy resources, the capabilities of DRMS have evolved to increasingly resemble those of DERMS [5]. Both DRMS and DERMS are capable of monitoring, controlling, and dispatching DERs. However, DERMS has a superior ability to integrate real-time data and execute advanced functions such as Volt/VAR optimization, renewable energy smoothing, providing ancillary services, curtailment, and managing transactive energy exchanges. This makes DERMS more adept at offering comprehensive and dynamic DER management. Many DRMS vendors now include modules or complete DERMS solutions in their offerings, blurring the lines between the two systems. DERMS is increasingly seen as an advancement from DRMS, providing better real-time data integration and sophisticated functionalities needed for effective modern grid management [5].

2.2.6 ADVANCED DISTRIBUTION MANAGEMENT SYSTEM (ADMS)

A Distribution Management System (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 [9].

Advanced Distribution Management Systems (ADMS) combines the functionalities of traditional Distribution Management Systems (DMS) and Outage Management Systems (OMS) with the services provided by distributed energy resources to produce overall improved system responses—as an enhanced DER-ready DMS[2]. This integration makes it possible to handle the complexities arising from the widespread deployment of DERs at both the utility and customer levels, which traditional DMS and OMS systems struggle to manage [9], [32]. ADMS add levels of communication, intelligence, and visibility into the distribution grid, allowing utilities to better understand real-time conditions across their service territory [12]. Among the several functionalities commonly provided by ADMS, the following can be mentioned:

1) *Automated Fault Location, Isolation, and Service Restoration (FLISR)*: this function enhances the ability to quickly locate and isolate faults within the distribution network and restore service to unaffected areas in the shortest possible time. ADMS improves system reliability metrics like System Average Interruption Duration Index (SAIDI) and System Average Interruption Frequency Index (SAIFI) by using data from smart meters, fault indicators, and other sensors to accurately identify fault locations and coordinate service restoration [12], [32].

[2] A DER-Ready DMS enhances the capabilities of a traditional DMS by incorporating services provided by distributed energy resources (DERs) into its conventional controls and optimization processes to produce overall improved system responses [9].

2) *Volt/VAR Optimization*: ADMS power flow analysis and calculation tools allow for optimizing the voltage and reactive power in the distribution system. This improves efficiency and reduce power losses [12].
3) *Conservation Voltage Reduction (CVR)*: CVR is a volt-var control technique aimed at reducing energy consumption by lowering the voltage supplied to loads—within acceptable voltage limits—while maintaining service quality. In this regard, ADMS facilitates precise measurement and control of voltage to achieve energy savings and reduce line losses [12], [32].
4) *Demand Response:* DR involves managing end-user loads in response to utility signals—reliability- or market-based—to modify demand patterns, particularly during peak periods. ADMS supports DR by enabling two-way communication between utilities and customers, allowing for dynamic load adjustments and integration with DERs to achieve energy efficiency and reliability [32].

An Advanced Distribution Management System is designed to run power flow analysis and execute operations on the distribution network. Its primary purpose is to ensure grid safety and reliability by managing traditional grid assets and performing real-time operational tasks [5], [9], [12]. ADMS can even incorporate some DER management functionalities to optimize their integration into the distribution grid and leverage their capabilities [32].

In comparison, a Distributed Energy Resource Management System (DERMS) builds on the capabilities of ADMS. DERMS is specialized in managing both front-of-the-meter (FTM) and behind-the-meter (BTM) distributed energy resources (DERs) without necessarily involving the power system model, and often lacking grid visibility and operational context. While ADMS focuses on overall grid management, DERMS specifically addresses the complexities of integrating and optimizing DERs [5], [9], [12]. DERMS has the potential to enhance the functionality of ADMS by enabling resource dispatching, advanced forecasting of supply and demand 24 to 48h in advance, and integration with AMI, outage management, and weather systems. DERMS add capabilities for managing both utility-side and customer-side resources, supporting islanding, and microgrid operations [12].

Utilities aim to manage both DERs and traditional grid assets comprehensively. Some vendors offer DERMS as modules within ADMS—the latter determines optimal control strategies, and DERMS then executes these strategies by managing the DERs—, while others provide them as separate applications that leverage ADMS capabilities. The integration between ADMS and DERMS will depend on the specific use case and the extent to which network knowledge and analysis is required, but it could well consist of DERMS utilizing ADMS' power flow capabilities for managing DERs and providing integral grid management [5].

In conclusion, 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 optimizing the bi-directional power flows and facing the dynamic nature of the modern power system. This backdrop sets the stage for the emergence of Distributed Energy Resource Management Systems, and for their potential integration with these previous solutions. DERMS represent a significant evolution in grid management, enabling more efficient, reliable, and resilient operation of the distribution network in the face of rapidly growing DER penetration. The following section will delve into a thorough literature review of the DERMS term, examining the hierarchy of DERMS solutions, their stakeholders, functional specification, DER control strategies and architectures, enabling protocols between devices and operators, and the latest legislative proposals.

Chapter 3. DERMS – STATE OF THE ART

Distributed Energy Resource Management Systems have emerged as key tools for transitioning to modern active and dynamic distribution network, in a context of increasing DER penetration. Despite the clear potential of DERMS, it appears that there is no agreed-upon definition or standard set of features, roles, and functionalities for these systems. The literature offers a wide variety of solutions, each with different goals and aimed at different users and stakeholders. However, by delving deeper into the research, one can form a unified understanding of what a DERMS is and its fundamental characteristics. This chapter aims to review and synthesize the various definitions, functional frameworks that can be found in the literature and within the industry, common standards and protocols, and the most relevant legislative proposals for DERMS deployment and implementation.

3.1 DEFINING DERMS

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, demand response, load control, and energy efficiency programs, often aggregating their capabilities to support system-wide benefits (see Figure 1 below) [1]-[4], [9], [12].

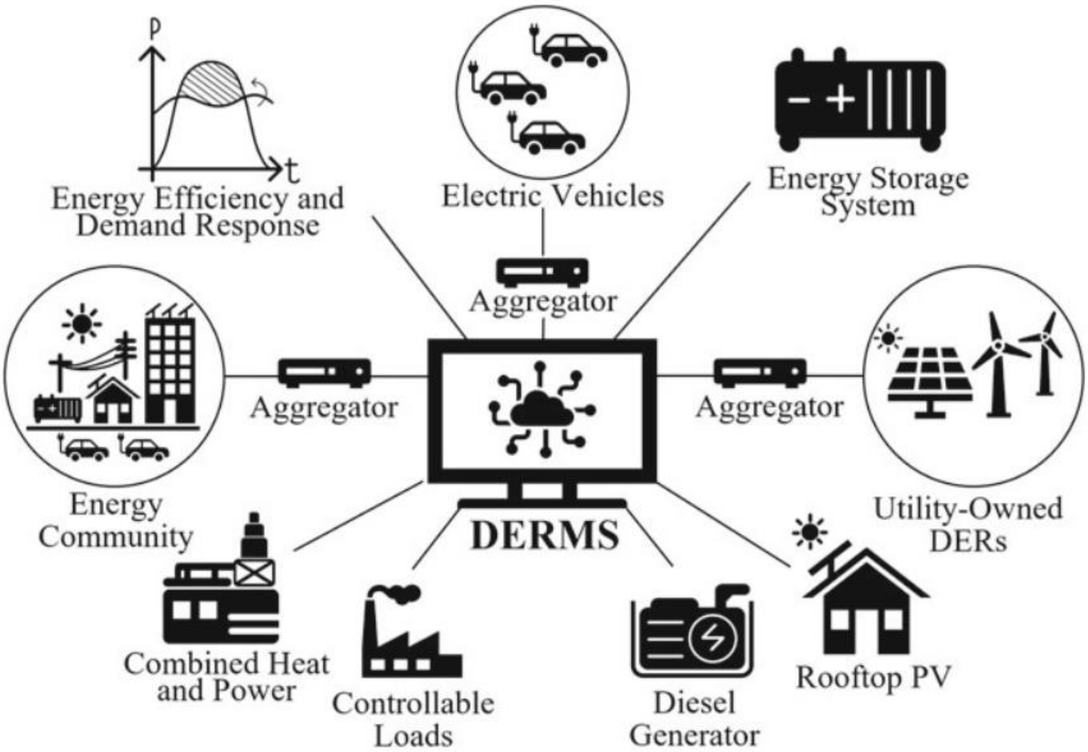

Figure 1. Different DER assets potentially aggregated and managed by DERMS [3].

While the grid functions assigned to a DERMS vary across the literature and the different vendors, it has been deemed appropriate to gather here some of the most typically associated to these management systems.

3.1.1 DERMS BASIC FUNCTIONALITIES

The main functionalities that a DERMS product must satisfy are presented below. They have been described here at a very high level and will be further discussed in later sections. These, along with the definition presented earlier, will allow for a more precise understanding of what a DERMS is and the minimum services it must provide to the electrical system, and more specifically, for the operation of the distribution network.

1) *DER Configuration, Monitoring, Analysis and Control*: the primary role of DERMS comprises configuring DER devices—including their registration in the DERMS software platform—, acquiring information on DER locations and sizes, analyzing and

optimizing their performance, and controlling their operations. These systems must be capable of monitoring DER inverter real-time outputs, ensuring they work in harmony with other grid control devices like smart inverters, load tap changers and voltage regulators at the local level [3], [5], [6], [8], [9], [11].

2) *DER Aggregation*: by combining the outputs of multiple DERs into virtual resources, the complexities of individual DERs are translated into simplified, aggregated services. In this way, DERMS facilitate overall DER management, expansion of prosumer participation, optimization of resource usage, translation of DER data into useful information for grid operators, and DER participation in electricity markets. This aggregated management results in economic benefits to both utilities and customers [3], [9]. The use of standardized communication protocols and interfaces is critical to ensure interoperability and seamless integration between DERMS, DER aggregators, and individual DERs [3], [4], [7], [10].
3) *Coordination and Optimization of DER Dispatch*: DERMS solve optimization problems using DER information and real-time measurements to send optimal operation set points to DERs. This involves creating, validating, and adjusting schedules for DERs—aggregated or individual—, ensuring compliance with grid constraints, and addressing potential violations using the available resources [2]-[4], [8]. They must be able to suggest power, energy, and service dispatch signals to connected DERs based on utility needs, verifying the resulting dispatch will not endanger grid operation reliability. Constant communication and coordination with TSOs/DSOs are essential in this regard [1], [4], [6], [8].
4) *Grid Support and Flexibility Services*: by the efficient use of DER flexibility—e.g., through demand response initiatives or controlling residential DERs (solar PV, EVs, smart appliances, etc.) aggregated as a VPP—DERMS manage grid constraints and provide grid services such as load balancing, volt/var optimization, peak load management, voltage regulation, frequency control, enhanced service restoration after faults, etc. This allows for enhancing grid stability and reducing the need for traditional grid investments [2]-[4], [7], [8], [11], [12].

5) *DER Participation in Electricity Markets*: DERMS enable the participation of small- and medium-scale DERs in local electricity markets by aggregating DERs and managing their dispatch to provide ancillary grid services such as load balancing, voltage support, load shaping, or constraint management [2]-[4], [7], [10]. Additionally, they facilitate aggregator data exchange, bidding, settlement, and dynamic pricing for energy markets, especially in the context of demand response transactions [3], [8], [10].
6) *Grid Awareness, Real-Time Monitoring, and Forecasting*: DERMS are continuously supplied with real-time data from SCADA systems, AMI, load and generation forecasts, topological information, switching states, etc. They collect real-time DER inverter outputs and grid measurements at all sensing locations, providing real-time visibility of grid conditions and situational awareness [1]-[3], [8]. These systems can also use weather data, historical load and generation profiles, scheduled operation of DERs, etc., to forecast generation and demand and prevent issues like overloads and voltage violations [1], [2], [4], [5].
7) *Coordination with ADMS for Advanced Network Management*: not only they must be capable of operating as a standalone application, but also of communicating and coordinating with other utility systems like Advanced Distribution Management Systems—for example, providing visibility and controllability of behind-the-meter DERs—to perform real-time optimization of grid usage and constraint management, monitor network safety, and resolve diverse issues [2], [3], [5], [12].
8) *Optimal Management and Control of Distribution Networks*: through the precise control over equipment like smart inverters, capacitor banks, on-load tap changers, voltage regulators, customer loads, and both utility-owned and BTM customer-owned resources like rooftop solar or EV chargers, DERMS enable utilities to manage grid events locally [11], [12]. They deploy advanced power flow and state estimation algorithms to ensure precise grid condition awareness in real time, optimize voltage and power flows along individual feeders, address issues like congestion and voltage violations, and enhance grid resiliency and efficiency [1], [2].

3.1.2 DERMS HIERARCHY & STAKEHOLDERS

A certain trend has been observed in the literature to systematically distinguish two different hierarchical levels of existing Distributed Energy Resource Management Systems. This section will highlight the roles and responsibilities of each solution within the hierarchy, focusing on differentiating centralized versus decentralized management systems. Following sections will examine the potential integration of these levels and how they collectively contribute to the efficient management of emerging distribution grids.

The 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], [8].

3.1.2.1 Centralized DERMS

All DERMS solutions have evolved from two different sources: (i) centralized enterprise solutions for distribution grid management and (ii) decentralized solutions for customer management [1], [2]. On the one hand, 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], [6]-[8]. In general terms, and related to some of the functionalities described in the previous section, centralized (Utility) DERMS must be capable of the following:

1) *Grid Awareness and Network Modeling*: Centralized DERMS must be grid-aware, providing accurate network models that consider all DERs and grid assets and their interactions. The ability to represent DERs accurately within these models is crucial, especially considering the timescales of interest for various grid operations. These models must include detailed DER characteristics such as rated powers, response times, ramping capabilities, number of phases, currents, voltages, internal impedance values, and PCC information, as well as inverter functionalities like grid-forming, frequency response, and voltage support [1]-[3], [6], [8].
2) *Real-Time Data Integration*: centralized systems are continuously performing power flow and state estimation algorithms to ensure precise grid condition awareness and control in real time. These algorithms are supplied with real-time data from SCADA systems, advanced metering infrastructure, load and generation forecasts, DER schedules based on market participation, real-time topology information, and as-operated switching states [1]-[3], [7], [8].
3) *Advanced Grid-Wide Control and Optimization*: Utility DERMS provide advanced applications for grid-wide control, optimization, and protection of distribution networks. These include features like voltage control, power quality management, and the ability to handle various constraint violations such as voltage fluctuations and reverse power flows, which are managed making optimal use of the flexibility provided by DERs and traditional network assets such as load tap changers, capacitors, and switches [1]-[3], [6]-[8].

In order to fulfill these functionalities, Utility DERMS typically consist of several modules, each encompassing a series of functions, integrated into a single solution. These will be further developed in later sections, but can include—and this is simply one way to structure

Utility DERMS's services found in the literature, not an established and unalterable functional architecture: (i) an enrolment module for DER registration and configuration [3]-[5]; (ii) a planning module for the analysis of DER integration, elaborating Hosting Capacity Heat Maps (HCHMs), load flow studies, and considering traditional network reinforcement and Non-Wire Alternatives (NWA) [1], [2]; (iii) a real-time module for monitoring, control, and active management of distribution grids [1]-[5]; and (iv) a certain type of a look-ahead, forecasting or short-term operation module to forecast future grid conditions and prevent potential constraint violations in different time scales [1]-[5].

However, other ways to structure these services can be also found in the literature. For example, [6] states that a DERMS should consist of three fundamental modules (although these do not distinguish between centralized and decentralized solutions): (i) an aggregation module to register DER and acquire information on their locations and sizes; (ii) a monitoring module to collect real-time DER outputs and grid measurements, and (iii) an optimal DER dispatch module sending the optimal operation set points to the DERs. The IEEE Std 2030.11-2021 also proposes a functional specification for DERMS (both centralized and decentralized as a whole) in which their functionalities are divided into base functions, optional functions, and grid services. In turn, base functions encompass (i) DER device information (registration, grouping, and capability), (ii) monitoring (DER status and grid measurements), and (iii) real-time operation (dispatch and scheduling) and control [3], [4], [33]. These functional designs and different ways to structure the services that a DERMS must provide will be developed in the following chapter.

3.1.2.2 Decentralized DERMS

Decentralized DERMS—also Aggregator DERMS [33], third-party DERMS [6], [7], [33], or simply non-utility DERMS [3], [33]—developed from customer-centric applications, enabling greater collaboration of end-users in energy management. Decentralized software solutions focus on the aggregation of multiple small-scale, behind-the-meter resources connected to the LV network (e.g., air-conditioning or heating systems, rooftop solar panels, small residential battery storage systems, EVs and their charging stations, and smart home appliances) with the objective of providing their services in an aggregated, optimized, simpler, and much more useful manner for both customers and 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 [3], and aim to enhance customer engagement, energy efficiency, and local generation and consumption management. They provide greater visibility and controllability of behind-the-meter DERs [1], [2], [7], [8], but typically do not have access to an accurate network model and are not fully aware of grid-level technical constraints—and this will be precisely considered as the boundary between Utility (Centralized) and Aggregator (Decentralized) DERMS [1], [2], [6]-[8]. Decentralized DERMS solutions are often categorized in the literature as follows:

1) *DER Aggregators*

DER aggregators play a crucial role in managing high amounts of DERs and dispatchable loads connected to the LV level, such as rooftop solar PVs, EVs, household batteries, and domestic controllable loads like smart thermostats. DER aggregators are the most typical and widely recognized decentralized DERMS, and this term is indeed often used to refer to decentralized DER management solutions in general terms [2], [8] . They aggregate small, usually behind-the-meter DERs into larger, controllable groups to provide flexibility and ancillary grid services to the DSOs and TSOs [1]-[3], [6]-[8]. Additionally, aggregators communicate with DERs and coordinate their operation to ensure that they can collectively respond to market signals and grid needs. In this regard, effective communication protocols and real-time data exchange are essential for optimizing the performance of DER aggregators [1]-[3], [8].

DER aggregators can encompass Building/Home Energy Management Systems ([6], [8]), energy communities ([3], [6]), VPP ([1], [3], [7]) and DR providers ([1], [2], [6], [8]) and even microgrid controllers ([1], [2], [5], [6], [8]) that will be discussed below. They directly manage individual behind-the-meter DERs and use them in an aggregated fashion to provide various services regarding customer engagement and operations, interfacing with higher platforms—such as Utility DERMS—which handle a portfolio of aggregators [1], [2], [7], [8]. Among the services that aggregated DERs can provide, one could mention supply-demand balancing, voltage control, and frequency regulation, which are critical for maintaining grid stability and optimizing the use of distributed resources [1]. Additionally, aggregators allow for small-scale DERs participation in electricity markets, demand response initiatives, energy efficiency programs, and load shedding for peak demand reduction [1], [2], [8].

2) Local Electricity Market Operators (LEMOs)

One of the primary barriers for DERs entering electricity markets is their small size, which makes individual participation inefficient for the system and economically unviable for DER owners. Aggregation of these small-scale DERs allows them to reach a critical mass necessary for market participation, providing essential services to DSOs/TSOs [1]-[3], [9]. LEMOs are responsible for organizing and operating local markets where DERs can trade energy and provide ancillary services.

Local electricity market operators facilitate the participation of DERs in local energy markets by aggregating multiple small-scale resources and ensuring DER schedules and market operations comply with local grid constraints and regulatory requirements—e.g., minimum power to enter the market. They play a key role in enabling peer-to-peer energy trading and other innovative market mechanisms [1].

One could appreciate a potential overlap between the roles of DER aggregators and LEMOs, as both entities work to aggregate and manage DERs for market participation—although DER aggregators' functions are broader and LEMOs specifically operate these local markets [1]. In any way, tight integration between both is essential for creating a sizeable quantity of flexible DER capacity to participate in electricity markets, and effective regulatory reforms are necessary to provide incentives and a clear framework for DER market integration [1], [3], [5], [10].

3) Microgrid Controllers

As developed in Section 2.2.3, MCs manage the operation of microgrids, ensuring they can function both as part of the main grid and in an islanded mode. Unlike DER aggregators, microgrid controllers handle distributed resources within a clearly defined geographical area, enabling them to operate independently and provide stability and support to the main grid—hence, it has been decided to consider it an independent decentralized DERMS, separate from DER aggregators [5], [24].

In grid-connected mode, MCs manage unit commitment, economic dispatch, and other services to optimize resource usage within the microgrid. At the same time, they coordinate with the main grid to offer flexibility to distribution system operators, e.g., handling excess power and dispatchable loads. These flexibility services allow for voltage control, load balancing, and support for NWA to defer costly network reinforcements. When disconnected from the main grid, microgrid controllers take on additional responsibilities, including grid-forming operations. They manage frequency and voltage regulation, balancing services for resource adequacy, and ensure the safety and reliability of the microgrid's energy supply [1].

3.1.2.3 Key Stakeholders for the Different DERMS Solutions

As a summary of what has been presented so far, Table 1 compiles these different levels of hierarchy among DERMS solutions, together with the key stakeholders interested in deploying DER management software and the goals and services that each of these entities aims to fulfill with their implementation. The literature presents less conventional ways for categorizing DERMS solutions. For instance, and in addition to Utility and Non-Utility, the IEEE Standard 2030.11 classifies DERMS into Aggregators, directly managing DERs and communicating with higher platforms; and Operators, which manage a portfolio of aggregators and optimize resource dispatch [3], [33]. However, these classifications are less common, and it has been decided to adhere to the division in Centralized (Utility) and Decentralized (Aggregator, third-party, or non-utility) DERMS for the remainder of this analysis.

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)
Distribution System Operator (DSO); planning departments in distribution utilities	Relieve congestion and voltage violations, defer network reinforcement, increase DER hosting capability, optimization of grid assets, grid edge stability	Centralized (aware of—at least—distribution network model)
Market participants and local market operators	Wholesale: optimize generation mix, minimize imbalance and energy-not-supplied costs. Retail: promote competitiveness and efficiency against high wholesale prices, new retail tariffs	Decentralized (not aware of network model)
DER aggregators (VPPs, BEMS, energy communities etc.), microgrid operators, DER owners and prosumers	Aggregate DERs for local energy management, optimize costs (energy and demand charges), integrate renewable DG, improve resiliency	Decentralized (not aware of network model)

Table 1. Different DER management solutions, their goals, stakeholders, and hierarchical structure [1], [2].

3.1.3 HYBRID DERMS: UTILITY & AGGREGATOR DERMS INTEGRATION

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], [8]. Purely centralized or decentralized systems may be independently implemented (although Aggregator DERMS typically require collaboration with a centralized management system to coordinate their offered flexibility as developed above), buy they present several limitations that could be mitigated if integrated in an intelligent manner. This would allow for fulfilling the complete spectrum of responsibilities that DSOs have for ensuring safe, secure, and optimal management of active and dynamically changing distribution grids with an increasing penetration of DERs [1], [2], [8]. Some these limitations, derived from the independent use of centralized or decentralized solutions, are summarized below:

1) *Lack of Grid Awareness*: DER aggregators, focused on local distributed resources, typically do not have access to accurate network models and are unaware of the grid-level technical constraints—such as transformer and line overloads, voltage limits, and reverse power flows [1], [2], [8].

2) *Need for Centralized Validation of DERs' Schedules*: in line with the above, without validation by a grid-aware system like a Utility DERMS or an ADMS, the optimized schedules and dispatches provided by DER aggregators and LEMOs might endanger grid assets and operations [1], [2], [8].
3) *Coordination Challenges for Leveraging DER Flexibility*: decentralized systems can face difficulties in coordination, especially when multiple aggregated DERs need to be managed for effectively using their flexibility and providing broader grid services. This lack of coordination with no control from a centralized software platform can lead to inefficiencies and suboptimal performance in managing the grid as a whole [1], [2].
4) *Scalability Issues*: centralized systems may struggle to scale efficiently as the number of DERs increases, since managing a large number of DERs from a single centralized point can difficult a fast and effective control and optimization of all network assets [1]. The need for DER aggregators to simplify the management of distributed small-scale resources becomes critical in this regard.
5) *Inconsistent Standards and Communication Protocols*: without common centralized systems integrating all decentralized solutions, these may use various communication protocols and standards and lead to interoperability issues when trying to use them in an aggregated fashion [1], [8].

Integrating centralized and decentralized DER management systems 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], [8], [9], in many cases still undeveloped or under development by different vendors, projects from international organizations (Platone Project [34]) or standards associations (such as the IEEE Std 2030.5 for communication between utilities and DERs—either through a DER aggregator or directly [35]). Moreover, managing real-time data and coordination 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], [8]. Cybersecurity becomes also critical due to increased connectivity and data exchange introducing potential vulnerabilities [3], [4], [33]. Finally, regulatory and policy frameworks must evolve to a large extent to support hybrid approaches [1], [2], [6], [10], [11]. In this regard, initiatives like the already mentioned FERC Order No. 2222 in the US supporting DER participation in wholesale markets [1], [3], [5], [10], or the EU DSO Entity and ENTSO-E's Proposal for a Network Code on Demand Response [20] contribute to define a regulatory framework that favour the development of comprehensive DER management solutions.

Despite these complexities, if properly integrated, these two often disaggregated solutions can perfectly complement one another to leverage the strengths of both systems while mitigating their individual weaknesses. Hybrid systems can leverage the comprehensive grid awareness and control capabilities of centralized solutions while utilizing the flexibility and resilience offered by Aggregator DERMS, ensuring that all DERs are optimally managed in a way that aligns with the grid's overall operational goals and constraints [1], [2], [8].

Through real-time or near real-time communications and data exchange with a utility DERMS, DER aggregators enhance DSO's awareness of behind-the-meter DERs and their impact on grid conditions, particularly in customer-related operations such as participation in electricity markets and DR or EE initiatives. This improved knowledge of the LV grid enables DSOs to successfully manage and optimize the emerging distribution systems with high penetration of DERs dispersed throughout the entire grid, from BTM to large-scale DERs connected to the MV distribution network [8]. DER aggregators could also help Utility DERMS managing the variability and intermittency of DER outputs so that they can dispose of increased flexible capacity [1], [2]. In addition, and when regulations allow DERs to enter electricity markets, the integration of Utility DERMS with Local Electricity Market Operators 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], [8]. Finally, hybrid systems enhance the scalability of DERMS software solutions by distributing some control and optimization functions to decentralized management systems, so that a larger number of DERs can be efficiently integrated. In this manner, decentralized systems could handle local control and aggregation, feeding relevant data back to the central system for comprehensive analysis and decision-making [1].

These ideas for Utility and Aggregator DERMS integration are perfectly summarized in [1], [2], and [8], to the extent that the author of this work has deemed it appropriate to literally transcribe here a passage from [2], which is also used in [8]: "[…] 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 DERMSs perfectly complement one another, and can provide a full spectrum of DER services regarding both customer- and grid-related operations, regardless of the DERs' sizes and locations".

Several pilot projects, such as some the ones described in [1]-[4] and [6]-[9], are testing the integration of Utility DERMS, DER aggregators, MCs, and LEMOs, and have demonstrated the benefits of integrating centralized and decentralized DER management solutions, including increased observability, constrain management, efficient scheduling, and economic optimization of DERs, showing promising results for full-scale deployment.

3.1.4 How to Move Forward – TSO/DSO Integration, Regulatory Framework, & Standardized Communication Protocols

A comprehensive and robust platform, capable of integrating, communicating with, monitoring, and managing all DERs, from behind-the-meter devices connected to the low voltage grid (rooftop solar, EVs, household batteries, domestic appliances, etc.) to large-scale DERs connected to the medium voltage distribution network, will be essential to transition into the new era of active and dynamic power system [1]. This platform should provide real-time awareness of the entire grid conditions, allowing network operators to analyze and control the influence of DERs on the different grid assets. It should manage, protect, control, and economically optimize complex systems with high DER penetration dispersed across all voltage levels. Moreover, and when regulations allow, it should facilitate efficient market participation for individual and aggregated DERs to achieve fair and profitable flexibility utilization [1], [6], [8].

However, such a complete management tool does not currently exist, but multiple different solutions are offered for covering the diverse responsibilities of TSOs and DSOs [1], [2]. Each of the various hierarchical levels of DER management systems described above provides only a portion of the necessary functionalities. For this reason, and following the reasoning from the previous section, a properly designed hybrid platform integrating Utility and Aggregator DERMS—DER aggregators, MCs, and LEMOs—should allow system operators and end users to optimize electricity use in the new context of modern distribution grids with high share of renewable DERs [1], [2], [6], [8]. Great effort should be invested in developing such an integrated end-to-end DERMS, but there are certain obstacles preventing a software solution like this to be successfully deployed.

