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PhD THESIS

Trading of Flexibility Products in Multi-DSO and Multi-Scale Electricity Markets

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Estudiante del programa de doctorado interuniversitario en Sistemas de Energía Eléctrica de la Universidad de Málaga, autor/a de la tesis, presentada para la obtención del título de doctor por la Universidad de Málaga, titulada:

OPERACIÓN DE PRODUCTOS DE FLEXIBILIDAD EN MERCADOS ELÉCTRICOS MULTI-DSO Y MULTI-ESCALARES

Realizada bajo la tutorización y dirección de José Antonio Aguado Sánchez.

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Autorizo su presentación para la lectura y defensa de la tesis doctoral ante el tribunal, que ha de juzgar su mérito y calidad científica en la Universidad de Málaga, para que así conste a efectos de lo establecido en el artículo octavo del Real Decreto 99/2011, de 28 de enero, por el que se regula el sistema de doctorado en España.

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Resumen

Durante décadas, los mercados de energía eléctrica operaron bajo un modelo de despacho centralizado, donde un único operador de mercado despachaba las unidades de generación en función de la minimización de costes. Este despacho se llevaba a cabo a diario y funcionó bien durante mucho tiempo para las plantas de energía convencionales. Sin embargo, en busca de un suministro eléctrico eficiente, la Unión Europea inició la liberalización de los mercados de energía a principios de siglo, con el objetivo de integrar fuerzas competitivas y regulaciones para aumentar la eficiencia. Esto llevó a la fragmentación de las compañías eléctricas integradas verticalmente y a la creación de la estructura de mercado actual y competitiva a nivel nacional, lo que redujo los precios y aumentó la eficiencia del sector energético.

Actualmente, el sector energético está experimentando un cambio transformador impulsado por las tres D: digitalización, descarbonización y descentralización. La digitalización utiliza tecnologías avanzadas y soluciones digitales para optimizar los recursos energéticos e integrar nuevos actores energéticos, como comunidades energéticas, vehículos eléctricos o sistemas de calefacción eléctrica. La descarbonización se centra en reducir las emisiones y pasar a la generación renovable. La descentralización empodera a los consumidores para participar en el mercado energético a través de REDs.

Se han realizado esfuerzos para implementar estas medidas, y en los últimos 20 años se ha logrado reducir 1.000 Mt de CO_2, lo que representa una reducción del 25 % en las emisiones del sector energético en comparación con 1990 [1]. Estas medidas han sido especialmente efectivas en el caso de España, donde la intensidad de CO_2 en la generación eléctrica se ha reducido en un 60 % en los últimos 20 años [2]. Sin embargo, se necesitan medidas adicionales para alcanzar las emisiones netas cero establecidas por la Unión Europea para 2050 [3].

La generación distribuida (GD) se define como la generación de electricidad a partir de instalaciones de pequeña escala, generalmente ubicadas cerca de los puntos de consumo. Estos elementos son clave para lograr la descarbonización del sector energético, ya que generalmente se basan en fuentes de energía renovable, como paneles solares fotovoltaicos o aerogeneradores. Además, la electrificación de los sectores de calefacción y transporte aumentará la demanda de electricidad, lo que requerirá una mayor participación de fuentes de energía renovable en la mezcla energética. Sin embargo, si todos estos elementos están bien integrados en la red, también pueden ser una fuente de flexibilidad que se puede utilizar para adaptarse a la variabilidad de las fuentes de energía renovable y reducir la necesidad de refuerzos en la red. Este es un aspecto exigente, especialmente en el caso de las redes de distribución, que no fueron diseñadas en el pasado para estos nuevos requisitos. Esta tesis tiene como objetivo contribuir a alcanzar este objetivo proponiendo nuevos modelos y métodos para gestionar la flexibilidad de los REDs (REDs) en las redes de distribución. En este sentido, las principales contribucio-

nes de esta tesis se encuentran en el campo de la caracterización de la flexibilidad en las redes de distribución, algoritmos para el despeje de los MLFss y la gestión de los REDs para la acumulación de beneficios por la comercialización de flexibilidad en mercados naciones y locales.

Contexto y motivación

Las redes de distribución modernas están experimentando una profunda transformación debido a varios factores, entre los cuales es preciso destacar tres de ellos. En primer lugar, la penetración cada vez mayor de recursos energéticos renovables distribuidos de pequeña escala cerca del cliente final. En segundo lugar, la integración de nuevos actores en la red, como almacenamiento de pequeña escala, activos de movilidad eléctrica y la electrificación de la calefacción. En tercer lugar, un fuerte proceso de digitalización utilizando *Smart Meters* y un despliegue intenso de sensores y apartamentos de medición en toda la red de media y baja tensión.

Al mismo tiempo, hay un creciente interés en facilitar la integración y la participación libre de instalaciones de energía renovable y clientes finales en los mercados eléctricos. El objetivo principal de esta política es incentivar una gestión adecuada de su energía, permitiéndoles obtener mejores precios de mercado. En este contexto, la flexibilidad juega un papel fundamental como facilitador de la integración en el mercado de estos nuevos activos. Además de eso, la flexibilidad sirve como una herramienta de empoderamiento del consumidor final de energía, agregando valor a su gestión, tradicionalmente estática. Esta tendencia está alineada con la legislación europea que se deriva del denominado *Paquete de Energía Limpia*, y especialmente con la Directiva relacionada con el aumento de la participación de fuentes renovables limpias.

Sin embargo, estos activos no tienen una participación fácil en el mercado, ya que la mayoría de las estructuras de mercado tradicionales requieren ofertas mínimas altas, típicamente por encima del megavatio. En este sentido, los mercados de electricidad y energía locales surgen como una nueva capa de las estructuras de mercado tradicionales para facilitar la participación de activos distribuidos de mediana y pequeña escala. Los mercados locales se definen como un lugar donde los activos pueden intercambiar diversos bienes relacionados con la energía. Los activos cuyo punto de acoplamiento común se encuentra a nivel de distribución pueden participar en estas estructuras, lo cual generalmente requiere una oferta mínima baja o nula. Los consumidores con instalaciones de generación, productores de energía renovable, plantas de cogeneración, baterías e incluso agentes híbridos, donde se combinan varios tipos de agentes, se pueden beneficiar de este paradigma de mercado, y a los cuales se hace referencia como REDs. En general, cualquier instalación capaz de gestionar su consumo o inyección a la red puede incluirse en esta definición. Particularmente, los MLFss son aquellos en los que, debido a circunstancias específicas de la red, los intercambios de energía están técnicamente restringidos o deben realizarse mediante un conjunto determinado de instalaciones conectadas a un nodo determinado de la red. En condiciones normales de operación, se pueden comercializar productos de energía o servicios de flexibilidad en este tipo de mercados, lo que permite a los operadores de red solicitar una desviación del programa programado y a los REDs ofrecer estos servicios de flexibilidad.

Las bases para una participación activa de estos REDs en los mercados locales están establecidas, promoviendo la aparición de comunidades energéticas y la figura del agregador como gestor de múltiples activos de pequeña y mediana escala. Estas son herramientas clave que permiten a los ciudadanos beneficiarse directamente de un mercado eléctrico interior, lo que facilita la penetración de energías renovables al tiempo que proporciona a los operadores del sistema herramientas de flexibilidad para evitar costosos refuerzos de la red. Las centrales convencionales coexistirán con estos nuevos recursos distribuidos, que serán gestionados por agregadores, también denominados en la literatura como PSFs. Estos nuevos actores energéticos adquirirán diferentes servicios, que serán coordinados por el Operador de la Red de Distribución (ORD) y el Operador del Mercado Local (OML) para garantizar la seguridad del sistema.

En este contexto, se necesitan un conjunto de herramientas para que estos actores faciliten la gestión e integración de estos nuevos recursos. Esta tesis contribuye a este objetivo proponiendo nuevos modelos de caracterización de flexibilidad desde el punto de vista del ORD, nuevas arquitecturas de mercado local desde el punto de vista del OML y nuevos enfoques de acumulación de ingresos desde el punto de vista del Proveedor de Servicios de Flexibilidad (PSF).

Con este objetivo en mente, en esta tesis se desarrollan varias estrategias matemáticas utilizando principalmente la teoría de optimización. Este es el esquema clásico para el proceso de toma de decisiones, que utiliza datos para construir modelos predictivos de las variables que determinarán qué tan correctas serán nuestras decisiones. Una visión general del marco sobre el cual se construye esta tesis se muestra en la Figura 1. Se puede observar que las principales líneas de acción de la tesis se dividen en los tres actores mencionados anteriormente, mostrando la relación entre ellos.

Para lograr esto, esta tesis se basa en las siguientes hipótesis:

H1 La proliferación de las fuentes de energía distribuida requerirá su gestión a través de mercados locales. Dado el ritmo actual de integración de tecnologías de fuentes de energía distribuida en la red, el paradigma de la red de distribución está pasando de un papel pasivo a uno activo. Esto está ocurriendo actualmente, ya que la digitalización de la red permite monitorizar y gestionar el comportamiento de estos nuevos activos. Por lo tanto, se espera que estos mercados sean la piedra angular del nuevo paradigma energético, donde el consumidor final se beneficiará de su propia flexibilidad, generación de energía y almacenamiento. Por lo tanto, a medida que se despliegan estos mercados locales, se necesitarán nuevas herramientas para coordinar sus interacciones.