Firstly, with the proliferation of distributed energy resources connected to the distribution network, the role of DSOs is evolving and becoming increasingly important for the smooth operation of the power system. In this regard, much tighter and efficient coordination between TSOs and DSOs will be required as TSOs aim to leverage aggregated DERs to help balance supply and demand, regulate frequency, provide ancillary services, and even engage in energy trading [1]. There appears to be a certain consensus in the literature that the traditional separation between the TSO and DSO responsibilities is no longer viable, and new coordinated models need to be developed—examples are local ancillary service and flexibility markets where resources connected to the distribution grid can offer their flexible capacity (normally through an aggregator), shared balancing responsibilities models (these are divided between TSO and DSO according to a predefined schedule), TSO-DSO hybrid management models in which the DSOs control and optimize the use of DERs and validate the technical feasibility of the schedules received from the TSO, or even DSO-managed models where TSO's only role is to issue aggregated bids [10], [36], [37].

Each model has its unique approach to managing DERs and balancing responsibilities between TSOs and DSOs, but it is clear that none of these models can function sustainably without a robust DER management tool. A comprehensive DERMS solution would enable DSOs to monitor real-time and predicted outputs of aggregated DERs across all voltage levels, offering this flexibility to TSOs for their operational needs and facilitating a vertically integrated management of the grid [1], [6], [8]. Such a system could reduce reliance on expensive and polluting traditional power plants and defer or eliminate the need for investments in both transmission and distribution network by offering non-wires alternatives to solve congestion and technical issues [1].

Another great obstacle to achieving this integrated hybrid DERMS platform is the lack of a common, well-defined, regulatory framework on DER management, which does not vary widely across different regions [1], [2], [6], [10], [11]. Significant improvements have been made in this area with relevant legislative initiatives such as the FERC Order No. 2222 in the US [1], [3], [5], [10] or the EU DSO Entity and ENTSO-E's Proposal for a Network Code on Demand Response [20], but a long way remains to be covered. Certain areas still need to be clarified, such as whether DSOs should be responsible for directly interacting with flexibility providers, when aggregators should offer their capacity to DSOs and when directly to TSOs, or who should ensure reliability within the distribution grid in terms of market schedules and priorities [1]. Ultimately, a larger regulatory reform is necessary to address these issues, enabling the development of a robust hybrid DERMS solution meeting the requirements of TSOs and DSOs for the efficient and optimal operation of modern grids.

Finally, another major challenge is the lack of a universally accepted protocol and interoperability standard for communication between DER devices, between utilities and aggregators, and between aggregators and individual DERs [1]-[4], [8], [9]. On the contrary, different protocols are used for different purposes, and even for the same purpose by different vendors and utilities. Utility DERMS solutions from different vendors often use distinct protocols to communicate with DERs and DER Aggregators, and DER Aggregators use different protocols to connect with individual DERs which, in turn, may support different protocols for two-way communication with control centers and aggregators [1], [8].

Well recognized protocols such as the IEEE 2030.5—to be developed in later sections—are positioning themselves as the preferred alternatives for most applications, allowing two-way communication and data transfer between Utility DERMS, DER Aggregators, and individual DERs [1], [3], [4] [8]. The exchanged information normally consists of AMI measurements from BTM resources, forecasted production of individual small-scale DERs and DER aggregators, and their operation schedules. These data can then be used in real-time applications by Utility DERMS—i.e., state estimation, constraint management, grid optimization for both near real-time and forecasted periods, etc. Thus, a smoother data transfer through standardized communication protocols would improve both the real-time observability of grid conditions, and the ability to predict constraint violations [8]. Additionally, an agreed communication protocol would allow for seamlessly exchanging planned schedules of DERs and DER aggregators with a Utility DERMS, modifying schedules in real-time, and sending individual or group commands to inverters [1]. All this together would provide, therefore, the necessary infrastructure for the development of an efficient and integrated DERMS platform.

3.2 DERMS FUNCTIONAL SPECIFICATION

As mentioned in Section 3.1.2.1, the functionalities, services, and use cases of a DERMS have been structured in various ways in the literature over recent years. This chapter provides a comprehensive view of these perspectives by integrating the insights from 12 utilities and 11 vendors as provided by SEPA in [38], the functional specifications proposed by IEEE Std 2030.11-2021 ([33]), as well as other insights primarily gathered from [1]-[3]. It is worth noting that, 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—it has been deemed appropriate to try to draw a distinction between the specific use cases of each to properly emphasize the latter—in a context where the industry tends to view DERMS as a utility-exclusive product. A compilation of the DERMS functionalities and services most frequently found in the literature is shown in Figure 2 below.

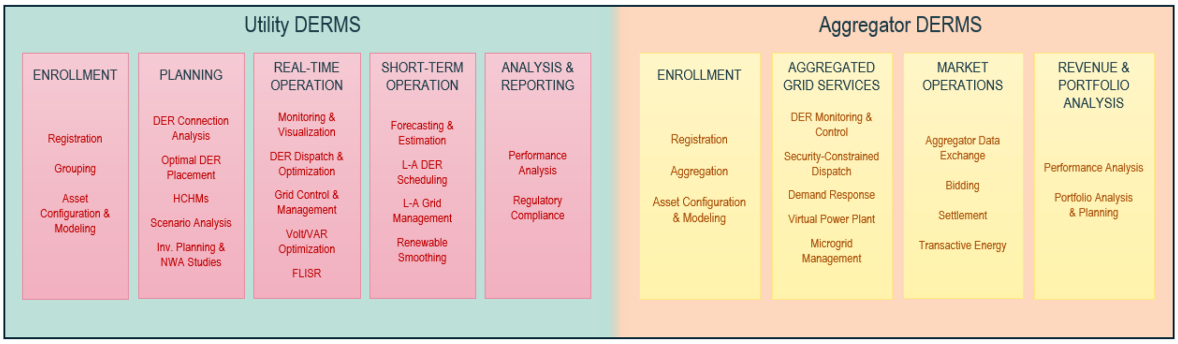

Figure 2. DERMS Functional Specification - State of the Art

3.2.1 CENTRALIZED/UTILITY DERMS

Typically deployed at the control centers of distribution system operators, Utility DERMS have complete access to the accurate network model and focus on grid-wide optimization and control. They aim to leverage 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 and providing technical, operational, and monetary benefits to power system [1]-[3], [6]-[8].

3.2.1.1 Enrollment

The Enrollment service enables that all DERs are properly identified, categorized, and managed to support further DERMS services. This includes 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 various grid services [33], [38]. It encompasses three main functions:

1) *Registration*: its purpose is to identify and validate the DER devices enrolled to the DERMS software platform, and to provide a comprehensive registry of all these DERs, ensuring that only compliant and validated devices are integrated into the management system [33]. The aim is to capture relevant asset, programmatic, and network information

about the different DERs—both utility owned DERs and DERs aggregated by third parties—to provide greater visibility to the utility or distribution system operator [38]. Registration information must include as much of the following as possible [33]:

- Nameplate Information: it provides the essential information for situational awareness, modeling, monitoring, and control. It includes DER type (e.g., microturbine, solar PV, battery, etc.), model, serial number, manufacturer, and ratings (e.g., nominal voltage, kVA, kWh, charging and ramp rates, thermal limits, short-circuit current, standard test conditions, efficiencies, etc.). A more detailed list of nominal values and performance parameters is provided in [33].
- Communication Information: it ensures that DERs support required communication protocols. More information on the most common and supported protocols is provided in section 7.3 of the IEEE Guide for DERMS Functional Specification (Std 2030.11) [33] and will be developed in following sections.
- Installation Information: physical installation details of each DER, including geographic coordinates, address, utility customer ID, and last inspection or repair date. The aim of these installation records is to support maintenance and operational planning.
- Programmatic Information: ownership and account information, aggregator ID or other third-party identifier, and operational constraints, requirements, or other limitations that prevent DERs from being utilized in utility programs (see *Programmatic Grouping* below) [38].
- Electrical Location & Network Information: identifies the electrical connection point of each DER within the distribution grid to allow for grid modeling and facilitate operational management. It includes the service delivery point, meter, feeder segment, and customer IDs, and phase information may be provided. Other necessary network information may include load zone, access codes, or encryption keys [38].
- Device Settings and Interconnection Rating: specifies operational settings and interconnection requirements and limits for each DER or aggregated DERs—

active power limits, voltage and frequency ride-through settings, and control mode functions (complete list of parameters provided in section 5.3.2 of [33]).

- In/Out of Service Dates: this allows for tracking the availability and operational status of DERs and develop and enables effective scheduling and management of DER resources. It details periods of availability, scheduled maintenances, and other operational constraints [33].
- DER Modeling Information: provides necessary data for accurate DER modeling in software applications to support precise grid planning and operational simulations. It includes electrical impedances, fault contributions, thermal limits, and scenario modeling data [33].

2) *Grouping*: it aims at organizing DER devices into logical groups for better management and control, simpler operations and enhanced efficiency. Grouping can attend to multiple considerations [33]:
   - Hierarchical Grouping: based on system connectivity. It can be done on an as-built or as-operated topology, with the purpose of simplifying the modeling, operation, and control of DERs within the distribution network.
   - Dynamic Grouping: it consists of altering the different hierarchical groups as the grid configuration and topology changes with real-time control actions. DERMS must notify the appropriate parties and adjust grid management according to these modifications.
   - Programmatic Grouping: based on DER participation in utility programs—i.e., commercial arrangements under which a certain aggrupation of DERs with common functional capabilities can be configured and controlled. Program management, encompassed under this Grouping function, includes: (i) the definition of the structure of the program, (ii) who and what type of resources can participate in it, and (iii) the description of when a particular program is applicable.
   - Capacity Grouping: in accordance with the capabilities dictated by the interconnection agreement, mainly in terms of response times and determinism.

Thus, the different DERs can be associated with certain types of control applications with different latency requirements—e.g., DERs directly communicated with the utility, DERs communicated with a distributed controller (such as a microgrid controller), DERs communicated with a non-utility aggregator (third-party DERMS), or those only monitored through an AMI.

- Resource Grouping: DERs can be simply grouped by type of resource—solar, wind, energy storage, etc.—, also specifying if the resource is managed by a certain aggregator. This grouping method would be useful when managing any resource type–specific function.

3) *Asset Configuration & Modeling*: it involves DER devices (on an individual or aggregated basis) notifying the system operator of their current and projected status, operational capabilities, and limitations, so that they can be utilized for network operation in a secure and efficient fashion. This must be done with an agreed periodicity and by using a common communication protocol for all DERs in the system. As much of the following information should be periodically communicated [33]:
   - DER/DER aggregator identifier
   - DER status and controllability
   - Current mode of operation and all the available modes of operation
   - Services in which the DER is participating
   - Real-time available capacity (P and Q)
   - Real-time output and other monitored values (P, Q, voltage, etc.)
   - Projected availability in different time scales (e.g., 24 h)

   This adds to the Registration and Grouping Information developed above and allows utilities for incorporating accurate real-time DER data to their digital models of the distribution network, which help visualize, control, and optimize both FTM and BTM distributed resources.

3.2.1.2 Planning

Planning functions facilitate long-term strategic planning for integrating distributed energy resources into the grid. It aims to ensure the grid can handle increasing DER levels without compromising stability and resilience. This module offers comprehensive studies and assessments, guiding utilities in infrastructure investments and operational strategies. The planning module involves creating detailed plans for grid upgrades and DER integration strategies. This includes hosting capacity analysis, studies of forecasted scenarios for DER integration, the evaluation of network expansion investments and non-wire alternatives, as well as the planning and preparation for black start and cold load pickup events [1], [2], [33].

1) *DER Connection Analysis (Hosting Capacity)*: it assesses the impact of new DER connections on grid stability and performance. It performs load flow studies on an accurate network model to evaluate a specific potential connection point for a DER or group of DERs, analyzing factors like DER rated power and technology type, but also voltage stability at the PCC, thermal limits, and congestion constraints. The objective is to estimate the capacity of a certain grid section to host additional DERs, as well as the required network upgrades for accommodating the new connection [1], [2].

2) *Optimal DER Placement*: similar to the previous, here the purpose is to be able to visualize the capacity of different grid sections to host new distributed energy resources without requiring costly network upgrades, identifying the optimal connection point for a specific DER capacity. Detailed reports can be elaborated on each potential connection point, including recommendations for optimal connection nodes and the necessary grid adjustments upstream [1], [2].

3) *Hosting Capacity Heat Maps (HCHMs):* the analysis from above can result in the creation of Hosting Capacity Heat Maps (HCHMs) highlighting areas with the highest potential to accommodate new DER installations without causing technical issues. These maps provide a starting point for more detailed DER integration studies and inform potential customers and DER developers about the grid's capacity, aiding in strategic DER placement [1], [2].

4) *Scenario Analysis*: the purpose is to explore various future scenarios to prepare for different DER adoption rates, various levels of electricity demand, as well as policy changes. It utilizes historical data, market trends, and policy impacts to forecast load growth and DER penetration and simulate the projected grid conditions. The output are comprehensive reports with insights into potential future challenges and strategic recommendations for different scenarios, aiding in capacity planning and resource allocation. This allows for identifying and mitigating some of the risks associated with DER integration—e.g., distribution grid congestion, voltage instability, and various operational challenges [1].

5) *Investment Planning & NWA Studies*: the previous studies can be utilized to guide decisions on grid infrastructure upgrades to support DER integration. This functionality analyzes cost-benefit aspects of potential investments in grid enhancements and elaborates investment plans that prioritize upgrades based on their impact on grid reliability and DER accommodation. However, it also explores alternatives to traditional grid reinforcements, such as flexible contracts, energy storage solutions, demand response capabilities, and other non-wire alternatives that constitute much more cost-effective and time-efficient methods to increase the DER capacity within the distribution grid. The aim is to determine whether NWA are sufficient to accommodate new DERs or if, on the contrary, costly network reinforcements are unavoidable [1], [2].

6) *Black Start & Cold Load Pick-Up Studies*: black start refers to the ability to restore the electrical system following a major outage. A DERMS could manage this process using DERs with grid-forming capabilities to establish a voltage and frequency reference for other DERs. During a black start, a reference generator is configured to facilitate power system restoration and the subsequent restarting and reconnection of the remaining DERs [33]. DERMS could also elaborate strategies to support power restoration after common faults within distribution feeders, managing connected DERs to counter the effects of cold load pick-up—possibly through interfacing with outage management systems (OMS) or with the corresponding modules of an ADMS.

Cold load pick-up and black start challenges often arise from a loss of load diversity, which can cause significant load fluctuations within certain time frames after power restoration, resulting in thermal stress and overloading of equipment, and great voltage deviations. DERMS can help mitigate these issues by staggering the restart of certain DERs as necessary, thus reducing the instantaneous power needed and the ramping requirements for restoration—e.g., instead of all EVs resuming charging at once, a DERMS could stagger their initial charging times. In the same way, DERMS can delay the reconnection of some inverters, creating a generation ramp rather than a sudden surge at—typically—300 seconds after power restoration [33].

3.2.1.3 Real-Time Operation

The Real-Time module focuses on monitoring and immediate operational control and optimization of distributed energy resources and grid assets. It ensures real-time visibility and dynamic management of DERs to maintain network stability and efficiency. This module integrates various real-time applications to monitor grid conditions and make necessary adjustments, either on the output of DERs or on other grid assets, to achieve the desired operational objectives [1]. This includes managing load, providing grid ancillary services, and enhancing system resiliency in general terms. Real-time services leverage information from the Enrollment module to understand the current state and capacity of the network and, particularly, of distributed energy resources, enabling active grid management and asset optimization [38]. It includes the following functions:

1) *Monitoring & Visualization*: DERMS must be capable of monitoring, sensing, and measuring not only general grid parameters but also critical operating values of the different DERs, often leveraging real-time data from SCADA and AMI systems to continuously provide updated information to utility operators and planners. Concerning DER parameters, and according to IEEE Std 1547-2018, a DERMS should be able to collect, at least, the following information: active and reactive power, instantaneous single- or three-phase RMS voltage, instantaneous RMS current, frequency, operational status (on/off), connection status (connected/disconnected), alarm status (active/not active), and operational state of charge (0-100%). Power factor, peak values and averages

over time intervals for voltage and current are not considered in this standard, but they may be also recorded if possible [33].

A critical feature is the visualization of this data, allowing operators to adjust DERs and grid assets either manually or automatically and to notify aggregators when necessary to support immediate response to grid conditions and optimal energy use [2], [3], [38]. This ensures compliance with customer programs and net metering limits, and it facilitates automatic updates for detecting anomalies and constraints [38]. The collected information can be also shared with other management systems like ADMS, using non-proprietary standard communication protocols, to ensure efficient and coordinated management of the distribution network [33]. The effectiveness of monitoring depends to a great extent on the granularity and frequency of data collection. For operational control, monitoring at the level of DER aggregators is typically sufficient, especially when these DERs are grouped by location into categories such as generation, flexible load resources, and storage. However, for purposes of system planning and performance analysis, detailed monitoring of individual DER devices is necessary [38].

2) *DER Optimization & Economic Dispatch*: a key role of every DERMS is to deliver requested grid services efficiently by using the best combination of DER assets, which helps to reduce costs, minimize wear, and maximize asset efficiency and general value. Different types of DERs—such as storage, electric vehicles, or solar PV—are commonly better suited for specific operational scenarios, so a DERMS is responsible of optimizing the sequence and priority of DER operations (e.g., coordinating the power delivered by smart inverters at every moment [1]) based on their capabilities and operating status so that they meet economic, reliability, or environmental goals while complying with their grid control objectives [38]. Optimization may be based on (i) cost merit (lowest cost resources are dispatched first), (ii) reliability (resources with larger reserves have priority), or (iii) response times (resources with the desired ramp rates) [33].

A DERMS provide utilities with the ability to dynamically perform economic dispatch of active and reactive power in response to price signals and market rates. This optimization process leverages these price signals and generation costs to support a security-constrained economic dispatch (SCED), focused solely on DERs under the DERMS's portfolio—either individual or grouped DERs—, and considering not only grid constraints but also DER operating limits, contracted periods and participation in utility programs, and even environmental considerations like greenhouse gas emission rates. Then, the DERMS communicate the resulting operational setpoints to individual assets or DER aggregators so that their power output is adjusted in accordance. This capability is closely tied to scheduling, and often involves the ability to perform dynamic re-optimization of DER schedules to maintain grid reliability and efficiency, quickly adapting to changes in DER available capacity, communication issues, or modifications in grid conditions that alter the requested outputs [33].

3) *Grid Management & Control*: this function—or set of functions—involves controlling DERs to achieve energy, capacity, and ancillary service goals. As DERs become more prevalent within the distribution network, managing their power output and load profiles is crucial for helping balance grid supply and demand in the most efficient fashion. A DERMS can leverage real-time monitoring of energy use and visibility into the impacts of DERs on net load to control DER outputs—e.g., decreasing their instantaneous power supply or shifting their energy delivery to peak demand periods—to balance the grid and provide a variety of ancillary services [38].

   Energy management is normally used for energy arbitrage, so it is purchased when prices are low, and sold with high prices. This can be achieved through ToU tariffs encouraging consumers to shift their energy use to low-price periods, or optimizing net DER energy output—for example, configuring the charging and discharging periods of BESS and EVs [38]. Additionally, a DERMS can control DER capacity to provide flexibility services to the grid through ramp rate control. A DERMS can manage the DERs within its portfolio to deliver or consume power, often using demand response instances or energy storage to support strategies like load shifting and peak shaving, or even DER curtailment to maintain voltage limits and protect power quality against feeder overloads. Energy and capacity management can enhance distribution efficiency and help mitigate issues related to the variability and unpredictability of renewable generation [1], [38].

The control of DER available energy and flexible capacity can be ultimately used for constraint management and ancillary grid services. In this regard, DERMS can coordinate DER active and reactive power outputs to match supply and demand and help alleviate system constraints, keep frequency and voltage within limits, avoid feeder overloads, and improve power quality [1], [38]. Frequency shall always be maintained within limits through continuous adjustments of DER outputs—with respect to their scheduled values—in the event of frequency deviations. Voltage support is provided through dynamic corrections of voltage excursions using reactive power and DER flexible capacity [38]. Control actions and modifications on DER operations and schedules must be always validated against grid constraints and requirements, technical capabilities, and contractual obligations before implementation [33].

DERMS' grid management and control function should also include the execution of control commands for DERs in real-time, ensuring that they provide the required capacities at the scheduled times according to the previously set economic, reliability, or environmental goals. This involves dispatching control signals for capacity, energy, and set points, managing response curves like frequency/watt and volt/VAR (Volt/VAR Control), as well as providing confirmation of the execution of these control commands and alerting operators if schedules are not being followed [33].

4) *Volt/VAR Optimization*: this consists of enhancing power quality through active grid management strategies, such as voltage support via Volt/VAR Optimization (VVO). VVO aims at reducing energy losses by decreasing reactive power flow through the distribution network. VVO devices receive system-wide voltage measurements to minimize power losses and boost system efficiency. In particular, Conservation Voltage Reduction (CVR) intends to manage the transmission and distribution system so that customer voltages are kept close to the lower end of the acceptable range and energy consumption and demand are reduced. CVR helps flatten load voltage profiles and lower overall system voltage while adhering to ANSI or IEC standards. The objective of volt/VAR optimization is, precisely, to manage and optimize voltage and reactive power at the same time through CVR and reactive power control [33], [38].

5) *Fault Location, Isolation, and Service Restoration (FLISR)*: as mentioned above, a DERMS can monitor the network and handle switches and traditional grid assets to locate and isolate faults, either on its own or through collaboration with an OMS or an ADMS. Additionally, during the power restoration phase, a DERMS can coordinate the DERs under its control to stage their restart—e.g., through smart inverter control or managing EVs' charging stations—and mitigate traditional effects of cold load pickup. With this gradual reactivation of DERs, the DERMS can reduce the instantaneous power and ramping requirements for restoration, preventing the surge in demand that typically follows an outage and ensuring a smoother and more stable restoration process. This capability can have a massive effect on response times to grid outages, highly impacting quality of service indexes like SAIDI (System Average Interruption Duration Index) and CAIDI (Customer Average Interruption Duration Index) [6], [33].

3.2.1.4 Short-Term/Look-Ahead Operation

The Look-Ahead module in a Utility DERMS 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. This proactive approach enables utilities and system operators to make informed decisions and adjustments to prevent outages and optimize DER operations [1], [2]. Look-ahead services also use information from the enrollment module to understand the historical and current operating conditions of the network and its distributed resources, so that they can perform short-term grid and DER analysis, predict potential violations, and propose optimization measures [38]. Most of the real-time operation functions developed above can also be performed in a short-term/look-ahead basis, so they will not be extensively described here. Short-Term operation encompasses the following:

1) *Forecasting & Estimation*: DERMS forecasting provides utilities with the ability to predict future energy demand, DER behavior, general grid parameters—such as voltage profiles and power flows through critical lines—and even market conditions [3]. This functionality enhances visibility of DERs at both aggregated and individual levels. Forecasting capabilities may vary, but typically include load and DER generation and

status—i.e., charging/discharging cycles of storage systems—forecasting using real-time and historical data (accounting for daily and seasonal variations), and sometimes integrating weather forecasts and market pricing data—such as wholesale prices and ToU rates—to better predict energy demand and DER behavior [1], [3] , [33], [38]. These forecasts allow for implementing look-ahead state estimation algorithms, which improve the situational awareness and visibility of the system, support grid stability, optimizing operations, and both short-term and long-term distribution planning [1], [38].

Advanced forecasting is often conducted on a continuous basis, involving interaction with DER metering devices to gather real-time data on load, capacity, power quality, historical performance data, usage profiles, and often integrating external pricing information from energy markets and weather data—such as temperature, solar irradiance, or wind speed [38]. These forecasts can even predict the potential load reduction available from, e.g., demand response programs, estimating the load that can be interrupted based on historical data and market participation [33]. This helps operators predict DERs' ability to meet demand and elaborate look-ahead DER schedules, making economically optimal decisions about when to dispatch or curtail DERs.

2) *Look-Ahead DER Scheduling (Unit Commitment)*: this function aims at optimizing the operation and energy delivery of individual DERs and DER groups over defined time intervals—hours, days, weeks, and even months. Look-ahead (L-A) Scheduling leverages forecasted energy demand, estimations of DER power outputs based on weather data and resource costs, projected electricity market prices, and estimated future network conditions to develop optimal DER schedules. The goal is to optimize the sequence and priority of DER operations to meet economic, reliability, and environmental goals while complying with grid constraints, DER operating limits, contracted periods and participation in utility programs, and various control objectives. DERMS support different types of scheduling, including energy (MWh), capacity (MW), and specific set points, and is often capable of integrating with other systems like ADMS for validation of this schedules [33], [38].

Renewable smoothing must be a primary factor to consider when defining schedules for DERs and groups od DERs. Smoothing the output of this resources would make them more consistent and reliable, so that they can be operated and dispatched in a more similar manner to baseload generation, with less voltage and frequency fluctuations. Renewable smoothing must be planned over different time frames, ranging from seconds to address power quality (real-time), to days for power purchase agreements and participation in day-ahead markets (short-term), and even to years to estimate future generation portfolio requirements (planning) [38].

3) Look-Ahead 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 transformer substations, 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], [33]. In this regard, a DERMS shall define operational boundaries—referred to as operating envelops—for, setting limits on DER production/consumption to prevent potential issues based on predicted grid conditions [1].

DERMS are also responsible for elaborating capacity plans to allocate DER capacity to meet the expected future load requirements while accounting for basic capacity services like load shaping and shifting, and ramping reserve capacity. This ensures the grid will be able to reliably meet demand, even during peak periods. L-A frequency control is another crucial aspect, which aims to maintain grid frequency within acceptable limits through the efficient use of DER resources. A DERMS shall utilize forecasted data to schedule frequency regulation services to ensure DERs are ready to provide support when needed. Voltage support is planned through voltage regulation activities to keep grid voltage within specified limits and minimize voltage fluctuations. Using forecasted data, DERMS shall define volt/var and volt/watt control strategies to ensure voltage stability through proactive planning of DER operations [33].

3.2.1.5 Analysis & Reporting

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 will allow for the economic compensation of customer- and utility-owned DERs—incentivizing DER adoption—and can serve as a basis for commercial and financial transactions, and for DER portfolio planning from either the utility's or the aggregator's perspective [38]. Customized reports shall be generated based on the needs of different stakeholders, such as utility operators, regulators, and customers. This module should cover, at least, the following areas:

1) *Performance Analysis*: assesses DER performance in providing grid or customer services by comparing pre-event and during-event energy usage. DERMS gather performance data from small DERs taking part in utility programs, large individual DERs, and third-party aggregated DERs, and combine it with customer meter data to ensure accurate billing and contractual compliance [38]. Reports should track critical metrics—such as energy production, power quality, DER efficiency, and status—, and analyze the broader impact of DERs on the grid, including contributions to frequency and voltage stability, and congestion management. Both real-time and historical data shall be included to provide a comprehensive view of DER performance over time, which helps identifying trends in DER performance and reliability, understanding long-term behaviors, and making informed decisions concerning DER portfolios. Detailed reports on specific events, such as demand response activations, fault clearances, and outage responses, are key to analyze DER performance and economic savings during critical periods [3], [33].

2) *Regulatory Compliance*: reports must be elaborated on how DERs meet regulatory standards and requirements. This includes monitoring compliance with local, state, and federal regulations to ensure legal and operational adherence, as well as maintaining detailed audit trails of DER operations and interactions to support regulatory audits and reviews. This documentation is essential for demonstrating compliance with nascent DER regulation and supporting DER adoption [3].

3.2.2 DECENTRALIZED/AGGREGATOR DERMS

Aggregator DERMS focus on the aggregation of multiple small-scale, often behind-the-meter resources connected to the LV network—e.g., rooftop solar, small residential battery storage systems, EVs, and smart home appliances—with the purpose of offering their services in an aggregated, optimized, and simpler manner for both customers and power system operators [1]-[3], [6]-[8]. Many of the functionalities included in this section are similar to those developed above but applied at the aggregator level; thus, some of them will not be described extensively here again. An overview of some of the DERMS aggregated systems and their interaction with utility systems is provided below.

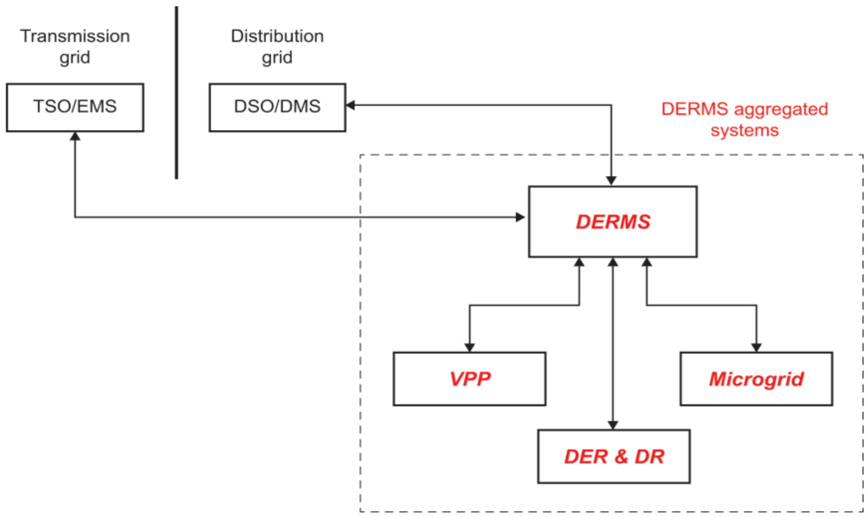

Figure 3. DERMS aggregated systems and interaction with utility EMS and DMS systems [33].

3.2.2.1 Enrollment

The Enrollment service of an Aggregator DERMS enables that all DERs are properly identified, categorized, and managed at the aggregator level to support further aggregated functions. As in the case of Utility DERMS, enrollment should include detailed information about each DER device in terms of identification, aggregation, and technical details and parameters, so that they can be properly controlled by the aggregator to provide a variety of grid services [33], [38].

1) *Registration*: this function is equivalent to that of Utility DERMS described above. It allows to identify and validate the DER devices that will be managed by a particular aggregator [33]. It provides a comprehensive registry of all these DERs, capturing relevant technical, programmatic, and network information about each of them, and enabling greater visibility to the aggregator [38]. Registration information must include as much of the following as possible (described in previous section): nameplate, communication, installation, programmatic, and DER modeling information, electrical location and other network information, device settings and interconnection rating, and in/out of service dates [33].

2) *Aggregation*: somewhat similar to the Grouping functionality of Utility DERMS. However, in this occasion, Aggregation is often performed by third-party entities that then interface with Utility DERMS to facilitate access to customer data and the visualization and management of BTM DERs. DER aggregation enables grid operators to monitor, control, and optimize multiple small-scale DER devices located close to consumption or even on the customer side of the meter—such as rooftop solar, EVs, or controllable loads—as a single, controllable entity [1], [38].
   This grouping can be based on DER type, technical characteristics, geographical factors, network topology, ownership, or communication methods, and allows to aggregate real-time data, energy, and active and reactive power outputs from various distributed resources for easier and more efficient DER and grid management. In this manner, system operators can have an aggregated view of DER data for effective decision-making and, crucially, only have to monitor the total energy and power injected into the grid—either positive or negative—instead of the outputs of each of the individual DERs [33], [38]. DER aggregations can be also incorporated to—or constitute on its own—virtual power plants and demand response programs (to be developed below) for localized grid services and DER participation in wholesale markets [38].

3) *Asset Configuration & Modeling*: equivalent to that of Utility DERMS, applied this time to the DERs included in a certain aggregator portfolio. It involves notifying the

aggregator of the status, operational capabilities, and limitations (current and projected) of each DER device under its management, so that they can be utilized for providing grid services in a secure and efficient fashion. This must be done with an agreed periodicity and by using a common communication protocol for all aggregated DERs. As much of the following information should be periodically communicated: DER identifier, status and controllability, current and available modes of operation, services in which the DER is participating, real-time active and reactive power output, voltage, available capacity, and projected availability in different time scales [33]. This information allows aggregators for incorporating accurate real-time DER data to the digital models of their DER portfolio, to visualize, control, and optimize their resources.

3.2.2.2 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:

1) *DER Monitoring & Control*: similar to Utility DERMS, 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. As developed in previous section, this collected information should include, at least, the following according to IEEE Std 1547-2018: DER active and reactive power output, instantaneous single- or three-phase RMS voltage, instantaneous RMS current, frequency, operational status (on/off), connection status (connected/disconnected), alarm status (active/not active), and operational state of charge (0-100%). This information can be either used by DERMS or shared with other management systems like ADMS—through non-proprietary standard communication protocols—to ensure efficient and coordinated management of the distribution network [33].

   DER control involves utilizing this real-time monitoring data to ensure DERs are providing the required capacities at the scheduled times according to the previously set economic, reliability, or environmental goals [33], [38]. This includes dispatching control signals for capacity, energy, and set points to DER aggregators, managing response curves like frequency/watt and volt/VAR, as well as providing confirmation of the execution of these control commands and alerting system operators if schedules are not being followed. Control actions and modifications on DER operations and schedules must be always communicated to a grid-aware management system and validated against network constraints and requirements, technical capabilities, and contractual obligations before implementation [33].

Another crucial responsibility of DER aggregators is to ensure that DERs providing multiple services or participating in more than one program do not exceed their ratings. An example are DERs used for continuous power injection and for providing reserve capacity for ancillary services like frequency or voltage regulation [33].

2) *DER & DER Portfolio Optimization*: a key role of DER aggregators is to deliver the requested grid services by optimizing the energy and capacity usage of the DERs within its portfolio. In this regard, Aggregator DERMS are responsible for optimizing the operation schedules of each of their individual DERs (unit commitment), and for performing an economic dispatch that maximizes overall DER value and minimizes total generation costs—considering electricity prices, DER operating limits, contracted periods, participation in utility programs, and even environmental considerations such as greenhouse gas emission rates—while meeting power and energy requirements, as well as the technical constraints imposed by Utility DERMS, to achieve economic, reliability, or environmental goals. Then, aggregators communicate the resulting setpoints to individual DERs so that their power output is adjusted in accordance [1], [38].

   Thus, Aggregator DERMS can coordinate the secure and efficient dispatch of their aggregated resources while ensuring system reliability and preventing overloading, voltage and frequency stability issues for the main grid. Dynamic re-optimization of DER schedules may be required in order to maintain reliability within the aggregator's local network, quickly adapting to changes in DER available capacity, communication issues, or modifications in grid conditions that alter the requested outputs [33].

3) *Demand Response (DR)*: this functionality encompasses a range of essential tasks for managing DR programs. These include customer enrollment, event scheduling, forecasting weather impacts and DER available capacity, communication of setpoints to the different resources (dispatch signaling), and measuring and verifying event outcomes—to be incorporated to the performance analysis functionality of the reporting module. DR provides Utility DERMS platforms with enhanced control and visibility over customer-owned DERs and allow them for leveraging their flexibility to balance supply and demand during peak periods or in response to grid constraints [2], [38].

   DR programs include both indirect behavioral DR, where customers receive notifications and adjust their load as needed, and direct control DR, capable of directly switching on and off certain smart devices. Dispatch strategies for these programs are typically triggered by the utility or system operator, and often rely on forecasting capabilities and incorporate price signals to determine the optimal DER utilization. In critical peak pricing or event-based DR scenarios, customers are usually notified in advance of upcoming DR events, allowing them to opt-out or modify their load reduction actions.

   DR programs can manage a diverse portfolio of DERs—from small residential smart appliances to larger commercial and industrial assets and loads—and must be capable of communicating effectively with various customer classes. Although economic settlement with customers is also part of the DR process, this is typically handled within the Settlement functionality that will be described below [38].

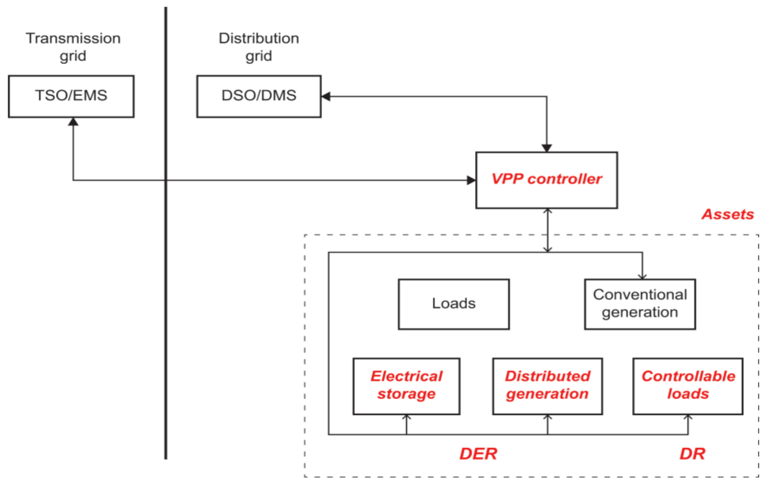

Figure 4. Possible VPP structure and interaction with utility EMS and DMS systems [33].

4) *Virtual Power Plant (VPP)*: VPPs combine various distributed energy resources into a single, dispatchable entity that can provide flexible capacity for enhanced system-wide resilience, efficiency, and a variety of grid services. This includes demand response capabilities, load balancing and frequency regulation, providing operational reserves, aggregated participation in ancillary service and wholesale markets, or peak load reduction, which are achieved by the effective coordination and optimal dispatch of DERs. A possible VPP structure, such as the one provided in Figure 4 above, may consist of a single type of asset, such as residential battery storage, or a mix of assets, including various distributed generation resources, electric vehicles, smart thermostats and other flexible loads, and commercial and industrial storage systems [1], [2], [26]-[28], [38].
Using an Aggregator DERMS to create and manage a VPP offers additional advantages, such as the possibility of integrating with grid-aware enterprise systems like Utility DERMS and/or ADMS, as well as with SCADA and AMI systems to provide localized grid services efficiently [1], [38]. Although VPPs were initially conceived for energy supply—and this is often its main application—, they can also serve DR and load reduction purposes, enhancing grid reliability and maximizing the value of a wide range of DERs aggregated under a single management framework [38].

5) *Microgrid Management*: this functionality requires interaction with grid-aware utility enterprise systems, so that microgrid controllers can enjoy access to accurate network information about local grid constraints and technical limits. It involves the secure and efficient operation of a microgrid, managing DERs and loads within clearly defined geographical boundaries, and enabling smooth transitions between grid-connected and islanded modes as required [1], [5], [24]. Microgrid management focuses on enhancing grid resilience at a localized level, maintaining frequency and voltage stability, and ensuring power supply against major outages caused by during external events like storms, floods, wildfires, and other extreme weather conditions. This involves leveraging microgrid assets both during normal grid-connected operation (blue-sky mode) and when operating independently from the grid (islanded mode) [38].

In grid-connected mode, microgrid management provides unit commitment, economic dispatch, and other services for the optimal operation of DERs within the microgrid. This ensures efficient resource usage and the positive contribution of the microgrid to the main grid. When disconnected from the network, it manages grid-forming operations, including frequency and voltage regulation, and balancing services to ensure resource adequacy and the stable and reliable microgrid operation [1], [33]. A potential microgrid structure is presented in Figure 5, together with its interaction with utility EMS and DMS systems.

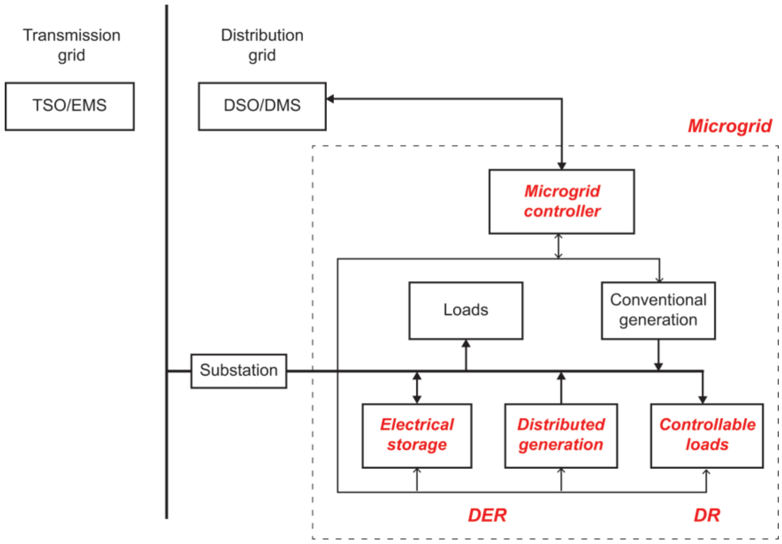

Figure 5. Possible microgrid structure and interaction with utility EMS and DMS systems [33].

Microgrid management provide utilities with greater control over both planned and unplanned islanding events, improving visibility and ensuring optimal DER performance within the microgrid. Through this functionality, Aggregator DERMS must be capable of dispatching and managing DER data to support grid operations, provide ancillary services, and even participate in energy markets. Then, centralized Utility DERMS can aggregate, oversee, and hierarchically manage and coordinate multiple microgrids with surrounding grid system for greater grid resilience [38].

3.2.2.3 Market Operations

The Market Operations module consist of a series of economic and transaction 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 [1], [38]. These systems shall be equipped to monitor, forecast, and provide information about market conditions—including Locational Marginal Prices (LMPs) and other relevant parameters—to optimize resource usage, energy purchases and sales, and coordinate with third-party entities managing BTM DERs. While this module has been primarily focused on Aggregator DERMS and the aggregated participation of small-scale DERs in both local flexibility and wholesale markets, it does not exclude the fact that some of the functionalities described below may be also applicable to larger individual DERs managed directly by the utility, which participate in the market through a Utility DERMS [1], [2], [38].

1) *Aggregator Data Exchange*: this functionality is essential for enabling utilities to interact and exchange data with small-scale, BTM, customer-owned, DERs normally managed by aggregators and third parties, and enable their participation in electricity markets. DER aggregators allow for a more efficient exchange of information and enhanced visibility and management of these individual resources, but they also create the need for customized interfaces to ensure secure and accurate data transfer between Utility DERMS and Aggregator DERMS. Effective data exchange is crucial for this interoperability and collaboration among different hierarchies of DERMS solutions, though further standardization of industry interfaces will be required for this purpose. Therefore, a DERMS should incorporate features to facilitate data exchanges with third parties and aggregators, supporting standardized data formats and allowing for market operations [1], [38].

2) *Bidding*: this functionality enables both individual utility-owned DERs and third-party aggregators managing small-scale DERs—which could not take part in electricity markets independently due to regulatory barriers—to actively submit bids and offers for

buying or selling energy in local or wholesale markets and for providing ancillary services. Market participants typically use a specialized trading system to create and format their bids and offers for market submission. Then, this trading system integrates all participants' bids and bilateral contracts to minimize electricity cost [38]. A DERMS could feed this trading system with multiple, very diverse, and detailed DER bids, offering a wide range of possibilities to optimize DER participation in energy markets and allowing for a more efficient electricity mix.

Additionally, DERMS can be used to monitor the status of DER bids into wholesale and ancillary markets. To comply with ISO/RTO tariffs under the competent regulation, utilities will need enhanced capabilities to review and approve DER aggregations formed by third parties before these bids are submitted to the wholesale market. This ensures that all bids adhere to regulatory requirements and are optimized for market participation [38]. Additionally, tight integration between Aggregator and Utility DERMS is required to ensure that DER bids and transactions are validated against grid constraints [1].[38]

3) *Settlement*: it involves comparing actual operations with planned or forecasted operations and making the required charges. Traditionally performed by a DRMS after load control events, this process can also be managed by a DERMS by analyzing a customer's baseline energy usage and comparing it against its consumption during demand response events [38], or the equivalent procedure for a generating unit increasing or decreasing its power output. Settlement takes place at both wholesale and retail levels. At the retail level, settlement may occur between utility and users participating in DR programs through an aggregator after load control events, using baseline and event consumption data to calculate the due monetary compensation—in the shape of rebates or credits. For wholesale settlement, utilities reconcile with the system operator based on planned vs. actual energy consumption or generation, creating settlement charges [38].

4) *Transactive Energy*: this functionality consists of coordinating producers and consumers' devices and equipment to communicate and exchange energy, virtually, dynamically, and in real-time, based on value signals and grid reliability constraints. In

a transactive energy system, participants are incentivized to buy and sell energy and ancillary services and negotiate between themselves through market mechanisms in response to changing generation capacities and load profiles. Transactive energy is usually associated with and supported by blockchain technology, as the energy exchange occurs in a decentralized manner (without the involvement of a central entity) and directly between participants (peer-to-peer) [39].

Aggregator DERMS facilitate transactive energy by enabling customers, individually or as groups, to participate in energy markets based on these value signals related to demand levels, energy prices, time of day, and other factors. The DERMS sends these signals to its customer DER devices, which have preset and automated features allowing them to respond appropriately according to the particular DER settings and the customer's flexibility and needs. Aggregator DERMS support scalable aggregation and near real-time management of small-scale DERs and, therefore, they can play a crucial role in transactive control and market-based coordination of BTM DERs [38].

3.2.2.4 Revenue & Portfolio Analysis

In a similar manner to the Analysis & Reporting service of a Utility DERMS, the objective of Revenue & Portfolio Analysis 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 [38]. Different reports may be generated based on the needs and interests of stakeholders, such as utility operators, regulators, and customers. This module should cover the following areas:

1) *Performance Analysis*: it assesses the performance of the different DERs under the aggregator management in providing grid or customer services by comparing pre-event and during-event energy usage. Aggregator DERMS gather performance data from small-scale, normally BTM, DERs and groups of DERs taking part in utility programs—such as DR—and combine it with customer meter data to ensure accurate billing and contractual compliance [38]. 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. Both real-time and historical data may be included to provide a comprehensive view of DER performance over time, which helps identifying trends in DER performance and reliability, understanding long-term behaviors, and making informed decisions concerning DER portfolios. Detailed reports on specific events, such as demand response activations, fault clearances, and outage responses, are key to analyze DER performance and economic savings during critical periods [3], [33].

2) *Portfolio Analysis & Planning*: overall, this functionality is 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 enhance the strategic management and planning of DER assets, looking to improve their technical and economic performance and ensuring they meet the future needs of the grid and customers effectively. It involves assessing the performance, capabilities, and potential of each DER asset, and its synergies with other assets, utilizing data on metrics such as energy production, power quality, DER efficiency, and operational status. In this manner, Aggregator DERMS aim at identifying trends in DER performance and reliability, understanding long-term behaviors, and making informed decisions about its DER portfolio. Changes in demand patterns, storage capabilities, market conditions, regulations, and technological advancements should also be considered.

3.2.3 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 collaboration with Minsait, company with which the author had the opportunity to work during the development of this project. The resulting classification is displayed in the graph 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).

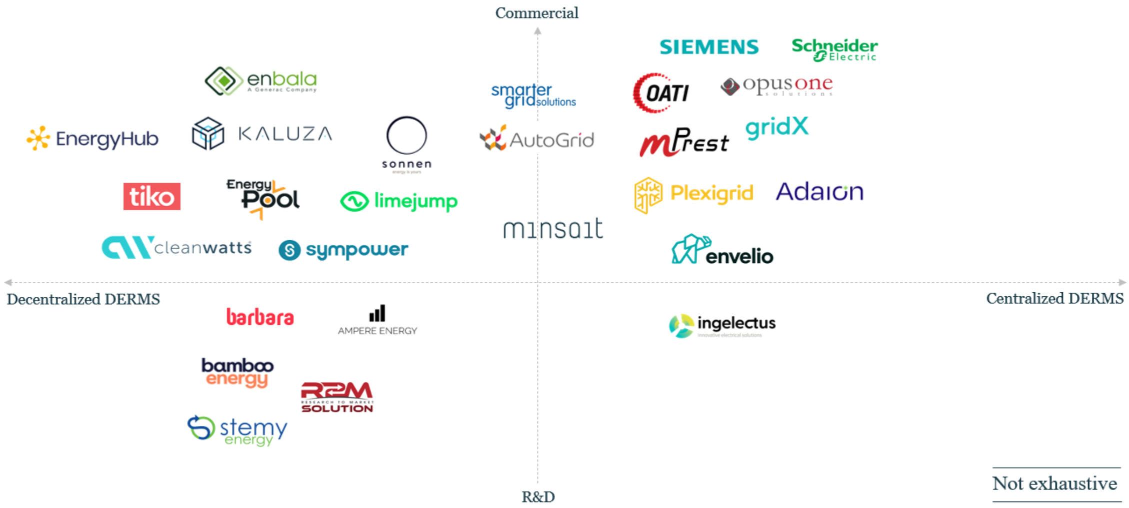

Figure 6. DERMS Vendors' Comparison. Source: Minsait.

It can be observed that 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 it has been already mentioned above, the industry often tends to view DERMS as utility-exclusive solutions.

3.3 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, between utilities and aggregators, and between aggregators and individual DERs [1]-[4], [8], [9]. Is the view of this work that Distributed Energy Resources Management Systems will be essential for managing and integrating distributed energy resources (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. The term *standards* may refer to two different aspects: (i) functional definitions or specifications about the expected functionalities and services that DERMS and DER devices should provide, and (ii) communication protocols and information models aimed at facilitating interoperability and allowing systems and applications from different providers to exchange data and to be integrated without requiring custom mapping between them [9].

The first has already been explored in Section 3.2 when discussing the state of the art about DERMS functional specification, where the perspective from the IEEE Std 2030.11 was collected together with those from other utilities and vendors. However, numerous additional protocols and Grid Codes with standard functional definitions and requirements exist for DERMS, such as the IEC 61850-7-520 for function definitions at the device level, the IEEE 1547.1 for functional testing, or the IEC 61968-5 (that will be also discussed below) for group-level function definitions. The reader is referred to Table 1 of [9] for a summary of standards and related documents describing DERMS interface functionalities. The second category of standards will be discussed in this section, highlighting some of the enabling communication protocols and information models for the sustainable and scalable implementation of DERMS, first focusing on the DER-group level interface and then at the device level as proposed in [3], [4], and [9] and displayed in Figure 7 below.

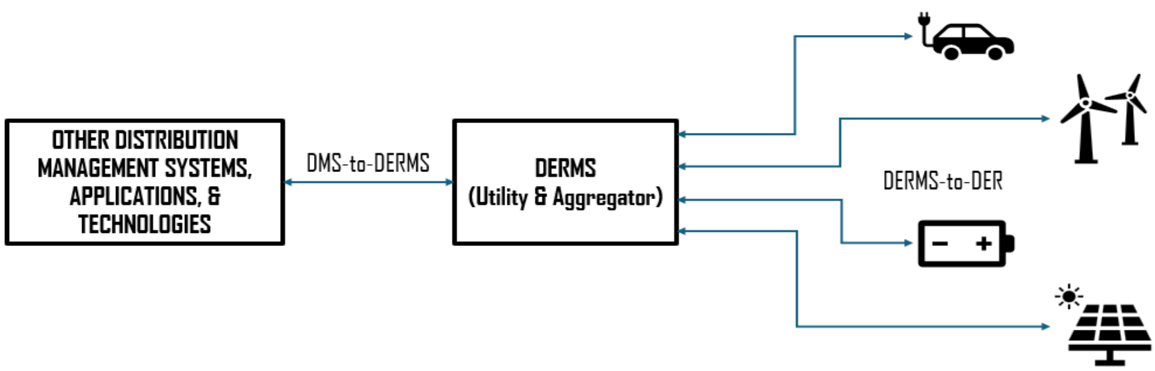

Figure 7. Overview of interface levels of the enabling protocols for DERMS implementation.

3.3.1 DMS-TO-DERMS LEVEL[3]

The development of SGs and the deployment of multiple measurement and information systems increase the complexity of effectively managing and integrating the vast amounts of data generated and stored across the network, originating from different sources. Without proper interoperability, this can lead to issues such as data duplicity, information mismatches, inconsistency, and incompatibility, which negatively impact utility operations, business decisions, and overall grid reliability. Effective data integration is therefore essential for optimizing the management of distributed energy resources, avoiding indirect costs associated with, e.g., development of translators and licensing, and ensuring smooth operations within the utility ecosystem [3].

In particular, utility enterprise integration is a vital concept for being capable of deploying and expanding various systems and technologies within distribution utilities, especially in a context of increasing adoption of SG solutions [40]. This has driven initiatives in pursuit of a standard supporting the integration between different applications and systems for efficient utility operations. In this regard, The Common Information Model (CIM) has gained the support of the industry and a wide recognition among utilities and vendors as a step forward towards the modernization of the electricity grid. CIM provides the necessary concepts and rules for managing communication among various applications, facilitating the integration of new measurement and management systems within the distribution network—as is the case of DERMS solutions [3], [41].

3.3.1.1 The Common Information Model (CIM)

The Common Information Model (CIM) is a family of standards developed to address data interoperability and standardization challenges in the exchange of information among different enterprise utility systems. Its primary objective is to create a detailed framework

[3] [3] and [9] generally refer to this interface level as the DMS-to-DERMS Level, aiming to encompass those protocols and standards enabling the integration and data exchange among different utility enterprise systems, applications, and technologies that contribute to the management of the distribution network—including DERMS. It does not imply that these protocols only allow for the interaction between DMS and DERMS.

for modeling the power system that avoids the need to maintain different databases in various formats across different subsystems within a utility enterprise network. The model consists of three fundamental working groups (WGs), each focusing on distinct areas. WG13 addresses definitions of electrical modeling with an emphasis on TSO perspectives. WG14 focuses on system interfaces for managing the distribution network, expanding the WG13 concepts to distribution utilities and DSOs, detailing DER modeling, unbalanced networks, and MV and LV networks. Finally, WG16 aims to support data interoperability and information exchange among energy markets participants, contributing to the continuous deregulation of electricity markets [3], [41].

WG14 is, therefore, the one on which the present work will focus at this stage. This working group has led to the development of the International Electrotechnical Commission (IEC) series of standards 61968, which extends CIM concepts to address data exchange, communication patterns and functional setup specifically for distribution management [4]. These standards provide comprehensive guidelines for integrating different applications and systems within a utility enterprise, providing a common framework for data modeling and supporting reliable operations. The IEC 61968 series include several subparts [3], [41], [42]:

1) *IEC 61968-1*: introduces the general recommendations and interface architecture for the interaction and message exchange among different enterprise systems—such as between an ADMS and a DERMS.
2) *IEC 61968-2*: IEC 61968 glossary.
3) *IEC 61968-3 – IEC 61968-9*: implementation interfaces to the typical distribution utility enterprise systems.
    - *IEC 61968-3*: interface for network operation.
    - *IEC 61968-4*: interface for records and asset management.
    - *IEC 61968-5*: interface standard for operational planning and distributed energy optimization.
    - *IEC 61968-6*: interface for maintenance and construction.
    - *IEC 61968-7*: interface for network extension planning.
    - *IEC 61968-8*: interface for customer support.

- *IEC 61968-9*: interface for meter reading and control.

4) *IEC 61968-11*: CIM extensions for data modeling in distribution networks.
5) *IEC 61968-13*: exchange format for the CIM Resource Description Framework model in distribution.
6) *IEC 61968-100*: definition of IEC 61968 implementation profiles and technologies to integrate other parts of the standard using common integration tools—e.g., Java Message Service (JMS), web services, and Enterprise Bus Technologies (ESB) [4].

3.3.1.2 IEC 61968-5 for DERMS Implementation

IEC 61968-5 is of particular importance for the deployment of DERMS solutions and their interaction with other utility enterprise systems. This subpart of the IEC 61968 standard details the scope and guidelines for incorporating DERMS functions, facilitating the efficient management of distributed energy resources and their integration into the utility's operational framework. Its primary focus is on the interaction between DMS/ADMS and DERMS, and on the DERMS effective management of DER groups [3], [4]. The scope of IEC 61968-5 includes several areas concerning the optimal management and operational efficiency of DER groups, establishing a set of rules for interaction and message exchange for DERMS. These guidelines apply to a series of use categories, namely [43]:

1) *Creation of DER groups*: involves the aggregation and coordination of existing DERs into manageable units. This process allows for a seamless integration of DERs, making it easier to manage and optimize their performance within the grid.
2) *Maintenance of DER groups*: encompasses the introduction, removal, and ongoing management of DERs within these groups. This functionality ensures that DERMS can adapt to changes in the DER landscape, maintaining an up-to-date and efficient operational framework.
3) *Deletion of DER groups*: ensuring that obsolete or redundant groups can be removed without disrupting overall system performance.
4) *Status & event monitoring*: it enables DERMS to determine and quantify the operational status of DERs within a group. This functionality is crucial for maintaining real-time

awareness of DER performance, allowing for conducting the necessary adjustments when required and for updating the system digital models.

5) *Forecasting*: allowing DERMS to predict future statuses and capabilities of DERs, which is essential for DER scheduling and for proactive grid management and planning.
6) *Dispatch*: which enable DERMS to request the available capacity of DER groups so that they can be dispatched to the grid to effectively to meet grid demands.
7) *Voltage ramp rate control*: to communicate specific ramp rate requirements to a DER group for, e.g., load balancing purposes, ensuring stable and reliable grid operations.
8) *Connection/disconnection*: to require individual DERs to connect and disconnect to and from the grid to optimize grid performance and reliability.

By adhering to the guidelines set by the IEC 61968-5, utilities can ensure that their DERMS implementations are robust, scalable, and capable of interacting with other information and management systems like ADMS. Reference [9] highlights some additional protocol encodings for DER groups, such as MultiSpeak 5.0, OpenFMB, or OpenADR 2.0. However, these will not be discussed here, and the reader is again referred to Table 2 of [9] for further information. As an example of this interaction between enterprise utility systems, the following figure shows a flow diagram illustrating a potential request submitted to a DERMS for the creation of a DER group.