H2 La transición energética y la descarbonización del sistema energético requerirán una

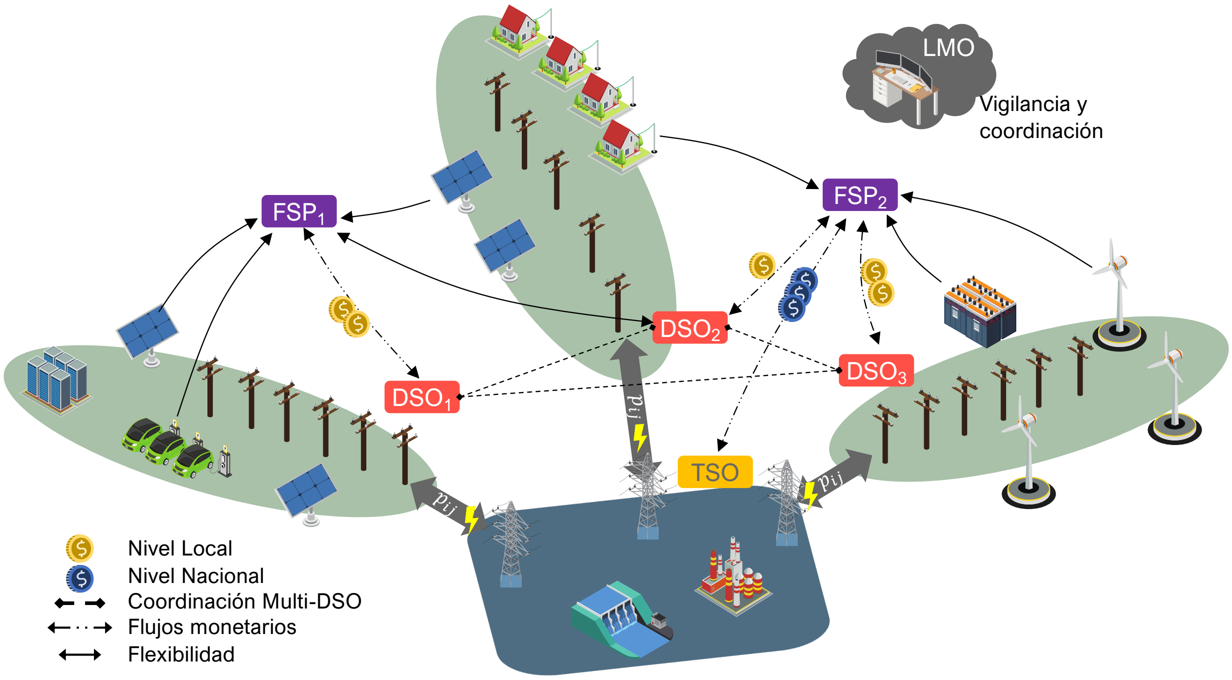

Figura 1: Arquitectura del Sistema Eléctrico de Potencia ideada para esta tesis. Múltiples ORDs interaccionan entre ellos bajo la supervisión del OML, permitiendo la participación de los PSFs.

gran cantidad de flexibilidad desde los mercados locales hasta los nacionales y mayoristas. Esta flexibilidad vertical se obtendrá de las fuentes de energía distribuida, creando nuevas oportunidades de negocio. Al abrir los mercados nacionales a la participación de actores agregados, surgirán nuevos modelos de negocio que fomentarán el despliegue de tecnologías de energía renovable y almacenamiento. Esto significa que el diseño de estos nuevos modelos de negocio agregados ayudará a mejorar la flexibilidad, sostenibilidad y seguridad del sistema. Al aprovechar tecnologías avanzadas y mecanismos de mercado, los PSFs optimizarán el uso de tecnologías de fuentes de energía distribuida, desbloquearán nuevas fuentes de ingresos y fomentarán la integración de recursos adicionales que contribuyan a la descarbonización.

¿Qué es la flexibilidad?

El diccionario Merrian-Wester define la flexibilidad como *capaz de ser flexionado: maleable*', *sensible a la influencia: tratable*' o '*caracterizado por una capacidad rápida para adaptarse a requisitos nuevos, diferentes o cambiantes*' [4]. La definición es amplia, pero refleja la esencia del concepto de flexibilidad. Los sistemas de energía actuales necesitan ser maleables, tratables y capaces de adaptarse a requisitos cambiantes; la flexibilidad en el contexto de los sistemas de energía se refiere a la adaptación eficiente del sistema a la variabilidad de la demanda de electricidad y la generación renovable. Para lograrlo, se requiere que los sistemas de energía modernos sean capaces de acomodar una amplia gama de fluctuaciones y nuevos actores, al tiempo que garantizan la estabilidad de la red y la seguridad del suministro en caso de eventos imprevistos. La flexibilidad se puede proporcionar a través de diversos medios, como el uso de sistemas de almacenamiento de energía, respuesta a la demanda o el uso de REDs flexibles, como demandas flexibles, generadores flexibles, baterías, vehículos eléctricos o HVACs. El objetivo es doble: optimizar la utilización de la infraestructura existente y promover la integración de fuentes de energía renovable para impulsar la descarbonización.

El concepto de flexibilidad no es nuevo, pero ha ganado importancia en los últimos años debido a la creciente penetración de fuentes de energía renovable y la electrificación de los sectores de transporte y calefacción. La integración de fuentes de energía renovable en el sistema eléctrico ha sido un factor clave para el desarrollo de soluciones de flexibilidad, ya que la variabilidad de estas fuentes puede causar desequilibrios entre la generación y la demanda, lo que puede llevar a problemas de inestabilidad de la red y seguridad del suministro. Además, se están haciendo esfuerzos hacia un sistema energético más orientado al usuario, donde los usuarios finales no solo sean consumidores, sino también productores y prosumidores, y puedan participar activamente en el mercado de energía. Este nuevo paradigma se basa en el uso de REDs y la participación activa de los usuarios finales en el mercado de energía, lo cual tiene el potencial de proporcionar las herramientas para resolver la creciente complejidad y restricciones técnicas de los sistemas eléctricos modernos.

A medida que aumenta la participación de fuentes de energía renovable, también aumenta la necesidad de flexibilidad, especialmente en la red de distribución, donde la integración de REDs es más desafiante debido a los niveles de voltaje más bajos y el mayor número de actores involucrados. Las redes de distribución no fueron diseñadas para acomodar este nuevo paradigma, y el enfoque tradicional de reforzar la red para resolver las restricciones técnicas no es sostenible a largo plazo. Por lo tanto, se necesitan nuevas soluciones para resolver las restricciones técnicas de la red, y la flexibilidad es una de las herramientas más prometedoras para hacerlo. La digitalización de estos sistemas de distribución está ocurriendo a un ritmo acelerado, lo que está llevando a estas redes hacia un sistema de energía más descentralizado, autónomo y orientado al usuario. Un sistema de energía orientado al usuario es aquel en el que las necesidades y preferencias de los clientes están en primer plano. Esta filosofía empodera a los usuarios finales para ser más activos, teniendo un mayor control y elección sobre su consumo, producción y almacenamiento de energía, lo que les permite tomar decisiones informadas sobre su uso de energía y participar en los mercados de energía. Además, estos sistemas mejoran la satisfacción del cliente fomentando una relación beneficiosa entre los usuarios finales y los operadores de red, minoristas y otros actores involucrados.

Este tipo de relaciones son la base para crear nuevas comunidades y mercados locales, que a su vez aumentan la resiliencia de la red debido a la integración de REDs y el uso de recursos flexibles locales para resolver las restricciones operativas. Por lo tanto, está claro que un sistema de energía centrado en el usuario es el camino a seguir, pero también es evidente que las redes de distribución actuales no están preparadas para acomodar este nuevo paradigma en su estado actual. Los mercados locales tienen el potencial de resolver las restricciones técnicas que pueden surgir en la red de distribución de manera resiliente debido a la proximidad a los puntos de consumo y generación. Esta proximidad entre los actores involucrados en los mercados locales permite una reacción rápida y receptiva a las restricciones técnicas y las transacciones de los operadores de la red de distribución y los usuarios finales, lo cual no es posible en los actuales mercados de energía centralizados con varias horas de anticipación. Además, los mercados locales se pueden utilizar para coordinar los diferentes actores involucrados en varias regiones, lo que promueve la eficiencia en costes. Por lo tanto, los mercados locales son un elemento clave para resolver las restricciones técnicas de la red de distribución de manera resiliente y son el elemento clave para crear un sistema de energía orientado al usuario.

Mercados locales de energía

El despliegue de las energías renovables ha aumentado significativamente en los últimos años. La capacidad renovable instalada ha aumentado un 89 % en los últimos 10 años en Europa [5]. Por ejemplo, España ha logrado un 50 % de participación en la producción de energías renovables en 2020 [6]. La imprevisibilidad de la energía solar fotovoltaica (PV) y de la energía eólica es una de las principales limitaciones al integrar las energías renovables. Parte de este despliegue se realiza a nivel de distribución con los REDs, usualmente sistemas PV. En consecuencia, las redes de distribución enfrentan desafíos como desequilibrios, desviaciones de voltaje y congestión de líneas.

En este contexto, los MLFss presentan una solución para el comportamiento intermitente de los REDs, utilizando productos de flexibilidad para resolver esos problemas. Sin embargo, actualmente los MLFss sufren de una falta de liquidez [7], lo que motiva un estudio sobre la influencia de un Mercado de Capacidad Local que funcione junto con un Mercado de Energía Local.

En la literatura, existen varios tipos de métodos para liquidar mercados locales. Centrándonos en los métodos basados en el mercado, estas técnicas incluyen: mercados locales de flexibilidad, técnicas de control basadas en precios y enfoques de Energía Transactiva [8]. Los esquemas de mercado son preferidos sobre las técnicas de control basadas en precios ya que protegen a los clientes finales y están alineados con las regulaciones de la Unión Europea [9]. Además, al ofrecer soluciones de alta calidad con recursos locales, las comunidades locales que operan mercados locales de flexibilidad están surgiendo a nivel organizativo [10].

En esta tesis, un Mercado Local de Flexibilidad (MLF) se define como un tipo de mercado donde es posible comerciar productos de electricidad en áreas geográficamente limitadas, es decir, pequeñas ciudades, vecindarios, comunidades o distritos [11]. Por lo tanto, involucran varios agentes que compran y venden productos, un operador de mercado y un mecanismo de compensación que case ofertas con demandas [12].

El número de agentes incluidos en el mercado varía en gran medida según el diseño del mercado. Sin embargo, los principales actores son: ORDs, Agentes Responsables del Balance (ARBs), Agregadores y OMLs [13]. Estas partes interesadas están interesadas en participar en el mercado ya que los ORDs resuelven la congestión y las desviaciones de voltaje, los ARBs optimizan sus carteras y los Agregadores obtienen beneficios de la gestión de sus recursos. Sin embargo, el papel de cada parte interesada difiere entre las propuestas. La referencia [14] considera la figura del Agregador como el OML, que proporciona diferentes servicios al ORD y a los ARBs. El mercado definido en [15], por otro lado, no incluye la figura del ARBs, fortaleciendo a los Agregadores como aquellos que supervisan el mercado, recopilando ofertas y demandas. Alternativamente, la referencia [16] propone una estructura de mercado donde no se presenta un Agregador y la flexibilidad se negocia considerando solo a los usuarios finales. Además, los autores de la referencia [17] reconocen a las comunidades energéticas como un actor clave al definir la estructura del mercado. Independientemente del enfoque considerado, ninguno de ellos explica claramente la relación entre los precios de los productos de flexibilidad y el mercado mayorista. Desde un punto de vista operativo, se están desarrollando varios proyectos piloto de mercados locales de flexibilidad en la Unión Europea. Algunos ejemplos son: IREMEL [18], InterFlex [19], EMPOWER [14] y DREAM-GO [17]. El proyecto español IREMEL aborda tres mecanismos principales para que el ORD obtenga flexibilidad: Gestión de Congestión, Productos de Flexibilidad Local y contratos a largo plazo utilizando Agregadores. El objetivo principal del proyecto InterFlex es crear mercados de energía locales que consistan en Agregadores, Clientes Industriales y Comunidades de Energía Local. Se centra tanto en versiones centralizadas como descentralizadas (P2P) del mercado. EMPOWER y DREAM-GO sitúan a los Agregadores como el actor central del mercados locales de flexibilidad que proporciona servicios de respuesta a la demanda al ORD. El beneficio social [20] o la minimización de costes para la adquisición de flexibilidad son los objetivos habituales que se buscan al definir el mercados locales de flexibilidad. La optimización de costes, dependiendo del punto de vista considerado, puede minimizarse para el Agregador [14], el OML [15] y el ORD [21]. Todas las referencias trabajan con problemas matemáticos complejos utilizando programación lineal entera mixta o técnicas de programación no lineal. A pesar de que se han propuesto metodologías de programación lineal en el campo de la optimización en bi-nivel [22], se han realizado pocas contribuciones al considerar el enfoque centralizado del mercados locales de flexibilidad.

En cuanto a los productos de flexibilidad, los autores en [13] identifican tres productos energéticos principales que se negocian en los sistemas de distribución: respuesta a la demanda por parte de los consumidores flexibles, restricción de generación por parte de los generadores flexibles y almacenamiento por parte de los sistemas de almacenamiento de energía. Los autores también destacan la figura del Agregador como el gestor de prosumidores modestos. Sin embargo, aunque han sido objeto de un análisis profundo, los productos de capacidad no se han abordado con suficiente detalle en la literatura en el contexto del mercados locales de flexibilidad.

Objetivos

Los objetivos de esta tesis se dividirán en objetivos generales (OX) y objetivos específicos (OX.Y), que se detallan a continuación.

O1 *Desarrollo de nuevos mecanismos de operación coordinada y descentralizada para la operación de mercados energéticos locales.* A medida que el sistema eléctrico evoluciona hacia una mayor penetración de fuentes de energía renovable y la participación de prosumidores, la flexibilidad se vuelve crucial para la estabilidad de la red y la integración de estos recursos. Los mercados locales proporcionan una plataforma para el comercio descentralizado y coordinado de flexibilidad, permitiendo la utilización óptima de la infraestructura existente y promoviendo la integración de las energías renovables. Además, facilitan la participación activa de los usuarios finales, promueven la resiliencia de la red y ofrecen soluciones más rápidas y receptivas a las limitaciones técnicas. Al establecer objetivos para el desarrollo de nuevas herramientas, podemos mejorar la comprensión, medición y utilización de la flexibilidad, permitiendo la transición hacia un sistema energético centrado en el usuario y desbloqueando todo el potencial de los REDs.

O1.1 *Desarrollo y definición de mecanismos de comercio coordinado para productos y servicios de flexibilidad.* El objetivo es desarrollar herramientas que faciliten la integración y coordinación de la flexibilidad en diferentes estructuras de mercados locales descentralizados, proporcionando definiciones claras y especificaciones de productos y servicios que pueden ser intercambiados entre diferentes actores en la red de distribución. El desarrollo de estas herramientas de operación determinista para mercados locales descentralizados tiene como objetivo definir y crear productos y servicios que permitan la utilización eficiente y confiable de la flexibilidad en diferentes mercados locales horizontales. Esto implica categorizar productos de flexibilidad, diseñar mecanismos de mercado, establecer requisitos técnicos, desarrollar algoritmos operativos y validar y refinar las herramientas a través de simulaciones y casos de estudios. El objetivo es dotar a los mercados locales descentralizados de mecanismos de comercio eficientes y transparentes que optimicen el valor de la flexibilidad entre ellos, al tiempo que garantizan la estabilidad de la red y cumplen con los requisitos operativos.

O1.2 *Operación estocástica. Desarrollo de nuevos mecanismos de operación y coordinación estocástica para los mercados locales. Análisis e integración de la incertidumbre de las fuentes de energía renovable distribuidas en los mecanismos de mercado.* Luego, el desarrollo de herramientas para la coordinación de mercados locales descentralizados se expande para incluir mecanismos de operación estocástica que abordan de manera efectiva las incertidumbres asociadas con las fuentes de energía renovable distribuidas. Esto implica el análisis e integración de factores de incertidumbre, como la variabilidad y los errores de predicción de las fuentes de energía renovable distribuidas, en los mecanismos de mercado, por ejemplo, mediante la inclusión de varios tipos de productos. El objetivo es mejorar la resiliencia y flexibilidad de los mercados locales al incorporar técnicas de optimización estocástica y descentralizada, métodos de predicción probabilístico y enfoques de gestión de riesgos. Esto permite la utilización eficiente de los recursos flexibles entre ellos, teniendo en cuenta su variabilidad e imprevisibilidad inherentes, lo que conduce a una mejor toma de decisiones, asignación óptima conjunta de recursos y operación confiable de los mercados locales.

O1.3 *Caracterización de los límites de flexibilidad en las redes de distribución considerando el efecto de las fuentes de energía renovable distribuidas y los mercados energéticos locales.* La caracterización de los límites de flexibilidad es crucial para aprovechar la flexibilidad de las fuentes de energía renovable distribuidas para lograr el objetivo de cero emisiones netas. Actualmente, existe una falta de definiciones claras y descripciones de la flexibilidad agregada de las fuentes de energía renovable distribuidas y cómo las restricciones de la red y los requisitos del mercado las afectan, especialmente en el caso de la implementación de mercados locales. Además, no se comprende bien el efecto del despliegue de sistemas de almacenamiento de energía en los límites de flexibilidad del sistema.

O2 *Desarrollo de nuevos modelos de negocio que mejoren la flexibilidad del sistema a través de la figura del PSF.* Esto implica diseñar e implementar nuevos marcos que permitan la agregación y coordinación efectivas de los recursos renovables distribuidos dentro de los mercados locales. El enfoque se centra en empoderar al PSF para optimizar la utilización de la flexibilidad de los recursos renovables distribuidos, facilitar la participación en el mercado y desbloquear nuevas fuentes de ingresos. Mediante el aprovechamiento de tecnologías avanzadas y mecanismos de mercado, el objetivo es permitir que el PSF gestione y monetice eficazmente la flexibilidad de los recursos renovables distribuidos, promoviendo así un sistema energético más resiliente, eficiente y sostenible. Además, permitirá fomentar la integración de más recursos si se disponen de más modelos de negocio.

O2.1 *Desarrollo de nuevos enfoques de acumulación de ingresos para la figura del PSF, basados en el conjunto de recursos disponibles en la red de media tensión (MT) y baja tensión (BT) que serán operados conjuntamente.* Esto implica diseñar modelos de negocio e innovadores mecanismos que permitan al PSF maximizar la utilización de los recursos disponibles en la red de distribución. Al identificar y combinar diversas fuentes de ingresos de diferentes recursos renovables distribuidos en la red, como respuesta a la demanda, baterías, GD y calefacción, ventilación y aire acondicionado (HVAC), el objetivo es crear estrategias optimizadas de acumulación de ingresos. Estos enfoques permitirán al PSF aprovechar el valor económico de los recursos de la red.

O2.2 *Análisis e integración de la incertidumbre de los recursos renovables distribuidos* *en los enfoques de acumulación de ingresos.* Esto implica desarrollar modelos y algoritmos avanzados que consideren la naturaleza estocástica de las decisiones de despacho e incorporen el comportamiento de los agentes del mercado. Además, el objetivo incluye abordar los desafíos de acceso limitado a la información mediante el diseño de esquemas de gestión de incertidumbre con la información disponible actualmente. El objetivo es mejorar la capacidad del PSF para optimizar las estrategias de acumulación de ingresos, teniendo en cuenta factores de incertidumbre como la variabilidad de la generación de energía renovable, las fluctuaciones de los precios del mercado y las acciones estratégicas de los competidores. Al lograr este objetivo, el PSF podrá tomar decisiones informadas y sólidas, integrar eficazmente diversos recursos y maximizar el potencial de ingresos en un entorno de mercado competitivo.

Contribuciones

Las principales contribuciones de esta tesis se enumeran a continuación y se dividen en tres categorías principales: caracterización y cuantificación de la flexibilidad, mercados locales de flexibilidad y apilamiento de ingresos de la flexibilidad de los recursos renovables distribuidos.