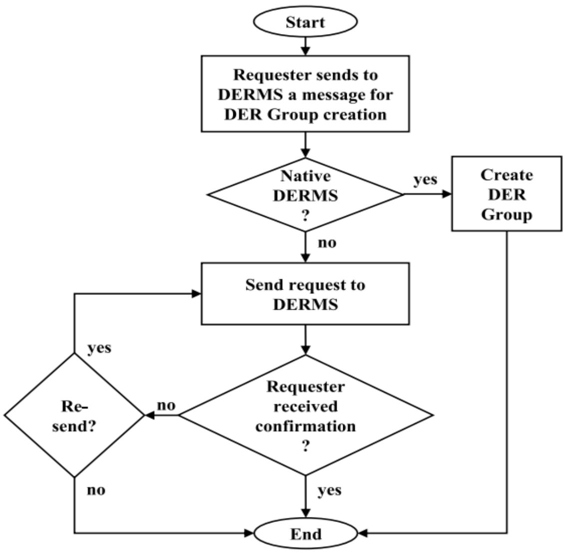

Figure 8. Flow diagram corresponding to the request for creating a DER group [3].

3.3.2 DERMS-TO-DER LEVEL[4]

At the DERMS-to-DER level, various communication protocols enable interaction between DERMS (Utility and Aggregator DERMS) and individual DERs deployed across the distribution network, ensuring reliable data exchange, real-time monitoring, and control of DER assets. The exchanged information normally consists of AMI measurements from BTM resources, forecasted production of individual DERs, and their operation schedules, which can then be used in real-time applications by DERMS and other enterprise utility systems like ADMS. Thus, a smoother data transfer through standardized communication protocols would improve the observability of grid conditions, but also the ability to share planned schedules of DERs, modify schedules in real-time, predict constraint violations, and send specific commands to inverters [1], [8].

Table 6 of section 7.3 of IEEE Std 2030.11-2021 ([33]) includes a list of common communication protocols that have been identified as viable alternatives for DERs. The protocol to be employed will be often determined by the competent power system operator of a particular area. However, the standard also emphasizes that additional proprietary protocols may be also used under agreement between the local power system operator and the DER service provider, as well as that a DERMS should be flexible enough to utilize other protocols [33]. Appearing on this list are some of the most used and widely recognized communication standards for DERMS such as IEEE Std 1815-2012 (DNP3), IEEE Std 2030.5-2018, OpenADR, and SunSpec Modbus, which will be the ones discussed in this section. However, other relevant standards include the IEC 61850 series, with a set of functional requirements for device-level communications (IEC 61850-7-420 for the definition of information models to be used during information exchange among dispersed DER devices, IEC 61850-8-1 and IEC 61850-8-2 for DER-level communication functions, etc.) [4], [9], [33]; or the IEC 60870-5-104 describing transmission protocols for telecontrol equipment and systems [4], [33].

[4] In this terminology, "DERMS" refers to both Utility and Aggregator DERMS.

Performance requirements for communication with DER devices are commonly unique for different regions and can be found in multiple Grid Codes worldwide and regulatory initiatives like the California Rule 21 [9]. A specific set of these requirements is included in Table 42 of IEEE Std 1547-2018 ([44])—which generally addresses the DER interconnection and interoperability with power system interfaces—but will not be developed here. Protocol testing is also covered in this standard [9].

3.3.2.1 IEEE Std 1815-2012 (DNP3)

The Distributed Network Protocol (DNP3) is one of the most widely used communication standards in North American utilities for power systems monitoring and control—although it has also been deployed in the water and wastewater industries. DNP3 is designed to facilitate interoperability between equipment from different vendors, allowing seamless communication within the same network [3], [45]. DNP3 is highly scalable, making it suitable for applications ranging from Remote Terminal Units (RTUs) and Intelligent Electronic Devices (IEDs) to complex automation systems in substations and master control centers. It focuses on reliability and robustness, ensuring that data transmission remains consistent and accurate even in noisy environments, which is achieved through features like error checking and sequence verification [45].

One of the key advantages of DNP3 is its event-driven reporting capability. Unlike protocols that rely solely on polling—process in which a central controller (master) periodically requests data from remote devices (slaves)—, DNP3 allows remote devices to autonomously report events to the master station as they occur. This makes the protocol more efficient and responsive to real-time changes. Additionally, DNP3 supports a wide range of data types, including binary inputs, analog inputs, counters, and control outputs, and can handle different data formats such as packed, unpacked, and BCD. It is also capable of operating over various physical media, including serial connections, TCP/IP, and radio, which enables deployment in diverse environments and network topologies. Lastly, time synchronization is another important feature, allowing precise timestamping of events for accurate data logging and analysis [45].

Originally, DNP3 did not include security features, but these were later incorporated through the DNP3 Secure Authentication (SA) as part of the IEC 62351-1 standard, which adds an additional security layer to the data package between the pseudo-transport and application layers [3]. This security layer includes features for authentication, encryption, and integrity, protecting the system against cyber threats and ensuring secure and reliable communication with DER assets. These characteristics distinguish DNP3 from other protocols, particularly in its application to critical infrastructure and automation within the utility sector [45].

DNP3's robustness and reliability make it a preferred choice for utility communication, particularly in applications that require high levels of reliability and security. Its ability to support a wide range of devices, data types and formats, and physical media, together with its time synchronization feature and its event-driven reporting capability make it a versatile protocol for DERMS implementations.

3.3.2.2 IEEE Std 2030.5-2018

The IEEE 2030.5-2018 standard, or IEEE Standard for Smart Energy Profile Application Protocol, is designed to operate at the application layer of the Open Systems Interconnection (OSI) network model, with support from the transport and Internet layers, ensuring seamless utility management of energy resources through TCP/IP functions [3], [35]. This standard is arguably the most relevant in terms of DERMS and DER-related applications, and regulatory initiatives like California Rule 21 have indeed established IEEE 2030.5 guidelines for monitoring and control as a reference for the communication interface between utilities, aggregators, and DER devices [4]. IEEE 2030.5 integrates elements from several existing standards, including IEC 61968 and IEC 61850, and provides extensive support for various grid services such as demand response, load control, time of day pricing, and the management of DG, ESS, and EVs [3], [35].

IEEE Std 2030.5-2018 incorporates robust security measures, including HTTPS (Hypertext Transfer Protocol Secure), mutual authentication based on device certificates, and encryption using AES-CCM (Advanced Encryption Standard - Counter with Cipher Block Chaining-Message Authentication Code) to ensure secure communication between energy devices and utility management systems. The standard is also designed to be extensible and flexible, supporting different physical layer protocols (e.g., IEEE 802.15.4, IEEE 802.11) and including mechanisms for future extensions to accommodate evolving technological needs. IEEE 2030.5-2018 includes detailed requirements for device capabilities, discovery, and registration, which facilitate the management and integration of various smart devices, and the seamless implementation of demand response and load control functionalities [35].

In essence, IEEE Std 2030.5-2018 is notable for its high interoperability, incorporating elements from other standards, and for establishing a comprehensive, scalable, and secure protocol for managing smart energy devices and DER assets. Its extensive support for a wide range of grid devices—such as such as storage systems, home appliances, Energy Management Systems (EMS) applications, DR, and smart meters [3]—makes it a preferred option for any DERMS implementation.

3.3.2.3 OpenADR

The Open Automated Demand Response protocol is a non-proprietary, open, standardized and secure interface designed by the Lawrence Berkeley National Laboratory to support dynamic pricing for energy markets, particularly in the context of DR transactions. Also implemented at the application layer of the OSI Model, OpenADR facilitates two-way internet protocol communication of demand side management signals between electricity providers and customers [3], [46].

The OpenADR 2.0 Profile Specifications define the framework for servers, known as Virtual Top Nodes (VTNs), and clients, known as Virtual End Nodes (VENs), including services, interactions, transport protocols, and security measures to ensure interoperability among different vendors. Key services of the standard include the *Opt Service* for VENs to communicate availability schedules to VTNs, the *Registration Service* to exchange necessary information for compatible payload (instructions, signals, DER responses, etc.) exchange between VENs and VTNs, and the *Poll Service* to request payloads from VTNs [45]. In terms of transport mechanisms, simple HTTP Transport is ideal for basic implementations where VENs pull information from VTNs, whereas XMPP (Extensible

Messaging and Presence Protocol) is commonly used for applications requiring near real-time data exchange, making it suitable for fast, bidirectional communication in DR and various DER services. Finally, the protocol employs TLS (Transport Layer Security) Security with Digital Certificates on both the server (VTNs) and client (VENs) sides to ensure secure communication, and it offers the option of using Digital Signatures for additional message encryption and non-repudiation [46].

This protocol is essential for enabling real-time communication and interoperability between service providers and aggregated loads participating in DR programs. Concerning OpenADR deployment in a DERMS, Utility DERMS would typically implement a compliant server-side VTN, while aggregators could either implement a client-side VEN or aggregate smaller distributed energy resources by acting as a VTN.

3.3.2.4 SunSpec Modbus

SunSpec Modbus is an open communication standard designed to enhance interoperability among DER systems [47]. It is an enhancement of the original Modbus protocol by the SunSpec Alliance to support communication with DERs. It is referenced in and compliant with the interoperability requirements of the IEEE 1547-2018 standard (in the same way as IEEE 2030.5 and DNP3), which mandates that DER systems provide a standard communications interface for grid interconnection. At the same time, the protocol ensures backward compatibility with the original Modbus implementation while facilitating communication with various types of solar inverters and other DERs [3], [47].

SunSpec Modbus defines common parameters and settings for monitoring and controlling DERs, including voltage regulation, setting power factor, and power export limiting. It structures data to increase interoperability, allowing applications to be written using a single, standardized view of the components comprising, e.g., a solar plant, independent of manufacturer and model. This open standard can reduce the cost of system implementation and enables devices to maximize their deployment possibilities by interoperating with applications and other protocols, such as IEEE 2030.5 and IEEE 1815, not to mention that the physical Modbus interface is built into approximately 80 percent of installed DER devices [47]. In summary, SunSpec Modbus is a standardized, cost-effective, easy-to-integrate, and interoperable communication interface that simplifies compliance with IEEE 1547-2018 and can enhance the functionality and deployment of DER management systems.

This section has reviewed the most common and relevant standards for the successful deployment of DERMS, organized in two interface levels. At the DMS-to-DERMS level, standards such as CIM and IEC 61968 ensure compatibility among systems from different service providers and vendors within the utility enterprise; at the DERMS-to-DER level, communication protocols like DNP3, IEEE 2030.5, OpenADR, and SunSpec Modbus enable reliable data exchange with individual DERs. As DER penetration intensifies, the importance of robust and standardized communication protocols and information models will only increase, as well as the necessity for system operators to agree on a certain set of standards for each of the different applications and needs within a DERMS platform.

3.4 DER CONTROL ARCHITECTURES

The increasing integration of grid-edge distributed energy resources 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 and services 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 [6]:

1) *Centralized Control*

This is the most frequently implemented control strategy in the power system. Centralized control involves a central controller gathering information about DERs, conventional loads, and network parameters to make optimal control decisions and dispatch the most effective set points to all DERs. The collected data may include generation cost functions, DER operating constraints, generation forecasts, customer preferences, etc. Centralized data collection and processing ensure comprehensive system visibility, which potentially allows for achieving global optimal solutions for grid operation. However, centralized control strategies present scalability issues due to the high computational and communication complexity, as well as the risk of disrupting the entire system if the central controller fails.

2) *Hierarchical Control*

Hierarchical control includes multiple layers—two or more—of controllers, each of them with some degree of autonomy but always in coordination with the controllers in upper and lower layers. In this manner, the top layer oversees the overall control strategy with a reduced number of variables, and controller in lower layers are responsible for managing local optimization and communicating with DERs. This configuration reduces the computational complexity that a centralized central controller had to handle and improves the scalability of the system and its capability to incorporate new DERs. On the other hand, a hierarchical control structure will require sophisticated coordination mechanisms between layers and may increase the latency of decision-making due to the need for information flow between controllers.

3) *Decentralized Control*

As opposed to the centralized strategy, decentralized control assigns each distributed resource to a specific local controller, which acts as an aggregator of various DERs—this could be a BEMS, energy community, DR provider, VPP, or microgrid controller—and operates independently without relying on a central controller. These controllers optimize the performance of their respective DERs based on local measurements and objectives. Decentralized structures add resilience to the system as it does not have to rely on a single central controller, as well as flexibility and autonomy, enabling fast responses to changes in local conditions. Nevertheless, decentralized control may find difficulties in achieving global optimization due to the lack of a centralized oversight, as local controllers could lead to a suboptimal overall performance.

4) *Distributed Control*

Distributed control improves the decentralized strategy by allowing local controllers to communicate and coordinate with each other to achieve overall optimal solutions. By sharing information between them, these controllers can align local management with broader system goals to meet global objectives. This combines the flexibility and resilience of decentralized control with a coordinated approach. The distributed structure preserves the privacy and autonomy of individual DERs while enabling collective optimization and enhancing system robustness through redundancy. However, it also adds complexity in designing effective and robust communication and coordination between controllers.

5) *Hybrid Control*

Hybrid control strategies incorporate elements from centralized, hierarchical, decentralized, and distributed control methods, which provides flexibility in adapting to different grid conditions and DER ownership structures. Hybrid control can be tailored to specific system requirements and new technological advancements, incorporating different control structures to achieve the most efficient grid-edge DER management, balancing global optimization with local flexibility and enabling smooth transitions between structures. The downsides are a greater implementation complexity, and potential integration challenges when combining different control paradigms.

A DERMS facilitates the scalable implementation of these control structures by providing a platform for the aggregation, monitoring, coordination, and optimization of DER operations. Various architectures for the integration and control of grid-edge DERs through a DERMS have been developed over recent years under different projects. These architectures are usually based on one of the control strategies described above, or on a combination of several of them. Two of these architectures, considered the most developed and analyzed in the literature, are discussed below. They will be presented only at a high level, as the intention is merely to ensure that the DERMS functional and technical architecture proposed in Chapter 4 is consistent and can be implemented under any of these DER control architectures.

3.4.1 HIERARCHICAL ARCHITECTURE

The hierarchical architecture for the control of behind-the-meter loads and grid-edge DERs involves a multi-layered approach that integrates various control levels to enhance grid reliability, resilience, and facilitate the efficient use of its resources. This system is designed to manage and coordinate different types of BTM DERs—including PV solar, energy storage systems, and flexible loads—in smart homes and energy communities, along with larger-scale unaggregated resources connected to the MV distribution network [6], [48]. A graphical illustration of the hierarchical architecture is displayed in Figure 9 below. It follows, as its name suggest, a three-layered hierarchical control structure, consisting of the following main components:

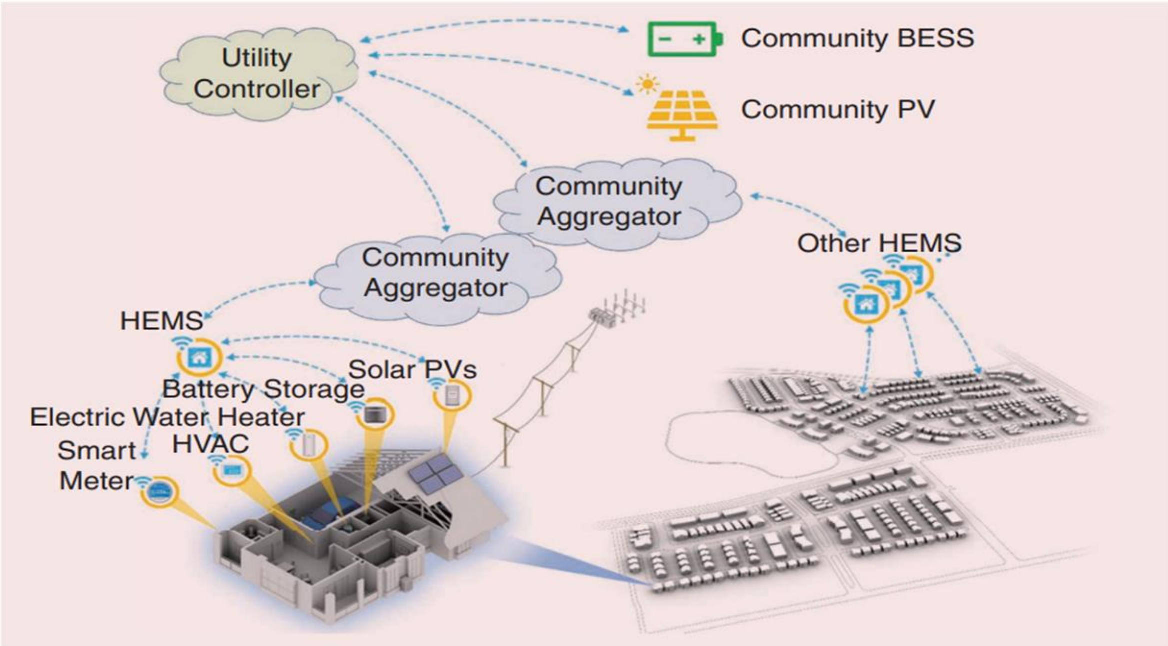

Figure 9. Hierarchical architecture for the control of BTM DERs in smart energy communities [6].

1) *Home Energy Management System (HEMS)*: a HEMS is responsible for managing individual household energy consumption and generation. It calculates the aggregated flexibility of all controllable behind-the-meter DERs inside the home—photovoltaic systems, batteries, and smart appliances—, considering customers' preferences, DER technical limits, and tariffs to optimize their energy use and provide value to the grid and to individual customers [6], [48].

2) *Community Aggregators*: they use the previous flexibility information to handle the operations of multiple HEMS within a community. Each aggregator performs a security-constrained economic dispatch of the community's aggregated flexibility, meeting the individual HEMS preferences and the technical constraints of the community network [6]. Community aggregators coordinate energy production and consumption among homes, optimizing the collective response to grid signals and ensuring that community level objectives, such as peak load reduction and voltage regulation, are met [48].
3) *Utility Controller*: this is the top-level control layer of the hierarchical architecture. The utility controller interacts with community aggregators and leverage their aggregated flexibility to solve system-wide problems. It oversees the larger distribution grid and ensures that the operations at the community level align with grid stability and reliability requirements. The utility controller manages community aggregators along with larger-scale individual DERs, such as community PV systems and a BESS, to facilitate their participation in grid services [6], [48].

Therefore, this hierarchical architecture is characterized by a continuous flow of flexibility information from the lower levels (HEMS), through the Community Aggregators, up to the Utility Controller, and by the opposite flow of setpoints from the Utility Controller to the HEMS and, finally, to the BTM and grid-edge DERs. Dispatch signals can include on/off periods for heating, ventilation, and air-conditioning (HVAC) systems or electric water heaters (EWHs), power output set points to rooftop solar and BESS, etc. [6]. The hierarchical control system was deployed and tested in the Basalt Vista Field Pilot Study in Colorado under a variety of scenarios. This project involved 27 all-electric net-zero energy homes in an affordable housing community for local teachers and workforces. The primary goal was to demonstrate the ability for a distribution utility/DSO to control and dispatch DERs while providing value to both the grid and consumers, thereby validating the effectiveness of the hierarchical control architecture. In this occasion, system-wide analysis and DER optimization were performed with the help of an ADMS [48]. The results from Basalt Vista's case studies highlighted several achievements:

1) *Grid Reliability*: hierarchical control algorithms effectively reduced the frequency and severity of overvoltages. The results clearly showed significant improvements in maintaining voltage levels within acceptable ranges by making use of the flexibility offered by BTM DERs, particularly during high PV generation periods [6], [48].
2) *Grid Resilience*: during grid resilience experiments, the community operated as a "soft microgrid," with homes exporting excess power to the grid during the day and using stored energy to power critical loads at night—minimizing power import from the grid. Critical loads were always supported, and no overvoltage issues were observed, demonstrating the system's ability to maintain functionality during disturbances [48].
3) *Load Shifting and Peak Reduction*: a one-week field experiment demonstrated the capability of the hierarchical control system to shift loads away from peak pricing periods. For instance, one of the smart homes participating in the project achieved an average load reduction of 3.1 kW and a peak demand reduction of 4.65 kW during peak hours. Community aggregators allowed for reducing the peak load while ensuring HEMS priorities, trying to balance individual homes' optimal strategies with aggregator objectives [6], [48].

Thus, the hierarchical architecture for controlling behind-the-meter loads and energy resources has proven effective in improving grid reliability and resilience, as well as in optimizing the use of grid-edge DERs. The Basalt Vista pilot project successfully demonstrated the practical application of this control strategy, highlighting its ability to manage community-scale energy resources and making it scalable and adaptable for any DERMS implementation—where the functions of the utility controller would be performed by Utility DERMS, and the community aggregators and HEMS would fall under the decentralized solutions of Aggregator DERMS.

3.4.2 FEDERATED ARCHITECTURE (FAST-DERMS)

The Federated Architecture for Secure and Transactive Distributed Energy Resource Management Solutions (FAST-DERMS)—developed under the FAST-DERMS project funded by the DOE's Grid Modernization Laboratory Consortium (GMLC) program—aims to provide reliable transmission and distribution (T&D) services through the scalable aggregation and near real-time management of different grid-edge DERs. This architecture integrates the centralized, hierarchical, and distributed control structures to efficiently coordinate both individual and local groups of DERs like buildings (B) or microgrids (MG) [6], [8], [49]. It includes several components that work together to optimize the operation of distributed energy resources. These are displayed in Figure 10 and described below:

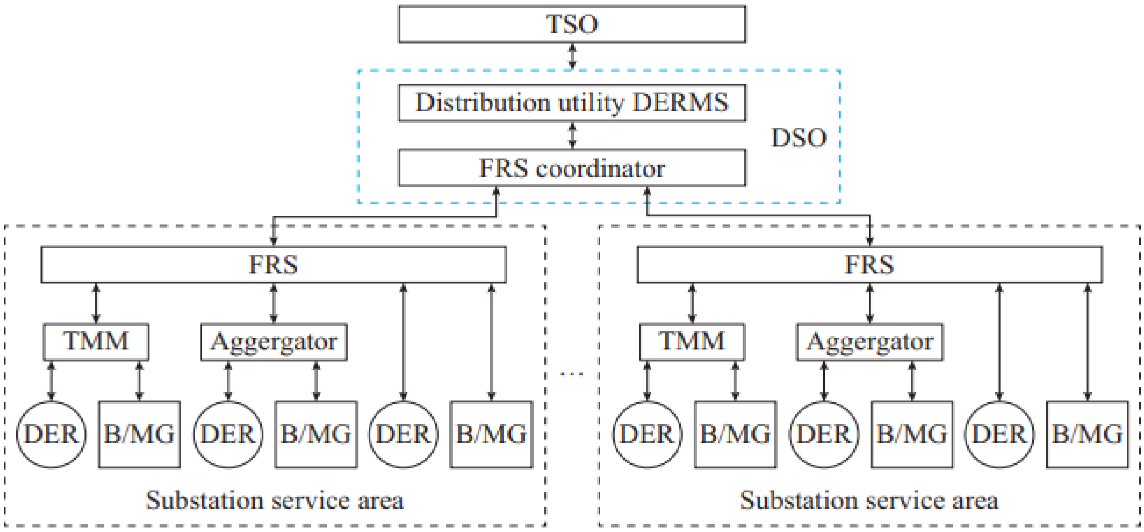

Figure 10. Conceptual schematic of FAST-DERMS [8].

1) *Distributed Energy Resources (DERs)*: solar PV, BESS, EVs, and other distributed generators, controllable loads, demand response programs, etc. These resources can participate in grid operation individually or as part of aggregated groups managed by systems like building energy management systems (BEMS) or microgrid controllers (MGCs). Additionally, any DER or group of DERs shall choose the type of incentive they would like to receive and indicate the degree of aggregation they belong to. This allows for leveraging all types of resources, including those that can autonomously respond to real-time changes in price signals and those that prefer to be directly controlled by another entity and receive a capacity payment [49].
2) *Flexible Resource Scheduler (FRS)*: this is the key optimization and control component responsible for generating firm offers to the wholesale market. Operating at the substation level, the FRS performs a reliability-constrained economic dispatch of the

DERs within its service area. FRSs aggregate and optimize all DER types downstream of a given substation—multiple FRSs will exist to cover the entire distribution system—with limited supervision from central distribution utility management systems. It coordinates DER flexibility and computes aggregated bids or schedules for wholesale and ancillary service markets, ensuring voltage and equipment loading remain within safe limits. Finally, it is responsible for disaggregating grid control signals to subscribed resources on timescales consistent with both day-ahead and real-time markets. Both individual DERs and local aggregations of DERs managed by a building management system or a microgrid controller can subscribe directly to the FRS (direct/centralized control), through an aggregator (hierarchical control), or through a transactive market manager (distributed control) [6], [49].

3) *FRS Coordinator*: it supervises, aggregates, and coordinates distribution substations operated by individual FRSs, aligning them with the corresponding TSO wholesale market pricing nodes. It enables the different FRS to interact with distribution utility management systems—such as ADMS or Utility DERMS—to ensure they have updated network measurements and constraints, so that they can optimize their substation service areas and make reliability-aware bids into wholesale markets. Lastly, the FRS Coordinator interfaces—either directly or through an existing distribution management system—with the TSO to negotiate the provision of energy and transmission grid services and redirects TSO dispatch and control signals to each particular FRS [49].

4) *Aggregators*: third-party or utility-owned entities that consolidate and control multiple DERs—such as building loads, or even microgrids to act as a single participant in power system operations and in electricity markets. They directly interact and provide aggregated flexibility to the FRS, enhancing the scalability and the technical and economic viability of DER participation in grid and market operations [49].

5) *Transactive Market Manager (TMM)*: it serves both as another method to aggregate and control DERs and as a market maker, facilitating price negotiations between different parties and managing transactive resources through a subscription to the FRS. The FAST-DERMS project contemplates two TMM schemes: (i) a one-way communication scheme, where DERs receive and respond to given price signals and price formation is

adjusted with respect to DER responses; and (ii) a two-way communication scheme where DERs submit bids/offers, directly influencing price formation. TMMs could allow, e.g., for recruiting and rewarding load flexibility resources from both energy efficiency and demand-side management programs [49].

FAST-DERMS provides a scalable approach to integrating DSO-managed grid-edge DERs into wholesale electricity markets and transmission system operations following a total-DSO model. This approach emphasizes that all resources within a distribution network should be aggregated through the distribution utility—or its representative. This ensures that the DSO maintains a comprehensive control over its network, managing the objectives of T&D systems and providing necessary grid services. By managing DER flexibility and incorporating it into the broader grid operations, a total-DSO model can balance local and system-wide reliability and economic objectives [49].

The FAST-DERMS architecture that has been described here essentially proposes a distribution utility DERMS, which is perfectly compatible with the conception of DERMS developed in this work. In this regard, Utility DERMS would incorporate the functions of the FRS Coordinator, and each FRS could be simply an Aggregator DERMS serving as a complement to the Utility DERMS—or even to an ADMS with DER control capabilities in the absence of the first—and providing aggregation, optimization and market participation functions for BTM DERs. However, the coordination between the FRS and Utility DERMS would vary significantly with respect to that of Aggregator DERMS depending on whether the FRS can schedule larger-scale DERs connected to the MV distribution network—normally operated directly by Utility DERMS—or not. If the FRS can schedule these DERs, it would have to obtain DER data from the Utility DERMS and manage them as a group of flexible resources, with the Utility DERMS controlling them in accordance with the FRS schedules. If it is the Utility DERMS who is responsible for directly scheduling these DERs (as has been developed so far), the FRS will treat the schedules of utility-managed DERs as known, non-dispatchable loads [49].

3.5 EUROPEAN REGULATORY FRAMEWORK

As the concept of electricity grid evolves due to the increasing penetration of distributed energy resources, with distribution networks becoming more active and dynamic, it becomes critical for regulation to accompany this transition. 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. Multiple areas remain to be clarified: if DSOs should be capable of directly using the flexibility provided by DERs, whether aggregators should offer their capacity to DSOs or directly to TSOs, or who should ensure the feasibility of market schedules within the distribution grid [1].

In this context, several organizations and industry and DSO associations will have to play a role in updating and shaping policies and ensuring regulatory uniformity across different regions. These entities collectively ensure the coordination, regulation, and advocacy necessary for a reliable and integrated European network operation, as well as the proper functioning of electricity markets. This chapter will provide an overview of the main European regulatory bodies in the field of electricity, and then delve into various aspects of the most current regulatory framework concerning distributed energy resources and their management.

3.5.1 COMPETENT REGULATORY ORGANIZATIONS

The most relevant European organizations in terms of electrical regulation are presented below. These entities include regulatory institutions such as ACER (Agency for the Cooperation of Energy Regulators), ENTSO-E (European Network of Transmission System Operators for Electricity), the EU DSO Entity, or CEER (Council of European Energy Regulators). DSO and industry associations—advocate for the interests of national DSO and industry participants—like E.DSO (Europe's Distribution System Operators), CEDEC (European Federation of Local Energy Companies), GEODE (Groupement Européen des Entreprises et Organismes de Distribution d'Energie), Eurelectric, and smartEn (Smart Energy Purpose) are also considered in this section.