C1 *Procedimientos de liquidación para mercados locales coordinados horizontalmente*. El desafío de una liquidación conjunta de diferentes mercados locales se aborda formulando y resolviendo problemas de liquidación de mercado para varios tipos de productos que podrían adquirirse. Estos problemas de liquidación de mercado tienen en cuenta las características y requisitos específicos de los diferentes actores involucrados, asegurando una asignación eficiente de recursos. Luego, se propone una nueva metodología para coordinar y descentralizar estos mecanismos, abordando las preocupaciones de privacidad asociadas con el intercambio de información confidencial entre los participantes del mercado. Esta metodología utiliza algoritmos basados en descomposición lagrangiana aumentada, comúnmente conocidos como ADMM por sus siglas en inglés, para permitir transacciones seguras y preservadoras de la privacidad en los mercados locales, fomentando la confianza y facilitando interacciones de mercado efectivas al proporcionar los mismos resultados económicos que los mercados centralizados. Además, se analizan los factores de incertidumbre y se caracterizan los límites de flexibilidad en este contexto, como se explica en los puntos siguientes.

C1.1 *Una definición clara y concisa de diferentes productos de flexibilidad que pueden adquirirse en el contexto de los mercados locales*. Esta tesis proporciona una definición clara y concisa de diversos productos de flexibilidad que pueden adquirirse en el contexto de los mercados locales. Estos productos de flexibilidad son cruciales para gestionar de manera efectiva la variabilidad de los REDs y abordar las restricciones de la red en la red de distribución local. La definición de estos productos sirve como una referencia valiosa para los participantes del mercado, los reguladores y los operadores del sistema, facilitando una comprensión común de las opciones de flexibilidad disponibles y permitiendo la toma de decisiones informadas.

C1.2 *Un procedimiento de liquidación de mercado que maneje productos de flexibilidad energética para reducir congestiones y desequilibrios en las redes de distribución*. El procedimiento de liquidación de mercado diseñado aborda los desafíos de congestión y desequilibrio en las redes de distribución al permitir que el ORD adquiera productos de flexibilidad de los DERs en el mercado local. Este procedimiento está diseñado para mejorar la capacidad del ORD para gestionar los DERs y reducir la necesidad de costosas mejoras en la red.

C1.3 *Un algoritmo basado en descomposición lagrangiana aumentada (ADMM) que puede manejar productos energéticos de manera descentralizada en varios mercados coordinados horizontalmente*. Específicamente, el algoritmo incorpora una metodología novedosa basada en la descomposición dual de las señales económicas asociadas con la adquisición de flexibilidad. Este enfoque permite la desagregación del problema de optimización en subproblemas más pequeños que pueden resolverse de manera independiente por los ORDs, al tiempo que garantiza la coherencia y coordinación del sistema en general.

C1.4 *Una propuesta de mercado que puede acomodar productos de capacidad y energía de manera descentralizada y coordinada*. La introducción de productos de capacidad en el marco del mercado como un producto diferente de los productos de energía es una contribución novedosa de esta tesis. Estos productos de capacidad aprovechan las capacidades de los DERs para proporcionar flexibilidad, y al incorporarlos, el mercado gana liquidez mejorada, ya que los participantes del mercado tienen la oportunidad de comprar o vender la capacidad de reserva de los DERs, mejorando así la eficiencia y confiabilidad general del sistema. El diseño de mercado propuesto considera las características únicas de los DERs y garantiza su participación activa, fomentando un sistema energético más dinámico y receptivo. Esta contribución no solo amplía la gama de productos disponibles, sino que también fomenta la utilización óptima de los recursos.

C1.5 *Análisis e integración de las fuentes de incertidumbre en las arquitecturas de mercado descentralizadas y coordinadas*. Al considerar la variabilidad e imprevisibilidad inherentes de los DERs, la arquitectura de mercado propuesta tiene en cuenta la incertidumbre en la disponibilidad y generación de recursos renovables. Además, se presenta una metodología novedosa para capturar y modelar la incertidumbre en la activación de recursos de flexibilidad dentro del mercado. Al permitir una representación más precisa de la incertidumbre en el mercado, esta metodología proporciona un enfoque más realista para la adquisición de productos de flexibilidad.

C1.6 *Un problema de optimización lineal y escalable para la evaluación de la región de flexibilidad en los Mercados Locales Coordinados de Multi-ORD. Un análisis de la influencia del Operador de la Red de Transmisión (ORT) en la adquisición de flexibilidad de múltiples ORD*. Se propone una metodología novedosa que evalúa el potencial de flexibilidad de estos mercados entre ellos utilizando un problema de optimización lineal. Este análisis incluye una exploración de los mapas de costes asociados con el proceso de adquisición de flexibilidad. Al examinar las interacciones entre el ORT y los ORDs, y considerar los diversos factores de costo involucrados, esta investigación proporciona una comprensión integral de las implicaciones financieras de la adquisición de flexibilidad. Los mapas de costes resultantes ofrecen información valiosa sobre los aspectos económicos de la provisión de flexibilidad, lo que permite una toma de decisiones más informada tanto por parte del ORT como de los ORDs en la optimización de sus respectivas carteras de flexibilidad.

C2 *Desarrollo de nuevas estrategias de oferta y modelos de negocio para la figura del PSF*. Estas estrategias innovadoras van más allá de los enfoques tradicionales y tienen como objetivo crear nuevos modelos de negocio que promuevan activamente la integración de los recursos renovables distribuidos en la red de distribución. Al aprovechar la flexibilidad y las capacidades de estos recursos, las estrategias de oferta propuestas permiten a los actores activos en la red de distribución maximizar su participación y oportunidades de ingresos. Estas estrategias tienen en cuenta factores como las condiciones del mercado, la disponibilidad de recursos y las limitaciones del sistema, lo que permite a los actores activos optimizar sus decisiones de oferta y mejorar su viabilidad económica. Los modelos de negocio resultantes ofrecen una propuesta de valor convincente para los actores activos, fomentando su mayor participación y contribución a la flexibilidad general del sistema.

C2.1 *Un marco novedoso y escalable que admite la participación simultánea de recursos renovables distribuidos en mercados nacionales y locales que se liquidan secuencialmente*. Con este fin, se propone y resuelve un problema de optimización de tres niveles utilizando un algoritmo innovador que permite tener en cuenta la liquidación secuencial de los mercados. Esta metodología también puede abordar la interfaz física que aparece entre los mercados nacionales y locales. Los precios de mercado esperados se generan de forma endógena mediante el algoritmo, lo que permite que el PSF tome decisiones óptimas de oferta basadas en información mucho más precisa.

C2.2 *Integración de múltiples tecnologías de recursos renovables distribuidos en estrategias de oferta para aumentar la flexibilidad y el valor de los recursos*. Esta integración permite una participación más amplia y efectiva de los recursos renovables distribuidos en los mercados, ya que se aprovechan las sinergias entre diferentes tecnologías y recursos energéticos. Las estrategias de oferta propuestas incluyen el uso coordinado de cargas flexibles, GD y baterías para maximizar la flexibilidad y los ingresos. Además, se exploran nuevos enfoques para la participación de los vehículos eléctricos, que pueden actuar como recursos de flexibilidad y proporcionar servicios adicionales al sistema.

C2.3 *Modelos de negocio para el PSF que demuestran su viabilidad económica y su capacidad para aumentar los ingresos*. Al considerar diferentes escenarios de mercado, condiciones operativas y combinaciones de recursos, se presentan varios modelos de negocio para el PSF. Estos modelos de negocio demuestran cómo el PSF puede aprovechar las oportunidades de ingresos existentes y emergentes al participar en los mercados locales y nacionales. Los resultados muestran que la figura del PSF puede ser económicamente viable y contribuir significativamente a los ingresos de los recursos renovables distribuidos, al tiempo que proporciona flexibilidad y servicios de calidad al sistema.

En general, esta tesis aborda los desafíos clave asociados con la integración de los recursos renovables distribuidos en los sistemas eléctricos, centrándose en la flexibilidad y los mercados locales. Las contribuciones realizadas proporcionan una base sólida para la implementación de estrategias y políticas efectivas que fomenten la participación activa de los recursos renovables distribuidos en la red de distribución, maximicen el valor de estos recursos y mejoren la eficiencia y resiliencia del sistema eléctrico en general.

Estructura de la tesis

La tesis se organiza de la siguiente manera:

- *Capítulo 2: Gestión de la Flexibilidad en los Mercados Energéticos*. Este capítulo analiza la importancia de la flexibilidad en los sistemas energéticos, abordando los desafíos en su caracterización y presentando dos enfoques: índices de flexibilidad y envolventes de flexibilidad. También introduce el concepto de MLF (MLF) como plataforma para el comercio de productos relacionados con la energía para respaldar la operación del sistema y destaca los beneficios y desafíos de la coordinación entre múltiples MLFs, incluida la acumulación de ingresos para maximizar los beneficios económicos.

- *Capítulo 3: Proceso de Coordinación de Mercado para Mercados Locales de Múltiples ORD*. Se presentan varias metodologías y marcos para aprovechar la flexibilidad de los REDs en la red de distribución. Se presta especial atención a la descentralización y coordinación de estos mercados, así como a las propiedades del mercado deseables para lograrlo.

- *Capítulo 4: Acumulación de Flexibilidad en Múltiples Mercados*. Se presentan nuevos modelos de negocio desde la perspectiva de la figura del PSF. Estos modelos se basan en la participación del PSF en múltiples mercados, tanto nacionales como locales, y en la acumulación de ingresos a partir de la flexibilidad de los REDs. En la segunda parte del capítulo, también se integran fuentes de incertidumbre en el marco propuesto.

- *Capítulo 5: Conclusiones*. Este capítulo resume los trabajos que respaldan la tesis, extrae las conclusiones y presenta las futuras líneas de investigación.

Resumen de los trabajos publicados

Los contenidos de esta tesis se incluyen en los artículos publicados [23], [24], [25], [26], [27], [28], y [29]. Las principales contribuciones de la tesis se resumen de la siguiente manera:

- **Conferencia [23]**: presenta una formulación eficiente para los MLFs, donde se comercian productos de flexibilidad para resolver problemas de la red en sistemas de energía. Este artículo propone un enfoque centralizado que considera tanto productos de capacidad como de energía, utilizando optimización de programación lineal para la liquidación del mercado. El estudio asume que los Agregadores gestionan los activos de flexibilidad en la red de distribución. Los resultados obtenidos de este enfoque centralizado demuestran la viabilidad del método propuesto para resolver de manera efectiva los problemas de la red a nivel de distribución en diversos escenarios.

- **Artículo [24]**: aborda la aparición de los mercados locales de energía como nuevas capas en los diseños de mercado actuales, permitiendo el comercio local de productos de flexibilidad. Sin embargo, la implementación de mercados locales de energía que involucran múltiples operadores de la red de distribución plantea preocupaciones sobre la privacidad de la información mientras se busca la eficiencia en todo el sistema. El artículo propone un diseño de mercado para mercados locales de energía Multi-ORD donde los operadores de la red de distribución pueden comerciar entre diferentes áreas bajo la coordinación de un operador de mercado local. El enfoque de coordinación y descentralización se basa en el Método del Multiplicador de Direcciones Alternativas, con cada ORD programando sus activos de manera independiente en respuesta a las señales del mercado para satisfacer las solicitudes de flexibilidad de sí mismo u otros operadores de la red de distribución. El marco propuesto se prueba utilizando un estudio de caso ilustrativo basado en los sistemas de prueba IEEE 123 bus.

- **Conferencia [25]**: En este artículo, se propone una solución alternativa para la mitigación de congestiones y desequilibrios utilizando productos de flexibilidad de capacidad y equilibrio. Los precios de estos productos se determinan en función de su relación con los mercados tradicionales, asegurando la compatibilidad y facilitando la implementación de mercados locales de flexibilidad. El artículo también presenta un algoritmo de ADMM adaptativo que resuelve el problema de liquidación del mercado en un entorno de múltiples áreas mientras se preserva la privacidad de la información. La viabilidad del enfoque propuesto se demuestra utilizando el sistema de bus IEEE 34, donde la solución para un MLF de dos áreas se obtiene en unas pocas decenas de iteraciones. Además, un análisis de escalabilidad revela una relación lineal entre el número de áreas y el tiempo de convergencia.

- **Artículo [26]**: aborda los requisitos operativos relacionados con los servicios de mitigación de congestiones y desequilibrios en un escenario con una alta penetración de recursos renovables distribuidos en diferentes jurisdicciones de los operadores de la red de distribución. El enfoque propuesto es un MLF de ORD multi-ORD que tiene en cuenta la incertidumbre y utiliza productos de flexibilidad para gestionar las congestiones y desequilibrios entre los operadores de la red de distribución. La configuración del mercado implica productos de capacidad que retienen la flexibilidad de los recursos renovables distribuidos en previsión de contingencias, activando productos de energía si se produce el evento. La metodología se resuelve utilizando ADMM de manera coordinada y descentralizada, garantizando la privacidad de los participantes. La incertidumbre de los recursos renovables distribuidos y la duración de los eventos de energía se modelan a través de optimización lineal con restricciones de probabilidad. La metodología propuesta se evalúa a través de un estudio de caso utilizando conjuntos de datos y sistemas de distribución radial realistas.

- **Conferencia [27]**: aborda los desafíos operativos que surgen en los sistemas de energía cuando los operadores de la red de distribución intentan caracterizar los rangos de flexibilidad de la red de distribución dentro del paradigma del MLF. Esta contribución introdujo un nuevo enfoque lineal para evaluar la región de flexibilidad y los costes asociados para los operadores de la red de distribución en los MLFs Multi-ORD, permitiendo el análisis de recursos renovables distribuidos no lineales como las baterías. La viabilidad de este enfoque se demuestra a través de un estudio de caso que involucra dos sistemas de bus IEEE 34 que representan diferentes operadores de la red de distribución que participan en un MLF Multi-ORD. Los resultados resaltan la adquisición efectiva de flexibilidad por parte de los recursos renovables distribuidos en escenarios de interconexión activos y congestionados, capturando de manera precisa el comportamiento no lineal de estos recursos.

- **Artículo [28]**: se discuten los desafíos y oportunidades presentados por el creciente número de recursos renovables distribuidos flexibles para alcanzar los objetivos de Cero Emisiones Netas. Actualmente, los recursos renovables distribuidos enfrentan limitaciones para participar en múltiples mercados, lo que dificulta su rentabilidad. Para abordar este problema, el documento propone un problema de optimización de tres niveles que se centra en maximizar los ingresos de los recursos renovables distribuidos. El problema de optimización tiene en cuenta la participación simultánea de varios recursos renovables distribuidos flexibles, como vehículos eléctricos, baterías y HVACs, en mercados nacionales y locales. Al liquidar secuencialmente los mercados y utilizar una formulación dual y una condición de dualidad fuerte, el enfoque propuesto demuestra su efectividad para aumentar los beneficios en comparación con un escenario de referencia, como se evidencia en un estudio de caso realizado en redes de sistemas de energía realistas.

- **Artículo en revisión [29]**: amplía la contribución anterior en el apilamiento de ingresos para la figura del PSF que gestiona la incertidumbre del despacho, los recursos renovables distribuidos que gestiona y los agentes rivales en un escenario de información limitada. El método propuesto basa su modelo de mercado en un problema de optimización estocástica robusta y se utilizan restricciones de probabilidad para capturar la naturaleza no determinista de los recursos renovables distribuidos del PSF. El enfoque propuesto se evalúa a través de un estudio de caso utilizando conjuntos de datos y sistemas de distribución radial realistas. Los resultados se comparan mediante un análisis fuera de muestra que ayuda a comprender los riesgos asociados con las estrategias de oferta determinadas.

Lista de los trabajos publicados

El autor fue introducido al campo de investigación de esta tesis en la siguiente publicación, donde se realizó una nueva metodología para caracterizar y predecir la flexibilidad en la red de distribución basada en índices de flexibilidad:

A J. Leiva, J. A. Aguado, **Á. Paredes**, and P. Arboleya, “Data-driven flexibility prediction in low voltage power networks,” *International Journal of Electrical Power & Energy Systems*, vol. 123. Elsevier, p. 106242, 2020. doi: 10.1016/j.ijepes.2020.106242.

Después de eso, el autor ha participado en las siguientes publicaciones, donde se presentan las principales contribuciones de esta tesis.

B **A. Paredes** and J. A. Aguado, “Capacity and Energy Local Flexibility Markets for Imbalance and Congestion Management,” *2021 IEEE International Smart Cities Conference (ISC2). IEEE*, 2021, pp. 1–7, ISBN: 978-1-6654-4919-9. doi: 10.1109/isc253183.2021.9562971.

C **A. Paredes** and J. A. Aguado, “Coordinated Trading of Capacity and Balancing Products in Multi-Area Local Flexibility Markets,” *2022 IEEE Electrical Power and Energy Conference (EPEC)*. IEEE, Dec. 05, 2022. doi: 10.1109/epec56903.2022.10000246.

D J. A. Aguado and **Á. Paredes**, “Coordinated and decentralized trading of flexibility products in Inter-ORD Local Electricity Markets via ADMM,” *Applied Energy*, vol. 337, no. May 2023, p. 120 893, 2023, ISSN: 03062619. doi: 10.1016/j.apenergy.2023.120893.

E **Á. Paredes**, J. A. Aguado, and P. Rodríguez, “Uncertainty-Aware Trading of Congestion and Imbalance Mitigation Services for Multi-ORD Local Flexibility Markets,” *IEEE Transactions on Sustainable Energy*, pp. 1–13, 2023, ISSN: 1949-3029doi: 10.1109/tste.2023.3257405.

F **A. Paredes** and J. A. Aguado, “On the Assessment of the Flexibility Region in Inter-ORD Local Markets,” accepted for publication in *IEEE PowerTech 2023*, Belgrade, Serbia.

G **Á. Paredes**, J. A. Aguado, C. Essayeh, Y. Xia, I. Savelli, T. Morstyn, “Stacking Revenues from Flexible DERs in Multi-Scale Markets using Tri-Level Optimisation,” *IEEE Transactions on Power Systems*. Jun, 2023. doi: 10.1109/TPWRS.2023.3286178

H **Á. Paredes**, J. A. Aguado, C. Essayeh, T. Morstyn, ‘Robust and Stochastic Revenue Stacking from Aggregated Flexible DERs in Sequential Markets,’ submitted 20/07/2023, first round of review. *IEEE Transactions on Power Systems* ID: TPWRS-01137-2023.

Trabajos futuros

La siguiente lista de trabajos futuros se propone para continuar la línea de investigación de esta tesis:

- El desarrollo de modelos de oferta para las baterías con una representación más realista de las características de las baterías y la activación de los productos energéticos, asegurando la disponibilidad en tiempo real de la energía en un escenario de apilamiento de ingresos de múltiples mercados. Estas características no se consideran en la versión actual del modelo, lo que podría llevar a estrategias de oferta poco realistas dada la degradación de la batería y la activación de los productos energéticos.

- El desarrollo de modelos de oferta para la incipiente figura de los electrolizadores de hidrógeno en un escenario de apilamiento de ingresos de múltiples mercados. Se espera que el despliegue de esta tecnología aumente en los próximos años, lo que brinda nuevas oportunidades para integrar la energía renovable en el sistema eléctrico. Sin embargo, se necesita una caracterización detallada de la tecnología para desarrollar los modelos de oferta.