1) ACER (Agency for the Cooperation of Energy Regulators)

ACER, established by Regulation (EC) Nº 713/2009 and officially launched in March 2011, is headquartered in Ljubljana, Slovenia. It ensures the proper functioning of the single European market in gas and electricity by assisting and coordinating national regulatory authorities. ACER plays a key role in integrating EU energy markets, providing regulatory clarity and certainty. Among its main responsibilities and activities, the following could be highlighted [50]-[52]:

1) Complements the work of national regulatory bodies and coordinates cross-national regulatory action.
2) Collaborates in the formulation of European network codes.
3) Takes binding decisions on terms and conditions for access and operation of cross-border infrastructure.
4) Advises European institutions on issues relating to electricity and natural gas, including measures to support the energy transition.
5) Monitors the internal electricity and natural gas markets and elaborates reports on key findings.
6) Monitors wholesale energy markets to detect and deter market manipulation and abusive behaviors, collaborating closely with national regulatory authorities.
7) Coordinates regional and cross-border infrastructure initiatives, such as capacity allocation and congestion management.
8) Issues non-binding recommendations to TSOs, regulatory authorities, the European Parliament, the Council, and the European Commission.

2) ENTSO-E (European Network of Transmission System Operators for Electricity)

ENTSO-E, representing 42 transmission system operators from 36 countries, was established under Regulation (EC) Nº 714/2009 as part of the 3rd Energy Package. It promotes the implementation of EU energy policy and the achievement of energy and climate goals. ENTSO-E acts as the common voice of TSOs, supporting the integration and efficient functioning of the European internal electricity market, and coordinating the operation of Europe's electricity system. Its main responsibilities include [50], [53]:

1) Promotes cooperation and engages in technical cooperation among European TSOs to support pan-European energy policy implementation.
2) Develops and implements standards, network codes, and platforms.
3) Ensures power system security in all time frames, market integration and optimal functioning, and network development at pan-European level.
4) Achieves energy policy and climate goals.
5) Facilitates the integration of renewable energy sources and emerging technologies.
6) Develops long-term pan-European network plans (TYNDP).

3) EU DSO Entity

The EU DSO Entity, established under Regulation (EU) 2019/943 as part of the Clean Energy Package (CEP), represents over 900 DSOs and was formally established in June 2021. It aims to enhance the coordination and optimization of DSO and TSO networks, promoting efficient and secure operation of electricity distribution systems [50], [54]:

1) Promotes optimal and coordinated operation and planning of DSO/TSO networks.
2) Participates in the development of network codes relevant to DSO networks.
3) Shares best practices and provides expertise on distribution grids.
4) Collaborates in research and development initiatives to improve network management and resilience.
5) Facilitates data exchange and digitalization within the electricity distribution sector.

4) CEER (Council of European Energy Regulators)

Founded in March 2000, CEER is a non-profit association enabling cooperation, information exchange and assistance between Europe's national energy regulators. It facilitates the creation of a competitive, efficient, and sustainable single internal market for gas and electricity. CEER also shares regulatory best practices worldwide through its membership in the International Confederation of Energy Regulators (ICER). CEER is responsible for [50], [55]:

1) Supporting national regulators in fulfilling their European responsibilities.
2) Helping to create a fair and efficient internal gas and electricity market in the EU.
3) Providing a platform for cooperation, information exchange, and assistance between Europe's national energy regulators.
4) Responding to consultations and providing recommendations to regulatory authorities.
5) Collaborating in training and capacity-building programs for regulatory authorities.
6) Conducting studies and publishes reports on market developments and regulatory issues.

5) DSO & Industry Associations: Eurelectric, EDSO, CEDEC, GEODE, SmartEn

These entities collectively represent and advocate for the interests of various national distribution system operators as well as energy—electricity and gas—generation, distribution, and supply companies at the European level. They aim to promote efficient, sustainable, and competitive energy markets while ensuring the secure operation of distribution networks. For this purpose, these organizations offer policy advocacy, technical cooperation, and support for the integration of renewable and smart grid technologies. Their primary responsibilities typically include [50]:

1) Act as interfaces between DSOs and EU bodies and defend the interests of DSOs.
2) Facilitate cooperation on regulatory and technical issues among DSOs.
3) Advocate for the electricity industry and facilitate the dialogue between industry stakeholders and policymakers—e.g., smartEn's members include industry leaders like Siemens and EnelX.
4) Drive the decarbonization of the energy sector, developing industry standards and best practices for clean energy technologies.
5) Support the integration of distributed energy resources, enhancing energy flexibility and grid resilience.
6) Promote innovation and smart grid technologies within the distribution networks.

7) Respond to consultations and provide recommendations to European bodies.

8) Engage in lobbying activities.

All the regulatory institutions and DSO/industry associations described above are fundamental to shaping the future of electricity regulation in Europe in the context of an ever-evolving electrical system. With respect to DER integration and management, significant improvements have been made over the last years with new legislative proposals addressing the development of rules for demand response, energy storage, distributed generation, demand curtailment, TSO-DSO coordination, DER aggregation, and ensuring non-discriminatory access and effective competition in electricity markets. 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 concerning DER integration and management at European level. The following section will explore some of its most relevant provisions for the scope of this work.

3.5.2 EU DSO ENTITY AND ENTSO-E'S PROPOSAL FOR A NETWORK CODE ON DEMAND RESPONSE

This network code ([20]) is intended to target transmission and distribution system operators, regulatory authorities and other relevant entities designated by the Members State (competent or relevant regulatory authority), European organizations such as the previously introduced ACER, ENTSO-E or the EU DSO Entity, but also third parties with delegated responsibilities, market participants, flexible customers and service providers (SPs) for demand response and other local grid services. The primary goals of this Regulation are:

(a) Define clear and objective principles for the development of national rules on aggregation models, demand response, energy storage, distributed generation and demand curtailment.

(b) Contribute to market integration, ensuring non-discrimination, effective competition and efficient functioning of the market.

(c) Ensure access and participation of all available resources and service providers to all electricity markets, including for balancing and local services such as congestion management and voltage control.

Three areas have been identified as of particular relevance to the interests and the scope of this work—which is the analysis of the current state of the art in the field of DER management solutions and the proposal of a single and comprehensive functional architecture for DERMS—and will be explored below [20].

3.5.2.1 Market Access & Participation

These sections aim to provide a framework for market access of service providers, defining the necessary aggregation models for distributed resources, the calculation of baselines for measuring and pricing the delivery of services, qualification requirements for service providers and their products, as well as directives for maintaining a flexibility register for the centralization and management of market data.

1) *Aggregation Models*

Aggregation models define participation rules for service providers that aggregate controllable units (CUs) in balancing, local services, or energy transfer. Each Member State must implement at least one aggregation model, which must include (i) a calculation approach for energy transfer, imbalance correction, and imbalance attribution to Balancing Responsible Parties (BRPs), and (ii) methods for financial transfer and compensation, adhering to specific articles and national regulations.

Aggregation models must define methods to quantify service delivery:

(a) If CUs lack measurement infrastructure or calculation methods, service performance is estimated based on accounting point[5] metering equipment (smart meter).

[5] Accounting point refers to a metering point or virtual metering point under balance responsibility of an entity where the energy supply is provided by an energy supplier, the settlement is performed and where energy supplier change can take place [20].

(b) If CUs have their own metering equipment or calculation method, it must be used for service delivery settlement and imbalance correction, requiring submeters or dedicated measurement devices (DMDs) to quantify power withdrawals/injections.

The delivery of the service must be validated by comparing the baseline of the accounting point with measurements from smart meters in case (a), the baseline of the CU with measurement values of its metering equipment or calculation method in case (b), or both in cases where multiple service providers are located behind an accounting point.

Roles and responsibilities of market participants and system operators in relation to aggregation models and quantification methods may vary per service type, but must include the following:

(a) TSOs and DSOs are responsible for: (i) the calculation and validation of the baseline of CUs and accounting points, (ii) collecting and processing the meter data sent by Metered Data Administrators (MDAs), (iii) validating the delivery of local services based on measurements and baselines, and (iv) collaborating with each other for the correct calculation and settlement of activated services.

(b) Customers must respect, with the activation of his CUs, the provisions of their connection agreement, grid prequalification, and temporary limits.

(c) Service providers shall be responsible for the settlement of financial transfers for energy delivered during upward activation of services, as well as for paying penalties to the requesting systems operators for deviations in delivered services.

(d) The BRP of the service provider shall receive relevant data for periods when its CUs provided a service and bear the aggregated deviation from the requested service—balancing or local service—during activation periods. The BRP of the accounting point is responsible for the imbalance caused by CUs in its portfolio, with potential allocation of proven consequences to the BRP of the service provider.

(e) The Supplier is responsible for settling financial transfers for energy delivered during downward activation of services.

Finally, [20] also defines the requirements for a financial transfer mechanism to limit the impact of balancing, local services, or energy service activation on market participants. This mechanism must have the following characteristics:

(a) Applicable only when customers are invoiced based on meter measurements.
(b) Should not create barriers to market entry.
(c) Covers both upward and downward service activation—from the service provider to the supplier and vice versa.
(d) Applies to non-consumed energy incurred by the supplier and over-consumed energy due to service activation.
(e) Based on a calculation method developed and published by the competent regulatory authority and subject to public consultation. This shall consist of either a specific formula or a financial amount and must be reviewed and updated every three years.
(f) Bilateral agreements between the supplier and the service provider may be allowed to negotiate financial conditions. If no agreement is reached within a defined time frame, default calculations apply.
(g) System operators may act as financial intermediaries facilitating the financial transfer process, e.g., by invoicing the affected parties.
(h) Member States may establish a financial compensation mechanism for additional costs incurred by the supplier due to service activation.

2) Baseline Calculation & Measurement

The Regulation establishes that different baselining methods can be implemented and applied nationally, depending on aggregation models, national market design, type of service, and type of controllable units. The definition, calculation, and validation processes of baselining methods shall be outlined in the national terms and conditions for local services and transfer of energy services. Service providers, BRPs, DSOs, TSOs, or third parties shall be capable of proposing new approaches for determining a baseline. These baselining methods must:

(a) Offer compliance with relevant European standards and regulations.
(b) Be recalculable and transparent.
(c) Prevent the manipulation of the baseline, intentional activation, deactivation, or contrary action of services.
(d) Provide reliable results.
(e) Use existing available data when possible.

Additionally,

(f) The defined baseline must ensure proper product activation, considering compensation and rebound effects.
(g) System operators must be able to monitor service delivery and verify baseline accuracy.

ENTSO-E and EU DSO entity shall maintain a baselining method register, updated yearly with new additions or removals from the national lists of approved baselining methods. Both the baselining methods published in this register and the general requirements for defining baselining methods shall be assessed within three years of the Regulation's entry into force, considering costs and benefits of further standardization.

3) Settlement

Systems operators must include procedures, in national terms and conditions, for calculating and validating local services energy. This includes:

(a) Comparing baselines with requested, metered, or calculated energy to calculate the final delivered energy volume.
(b) Calculating delivered services within activation periods.
(c) Checking the provided capacity and request the recalculation of activated volumes for local services.
(d) Validating constraints are respected when grid limitations or temporary limits are set.
(e) Validating any proven rebound effects from the activation of a service.

Each relevant system operator—procuring, connecting, or requesting system operator—is responsible for calculating and/or settling activated local services energy volumes for each market time unit, direction (energy withdrawal/capacity reduction or injection/capacity increase), SPU (Service Providing Unit), or SPG (Service Providing Group).

Imbalance settlements must account for corrections concerning the volumes of energy transfer from balance responsible parties. Each aggregation model must apply only one of the following imbalance settlement options for correct calculation and allocation of the imbalance to the BRPs of both the service provider and the accounting point:

(a) The BRP for an activated local service corrects its position via commercial schedules.
(b) The allocated volume of a BRP is corrected through the relevant system operator.
(c) An imbalance adjustment is applied to the concerned BRPs by the relevant TSO.

When the concerned balance responsible party is the BRP of the service provider, adjustments can be either based on the requested service, or on the measured or calculated provision of the service. When it is the accounting point's BRP, adjustments are made based on the measured or calculated provision of service.

4) Prequalification Requirements for Market Access

To participate in providing local or balancing services, a service provider must:

(a) Obtain qualification as a service provider through a recognized qualification process.
(b) Complete the necessary product prequalification or product verification for SPUs or SPGs, depending on the product.
(c) Fulfill the grid qualification requirements for SPUs or SPGs.

Additionally, the potential service provider must meet a series of requirements for the product it aims to provide, to be reviewed by the SP qualifying party before being granted access to balancing or local services markets, namely:

(a) Meet the financial requirements set in the particular national terms and conditions.

(b) Ensure ICT systems can: (i) receive and process necessary signals, (ii) exchange and process measurement data for baselining and settlement, (iii) monitor near real-time service execution, and (iv) exchange market and technical data.
(c) Conduct a communication test if requested by the qualifying entity.
(d) Provide detailed descriptions of the technical provision of the service, communication systems, availability, compensation effects, and rebound effects.

System operators in each Member State must outline the step-by-step implementation, requirements, and processes for service provider qualification, product prequalification, and product verification for different products. The qualification process is approved once all formal requirements, technical evaluations, and tests are satisfactorily completed. However, the qualification status can be revoked by system operators if there is non-compliance with relevant Union or national legislation for SPs or inadequate service provision.

National terms and conditions should define a simplified qualification process to prevent duplication when the service provider is already qualified for other markets. Besides, these national terms and conditions for SPs shall include:

(a) Thresholds for the capacity under which a controllable unit is considered small if it deviates from 25 kVA.
(b) Specification of the validity time for SPU or SPG qualification status if it deviates from the standard five years.
(c) Details, notice periods and conditions on switching processes for controllable units between service providers and within the same service provider.
(d) Provisions for the flexible customer's right to choose a new service provider.
(e) Procedures to ensure that a controllable unit is assigned to only one service provider within the same day.
(f) Specifications for the provision of data from DMDs, rules for data quality verification, and principles for data management and storage.

Concerning the data to be submitted by service providers for their SPUs and SPGs, the required content, level of detail, and granularity should be dependent on the technical needs of the particular service. This data shall include but not be limited to:

(a) Structural data: maximum flexibility capabilities of CUs, metering points for each CU, or maximum deliverable services for congestion management or voltage control per CU within a SPU or SPG.

(b) Schedule data: program schedules or baselines for SPUs and SPGs, scheduled periods of unavailability, contributions from particular parts of a SPG to the SPG bid, and contributions of SPUs, SPGs, or parts of SPGs to the bids of a BRP. This should be delivered at least in a day-ahead time frame and updated after each market session.

Real-time data: operational status of the SPU, active and reactive power flow of the SPU/SPG/parts of SPG, unexpected unavailability periods, voltage at the connection point, and state of charge of storage devices.

5) *Flexibility Data Management*

Each Member State must have a mechanism that centralizes all information objects and attributes within a flexibility register. This ensures that there is a single reference point for managing flexibility data. System operators in each Member State must collaboratively design a data management structure for the flexibility register. This structure can include one or multiple platforms, each containing one or various modules, such as the single and common front door, a CU module, a SP module, or a combination of the previous. Further information on CU and SP modules and on the requirements for flexibility register platforms' operators can be found in Articles 41-43 of the network code [20].

Flexibility register platforms must have a unified access point at the Member State level, so that service providers and other authorized actors can read, register, or update information about SPUs, SPGs, and CUs. If a Member State's flexibility register includes multiple platforms, national terms and conditions must ensure that there is a nationally harmonized online application with a graphical user interface and an API for consistent interaction. Flexibility register's platforms must collaborate to ensure interoperability, so service providers and CU operators only need to register or update information once.

6) *Product Prequalification & Verification Requirements*

Before applying for product prequalification, the SP must hold a valid service provider qualification for the respective product and ensure relevant CU data of the potential SPU or SPG is registered and updated in the SP and CU modules of the flexibility register (more information on this flexibility register below). The procuring system operator shall be the responsible for conducting the prequalification or Product Prequalifying Party (PPP). The prequalification process must start within one business day after submitting the product application.

Service providers must ensure their potential SPUs or SPGs meet the technical requirements of the product. They must be prepared to provide the PPP with necessary technical and measurement data, including documentation for baselining and settlement. The PPP evaluates whether the potential SPU or SPG can provide the expected product by comparing its characteristics with the product requirements. This evaluation considers integrated scheduling processes if a central dispatching model is use and may include an activation test in cases when high service delivery reliability is needed.

SPs applying for standard balancing products or those activated automatically based on system frequency shall only undergo product prequalification at SPU or SPG level, whereas those applying for specific balancing products, congestion management, or voltage control products are generally subject to product verification at SPU or SPG level. In the latter case, the PPP may require product prequalification instead of product verification under certain conditions, such as if the service provider is delivering the product for the first time or if the capacity exceeds specified thresholds.

During product verification, the PPP shall verify if the SPU or SPG meets all product requirements and criteria defined in national terms and conditions, based on the performance during requested activations and compliance with product requirements. The PPP may grant a temporary qualification to allow preliminary market participation until verification is completed. System operators must define verification criteria for each product in national terms and conditions, including:

(a) Minimum percentage of service deliveries.
(b) Minimum percentage of quantity delivered from all activations.
(c) Minimum percentage of quantity delivered from a single activation.
(d) Combination of the above criteria or other criteria as deemed necessary.
(e) Maximum time frame for completing the verification.

In case of modifications to an SPU, SPG, or CU, the service provider must update the SPU or SPG data in the SP module and the CU information in the CU module no later than 10 business days before the modification. The PPP can reassess and require a full or partial repetition of the prequalification or verification process under specific circumstances:

(a) Significant changes in the capacity or technology of controllable units (modifications greater than 10 % or 3 MW, whichever is lower).
(b) Repeated service provision errors.
(c) Changes in product requirements.
(d) Using different types of technical resources than previously verified.

3.5.2.2 Market Design

The primary directives for market design for the provision of local services are outlined below, with particular consideration to procurement and pricing rules, flexible connection agreements, the coordination between local and day-ahead, intraday, and balancing markets, and the main roles of local market operators.

1) *Market Design for Local Services through Active & Reactive Power*

System operators must select the most efficient and effective methods to address congestion and voltage issues. Options include grid upgrades, flexible connection deals, grid tariffs, technical measures, non-costly fixes, activating local services, and re-dispatching. The criteria for selecting these solutions should be clear and coordinated and can even vary for different time frames, always ensuring power system and network safety.

The procurement of local services must follow a market-based, transparent, and non-discriminatory approach. Exceptions are allowed if national authorities have previously established (before the implementation of this regulation) rules-based mechanisms. In this scenario, system operators may also present proposals for market-based procurement to complement existing rules-based mechanisms.

Non-market-based solutions can only be used if considered as economically inefficient by the national regulatory authority. This economic efficiency evaluation shall consider different grid parts, voltage levels, regions within the Member State, short term vs. long-term products, etc., and must be publicly available. Regulatory authorities must review every two years, or upon request, if conditions for non-market-based solutions have significantly changed and are no longer applicable.

System operators are also responsible for managing reactive power flows and maintaining voltage within operational limits in their control area. They shall have access to pertinent data from market participants or national flexibility registers to carry out tasks related to the procurement of reactive power services. When reactive power needs are identified, system operators must:

(a) Quantify and outline the time frame for these needs (deficits or surpluses).
(b) Identify potential solutions, such as specific grid investments, procuring reactive power via voltage control services, or other technical methods.
(c) Develop and implement an action plan based on these evaluations and identified solutions.

Market-based mechanisms are also preferred for meeting reactive power needs. Rule-based procurement may be utilized if market-based options are not economically viable, no market-based alternatives exist, all available market-based resources have been exhausted, or there are too few potential providers to ensure a competitive market. In any case, procurement rules must be clear, non-discriminatory, and technologically neutral, and they must be submitted to the relevant national regulatory authority.

2) Procurement & Pricing for Market-Based Local Services

Systems operators in each Member State shall develop a common proposal of national terms and conditions for market design for local grid services through active and reactive power and submit it to the relevant regulatory authority. This proposal should, specifically, address which entity will be responsible for selecting and activating bids and how the validation and settlement of the service provision will be performed. Procurement rules in these national terms and conditions must:

(a) Allow participation from any resource, including production, consumption, or energy storage, whether single or aggregated.
(b) Be non-discriminatory and technology neutral.
(c) Ensure data protection and confidentiality, as well as transparency in the procurement process.
(d) Ensure that the volumes and product characteristics requested by the procuring system operator are met.
(e) Coordinate system-wide objectives with regional processes.
(f) Follow the applicable TSO-DSO coordination processes.
(g) Allow for the activation of a bid for various purposes or the same purpose in different grids if technically feasible (bids can only be compensated once).

The pricing mechanism for market-based procurement of local services should:

(a) Ensure fairness and competitiveness, and
(b) Guarantee economic and efficient activation.
(c) Reflect the actual market structure and concentration.
(d) Incentivize long-term market development.
(e) Provide equal treatment to service providers and remain technologically neutral.

(f) Allow for variations for different products, voltage levels, time frames, market liquidity, and national or local characteristics.
(g) Allow for predefined prices for the availability and/or activation of resources contracted in advance, subject to an economic efficiency review. When local services are procured in advance as capacity products, the activation of bids from previously contracted resources must compete with other available voluntary bids in the market.
(h) Enable both energy and capacity payments, subject to an economic efficiency review.
(i) Allow for certain deviations from general pricing mechanisms when services are procured in long-term, day-ahead, intraday, or balancing markets.

3) Flexible connection agreements

When the national regulatory framework stipulates that the activation of flexible connection agreements should be conducted outside of local markets, system operators must regularly examine if a more efficient solution can be achieved through procuring local services based on market principles. Non-market-based flexible connection agreements must not cause market distortion and must meet the following criteria:

(a) System operators should not unjustifiably restrict market participation for system users connected under flexible agreements.
(b) Activation of flexible connection agreements must be coordinated with available activation products in the local services market through a mechanism that ensures effectiveness and efficiency (to be specified in national terms and conditions).
(c) In case of system imbalance due to activation of a flexible agreement, it must be resolved using a method proposed by system operators and agreed upon by relevant national authorities, which should be effective, efficient, and avoid risks to the load-frequency control processes.
(d) If flexible connection agreements pose a risk to a resource's ability to deliver a local or balancing service, participation in that market may be limited for that particular time frame. Connecting and affected system operators must be able to communicate the corresponding restrictions in these scenarios.

The national regulatory framework must ensure that the activation of the conditions defined in flexible connection agreements does not compromise power system's normal operation and reliability.

4) Coordination between Local & Day-Ahead, Intraday, & Balancing markets

National terms and conditions for market design for local services must ensure that local markets are aligned with day-ahead, intraday, and balancing markets. This coordination should allow resources to participate across different markets without compromising market integrity, power system security, or the accuracy of imbalance settlement. The procurement of local services must respect the functioning rules of all these markets, particularly pricing mechanisms. With regard to the coordination between local and other electricity markets, national terms and conditions for the market design for local services must:

(a) Ensure efficient access to local markets for service providers and system operators.
(b) Outline the interaction processes between local and other electricity markets in different time frames, including scheduling processes.
(c) Describe how bids from day-ahead, intraday, and balancing markets can address congestion or voltage issues (in addition to those offered in local markets).
(d) Ensure market design minimizes capacity withholding and market abuse.
(e) Provide efficient solutions for procuring local services and avoid excessive market fragmentation that may lead to inefficiencies.
(f) Allow bids not awarded in one market to be offered in another, meeting specific requirements.
(g) Allow for different granularity and minimum bid sizes for local services markets, compared to other electricity markets.
(h) Have rules to prevent the same bid from being selected twice, particularly when a SPU or SPG is participating in more than one market.
(i) Describe the market processes (sequential, parallel, simultaneous) used for the procurement of local services and for the coordination between markets.
(j) Consider the impact of local markets on other wholesale market prices.

(k) Clarify if CUs can participate in different SPGs for various services, ensuring no double activation.
(l) Ensure resources offering capacity in local markets can participate in other markets if not needed in the relevant time frame by the initial procuring system operator.
(m) Define conditions under which bids can be combined and forwarded to other markets.
(n) Include requirements for combining/forwarding bids, handling consent, maintaining transparency for transferred bids, changing bid pricing and volumes or withdrawing bids, and compensating service providers.

5) Local Market Operators

Systems operators must define the functional needs for operators of local markets in their national terms and conditions for market design for local services. Local market operators can be: (i) the TSO(s) or DSO(s) that procure the services, either alone or together, (ii) another TSO or DSO, either alone or together; or (iii) a third party. In any case, operators of local markets in a Member State shall have a common information platform on market-based procurement for local services, standardized definitions, and standardized use of locational information. Local market operators are required to operate with IT systems that can:

(a) Handle bids and create a merit order list, facilitating the matching of bids with system operators' needs according to procurement and pricing rules.
(b) Communicate with service providers and system operators about bids, network needs, temporary limits, and market results.
(c) Share relevant information with other market operators and participants as necessary.
(d) Collect and exchange information necessary for settling local service markets.
(e) Interface with flexibility register platforms as required.

Local market operators must also coordinate with operators of other markets as specified above, adhering to national terms and conditions, ensuring transparency and following established pricing mechanisms and settlement principles, also when allowed to combine or forward bids to other markets. They are obliged to publish market results too, ensuring they avoid market distortion and respect commercial confidentiality according. Finally, local market operators are prohibited from performing any arbitrage in the choice of bids and from acting as market participants in the markets they operate.

3.5.2.3 TSO-DSO & DSO-DSO Coordination

System operators shall develop a common proposal for national terms and conditions for TSO-DSO and DSO-DSO coordination, in which the following issues must be described.

1) *DSO Observability Area*

DSOs and TSOs must work together to develop criteria for defining DSO observability areas, considering factors like electrical topology, grid voltages, standard network configurations, and potential congestion or voltage issues affecting the DSO network. The observability area specifies the range within which the DSO can access necessary information about grid elements and system user installations, including structural, scheduled, forecast, and, if needed, real-time data.

DSOs must define their observability area by evaluating the potential influence of other system operators, which shall identify the network elements and system users to be included. The initial definition of DSO observability areas should be completed within one year of approving national terms and conditions for TSO-DSO and DSO-DSO coordination, with reviews every two years or upon request by relevant parties.

2) *Forecasting, Identifying, & Solving Congestion & Voltage Issues*

Each system operator at the national level is tasked with forecasting and identifying potential congestion and voltage issues in its network. They must initiate the appropriate procedures with other relevant system operators to address these issues at different time frames, in line with regional security coordination methodologies. Time horizons for these processes include day-ahead, intraday, outage planning, and closer to real-time planning. However, operators may skip processes for certain time frames where they anticipate no congestion or voltage issues.

Forecasts looking for congestion and voltage issues must consider various factors including different network configurations, voltage levels, generation and consumption schedules, actual or planned grid configurations, operational limits, and other relevant information of the national grid. Once identified, system operators should explore network reconfigurations to prevent or minimize constraint violations on their own grid, as well as to contribute to resolve issues on other grids.

If network reconfigurations do not suffice, the corresponding system operator shall take efficient and effective measures to directly solve these congestion or voltage issues through the procurement and activation of local services, always while respecting the operational limits of the affected grids. The system operator of the grid where the issue occurs is generally responsible for procuring and initiating actions to activate local services, unless otherwise agreed or specified.

3) Data Exchange between DSOs-DSOs & DSOs-TSOs

DSOs must receive information for their observability areas from other DSOs and relevant TSOs. This includes:

(a) Structural data: information about substations, connecting lines, substation transformers, significant grid users (SGUs), CUs, SPUs and SPGs, and capacitors/reactors connected to substations.
(b) Scheduling and forecast data: planned outages, forecasts of congestion and voltage issues, remedial actions, schedule data from SGUs, impacts of connected SPU or SPG on network flows, and temporary limits that need to be shared to relevant system operators and TSO(s).
(c) Real-time data: actual grid topology, busbar voltage, active and reactive power flows, and real-time measurements of SPUs, SPGs and significant grid users.

Data about the procured and activated local services must be submitted with the specific periodicity and granularity to the connecting system operator, requesting system operator, affected systems operators, and the TSO(s) as defined in national terms and conditions.

Additionally, TSO(s) should be capable of requesting to DSO(s) additional data from service providers and system users if necessary for the efficient and secure network operation.

3.5.2.4 Takeaways

Previous sections have outlined the provisions of [20] that have been considered most relevant for the integration of DERs into the power system operation and their participation in electricity markets. As has been observed, European-level regulation is still ambiguous and poorly defined in many of the terms relevant to the deployment of DERMS solutions, and it often limits to establish that Member States shall develop their own national terms and conditions for each of these aspects. Specifically, Article 84 of this regulation requires ACER to define a process for monitoring and assisting in the implementation of these directives on aggregation models, methods for quantifying services, prequalification and verification of products, market design—particularly procurement and pricing—for local services, and coordination between system operators in each Member State.

This circumstance only underscores the importance of a single, comprehensive DERMS solution that is modular and adaptable to different regulatory frameworks, stakeholders, and use cases. This is precisely what we aim to achieve with the functional architecture for DERMS presented in the following chapter.