- El desarrollo de algoritmos de Reinforcement Learning para determinar la estrategia de oferta óptima para los REDs en un escenario de apilamiento de ingresos de múltiples mercados. El uso de estos algoritmos podría proporcionar otra capa de protección de privacidad para los REDs al permitirles aprender la estrategia de oferta óptima en un entorno de información limitada.

- El desarrollo de mecanismos de coordinación conjunta entre los operadores de la red de distribución y transmisión para garantizar el uso eficiente de la flexibilidad. Hasta el momento, los mecanismos de coordinación desarrollados se han centrado en la dimensión horizontal. Sin embargo, es importante considerar la dimensión vertical para brindar servicios de flexibilidad al operador de la red de transmisión.

- La previsión de los límites de flexibilidad de los REDs que ayudan a los operadores de la red de distribución a determinar la operación óptima de la red de distribución.

- El desarrollo de mecanismos de coordinación basados en el uso de los límites de flexibilidad y costes. El uso de estos límites podría proporcionar un enfoque sin modelo para la coordinación de los operadores de la red de distribución en los mercados energéticos locales. En este sentido, estos límites podrían usarse para determinar directamente el plan de operación óptima en la interfaz, y luego la operación óptima de cada una de las áreas involucradas en la operación.

Abstract

This thesis focuses on the management of flexibility in distribution networks, particularly in the context of integrating distributed energy resources (DERs) and establishing local energy markets. The transition towards a more sustainable and decentralized energy system requires effective utilization of flexibility, which can help accommodate the variability of renewable energy sources and reduce the need for network reinforcements.

The research presented in this thesis is motivated by the shift from centralized dispatch to a competitive and decentralised market structure and the increased penetration of DERs, such as solar photovoltaic panels and wind turbines, in the energy mix. While these developments have increased the efficiency of the market and reduced their carbon footprint, further measures are needed to achieve the net-zero emissions target set by the European Union for 2050. Thus, the thesis aims to address the challenges associated with integrating DERs and managing flexibility in distribution networks while providing new business cases for the agents involved in this transition.

To provide a comprehensive understanding of the subject, the thesis begins by introducing the background and context of the research. It highlights the three main factors driving the transformation of distribution networks: the increasing penetration of renewable DERs, the integration of new players such as small-scale storage and electric mobility assets, and the digitalization of the grid. These factors together necessitate the development of new tools and mechanisms to effectively manage flexibility and enable the participation of DERs in energy markets.

The thesis is structured around two main areas of contribution: local market-clearing algorithms, and DER management for revenue stacking in multi-scale markets. In the area of new algorithms for the decentralised and coordinated trading of flexibility products, the thesis emphasizes the importance of developing coordinated and decentralized coordination mechanisms for local markets. A clear definition of products and services for local markets is presented, which enables the efficient trading of flexibility among different actors in distribution networks. The thesis also considers stochastic operation mechanisms to address uncertainties associated with DERs, such as their variability and forecast errors, and the activation of previously settled products. By focusing on these market processes, the thesis aims to provide practical solutions for integrating DERs into the existing local energy market frameworks while promoting a transparent and fair behaviour among the markets. Besides, it provides a new model to quantify and characterize the flexibility within this new local markets frameworks.

Regarding the DER management for revenue stacking, the thesis explores new business models that empower Flexibility Service Providers (FSPs) to optimize the utilization of DER flexibility. It investigates revenue stacking approaches that combine multiple revenue streams from diverse DERs, such as demand response, batteries, distributed generation, and heating, ventilation, and air conditioning systems. The thesis also considers

the integration of uncertainties related to renewable energy generation in these revenue stacking approaches. These contributions aim to unlock new revenue streams for FSPs and promote the efficient utilization of DER flexibility.

To sum up, this thesis contributes to the efficient management of flexibility in distribution networks through the development of new models, methods, and market coordination mechanisms. By addressing the challenges associated with integrating DERs and managing flexibility, the thesis supports the transition towards a more flexible, customer-centric, and sustainable power system. Besides, through the effective utilization of flexibility and the participation of DERs in multi-scale markets, the research presented in this thesis aims to enhance the number of business cases for these new market actors.

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Nomenclature

Parameters are in upper case letter X and variables in lower case letter x. $|\Omega|$ denotes the cardinality of the set Ω. Overline $\overline{X}$ and underline $\underline{X}$ denote upper and lower bounds of X, respectively. Superscripts add information to the variable in form of acronym, e.g., X^u and X^d denote upward and downward directions, respectively. The rest of the nomenclature is introduced in the text. Vector and matrices are denoted by lower and upper case **bold** letters.

Acronyms

ADMM	Alternating Direction Method of Multipliers.
AI	Artificial Intelligence.
ATC	Analytical Target Cascading.
BESS	Battery Energy Storage System.
BRP	Balance Responsible Party.
CC	Chance Constraint.
CDF	Cumulative Density Function.
DAM	Day-Ahead Market.
DER	Distributed Energy Resource.
DG	Distributed Generation.
DN	Distribution Network.
DSO	Distribution System Operator.
DSR	Demand Side Response.
EV	Electric Vehicle.
FG	Flexible Generator.
FL	Flexible Load.
FSP	Flexibility Service Provider.
HVAC	Heating, Ventilation and Air Conditioning.
ICDF	Inverse Cumulative Density Function.
LEM	Local Energy Market.
LFM	Local Flexibility Market.
LMO	Local Market Operator.
LR	Lagrangian Relaxation.
LV	Low Voltage.
MO	Market Operator.
MV	Medium Voltage.
OCD	Optimality Conditions Decomposition.

PDF	Probability Density Function.
PMP	Proximal Message Passing.
PSO	Particle Swarm Optimization.
PV	Photovoltaic.
RDER	Renewable Distributed Energy Resource.
RE	Renewable Energy.
RL	Reinforcement Learning.
RM	Reserve Market.
RMA	Rival Market Agent.
RSO	Robust Stochastic Optimization.
SL	Static Load.
SOC	State of Charge.
TN	Transmission Network.
TSO	Transmission System Operator.

Indices and sets

t, Ω_t	Index and set for time periods, $t \in \Omega_t$.
i, j, Ω_n^{TN}	Indexes and set for buses of the TN, $(i, j) \in \Omega_n^{TN}$.
a, b, Ω_n^{DN}	Indexes and set for buses of the DN, $(a, b) \in \Omega_n^{DN}$.
$(i, j), \Omega_l^{TN}$	Index and set for branches of the TN, $(i, j) \in \Omega_l^{TN}$.
$(a, b), \Omega_l^{DN}$	Index and set for branches of the DN, $(a, b) \in \Omega_l^{DN}$.
a, Ω_a	Index and set for flexible agents $a \in \Omega_a$.
$-i, \Omega_n$	Index and set for RMAs at node i, $i \in \Omega_n$.
r, Ω_r	Index and set for DERs $r \in \Omega_r$.
l, Ω_l	Index and set for SLs, $l \in \Omega_l$.
f, Ω_f	Index and set for FLs, $f \in \Omega_f$.
g, Ω_g	Index and set for FGs, $g \in \Omega_g$.
s, Ω_s	Index and set for BESSs, $s \in \Omega_s$.
b, Ω_b	Index and Set for HVACs $b \in \Omega_b$.
n, Ω_n	Index and set for DSOs of the market $n \in \Omega_n$.
p, Λ^p	Index and Set for interconnecting buses of the DSO $p \in \Omega_p$.
h, Ω_h	Index and set for McCormick Envelopes $h \in \Omega_h$.
e, Ω_e	Index and set for scenarios, $e \in \Omega_e$.
ξ, Ω_ξ	Index and set for scenarios in RSO $\xi \in \Omega_\xi$.
k	Iteration counter.

Parameters

Δt	Time interval duration (h).
γ	ADMM Penalty factor (p.u.).
γ_k	ADMM Penalty factor at iteration k (p.u.).
ε	Convergence tolerance (p.u.).

φ_t	Duration of the energy event in time slot t (h).
α	Uncertainty level for the ICDFs.
Γ	Uncertainty control parameter for the RSO (p.u.).
$B_{i,j}$	Susceptance of the branch i, j (S).
$G_{i,j}$	Conductance of the branch i, j (S).
$\overline{V}_i, \underline{V}_i$	Upper and lower voltage magnitude bounds of bus i (p.u.).
$\overline{P}_{i,j}, \overline{S}_{i,j}$	Thermal limit of branch (i, j) (kW,kVAr).
$P_{a,t}^{sch}, Q_{a,t}^{sch}$	Scheduled sch active and reactive power for agent a in period t (kW, kVAr).
S_t	Bid Price of energy in the wholesale market at period t (€/kWh).
$S_{a,t}^{e,u}, S_{a,t}^{e,d}$	Bid price of upward u and downward d energy products e of agent a in time period t (€$/kWh$).
$S_{a,t}^{c,u}, S_{a,t}^{c,d}$	Bid price of upward u and downward d capacity products c of agent a in time period t (€$/kW$).
$S_{a,t}^{c,u}, S_{a,t}^{c,d}$	Capacity c product prices of agent a in period t in upward u and downward d directions (€/kW).
$S_{a,t}^{b,u}, S_{a,t}^{b,d}$	Balancing b product prices of agent a in period t in upward u and downward d directions (€/kWh).
S_t	Wholesale market price at period t (€/kWh).
$P_{l,t}^{sch}, P_{f,t}^{sch}$	Scheduled sch demand for SL l and FL f at period t, respectively (kW).
$P_{l,t}^{am}$	Power demand after market am clearing for SL l at period t (kW).
$Q_{l,t}^{sch}$	Scheduled sch reactive demand for SL l at period t (kVAr).
$P_{g,t}^{sch}$	Scheduled sch generation for FG g at period t (kW).
$Q_{g,t}^{sch}$	Scheduled sch reactive generation for FG g at period t (kVAr).
$\overline{P}_f, \underline{P}_f$	Upper and lower demand bounds for FL f at period t (kW).
$\overline{P}_g, \underline{P}_g$	Upper and lower generation bounds for FG g at period t (kW).
P_s^{conv}	BESS converter power rating $conv$ for BESS s (kW).
$\overline{SOC}_s, \underline{SOC}_s, SOC0_s$	Upper bound, lower bound and initial SOC of BESS s (kWh).
η_s^C, η_s^D	Charging C and discharging D efficiencies for the BESS s (p.u.).
$\tau_{b,t}^{out}$	Outdoors out temperature of the building b in time period t (°C).
C_b, R_b	Thermal constants of the building b.
η_b^{he}, η_b^{co}	Heating he and cooling co efficiencies of HVAC system b.
$\overline{P}_b^{he}, \overline{P}_b^{co}$	Heating he and cooling co rating of HVAC system b (kW).
R_t^u, R_t^d	Upward u and downward d reserves in time period t (kW).
$\boldsymbol{A}_m, \boldsymbol{B}_m$	Matrix of coefficients of market m.
$\boldsymbol{b}_m$	Vector of independent terms of market m.