Chapter 4. A NEW END-TO-END FUNCTIONAL ARCHITECTURE FOR DERMS

Once this thorough analysis of the literature has been conducted, the aim is to propose a functional architecture for the DERMS solution, which shall be unique yet adaptable to the different potential client typologies and various use cases. In order to achieve this, this chapter will begin by synthesizing the above information to narrow down the concept of DERMS and its scope of application. A standard definition of the term DERMS will be provided, their main functionalities and critical responsibilities will be reviewed, as well as the different hierarchical levels of DERMS and the underlying interest in the unification of all these solutions to obtain an efficient, end-to-end solution for DER integration in the distribution grid. Then, the following aspects will be covered regarding the proposed DERMS functional architecture:

1) *Preliminary considerations*: the general structure of the architecture and the rationale behind its development will be presented, as well as how certain aspects of the schematics should be interpreted.
2) *Architecture overview*: the different functionalities and services will be described, along with the reasons for their positioning in the architecture, and the potential interaction between the different layers and modules.
3) *DERMS 'Declinations'*: this section will particularize the general DERMS architecture for the different clients that have been considered, namely, aggregators, niche vertical platforms, DSOs in a context of unbundling aiming to integrate an ADMS software with the DERMS and those that do not wish to preserve it, and vertically integrated utilities also with and without ADMS.
4) *Modularization Strategy*: the previous declinations will be utilized to design the opening points of the proposed DERMS architecture, and to determine how the different functions and services can be modularized and decoupled so that the DERMS solution can be implemented onto every client, integrating with or replacing its own software.

4.1 DERMS – UNIFIED DEFINITION & SCOPE OF APPLICATION

Distributed Energy Resource Management Systems are aimed at providing a comprehensive solution for monitoring, controlling, and optimizing the increasing number of DERs into the power grid. Nonetheless, the relatively recent introduction of the term has resulted in varying conceptions of what constitutes a DERMS, as well as of its scope of application. Despite the potential of DERMS solutions, it appears that there is no agreed-upon definition or a standard set of core functionalities for these systems. The literature presents a wide variety of solutions, each often with different purposes and aimed at different stakeholders, which is exacerbated by the fact that the different vendors and competitors offering this type of services are still establishing themselves in the market.

As extensively developed above, there seems to be a common understanding in the literature of dividing DER management systems into centralized or Utility DERMS and decentralized or Aggregator DERMS. Utility DERMS emerge from traditional grid management systems and focus on grid-wide optimization and control. They have access to an accurate network model and are responsible for using 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 manage technical constraints and optimize grid operation. Aggregator DERMS are aimed at enabling greater collaboration of end-users in energy management, providing technical, operational, and monetary benefits to both system operators and end-users. They focus on the aggregation of multiple small-scale, often BTM resources connected to the LV network (e.g., air-conditioning or heating systems, rooftop solar, residential BESS, EVs, and smart appliances) and offer their flexible capacity in an aggregated, optimized, simpler, and much more useful manner for grid services—e.g., participating in local electricity markets or through demand response initiatives. However, they do not typically have access to the distribution network model and are not aware of technical constraints, thereby requiring a Utility DERMS or a DMS to validate their operations and schedules.

Despite this circumstance, there seems to be a tactful agreement to suggest the need, or at least the desirability, for a comprehensive tool for the integration and optimal management of all types and scales of DERs. In fact, previous chapters have shown that, even though this conceptual division is still present, the literature does not often distinguish between functions assigned to Utility and Aggregator DERMS. This is clearly exemplified by the collection of DERMS functionalities and use cases conducted by SEPA in [38], gathering the perspectives of 12 utilities and 11 vendors in the marketplace, as well as by the functional specification proposed by the IEEE Std 2030.11-2021 in [33]. In Section 3.2, it was deemed appropriate to draw this distinction between functionalities assigned to Utility and Aggregator DERMS in order to emphasize the relevance of the latter in a context where the industry tends to consider DERMS as a utility-exclusive product. Nevertheless, it is still the purpose of this work to propose a complete DERMS solution that can address every use case and stakeholder with no distinction between centralized and decentralized solutions.

Therefore, and taking all of the above into consideration, a DERMS will be understood in the remainder as a software solution designed to: (i) assist system operators, utilities, and grid planners, in managing and leveraging the increasing penetration of distributed energy resources in distribution grids in a secure, efficient, and economically optimal manner; and (ii) enable end-customers and prosumers to actively participate in power system operations and capitalize on the flexible capacity. DERMS shall allow for real-time monitoring, control, aggregation, and coordination of DERs, optimizing their flexibility to offer technical, operational, and monetary benefits to both system operators and network users. A DERMS shall be used by DSOs, vertically integrated utilities, DER aggregators, microgrid operators, or industry verticals, not only to mitigate the potential negative impacts of the increasing DER integration, but also to take advantage of their flexible capacity for grid management. DERMS enable the integration of renewable and non-renewable distributed generation—such as rooftop solar panels, small wind turbines, combined heat and power, or diesel generators—, ESS, EVs, DR, controllable loads, and energy efficiency programs, and are capable of aggregating and coordinating their capabilities to support system-wide benefits and manage grid issued and constraints in an economically optimal fashion.

As demonstrated above, European regulation is still imprecise and poor in many of the most relevant aspects for the deployment of DERMS software solutions, and it often limits to establish that it is up to each Member State to develop their own national terms and conditions. Therefore, a single, comprehensive DERMS solution that is modular and adaptable to different regulatory frameworks, stakeholders, and use cases is fundamental. Additionally, the graph in Section 3.2.3 showcases that Minsait is considered to have a significantly more global and holistic view of DERMS solutions in comparison with the majority of competitors in this sector, typically more focused on either purely centralized solutions for utilities/DSOs—similar to an ADMS with DER capabilities—or tools only for aggregators—such as VPP or DR management systems. Minsait seeks indeed a single and comprehensive DERMS solution that can address all possible needs of the greatest number of stakeholders, across the widest range of countries and regulatory contexts, which is fully aligned with the objective of this work and highlights the underlying interest that has been identified in the literature, even though it has not yet translated into market solutions.

Therefore, their product and this their interpretation of what a DERMS should offer have been taken as the starting point for reasoning and developing the functional architecture presented in the following section. The aim has been to align and integrate Minsait's perspective with the DERMS functional specification included in Section 3.2, and the general conclusions regarding the concept and the scope of a DERMS derived from the analysis of the state-of-the-art. 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 software solutions if necessary.

4.2 DERMS FUNCTIONAL ARCHITECTURE

As explained above, the architecture proposed here aims to integrate the functional specification developed in Section 3.2 of the state-of-the-art—based on the information presented in [1]-[3], the IEEE Std 2030.11-2021 as in [33], and the collection of services and use cases from SEPA in [38]—with the idea of a comprehensive and global solution that addresses the needs of the majority of stakeholders across the widest range of countries and regulatory frameworks. This vision is shared by certain competitors in the sector, such as Minsait, which seeks to achieve this integrated solution with its products. Therefore, the functional architecture described below draws inspiration from its DERMS solution—which has been partially or fully implemented and tested in various projects with different types of clients—and is complemented with the most relevant functionalities frequently referenced in the literature and by the general knowledge gained from the thorough analysis of the previous state-of-the-art.

4.2.1 PRELIMINARY CONSIDERATIONS

The DERMS functional architecture is presented in Figure 11Figure 11 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, as will be explained later. Certain aspects must be noted first so that the reader can understand the reasoning behind the development of the architecture, as well as the way in which the schematic shall be interpreted:

1) 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 for the management of both small-scale DERs through aggregators and larger utility-owned DERs. This is the case of enrollment functions as

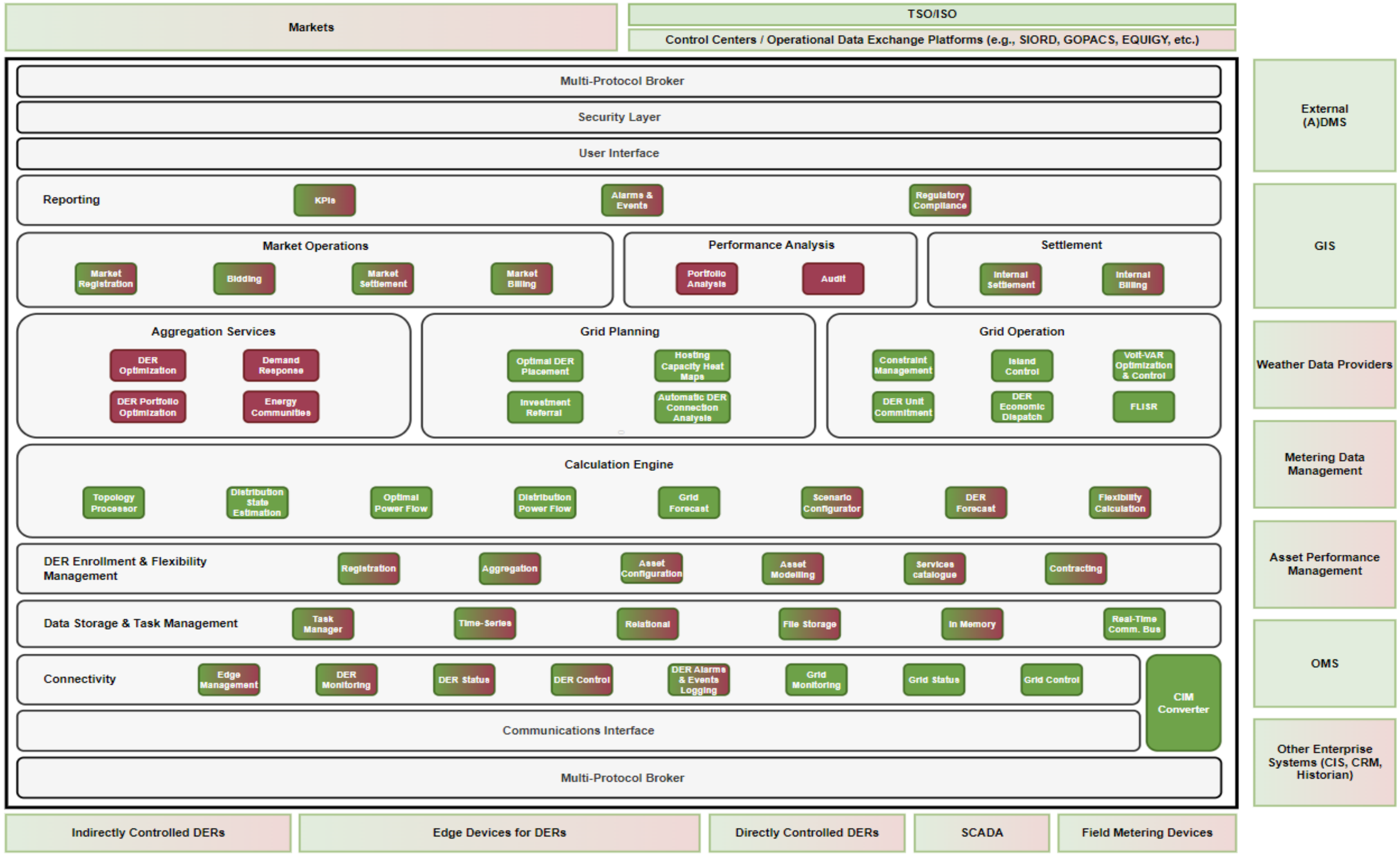

Figure 11. DERMS Functional Architecture: Utility-exclusive components in green, exclusive to aggregators in red, applicable to both in green and red.

one can check in the architecture schematic. In the same way, others that were previously assigned exclusively to Utility or Aggregator DERMS have seen their scope expanded and now apply to all scales of DERs. Examples are DER monitoring and control functions, market operations, or reporting services. Despite this, some functionalities remain decoupled for aggregator and DSO/utility levels, to enable the subsequent adaptation of this architecture to different types of clients only requiring services at one of these levels. This is the case of DER optimization functions, which can be applied either for a single aggregator's portfolio (DER and DER portfolio optimization), or globally to all aggregators and larger-scale DERs managed by the utility (DER unit commitment and economic dispatch).

2) The reader can check that the distribution of functionalities and services has been partly modified with respect to what was presented in the functional specification of Section 3.2, that some additional functions have been incorporated to the architecture, and that others that were described above are no longer considered. The latter attends to two main reasons: (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 by combining some of its specific functionalities: DER registration and aggregation, contract and service management, portfolio optimization, market functions (like bidding and settlement), and performance analysis (e.g., auditing and billing), etc., and integrating with grid-aware enterprise systems to provide grid services. Similarly, DERMS allow for microgrid management, both in grid-connected (as a DER aggregator, utilizing very similar functionalities to those a VPP might use to provide grid services) and in island mode (requiring a network model and other calculation tools and grid operation services also included in the DERMS solution). A specific adaptation of the DERMS solution for microgrid controllers will be presented in the following section.

3) The different components and services in the architecture have been structured from the bottom up, following the information flow and the order of processes from field

devices—DERs, SCADA systems, and metering devices—to, if desired, electricity markets or the TSO. In this manner, the fundamental functionalities that only require field information and not the completion of previous processes are located at the bottom, while the more complex services or those that necessitate the execution of other lower-level functions are positioned towards the top of the architecture.

4) 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—e.g., for maintenance planning—, and other enterprise systems like Component Information System or Customer Relationship Management), geographic and climatological information systems (GIS and weather data providers), competent system operators, and electricity markets which the DERMS must be capable of interacting with if necessary. 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 to the schematic as a possible necessary intermediary in the communication and information exchange between all these different stakeholders. All these components have been accordingly highlighted in green and/or red, depending on whether they are subject to the interaction only with utilities (such as TSOs, DMS, OMS, or GIS, given that aggregators are not responsible for network management), only with aggregators, or with both.

4.2.2 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. It is necessary at this point to highlight the particularities of the different types of DER devices that will be managed by the DERMS:

- *Directly Controlled DERs*: directly managed by the utility in real-time (milliseconds)—although it could also be by an aggregator in near real-time—through a SCADA system. Examples include FTM assets such as large utility-owned batteries (for, e.g., island control or scheduled maintenance), PV plants connected to the MV distribution network, EV charging parks, etc. They typically use industrial or telecontrol communication protocols.
- *Indirectly Controlled DERs*: indirectly managed by the utility or aggregator typically through third parties. These assets are not connected in real-time and can only be used for applications with less demanding time and reliability requirements (minutes-ahead at most). An example are third-party vertical niche platforms: EVs, batteries, solar inverters, or thermostats. They are usually BTM assets but can also be FTM, using standards such as OpenADR or 2030.5.
- *Edge Devices for DERs*: additional monitoring and control devices deployed in the field to enable communication with DERs. Particularly common in the commercial and industrial sectors where the devices are used not only to participate in grid services (as if they were indirectly controlled) but also to provide local optimization services. These devices are used in cases where there is no monitoring system or other types of communication (such as a local network without internet access), allowing to reach assets that would otherwise be inaccessible. They typically communicate locally using building protocols such as Modbus and upstream via MQTT.

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*[6] *Monitoring* (measurements acquisition on a periodic basis), *Status* (tracking of parameters such as

[6] In this context, *grid* refers to traditional grid elements, such as transformer load tap changers, switches, capacitors, etc.

operational mode, state of charge, connected/disconnected, etc.), and *Control* (sending of commands, checking the different assets 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, whether they are reporting or not, authentication to ensure only verified devices can send data to the DERMS, etc.). One can check that all DER functionalities—i.e., DER Monitoring, Status, Control, Alarms & Events Logging, and Edge Management—are common for utilities and aggregators, since they are applicable to both small-scale aggregated DERs and larger utility-owned DERs, whilst grid monitoring and control functions are exclusive to the utility. A ***CIM Converter*** is included in parallel to the CI and the Connectivity module to make the DERMS compatible with external GIS or other enterprise systems exporting network topology files in CIM format.

The ***Data Storage & Task Management*** module is placed directly above the connectivity layer, also encompassing necessary functionalities to be able to provide all services that are disposed above them. These include (i) the *Task Manager*, responsible for the inventory and the execution of scheduled—both DSO and aggregator—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, namely:

- *Time-Series*: for information recorded periodically at regular intervals, e.g., DER output power monitored on a minute-by-minute basis.
- *Relational*: traditional relational database in table format.
- *File Storage*: cloud repository of files including, for example, forecast and schedule files, or executable files of trained models are stored.
- *In-Memory*: in-memory storage where data is not saved but temporarily stored, used, and then discarded.

The first layer offering services for the client consists of the ***DER Enrollment and Flexibility Management*** module, where the *Registration* of both individual DERs and DER groups in the DERMS platform are conducted, including the *Aggregation* of DERs, the *Configuration* and digital *Modeling* of these assets (all these functions already described in Section 3.2), *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 minimum/maximum capacity, minimum/maximum activation time, or minimum preparation time for the delivery of these services.

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., from 12 pm to 4 pm consumption cannot be modified; from 4 pm to 8 pm, up to 50% of consumption can be shifted; temperature within a range of hours must be within a certain range; SOC cannot be below or above a certain value, etc.). Most of these functionalities are exclusive for utilities and system operators, since aggregators lack a network model to perform grid analysis calculations. However, DER Forecasting, Flexibility Calculation, and the Scenario Configurator have been considered to be applicable both at the utility level—to account for utility-managed DERs—and within the aggregator portfolio. Note that the Forecasting functionality has been divided here into grid and DER forecasting—the latter being the responsibility of both utilities and aggregators—compared to the state of the art where it was a single functionality assigned only to the utility.

The next layer encompasses all *Grid Planning* and *Grid Operation* services (to be carried out exclusively by the utility or DSO) 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 the previously explained VPPs and microgrids, which could be reduced to use cases of a DERMS as a whole, Demand Response 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 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 Real-Time and Short-Term Operation modules of the functional specification of Section 3.2, 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 even for energy efficiency reasons, as well as the transition between grid-connected and island modes of microgrids.

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 already described in the state-of-the-art and applicable both to DERs participating in the market through an aggregator and to individual utility-owned DERs. Note that Transactive Energy is not contemplated here, as it is understood as a use case resulting from the combination of other functionalities, such as DER and DER portfolio optimization, or even energy communities. Secondly, the ***Performance Analysis*** module was also considered in the above analysis of the literature and has been divided here into two different 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 (for example, reducing peak demand by 1 MW for 1 hour) vs. what was ultimately achieved. This can be a continuous process during the execution of the service, even with mechanisms for real-time correction of deviations. This functionality can also be found as Measurement & Verification (M&V) in the literature.

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). The Internal Settlement functionality is responsible for retrieving a certain set of events (e.g., related to the same service, between specific dates, etc.) and calculating the preliminary settlements. The simplest form is a quantity-times-price calculation, but they can be more complex, including incentive or penalty components. Internal Billing generates invoices from settlement data, either directly by the DERMS or through an external system like SAP if the client already has a suitable one. These modules have been placed above the previous aggregation, grid planning and operation services because they are subsequent (at least conceptually) to the provision of these—i.e., an aggregator or a DER can place a bid in the market offering its flexible capacity for DR, load shaping, or constraint management, but if the DERMS is not capable of providing a certain service, there can be no bid for it.

Finally, a ***Reporting*** module is included to develop 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. Reporting, along with the above Economic Performance Analysis module, cover the previous Analysis & Reporting assigned to Utility DERMS and the Revenue & Portfolio Analysis of Aggregator DERMS that were developed in the state-of-the-art, together with some additional functionalities that had not been contemplated—such as Internal Settlement and Bidding. 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.

4.2.3 DERMS DECLINATIONS & USE CASES

It is fundamental 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 even 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 previously developed DERMS architecture have been considered, with the aim of covering the possible needs of each respective type of client. It is worth noting that all the functionalities included in each of these variations meet potential requirements for a specific client and use case, which does not imply that every single function will be required in all instances. These seven *declinations* of the DERMS solution will be taken as a basis, depending on the groups of functionalities and services assigned to each of them, to subsequently define the architecture's modularization strategy.

4.2.3.1 DERMS Aggregators

DER aggregators allow for managing high amounts of DERs and dispatchable loads connected to the medium and low voltage networks, such as rooftop solar PVs, EVs, household batteries, and domestic loads like smart thermostats. They aggregate small, usually behind-the-meter DERs into larger, controllable groups to provide flexible capacity and ancillary services to the DSOs. Additionally, aggregators allow for the participation of these small-scale DERs in electricity markets, demand response initiatives, energy efficiency programs, and coordinate their operation to ensure that they can collectively respond to value signals and grid reliability needs. DER aggregators can encompass BEMS, energy communities, VPPs, and DR providers and even microgrids controllers providing aggregated services to the main grid [1]-[3], [6]-[8].

As a result, this adaptation of the DERMS solution for aggregators incorporates, as fundamental components, all aggregation services—i.e., DER and DER portfolio optimization, and the management of DR programs and energy communities—, in addition to all the functionalities necessary for the registration, grouping, configuration, and modeling of DERs in the aggregator's portfolio, and flexibility management (service catalog and contract management). DER forecasting, flexibility calculation and scenario configuration are also included, along with the data storage and task management module—excluding real-time information exchange capabilities for the reasons mentioned above—, DER monitoring, status, and control functions, DER alarm and event logging, and edge device management. Grid monitoring, status, and control, grid operation and planning services, and the remaining pure network functionalities of the calculation engine module (grid forecasting, topology processor, state estimation, and power flow analysis), are excluded in this case for not being within the scope of the aggregator. The schematic of this adaptation of the DERMS solution, where those functionalities and services that need to be incorporated have been highlighted, is depicted in Figure 12.

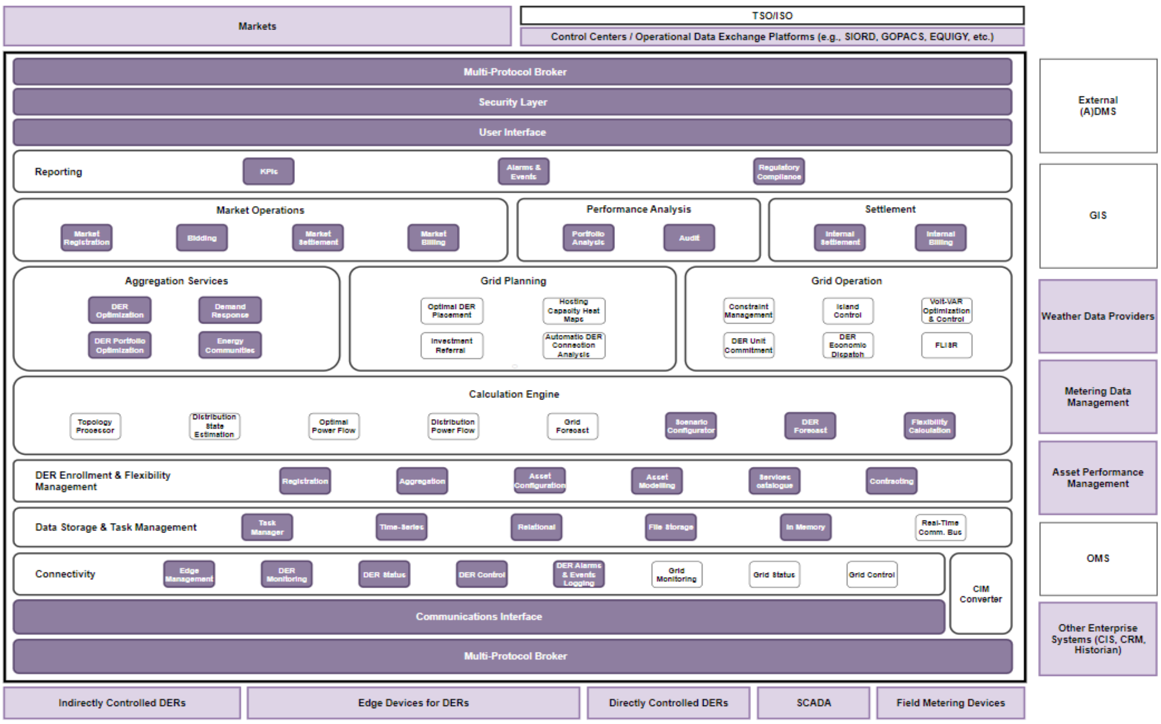

Figure 12. DERMS Functional Architecture - Aggregators.

At the top level, all market operations are maintained due to the aggregator's role in enabling the aggregated participation of the DERs within its portfolio in local and wholesale electricity markets, as well as performance analysis functions for auditing the provided capacities and analyzing the overall technical and economic performance of its portfolio, and the settlement module for the internal settlement and billing of the provided services by each specific DER. Reporting, fundamental for any type of client and their respective DERMS solution, is also included, along with the user interface, security layer, and multi-protocol broker to enable information exchange with various field devices, measurement systems, electricity markets, and control centers and operational data exchange platforms—such as GOPACS in the Netherlands for the communication with DSOs.

Regarding this 'periphery' of the DERMS solution, direct interaction with TSOs is not contemplated for aggregators (it would be through the control centers 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.

4.2.3.2 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. Their specialization involves very high barriers to the entry of new companies. Examples of niche verticals or vertical markets within the electricity sector include providers and managers of EV charging stations, battery energy storage systems, PV inverters, or smart thermostats, among others [56].

The adaptation of the DERMS functional architecture for niche verticals is very similar to that of DER aggregators, so it will not be extensively described here again. The reason is simple: niche vertical companies are, after all, aggregators of DERs of the same type of resource, with the fundamental characteristic that this time the niche vertical is owner of the DERs in its portfolio, and these do not belong to third parties or individuals. Consequently, the only difference in the included functionalities and services with respect to the previous declination of the DERMS solution is the exclusion of internal settlement and billing—as the niche vertical would be settling and billing its own products. The DERMS functional architecture for niche verticals is shown in Figure 13 below.

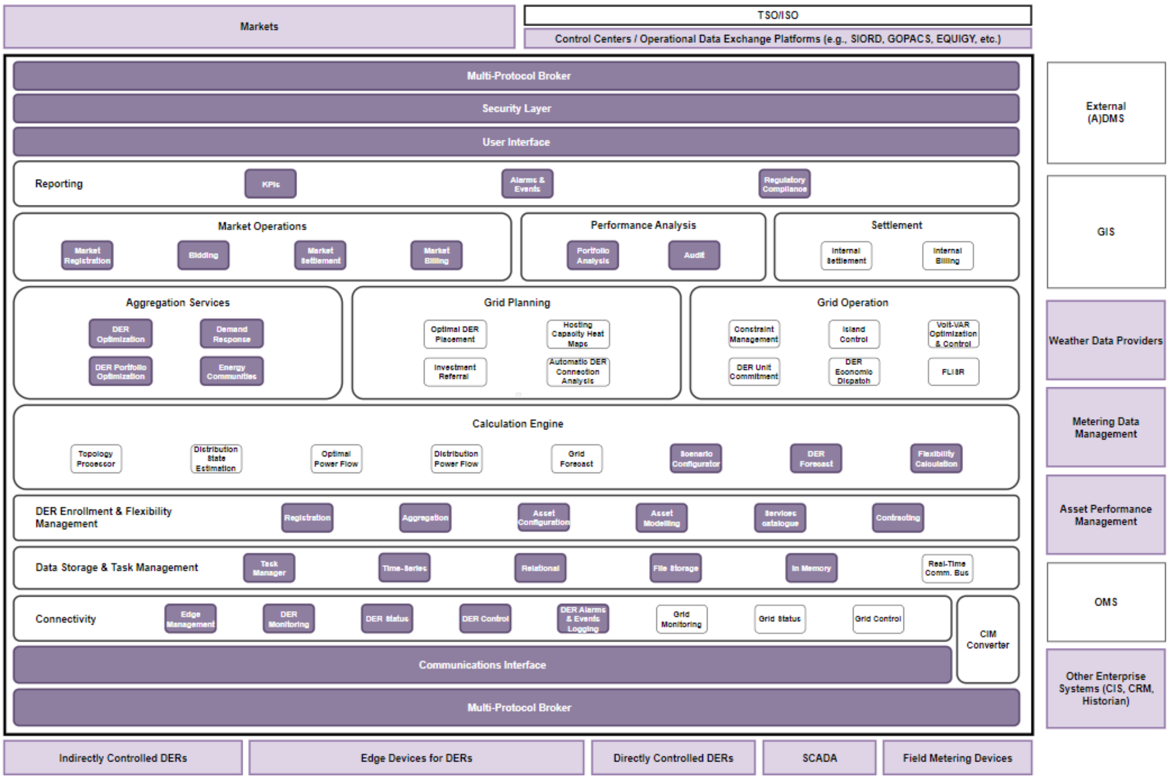

Figure 13. DERMS Functional Architecture - Niche Verticals.

4.2.3.3 DERMS Microgrids

Microgrid management involves the secure and efficient operation of a microgrid, managing DERs and loads within clearly defined geographical boundaries, and enabling smooth transitions between grid-connected and islanded modes as required. It allows for enhancing grid resilience at a localized level, maintaining frequency and voltage stability, and ensuring power supply against major outages. Moreover, microgrids must be capable of operating both in grid-connected mode, performing local optimization and ensuring efficient resource usage to provide balancing and other ancillary services to the main grid, and islanded, managing grid-forming operations, load balancing, and frequency and voltage regulation to ensure the stable and reliable operation of the microgrid [1], [5], [24], [33], [38].

Consequently, given the extensive and complex role of microgrid controllers, this DERMS declination must incorporate—again, potentially—nearly all its functionalities, except for the network planning services that are reserved for DSOs. This involves all those functions already included above for aggregators, so that microgrid controllers can register, configure, monitor, control, and locally optimize its flexibility resources, participate in electricity markets, analyze the performance, audit, settle, and bill the DERs within its portfolio, generate reports, etc., but also all pure grid services and network calculation functionalities—grid monitoring, control, state estimation, power flow analysis, topology processor, grid forecast, and real-time data exchange capabilities—to be able to autonomously manage the microgrid in island mode. The DERMS functional architecture for microgrids is presented below.

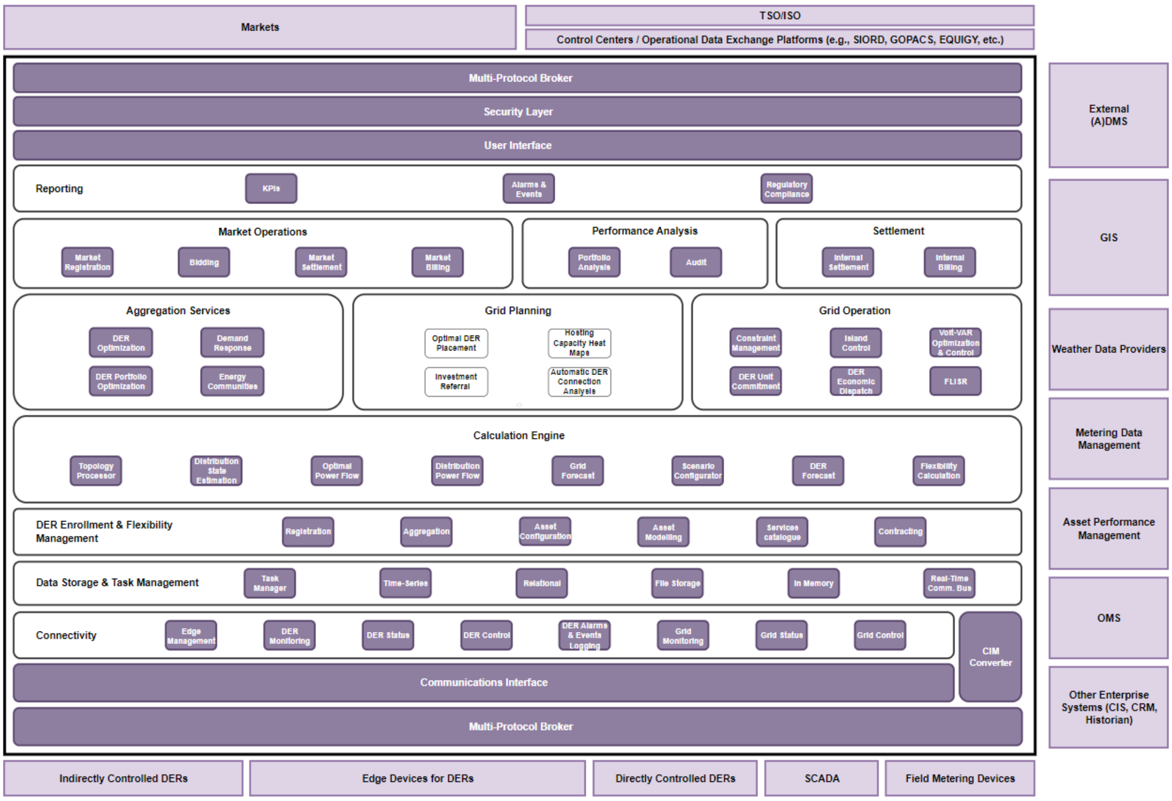

Figure 14. DERMS Functional Architecture - Microgrids.

Similarly, microgrid controllers 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 and operational data exchange platforms.

4.2.3.4 DERMS DSOs

DSOs are responsible for managing the local and regional low and medium voltage distribution networks. This involves grid planning, real-time monitoring and controlling of grid conditions—congestions, voltage levels, transformer loads, etc.—, coordinating local assets and optimizing DERs for distribution-level grid services—such as load balancing, peak shaving or voltage control—to meet system requirements, forecasting load and generation to anticipate potential network issues and schedule and dispatch resources, leveraging DER's value in the electricity markets, determining compensation for resource proprietors and aggregators proving services to the grid, as well as interacting with TSOs for meeting broader grid requirements [57].

This implies that the DERMS solution for DSOs shall incorporate—potentially—all grid planning and grid operation services, along with the full calculation engine to perform state estimation, power flow analysis, topology processing, network scenarios configuration, grid forecasting, as well and DER forecasting and flexibility calculation for DSO-owned DERs. The enrollment and flexibility management module must also be included to be able to register and manage both utility-owned DERs and third-party aggregators, as well as all data storage and task management functionalities—including the real-time communication bus for real-time grid control requirements. The connectivity module must be fully incorporated as well, so that the DSO is capable of monitoring and controlling both traditional network assets and DERs under its direct supervision. CIM converter is also included so that externally provided network models in CIM format can be interpreted by the DERMS.

On top of the architecture, market functions—registration, bidding, settlement, and billing—are fundamental to enable utility-owned DERs to participate in electricity markets, but also so that the DSO can acquire flexibility products from third-party aggregators and independent service providers to meet distribution system requirements. The settlement module shall also be incorporated to be able to settle and bill DSO-managed DERs not participating in the markers, e.g., subject to bilateral contracts, as well as the reporting functionalities. Performance analysis functionalities and aggregation services—local optimization, DR, and EC—are not initially considered for the standard DSO's DERMS solution, as these functions are exclusive for aggregators. DSOs must be also capable of interacting with all types of DERs and field metering devices, enterprise utility management systems, GIS, and TSOs—possibly through control centers and/or operational data exchange platforms.

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. These four variations of the DERMS solution are presented below, with relevant comments on their main nuances and key differences between them.

4.2.3.4.1 DERMS DSOs w/ ADMS – Unbundling

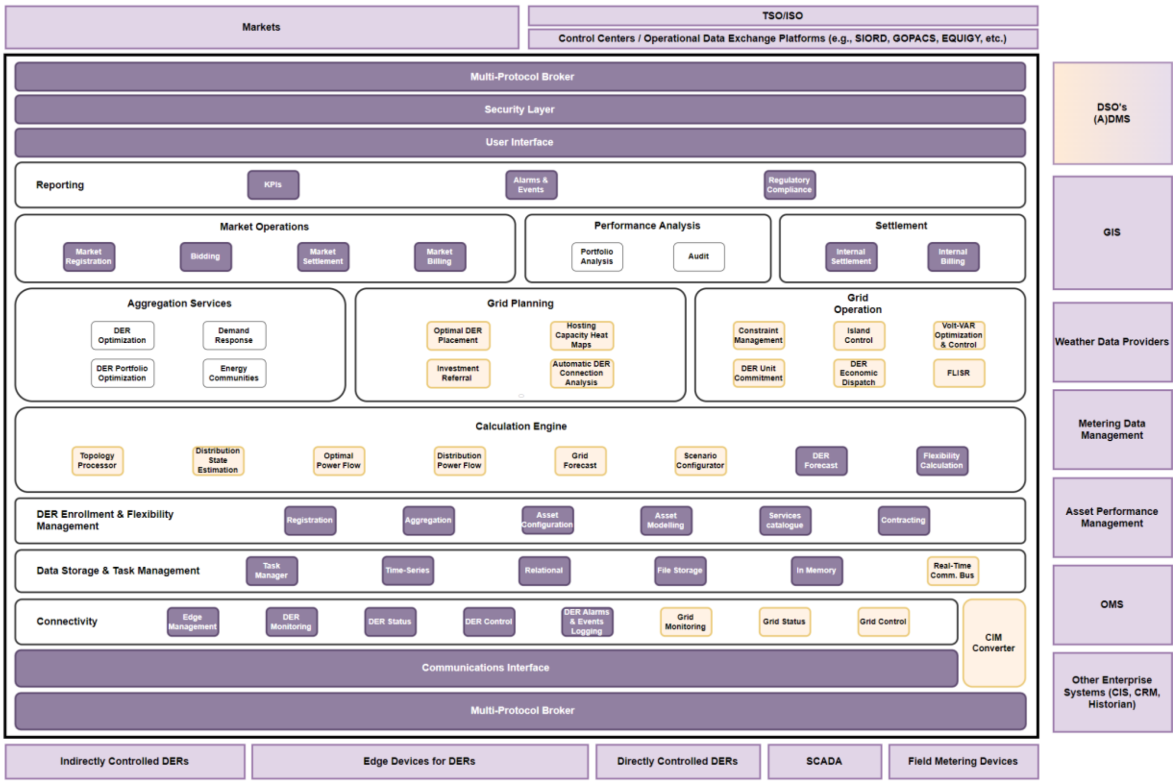

Figure 15. DERMS Functional Architecture - DSO w/ ADMS (Unbundling).

In this first scenario, all grid planning and operation services, core grid functionalities of the calculation engine—topology processor, optimal and distribution power flow, grid forecast and scenario configurator—, grid monitoring and control, real-time communication bus, and CIM conversion of network models shall be covered by the DSO's own ADMS software (in yellow in Figure 15 above), whilst the rest of functions described above are to be provided by the DERMS. Note that the *External (A)DMS* component on the right-hand side of the schematic has been replaced by the utility's own ADMS, part of whose capabilities will be integrated with the DERMS to carry out all these functionalities (yellow half of the component), while others will continue to perform their own tasks (half colored in purple).

4.2.3.4.2 DERMS DSOs w/o ADMS – Unbundling

Similarly, everything mentioned above applies again 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 functions included in this alternative now belong to the DERMS and the ADMS is considered as a purely external element. The architecture of this declination is shown below:

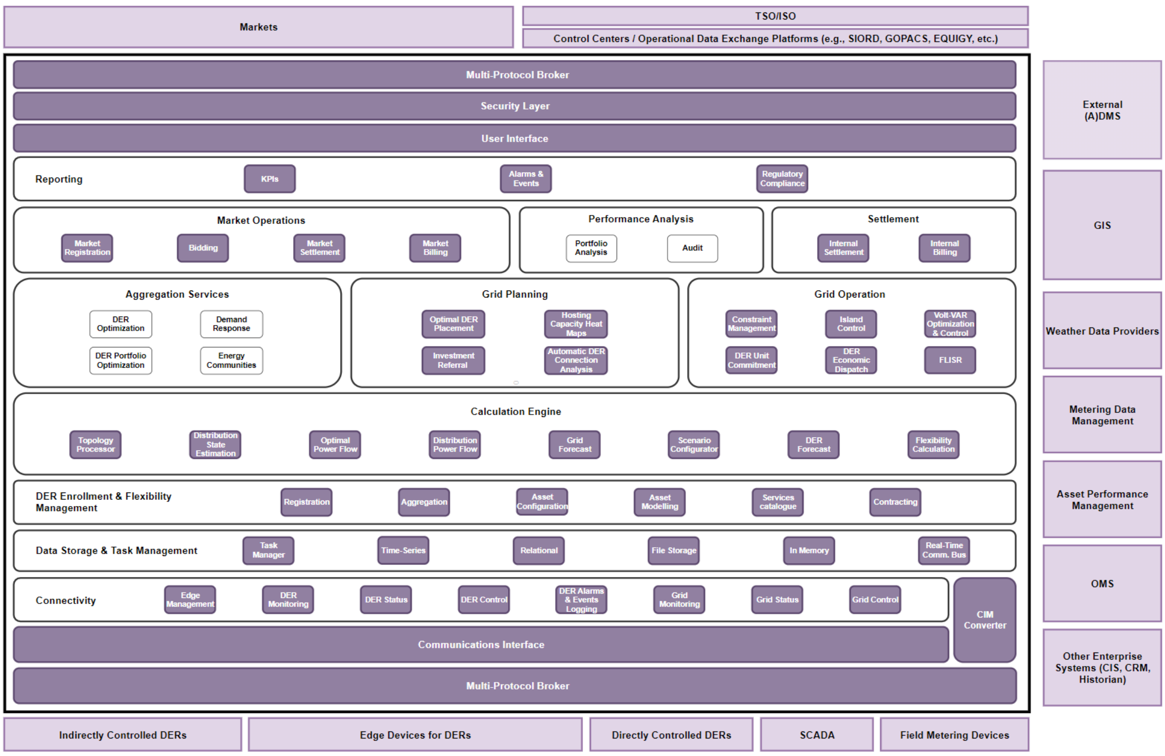

Figure 16. DERMS Functional Architecture - DSO w/o ADMS (Unbundling).

4.2.3.4.3 DERMS DSOs w/ ADMS – Vertically Integrated Utility

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, since the DSO can now perform aggregation and retailing functions. One can check in Figure 17 below that market operations also 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, as well as for the participation in wholesale markets alongside other utility companies.

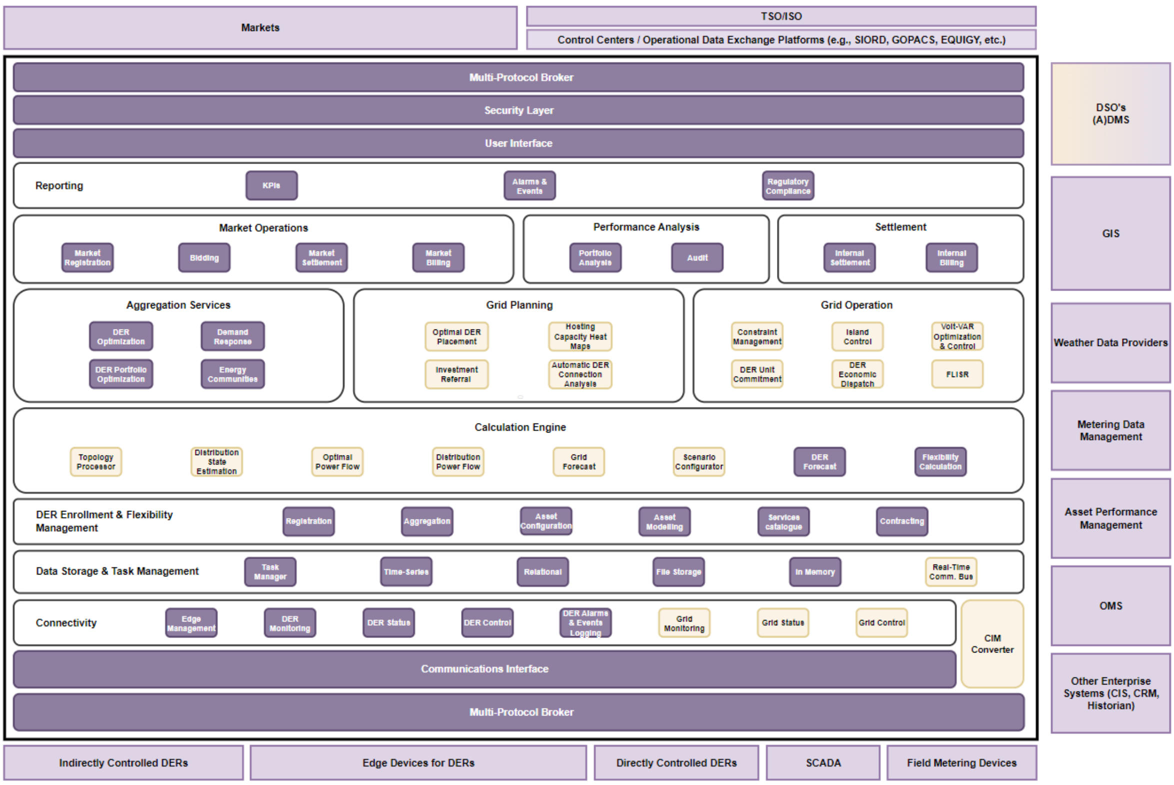

Figure 17. DERMS Functional Architecture - DSO w/ ADMS (Vertically Integrated).

Additionally, control centers and/or operational data exchange platforms for communication with TSOs/ISOs might be integrated within the same vertical utility—just like the TSO itself—but they are still considered in the DERMS architecture schematic in the case the utility company exclusively manages distribution and retail.

4.2.3.4.4 DERMS DSOs w/o ADMS – Vertically Integrated Utility

Finally, in line with everything that has been developed so far, 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 (see Figure 18). This would arguably constitute the ideal type of client for the deployment of the DERMS functional architecture that has been proposed in this work.

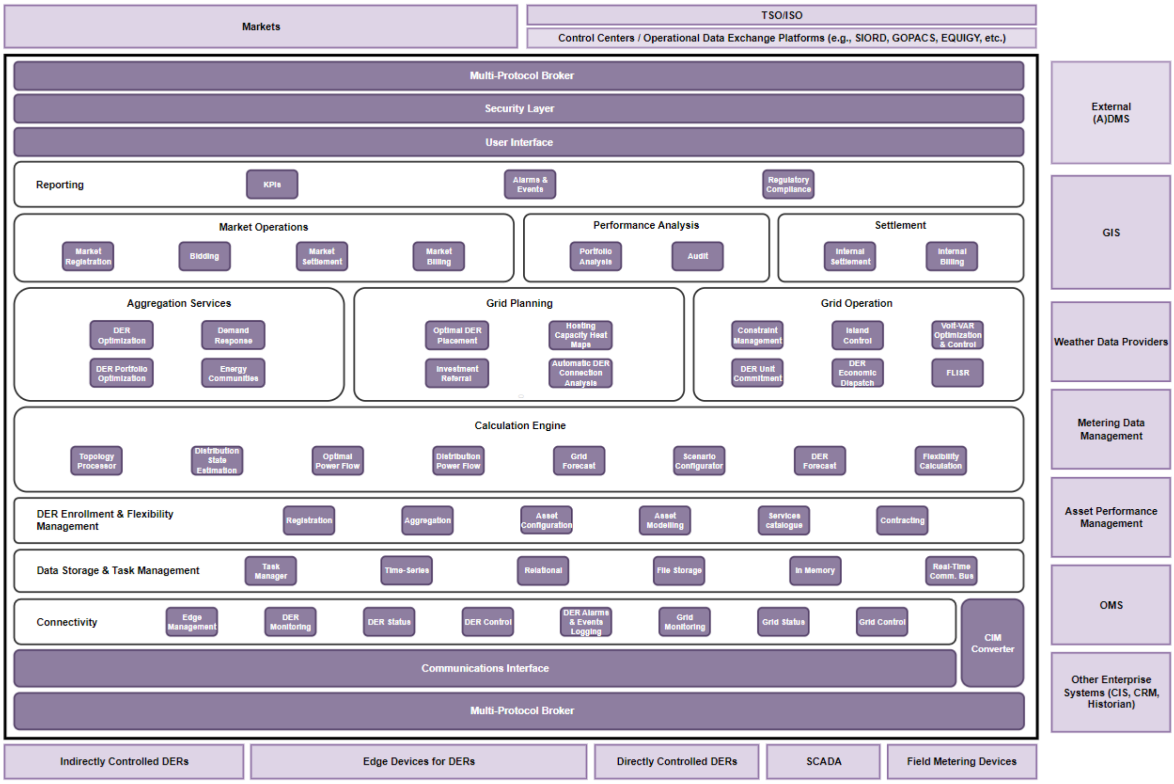

Figure 18. DERMS Functional Architecture - DSO w/o ADMS (Vertically Integrated).

4.2.4 MODULARIZATION STRATEGY

Returning to the main objective of this work, which is to develop a unified and comprehensive functional architecture for DERMS that can cover the widest possible range of use cases for all potential stakeholders—namely, DSOs, vertically integrated utilities, aggregators, niche verticals, and microgrids as exposed in the previous section—across different countries and regulatory contexts, 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. It is worth mentioning that this modularization also considers a more technical component, making Minsait's insights and experience in several projects crucial for ensuring its feasibility in this aspect. This subdivision is displayed in Figure 19, while certain modules align with the previously discussed functional division and do not require further elaboration, there are certain aspects that need to be clarified:

1) Connectivity functions are divided into two independent modules: *DER Connectivity* and *Grid Connectivity*. This allows for the separate implementation of DER Connectivity in the case of DERMS solutions for aggregators or niche vertical platforms, or for a DSO aiming to maintain its ADMS software. Note that (i) the CIM Converter is included in Grid Connectivity, as it is always offered together with grid monitoring and control functionalities, and (ii) that both the Communications Interface and the MPB are incorporated to both modules. This ensures they are included in the DERMS solution if only Grid Connectivity is required, but they are deployed only once—and not duplicated—in the case where both Connectivity modules are needed.
2) *Data Storage & Task Management* remains as a single module despite incorporating elements that are not necessary in all use cases—such as real-time information exchange capabilities for aggregators or DSOs with ADMS. The reason is that it is a module of a more technical nature, whose data storage and management functionalities can be used independently as required by each specific application.
3) *DER Enrollment & Flexibility Management* also remains as an independent module, which, additionally, shall be deployed for all clients and use cases that have been considered above for the registration, aggregation, configuration, and digital modeling of DERs, as well as for the management of contracting and of the offered flexibility services. The same occurs for the *Reporting* functionalities, which shall be also included in the DERMS solution on all occasions to enable the tracking of KPIs, specific alarms and events, and to ensure regulatory compliance.

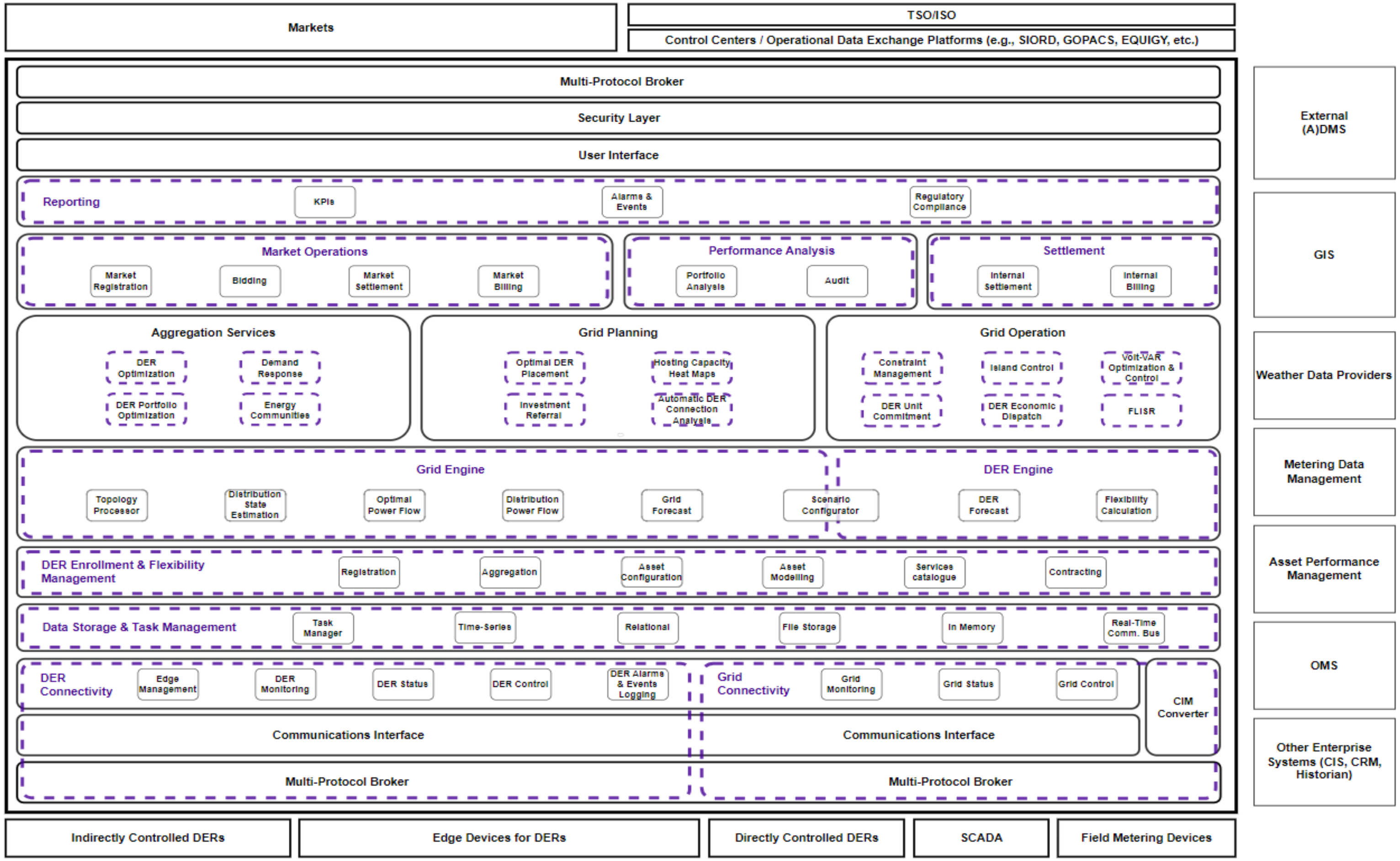

Figure 19. DERMS Functional Architecture - Modularization Strategy.

4) The Calculation Engine is also divided into two separate modules for grid and DERs, so that the *DER Engine* can be included alone in the DERMS solutions for aggregators, niche verticals, and DSOs with ADMS, and together with the *Grid Engine* for microgrids and DSOs that do not wish to integrate the DERMS software with their ADMS. Note that, similar to the CI and MPB, 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.
5) All planning, grid operation, and aggregation services are considered independent modules, allowing each client to decide which ones to incorporate into their solution and which are deemed unnecessary. These services rely on lower-level functionalities to carry out specific tasks, which may or may not be part of the DERMS solution for a particular stakeholder and shall be easily excluded from the rest of the architecture—i.e., an aggregator might require local optimization but not DR or EC capabilities, or a DSO may not need a FLISR service because it performs it through a different software.
6) The groups of function of *Market Operations*, *Performance Analysis*, and *Settlement* also form independent modules. While Market Operations has been included in all DERMS declinations considered in the previous section, Performance Analysis has been excluded from DSO solutions with unbundling (as they would not perform any aggregation tasks), and Settlement does not apply to niche verticals (they would be settling and billing their own products). Thus, it is essential for the latter two modules to constitute independent components that can be easily decoupled from the rest of the software solution.

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 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. The next chapter will validate this architecture by demonstrating (i) the technical feasibility of the modular approach through several projects conducted by Minsait using the same pieces of software for very different clients, and (ii) the existence of an underlying interest within the industry in a solution such as the one proposed here.

Chapter 5. 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 worldwide DERMS service providers will be presented in order to justify Minsait's relevance in the international DERMS landscape. This will further reinforce the work proposed here, which has been developed in collaboration with this company and has benefited from their forward-looking vision. Then, an overview will be provided of several projects conducted by Minsait, which successfully implement some parts of the proposed architecture. These projects demonstrate that the same units of software can be used for very different client profiles, supporting the idea of a comprehensive and modular DERMS solution targeting the needs of multiple stakeholders in a variety of use cases. Finally, the most relevant conclusions drawn from a questionnaire distributed among members of TSO/DSOs, aggregators, and the academic community will be reviewed. Their responses will serve to assess the interest of the electricity industry in what has been discussed here and justify the approach and the conclusions of this work.

5.1 IDC MARKETSCAPE - DERMS SERVICE PROVIDERS 2024

This IDC MarketScape evaluated service providers with a global perspective on DERMS actively working with clients and/or collaborating with utilities—through leadership, technology guidance and strategy, road map assistance, DERMS integration, or application development—for monitoring, control, operation, planning, and customer engagement activities related to distributed energy resources. The study provides both quantitative and qualitative assessments of vendors' capabilities and initiatives, with leading service providers being noted for their forward-looking strategies, innovation, and ability to help utilities navigate the evolving energy landscape marked by the rapidly increasing DER integration [58].

IDC analysts acknowledge the tendency in the electricity industry to distinguish between FTM or utility-connected distributed resources and BTM customer-owned DERs. This significantly affects the offerings in the DERMS space, with two primary solutions available: grid DERMS (or utility DERMS as it has been mainly referred to in this work) and grid-edge DERMS respectively. As mentioned, the IDC MarketScape evaluates the ability of each SP to assist utilities and market participants to optimally manage the power grid, which they consider to be particularly affected by BTM DERs and, therefore, special attention is paid to decentralized DERMS solutions. To be included in this IDC MarketScape for worldwide DERMS service providers, vendors had to meet the following criteria [58]:

1) Engagement in DERMS projects with utilities.
2) Experience supporting DERMS projects for at least two clients across two or more regions (Europe, the Middle East, Africa, Asia/Pacific, or America).
3) Provision of a minimum of two customer references.