Variables

$\Delta p_{a,t}^n, \Delta q_{a,t}^n$	Active and reactive flexibility products of agent a in period t in upward (≥ 0) and downward (≤ 0) directions (kW, kVA).
$F_{p,t}^n, F_{q,t}^n$	Total quantity of active p and reactive q flexibility traded by DSO n in time period t (kW, kVAr).
$c_{f,t}, c_{g,t}, c_{s,t}$	Cost of the flexibility products traded by FL f, FG g and BESS s, respectively,

	at period t (€).
$\omega^u_{f,t}, \omega^d_{f,t}$	Upward u and downward d energy flexibility product from FL f at period t (kWh).
$\omega^u_{g,t}, \omega^d_{g,t}$	Upward u and downward d energy flexibility product from FG g at period t (kWh).
$\omega^u_{s,t}, \omega^d_{s,t}$	Upward u and downward d energy flexibility product from BESS s at period t (kWh).
$\nu^u_{a,t}/\nu^d_{a,t}$	Upward u / downward d capacity product c from agent a at time period t (kW).
$p^c_{a,t}, p^e_{a,t}$	Power of agent a after capacity market clearing c and after energy asks e (kW).
$p^{am}_{f,t}, p^{am}_{s,t}$	Power demand of FL f and BESS s, in period t after market clearing am, respectively (kW).
$p^{am}_{g,t}$	Power generation of FG g at period t after market am clearing (kW).
$soc_{s,t}$	State of charge of BESS s at period t (kWh).
$\tau_{b,t}$	Temperature of building b in time period t (°C).
$v_{i,t}$	Voltage magnitude in bus i at period t (pu).
$\theta_{i,t}$	Voltage phase angle in bus i at period t (rad).
$p_{i,j,t}, q_{i,j,t}$	Active and reactive power flow between buses i and j at period t (kW, kVAr).
$p_{i,t}$	Active power exchanged at the point of common coupling i at period t (kW).
$q_{i,t}$	Reactive power exchanged at the point of common coupling i at period t (kVAr).
$\tilde{m}^{\theta,k}_t$	Complicating constraint associated with the voltage phase angle at the interconnection θ at period t in iteration k (rad).
$\tilde{m}^{I,k}_t$	Complicating constraint associated with balance I at period t in iteration k (kW).
x^p	General variable x of DSO p.
$\lambda^{\theta,k}_t$	Lagrange multiplier associated with the voltage phase angle θ constraint at the interconnection in iteration k and period t (€/rad).
$\lambda^{v,k}_t$	Lagrange multiplier associated with the voltage magnitude v constraint at the interconnection in iteration k and period t (€/rad).
$\lambda^{I,k}_t$	Lagrange multiplier associated with balance constraint I in iteration k and period t (€/kWh).
$\lambda^u_t \lambda^d_t$	Lagrange multipliers associated to upward u and downward d capacity restrictions in period t (€/kW).
x^p	General variable x of area p.
$\boldsymbol{x}_m$	General vector of variables for market m.
λ, μ	Dual variables associated to equality and inequality constraints (€/kW, €/kWh).

Functions

$\mathcal{P}\{X \leq \xi\}$	Probability of the uncertain parameter X being lower or equal than ξ.
$\phi^{-}_{X}(\cdot)$	ICDF of uncertain parameter X.

CHAPTER 1

Introduction

Contents

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For decades, electrical energy markets operated under a centralized dispatch model, where a single market operator dispatched generation units based on cost minimization. This dispatch was carried out in a daily basis, and it worked well for a long time for conventional power plants. However, in pursuit of efficient electricity supply, the European Union initiated the liberalization of energy markets in the change of the century, aiming to integrate competitive forces and regulations for increased efficiency. This led to the breakup of the vertically integrated utilities, and the creation of the current and competitive market structure at national level, which reduced prices and increased the efficiency of the energy sector. Currently, the energy sector is undergoing a transformative shift driven by the three D's: digitalization, decarbonization, and decentralization. Digitalization uses advanced technologies and digital solutions to optimize energy resources and integrate new energy actors such as energy communities, Electric Vehicles (EVs) or electric heating systems. Decarbonization focuses on reducing emissions and transitioning to renewable generation. Decentralization empowers consumers to participate in the energy market through Distributed Energy Resources (DERs). Efforts towards this measures were done, and a reduction of 1,000 Mt of CO_2 has been achieved in the last 20 years, which represents a 25% reduction in the emissions of the energy sector compared to 1990 [1]. Specially effective were these measures in the case of Spain, where the CO_2 intensity of power has been reduced by a 60% in the last 20 years [2]. However, further measures are needed to achieve the net-zero emissions targeted by the European Union for 2050 [3].

Distributed Generation (DG) is defined as the generation of electricity from small-scale facilities, usually located near the consumption points. These elements are key to achieve the decarbonization of the energy sector, as they are usually based on renewable energy sources, such as solar photovoltaic panels or wind turbines. In addition, the electrification of the heating and transport sectors will increase the demand for electricity, which will require a higher share of renewable energy sources in the energy mix. However, if all these elements are well integrated in the grid, they can also be a source of flexibility, which can be used to accommodate the variability of the renewable energy sources, and to reduce the need for network reinforcements. This is a demanding aspect, especially in the case of the distribution networks, which were not designed in the past to these new requirements. This thesis aims to contribute to achieve this goal by proposing new models and methods to manage the flexibility of the DERs in the distribution networks. In this sense, the main contributions of this thesis are in coordinated market-clearing designs for Local Flexibility Markets (LFMs) and in the management of DERs for the revenue stacking in national and local markets.

This first chapter introduces the context and motivation of the thesis, set objectives, explain the contributions and list the publication associated to this thesis. A thesis outline for the rest of the document is also provided.

1.1 Context and Motivation

Modern Distribution Networks (DNs) are suffering a profound transformation due to several factors among which it is precise to highlight three of them. First, the ever-increasing penetration of small-scale Renewable Distributed Energy Resources (RDERs) close to the final customer. Second, the integration of new players into the grid, such as small-scale storage, electric mobility assets and the electrification of the heating. Third, a strong digitalization process using Smart Meters and an intense deployment of sensors and measurements apartments all over the Medium Voltage (MV) grid or event the Low Voltage (LV) grid network.

At the same time, there is a growing interest in facilitating the integration and free participation of renewable energy systems and end users in electricity markets. The main aim of this policy is to incentive an adequate management of its energy, allowing them to obtain better market prices. In this context, the flexibility plays a fundamental role as a facilitator of the market integration of these new assets. Besides of that, flexibility serves as a tool of empowerment of the final consumer of the energy, adding value to their traditional static management. This trend is aligned to the European legislation which has been derived from the entitled *Clean Energy Package*, and specially with the Directive related to the increase of share of clean renewable sources [30].

Managing DERs within current market structures presents significant challenges. DERs, such as solar panels and battery storage, face barriers due to their decentralized nature and the lack of appropriate algorithms for their management. Moreover, coordination and integration of diverse DER technologies requires robust infrastructure and communication systems. Overcoming these hurdles will require rethinking market designs, regulatory frameworks, and grid management strategies to recognize and value the capabilities of DERs. By doing so, the full potential of DERs can be unlocked and the transition to a sustainable and decentralized energy system can be accelerated.

In addition, these assets do not have an easy market participation, as most of traditional market structures requires high minimum bids, typically over one megawatt . To fill this gap, local markets arise as a new layer of traditional market structures to ease the participation of medium and small-scale distributed assets. Local Energy Markets (LEMs) are defined as a marketplace where assets can exchange diverse energy-related goods. Assets whose point of common coupling is at distribution level can participate in these structures, which usually requires low or no minimum bid. Consumers with generation facilities, renewable producers, co-generation plants, Battery Energy Storage Systems (BESSs) or even hybrid agents – where several types of agents are combined – fall under the paradigm of DER. Generally, any facility able to manage their consumption or injection to the grid can be included in this definition. Particularly, LFM are those which, due to specific circumstances of the network, energy exchanges are technically restricted or must be carried out by a determined set of facilities connected to a determined node of the network. Under normal operation conditions, energy products or flexibility services can be traded in LFMs, enabling network operators to ask for a deviation of the scheduled program and DERs to offer these flexibility services.

The basis for an active DERs participation in local markets is settled, promoting the emergence of energy communities and the aggregator figure as a manager of multiple small to medium scale assets. These are key tools that enable citizens to directly benefit from an interior electricity market, which at the end facilitates the penetration of RDERs while providing system operators with flexibility tools to avoid costly network reinforcements. In this sense, the future state of the energy systems is depicted in Figure 1.1, where it can be seen that the traditional top-down approach no longer holds, and that bi-directional flows are expected to be common in the network. Conventional power plants will coexist with RDERs, which will be managed by FSPs. Different services will be procured by these new energy actors, which will be coordinated by Distribution System Operators (DSOs) and Local Market Operators (LMOs) to ensure the security of the dispatch.