Each vendor was scored and positioned in the MarketScape according to the variety and maturity of their capabilities and services they could offer to utilities and other customers concerning DER management. In particular, the following areas were specially considered when evaluating DERMS service providers [58]:

1) *Power Grid Management and DERMS Expertise*: providers with deep expertise in both utility operations and DERMS were better rated, as DER management is a specialized area still unfamiliar to many.
2) *Technology Strategy and Vision*: the best providers account with a comprehensive technology strategy that addresses current challenges and anticipates future needs.
3) *Wide Range of Capabilities and Services*: a higher score is awarded to SPs offering a wide range of mature DERMS-related offerings, tailored to specific utility needs considering regional differences, different customer bases, supply and demand characteristics, etc.
4) *Experience with Communication and Control Protocols*: the study values better those vendors with knowledge and experience with a wide variety of communication and

control protocols necessary for managing BTMs DERs effectively, e.g., Open ADR, IEEE 2030.5, Open FMB, SunSpec Modbus, etc.

5) *Innovation and Thought Leadership*: providers who can foster innovation and provide strategic consulting, helping utilities adapt to the rapid growth in DER penetration, will be highly rated.

SPs were assessed based on detailed surveys and interviews with the vendors, publicly available information, end-user and customer feedback—in several areas such as QoS, DERMS expertise, innovation, and perceived value for money—, and inputs from IDC experts in each market in order to provide an accurate and consistent evaluation of each vendor's strengths and weaknesses, initiatives and strategies, and general capabilities [58]. The results of the IDC MarketScape vendor assessment are presented in Figure 20 below:

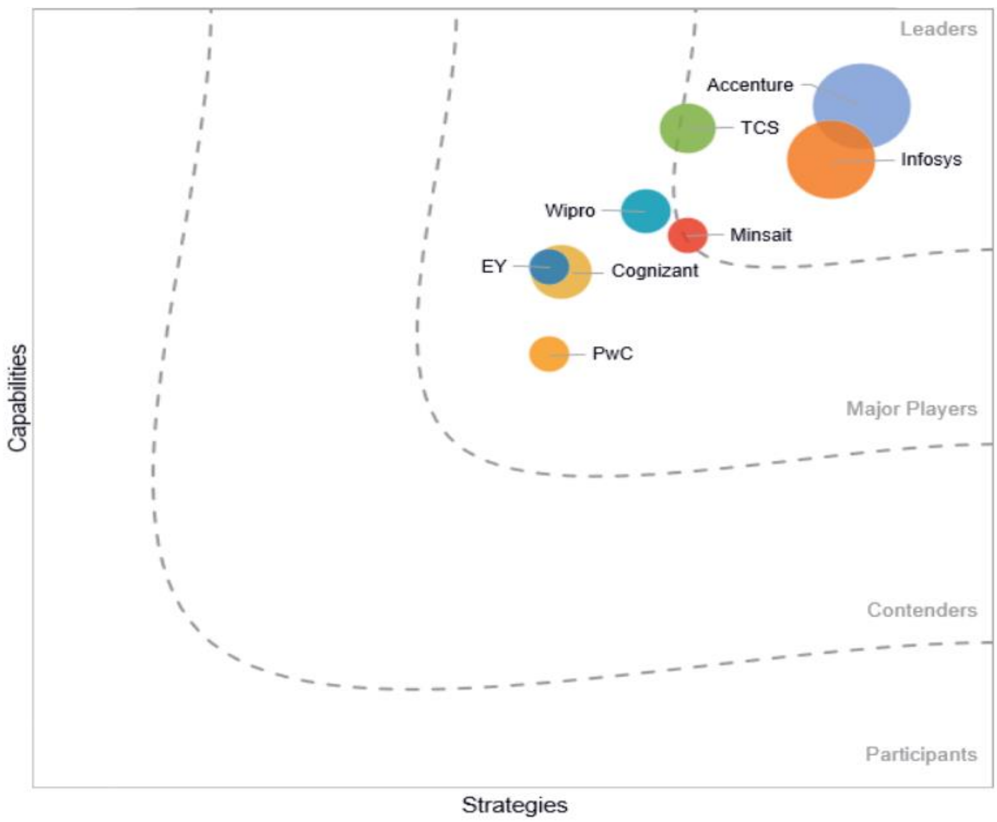

Figure 20. IDC MarketScape Worldwide DERMS Service Providers Vendor Assessment [58].

The IDC MarketScape graph shows vendors' position in the market with respect to two primary metrics [58]:

1) *Capabilities (Y-axis)*: reflects current capabilities and alignment of the service provider's offering with customer needs. This includes the effectiveness of a vendor's services and products in the present market.
2) *Strategies (X-axis)*: it indicates how well a vendor's future strategy on offerings, customer segments, and businesses aligns with anticipated customer needs over the next three to five years.

Finally, the size of the indicators on the graph represents IDC's estimate of the vendor's market share within the specific market segment. The reader can check that Minsait, although it is not the biggest firm in the study, falls into the *Leaders* category, highlighting its significance as a DERMS service provider. Additionally, it is important to note that the majority of companies considered in the MarketScape lack their own DERMS solution and must rely on external software vendors to provide DER management services. This is not the case of Minsait, which has its own proprietary software solution that is modular and adaptable to the diverse needs of very different clients in a variety of use cases, as will be described in the following section.

5.2 MINSAIT'S PROJECT REFERENCES

This section will 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 be briefly described, which illustrate five of the DERMS declinations considered in Section 4.2.3. This intends to demonstrate the technical feasibility of the approach proposed in this work, consisting of a single, comprehensive architecture, composed of independent modules that can be combined and integrated depending on the particular needs of each project and/or client profile. These projects are summarized below, arranged according to the DERMS declination within which they are framed:

1) *DERMS Aggregators*: Minsait partnered with Ferrovial to provide them with a DERMS designed for aggregators, with a similar structure to that presented in Section 4.2.3.1Parte I4.2.3.1. Ferrovial is a multinational infrastructure and services operator, primarily focused on the construction and management of infrastructures, including roads, airports, and urban services. In the electricity industry, Ferrovial operates as an aggregator, managing energy resources on behalf of its clients.

   The project's primary objective is to explore and optimize the integration of distributed energy resources such as on-site photovoltaic generation, battery storage, and demand response capabilities within commercial and industrial buildings. The solution focuses on leveraging Artificial Intelligence (AI) for battery operation, utilizing price arbitrage strategies to maximize energy savings and create new business models for Ferrovial's clients. The key technologies involved in this project include a 100 kWp PV system and a 250 kW lithium-ion battery. The DERMS integrates the monitoring of power meters, solar PV, batteries, and HVAC equipment under a unified platform. It employs economic optimization models based on historical demand, weather data, occupancy patterns, and ToU tariffs to determine optimal operation schedules. This integration and optimization aim to reduce energy costs and enhance the flexibility of energy usage, preparing the infrastructure for future participation in energy markets and grid services [59].

2) *DERMS Niche Verticals*: Minsait collaborated with Galp, a key player in the electric mobility sector, to implement a DERMS solution specifically tailored for the aggregation of electric vehicle (EV) charging stations. Galp is a major energy company with a diversified portfolio, including oil, gas, and renewable energy sectors. In the context of this project, Galp operates as a niche vertical platform in the EV sector, focusing on providing innovative solutions for electric mobility.

   This project aims to test and validate a new business model where Galp aggregates the demand flexibility from multiple EV recharge stations and actively participates in local energy markets. It involves eight EV charging stations with a total of 26 charge points, offering a combined fast and slow recharge power exceeding 2.5 MW. The initiative is part of a demonstration project in Spain, involving key stakeholders such as Etecnic, a platform for managing recharge sessions, and OMIE, the market operator for short-term local energy markets. This integration enables cloud-to-cloud communication and data exchange related to recharge sessions and market schedules, contributing to the regulatory framework for local markets and enhancing the DSO-Aggregator relationship model [60].

3) *DERMS Microgrids*: Minsait is involved in a collaboration with Monash University to support its ambitious Net Zero Initiative, aimed at transforming the Clayton Campus in Melbourne, Australia, into a sustainable net-zero embedded network. The project focuses on the implementation of a microgrid that integrates a wide range of DERs and energy efficiency solutions to facilitate the modernization of the campus grid. This initiative serves as a testbed for demonstrating the potential of grid modernization using readily available and affordable technology, setting an industry benchmark in Australia. The project involved the deployment of Minsait's solutions for distributed management of edge devices, and for active grid management, which also served as an Energy and Power Quality Management System (PQMS) and DER orchestrator, providing centralized monitoring, control, and management of resources across the campus. The microgrid encompassed 28 buildings, more than 40 distributed resources, and 11 secondary substations. Among the project's primary benefits, one could mention the establishment of a comprehensive test environment under real operational conditions, understanding the value proposition for both network and behind-the-meter assets, and setting up an Energy Competence Centre for the region. This initiative not only aims to achieve sustainability goals but also to contribute to the development of future regulations and best practices in microgrid management and DER integration [61].

4) *DSO with proprietary ADMS – Unbundling*: Minsait has partnered with Enel, one of the largest distribution system operators globally, to integrate its ADMS with Minsait's DERMS solution. Enel is a multinational energy company and a leading global player in the power and gas markets, responsible for the operation, maintenance, and development of the distribution network, ensuring the reliable delivery of electricity to end-users. The

collaboration with Minsait for DERMS integration reflects Enel's commitment to address the growing challenges posed by the increasing penetration of distributed generation, demand, and transport electrification, which introduce complexities such as reverse power flows, line congestion, and voltage regulation issues.

It is worth highlighting that the selection of Minsait as DERMS service provider was based on the modular and microservices-based architecture of its DERMS solution, which massively reinforces the main argument of this work. This modular and flexible approach allows for seamless integration with the existing ADMS, while ensuring minimal disruptions to critical operational functions. The project spans three regions, involving approximately 150 substations and engaging around 300 flexibility service providers. The DERMS solution is 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, ensuring that Enel can source the required grid flexibility to meet regulatory requirements and operational demands efficiently [62].

5) *DSO without proprietary ADMS - Vertically Integrated Utility*: Minsait will promptly deliver a comprehensive DERMS solution for Saudi Electricity Company (SEC) to manage its distribution operations in two of its control centers. SEC is the largest electricity utility in the Middle East and North Africa region and, for the interests of this validation, operates as a vertically integrated utility in Saudi Arabia. It is responsible for the generation, transmission, and distribution of electricity across the country, serving millions of residential, commercial, and industrial customers, and ensuring the reliability and stability of the national grid. The company is actively involved in modernizing its operations and infrastructure, particularly integrating renewable energy sources and enhancing grid management capabilities in line with the Saudi Green Initiative for 2030. The DERMS architecture was adapted to the client overall requirements, which include provisioning of full ADMS functionalities for planning and real-time operations,

together with functions for the management of aggregators and the growing number of distributed energy resources—mainly distributed solar generation and EV charging infrastructure. Aggregator DERMS functions will complement those natively covered by a traditional ADMS (in this case also covered by the DERMS), managing all indirectly controlled assets—i.e., FTM and BTM assets managed by third parties. Modules will be seamlessly integrated through the exchange of flexibility contractual information, monitoring data and control schedules.

These projects demonstrate that the same set of software modules (Minsait's offering is, like that of any other vendor, limited) can be used to address the needs of very different types of clients—from universities to vertically integrated utilities—in multiple application scenarios—from microgrid development to overall grid management. This only supports the idea of a comprehensive and modular DERMS solution, consisting of a set of common core functionalities, and a number of additional services specific to each particular use case.

5.3 INDUSTRY INTEREST ASSESSMENT QUESTIONNAIRE

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

1) Around the 80% of respondents affirm that DERMS (understood as Distributed Energy Resource Management Systems) are necessary for all stakeholders managing DERs, in spite of their different roles and responsibilities.
2) There seems to be a tendency to interpret that the main objective of DERMS solutions is to allow prosumers and demand-side aggregators to optimize the flexibility of their BTM resources, rather than to facilitate system operators the management of the distribution network—despite the fact that almost two thirds of the respondents belong to DSOs and TSOs and the rest of the sample is composed of members of aggregators and academics. This aligns with what has been emphasized throughout the paper regarding that DERMS

solutions are not exclusive for utilities, but they also target third-party aggregators and all stakeholders in the electricity industry managing BTM DERs.

3) A higher percentage (around 90%) supports that specific DERMS functions shall be required for the particular needs of each stakeholder (which justifies the seven DERMS declinations presented above), while a lower 70% is of the opinion that common core functions should exist for all stakeholders despite their diverse roles. This seems to be a less settled idea (a 20% strongly disagrees with it), and it aligns with the vendor review included in Section 3.2.3 where there are not so many vendors centered in the graph, but it allows, to some extent, to justify the suitability of a single, comprehensive DERMS solution.
4) There appears to be greater consensus on the need for new market mechanisms—such as local flexibility services markets—to optimize the value of DERs, compared to the perspective that the participation of these distributed resources in power system operations should be based on bilateral and flexible contracts.
5) Most respondents believe that the core functions (common for all DERMS declinations) of the DERMS solution should not be regulated by the competent authorities, unique, and shared among all stakeholders. Instead, they support the competitive specialization of these core services by different vendors and the existence of a market share for each.
6) There is consensus that the DERMS should be a new solution rather than an incremental addition to existing traditional enterprise system—e.g., ADMS with DER management capabilities. This supports our proposal for a new, unified, comprehensive, and adaptable DERMS solution that can adapt to multiple types of clients and use cases through its different declination.
7) Respondents tend to consider that the different vendors should focus on a certain stakeholder to offer them a specialized solution, rather than targeting multiple types of clients with different combinations of functions and services derived from a single solution. This clearly shows that there is still some opposition to the vision proposed here or, at least, some skepticism about its feasibility. However, at the same time, around 70% respond positively to the need for modularization and flexibility in the DERMS solution to adapt to different regulatory contexts and use cases.

Therefore, this assessment of the industry interest has served to justify the approach that has been 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 has also shown that the electricity sector still holds many convictions that are contrary to the vision advocated in this work, and that there will be, undoubtedly, some resistance to change in the coming years from various stakeholders.

Nevertheless, it is concluded that with these three arguments—the IDC MarketScape, Minsait's project references, and the industry interest assessment—the DERMS functional architecture is completely validated within the scope of this work, as it is the general vision that has been consistently maintained and that can be reduced to two key aspects: (i) DERMS solutions are not exclusively for utilities, as the industry often tends to assume, and (ii) the DERMS solutions must be unified and comprehensive, consisting of a set of core functionalities common to all stakeholders, along with additional features tailored to the specific needs and objectives of each client and use case.

Chapter 6. CONCLUSIONS & FUTURE WORKS

The electric power system is currently undergoing a significant transformation driven by the penetration of Distributed Energy Resources (DERs). Traditionally, grid operation consisted of large, centralized power plants generating electricity that was then transmitted over distances to end consumers. However, this model is rapidly evolving due to the rise of DERs, such as solar photovoltaic systems, wind turbines, energy storage systems, and electric vehicles, which are typically smaller in scale and located closer to the point of consumption. This shift has led to a more complex, active, and dynamic distribution grid, where power flows are often bidirectional, and new challenges such as voltage regulation, overload management, and protection coordination have emerged [1]-[4].

The integration of DERs, both in-front-of- and behind-the-meter, offers multiple opportunities and potential benefits for the technical and economic optimization of the power system, but also introduces significant challenges that traditional grid management tools are not equipped to handle [1], [2]. In response, utilities have been deploying various software solutions to interact with these grid-edge technologies (both utility- and customer-owned). Some of them are already mature, such as Virtual Power Plants (VPPs), Demand Response Management Systems (DRMS) services, or Advanced Distribution Management Systems (ADMS), while other are still relatively nascent. This is the case of Distributed Energy Resource Management Systems (DERMS), designed to provide a comprehensive approach to monitoring, controlling, and optimizing the integration of DERs into the power grid [1]-[3], [5], [6].

6.1 CONTRIBUTIONS OF THE WORK

DERMS solutions have been often categorized into centralized and decentralized systems both in the literature and in the marketplace. Centralized DERMS are typically used to manage FTM resources, connected to the utility's side of the meter and integrated into the broader distribution grid infrastructure. These include larger-scale resources such as solar farms, wind parks, and grid-scale storage systems. On the other hand, decentralized or aggregator DERMS are intended to manage BTM distributed resources, which are located on the consumer's side of the meter. These include residential solar panels, home battery energy storage systems, smart appliances, and EVs, and are primarily used to reduce consumers' energy costs and enhance security of supply [1]-[3], [5]-[8].

However, the distinction between centralized and decentralized DERMS is becoming increasingly blurred. Advances in DER management technologies, evolving regulatory frameworks, and the growing capabilities of DERs to provide multiple services to both consumers and the grid suggest that integrating both levels of DERMS into a single, unified solution could offer significant benefits. A comprehensive DERMS solution that bridges the gap between centralized and decentralized systems would enable more seamless and efficient operation of the grid, maximizing the potential of both FTM and BTM resources and ensuring optimal DER integration [1]-[3], [5]-[8]. In this regard, this work has focused on developing a functional architecture for DERMS that effectively addresses the complexities of modern energy systems and offers a complete tool for DER integration, capable of adapting to the diverse roles and responsibilities of multiple stakeholders in the electric value chain.

Firstly, after conducting a theoretical contextualization in the matter of DERs (Chapter 2), an exhaustive analysis of the current state-of-the-art of DERMS solutions (Chapter 3) and having narrowed down both the definition and the scope of application of DERMS (Section 4.1), the general schematic of the proposed DERMS functional architecture was presented in Section 4.2. Its various functionalities and services included were described in detailed, and both the reasoning process followed to develop the architecture and the way in which its diagram had to be interpreted were explained. Then, this architecture was adapted to different use cases and client typologies through seven distinct DERMS *declinations*, tailored to specific stakeholders, namely, aggregators, niche vertical platforms, microgrid controllers, DSOs, and vertically integrated utilities. A modular structure was also defined for the architecture, allowing for the implementation of the DERMS declinations across the different clients and easy integration with their existing software platforms. This modularity ensures that the core functionalities of DERMS are preserved while offering the flexibility to incorporate additional features based on the unique requirements of each customer and use case. This approach not only enhances the versatility and adaptability of the DERMS solution but also facilitates its adoption across a wide range of stakeholders and regulatory environments in the energy sector.

Finally, the validation of both the proposed functional architecture and the general approach of this work was conducted using several methods. The IDC MarketScape of worldwide DERMS Service Providers was used to benchmark Minsait, company with which the author had the opportunity to collaborate during the development of this project, against other vendors in the industry. The study shows that Minsait, although it is not the biggest firm in the MarketScape, falls into the *Leaders* category, reinforcing the work proposed in this document that has benefited from their feedback and forward-looking vision. Additionally, Minsait's project references provided practical insights into the architecture's real-world applicability and effectiveness, demonstrating that the same set of software modules can be used to address the needs of very different clients in multiple use scenarios, and supporting the idea of a comprehensive and modular DERMS solution. Lastly, the industry interest assessment questionnaire, distributed among TSO/DSO members, aggregators, and academics, offered valuable feedback and served to justify the approach that has been followed to develop the proposed comprehensive DERMS functional architecture, the need for its seven declinations, and the relevance of modularization.

However, this survey also showed that the industry still holds many convictions that are contrary to the overall vision presented in this work, and that there will be, undoubtedly, some resistance to change in the coming years from various stakeholders. This vision can be summarized in two key aspects that will be critical to the future of DERMS development. In the first place, it is crucial to recognize that DERMS solutions are not exclusively for utilities, which has been appreciated as a common pattern in the literature and within the industry. Therefore, the functional architecture developed here is versatile and adaptable, capable of serving a wide range of stakeholders—from aggregators to DSOs and vertically integrated utilities—to effectively manage and optimize their distributed energy resources.

Secondly, DERMS must be unified, end-to-end solutions, consisting of a set of core functionalities that are common to all stakeholders, along with additional features tailored to the specific needs and objectives of each client and use case. This flexible and modular approach ensures that DERMS can be customized to fit different regulatory contexts and technical requirements—such as the integration with existing enterprise software systems—without compromising the integrity and the effectiveness of the overall solution.

In summary, this work has successfully developed and validated a unified, comprehensive DERMS architecture that is both modular and adaptable to the particularities of various clients and use cases. It emphasizes that DERMS solutions are not 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.

6.2 AREAS OF FUTURE DEVELOPMENT

Despite the contributions made by this work to the understanding of the concept of DERMS and its scope of application, laying the groundwork for the theoretical design of DERMS solutions, several areas deserve further investigation and development. Future research shall focus on the issues below, most of which have already been suggested in previous chapters:

1) *Well-Defined Regulatory Framework*: as the energy landscape evolves, regulatory frameworks will need to adapt to support the widespread deployment of DERMS. A great obstacle to achieving a comprehensive DERMS platform is the lack of a common, well-defined, regulatory framework on DER management, which does not vary widely across different regions [1], [2], [10], [11]. Significant improvements have been made with legislative initiatives such as the EU DSO Entity and ENTSO-E's Proposal for a

Network Code on Demand Response, but a long way remains to be covered. As has been illustrated in Section 3.5.2, this European-level regulation is still ambiguous and poorly defined in many of the terms relevant to the deployment of DERMS solutions, and it often limits to establish that Member States shall develop their own national terms and conditions for each of these aspects. Certain areas still need to be clarified concerning DER aggregation models, methods for quantifying flexibility services, prequalification and verification of products, market design for local services, and DSOs-TSOs coordination in each Member State.

2) *Detailed DSO-TSO Coordination Models*: although included to some extent in the previous point, special focus has been given in the literature to this issue, and it seems clear that much tighter and efficient coordination between TSOs and DSOs will be required as TSOs aim to leverage aggregated DERs to help balance supply and demand, provide ancillary services to regulate frequency and voltage, and optimize energy use [1]. The traditional separation between the TSO and DSO responsibilities results no longer viable, and new coordination models need to be developed—examples are local markets where resources connected to the distribution grid can offer their flexible capacity directly or through an aggregator, shared balancing responsibilities models, TSO-DSO hybrid management models where the DSOs control and optimize the use of DERs and validate the technical feasibility of the schedules received from the TSO, or even DSO-only management models where TSO's only role is to issue aggregated bids [10], [36], [37]. However, further works proposing and validating new DSO-TSO coordination models are still highly needed.

3) *Standardized Communication Protocols and Information Models*: as DERMS solutions are adopted by a broader range of stakeholders, ensuring seamless interoperability between different systems and technologies will be crucial. In this regard, another major challenge is the lack of universally accepted standardized communication protocols and information models for interoperability between DER devices, between utilities and aggregators, and between aggregators and individual DERs [1]-[4], [8]-[9]. On the contrary, different protocols are used for different purposes, and even for the same purpose by different vendors and utilities, which massively complicates the integration

across various platforms and devices and, therefore, the deployment of a comprehensive DERMS solution that can be tailored to the specific requirements of the different stakeholders. A smoother data transfer through common standards would improve real-time observability of grid conditions, and the ability to predict and respond to constraint violations [8], the exchange of operation schedules between individual DERs or DER aggregators and the DSO, and the modification of setpoints in real-time [1], which are all crucial functionalities of a DERMS.

4) *Improved DER Integration Analysis*: accommodating as much renewable capacity as possible in the distribution grid is crucial for advancing towards a sustainable energy future. To achieve this, further research is needed to develop more sophisticated algorithms for connection analysis, optimal DER placement, and the creation of hosting capacity heat maps for user interaction. These tools are essential for identifying the best locations for DERs within the grid, ensuring that they can be integrated without causing stability issues or requiring costly upgrades. This would also allow for connection requests to be made directly at the most favorable nodes, significantly reducing permitting delays. By optimizing where and how DERs are connected to the grid, we can maximize the share of renewable energy sources in the energy mix, improve grid efficiency, and reduce the need for traditional, fossil fuel-based power generation.
5) *Advanced Optimization Algorithms*: the optimization of DER operations, both within an aggregator portfolio, or at the utility level, especially in real-time, remains a complex challenge. Research into more sophisticated optimal dispatch algorithms that can handle the intermittent and distributed nature of DERs, including factors such as weather variability and market fluctuations, would significantly enhance the efficiency of certain services of DERMS solutions.
6) *Integration with Emerging Technologies*: the integration of DERMS with emerging technologies such as blockchain or artificial intelligence holds great promise for enhancing the capabilities of these systems. An example of this is the use of blockchain for transactive energy operations as proposed by SEPA in [39]. Future research should investigate how these technologies can be leveraged to improve the security, transparency, and efficiency of DERMS.

7) *Software Development, Technical Architecture, Scalability, and Deployment*: while this work has demonstrated the theoretical feasibility of the proposed DERMs functional architecture, further work is needed to program the included functionalities and services and the interactions between them, to design the technical architecture of the solution, and to test its scalability and deployment in real-world scenarios. The references to Minsait's projects in Section 5.2, which successfully implement parts of the proposed architecture, suggest that a comprehensive, modular DERMS solution as the one described here is realistic and technically feasible. However, further case studies involving large-scale deployment of DERMS—such as the upcoming project that will be conducted with SEC—will be crucial in validating the architecture's effectiveness, finding elements that need to be modified, and identifying areas for improvement.

By addressing these future research areas, DERMS can continue to develop and perfectionate, ultimately leading to a unified, comprehensive, and versatile DERMS solution capable of adapting to the requirements and responsibilities of all potential stakeholders in the greatest variety of use cases and regulatory frameworks. Only in this manner will it be possible to optimize the management and fully leverage the value provided by DERs—in terms of resilience, technical and economic efficiency, and sustainability—to the electricity system.

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APPENDIX A. SUSTAINABLE DEVELOPMENT GOALS

Established by the United Nations in 2015, the Sustainable Development Goals (SGDs) were meant to be an appeal to end poverty, inequality, war and violence, injustice, and to fight the climate change and the degradation of the planet. These 17 principles lead the way to face the main global challenges and move towards a sustainable prosperity [63]. Even though the work that has been presented above cannot be clearly framed within a specific Sustainable Development Goal, it is aligned with the following SDGs and specific goals:

SDG Dimension	*SDG Identified*	*Role*	*Goal*
Society	SDG7: Ensure access to affordable, reliable, sustainable, and modern energy for all.	Primary	7.2 By 2030, significantly increase the share of renewable energy in the global energy mix. 7.3 By 2030, double the global rate of improvement in energy efficiency.
Economy	SDG9: Build resilient infrastructure, promote inclusive and sustainable industrialization, and foster innovation	Primary	9.4 By 2030, upgrade infrastructure and convert industries to make them sustainable, using resources more efficiently and promoting the adoption of clean and environmentally rational technologies and industrial processes.
Biosphere	SGD13: Take urgent action to combat climate change and its impacts.	Primary	13.2 Incorporate climate change measures into national policies, strategies, and plans.
Society	SDG11: Make cities and human settlements inclusive, safe, resilient, and sustainable.	Secondary	11.6: By 2030, reduce the adverse per capita environmental impact of cities, including by paying special attention to air quality and municipal and other waste management.
Economy	SDG12: Ensure sustainable consumption and production patterns.	Secondary	12.2: By 2030, achieve the sustainable management and efficient use of natural resources.

Table 2. Project alignment with the Sustainable Development Goals (SDGs) [63].

Table 2 shows the identified SDGs and their dimensions, the primary or secondary role in terms of alignment with this project, and their specific goals more related to the work developed throughout this document. Below, it is suggested how the project aligns with these sustainable development objectives.

- *SDG 7 – Affordable and Clean Energy*: this work ultimately focuses on improving the management of distributed energy resources, which is critical for increasing the share of renewable energy in the generation mix. DERMS support the efficient and reliable integration of renewable sources into the power grid, essential for reducing carbon emissions and achieving energy sustainability. By enhancing grid efficiency and enabling a secure penetration of renewables, this research contributes directly to SDG 7.
- *SDG 9 – Industry, Innovation, and Infrastructure*: the development of DERMS is closely related to upgrading energy infrastructure to be capable of handling the complexities introduced by decentralized energy resources. The work presented herein promotes innovative solutions that improve the efficiency, resilience, and sustainability of energy systems, aligning with the goal of fostering innovation and sustainable infrastructure.
- *SDG 13 – Climate Action*: again, by facilitating the integration of renewable energy sources and enhancing the efficiency of the electricity grid, this work contributes directly to reducing greenhouse gas emissions caused by fossil fuel-based generation and mitigating climate change, which are key objectives of SDG.
- *SDG 11 – Sustainable Cities and Communities*: although less strictly aligned with the project, DERs and their management solutions play a crucial role in making cities more resilient and sustainable, promoting the integration of renewable generation at the end-user level, and enhancing energy efficiency (reducing overall consumption). This alignment is relevant as cities increasingly rely on smart grid technologies and renewable energy systems to reduce their carbon footprint and enhance sustainability.
- *SDG 12 – Responsible Consumption and Production*: the optimization of energy resources facilitated by DERMS contributes to more responsible consumption patterns by reducing energy waste and promoting efficient resource use. While this is not the central focus of the work, the outcomes of effective DERMS implementation can contribute to minimizing the environmental impact of energy production and consumption, ultimately supporting this goal.

This analysis demonstrates the broader impact of this work on advancing towards efficient, renewable-based energy systems, supporting global efforts for sustainable development.