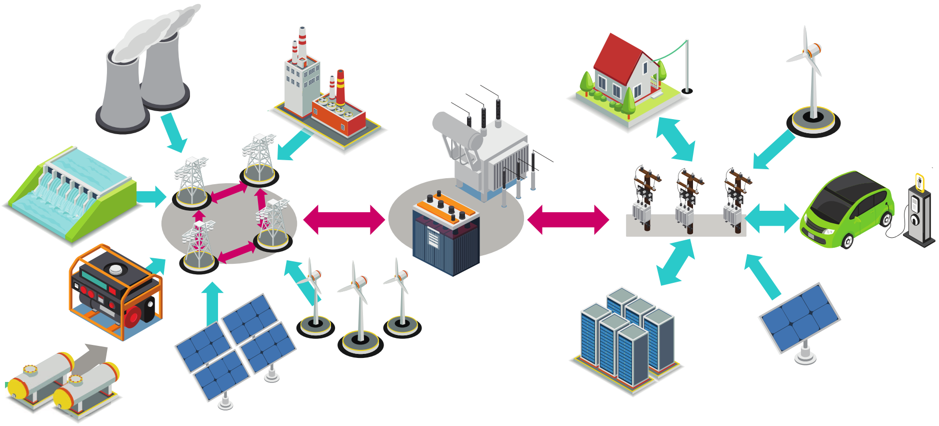

Figure 1.1: Future state of the energy systems.

In this context, a set of tools are needed for these actors to ease the management and the integration of these new resources. This thesis contributes to this goal by proposing new coordinated market-clearing procedures from the viewpoint of the LMO and new revenue stacking approaches from the viewpoint of the FSP.

With this objective in mind, several mathematical strategies are developed mainly using optimization theory. This is the classical scheme for the decision-making process, which uses data to build predictive models of the variables that will determine how correct our decisions would be. A general overview of the devised power system architecture upon which this thesis is built is depicted in Figure 1.2. It can be seen the relationship among the actors under the study of this thesis and their main characteristics.

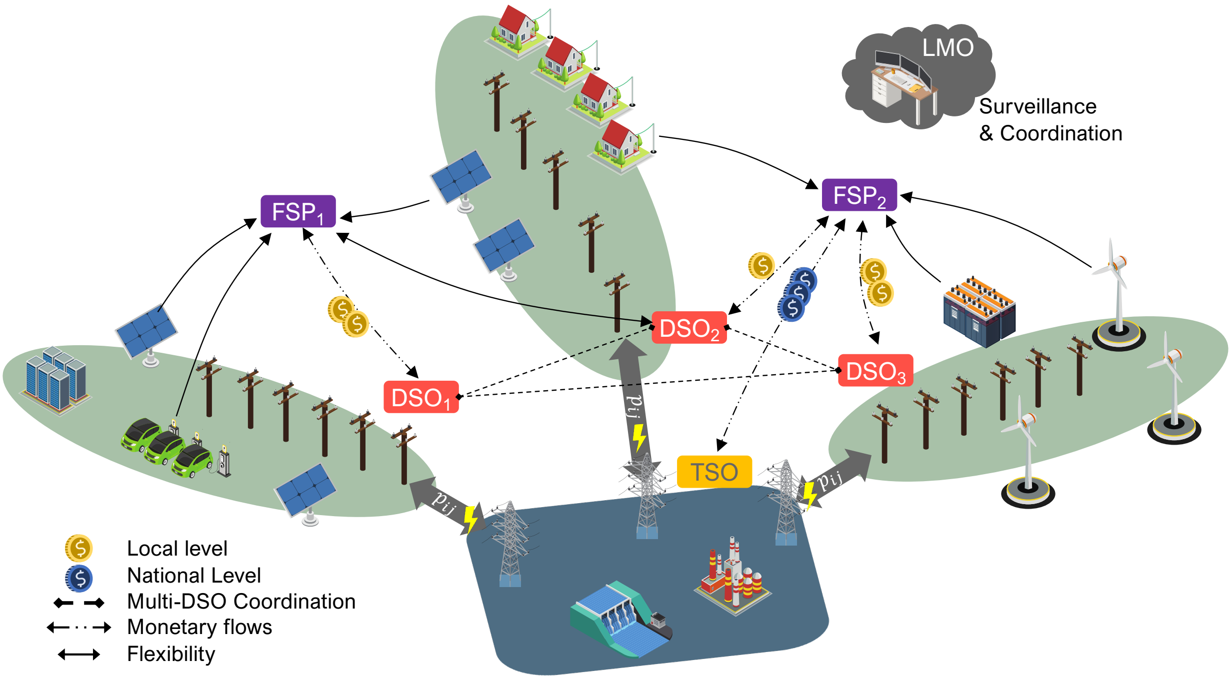

Figure 1.2: Devised Power System Architecture for this thesis. Multiple DSOs interacts with each other under the supervision of the LMO, enabling also the participation of FSPs.

In order to achieve this, this thesis is based on the following hypothesis:

H1 The proliferation of DERs will require their management by local markets. Given the current rate of integration of DER technologies in the network, the paradigm of the distribution network is shifting from a passive to an active role. This is currently happening, as the digitalization of the grid is enabling tracking and manage the behavior of these new assets. So, it is expected that these markets will be the cornerstone of the new energy paradigm, where the final consumer will benefit from its own flexibility, energy generation and storage. Thus, as these local markets are being deployed, new tools will be needed to coordinate their interactions.

H2 The energy transition and the decarbonization of the energy system will require a large amount of flexibility from local to national and wholesale markets. This vertical flexibility will be obtained from DERs, creating new business opportunities. Opening national markets to the participation of aggregated actors, new business models will arise, incentiving the deployment of renewable energy and storage technologies. This means that designing these new aggregated business models will help to improve the flexibility, sustainability and security of the system. By leveraging advanced technologies and market mechanisms, the FSP will optimize the usage of DER technologies, unlock new revenue streams, and foster the integration of additional resources which contribute to the decarbonization.

1.2 Objectives of the thesis

The objectives of this thesis will be divided into general (OX) and specific (OX.Y) objectives, which are detailed below.

O1 *Development of new coordinated and decentralized operation mechanisms for local energy markets operation.* As the power system evolves towards increased penetration of renewable energy sources and the participation of prosumers, flexibility becomes crucial for grid stability and integration of these resources. Local markets provide a platform for decentralized and coordinated trading of flexibility, enabling optimal utilization of existing infrastructure and promoting the integration of renewables. Local markets facilitate the active participation of end-users, promote grid resilience, and offer faster and responsive solutions to technical constraints. By setting objectives for the development of new coordination tools, we can enhance the understanding, measurement, and utilization of flexibility, enabling the transition towards a user-centric energy system and unlocking the full potential of DERs.

O1.1 *Development and definition of coordinating trading mechanisms for flexibility products and services.* The objective is to develop tools that facilitate the integration and coordination of flexibility across different decentralised local markets structures by providing clear definitions and specifications of the products and services that can be traded among different actors in the distribution network. The development of this deterministic operation tools for decentralised local markets aims to define and create products and services that enable efficient and reliable utilization of flexibility across different horizontally coordinated local markets. This involves categorizing flexibility products, designing market mechanisms, establishing technical requirements, developing operational algorithms, and validating and refining the tools through simulations and case studies. The goal is to empower decentralised local markets with efficient and transparent trading mechanisms that optimize the value of flexibility across them while ensuring grid stability and meeting operational requirements.

O1.2 *Development of new stochastic operation and coordination mechanisms for local markets. Analysis and integration of the uncertainty of the RDERs in the market mechanisms.* The development of tools for the coordination of decentralised local markets is expanded to include stochastic operation mechanisms that effectively address the uncertainties associated with RDERs. This involves the analysis and integration of uncertainty factors, such as variability and forecast errors of RDERs, into market mechanisms, e.g. by including several types of products. The goal is to enhance the resilience and flexibility of the local markets by incorporating stochastic and decentralised optimization techniques, probabilistic forecasting methods, and risk management approaches. This enables the efficient utilization of flexible resources across them while considering the inherent variability and unpredictability of them, leading to improved decision-making, joint-optimal resource allocation, and reliable operation of the local markets.

O1.3 *Characterization of the flexibility envelopes in distribution networks considering the effect of the DERs and LEMs.* The characterization of flexibility envelopes is crucial in harnessing flexibility from DERs for achieving net-zero objective. Currently, there is a lack of clear definitions and descriptions of aggregated DERs flexibility and how network constraints and market requirements impact them, specially for the case when local markets are deployed. In addition to this, the effect of the BESS deployment in the flexibility envelopes of the system is not well understood.

O2 *Development of new business models that improves the system flexibility through the FSP figure*. This entails designing and implementing novel frameworks that enable the effective aggregation and vertical coordination of DERs across different market scales. The focus is on empowering the FSP to optimize the utilization of DER flexibility, facilitate market participation, and unlock new revenue streams. By leveraging advanced technologies and market mechanisms, the objective is to enable the FSP to effectively manage and monetize the flexibility of DERs, thereby promoting a more resilient, efficient, and sustainable energy system. In addition, it will enable fostering the integration of more resources if more business cases are available.

O2.1 *Development of new revenue stacking approaches for the FSP figure, based on the set of available resources in the MV/LV grid, that will be jointly operated.* This involves designing innovative business models and mechanisms that enable the FSP to maximize the utilization of available resources in the distribution grid. By identifying and combining various vertical revenue streams from disparate DERs in the grid, such as demand response, BESS, DG, and Heating, Ventilation and Air Conditioning (HVAC), the objective is to create optimized revenue stacking strategies in multi-scale national and local markets. These approaches will enable the FSP to capitalize on the economic value of the resources of the grid.

O2.2 *Analysis and integration of the uncertainty of the RDERs in the revenue stacking approaches.* This involves developing advanced models and algorithms that consider the stochastic nature of dispatch decisions and incorporate rival market agents' behaviour. Additionally, the objective includes addressing the challenges of limited access to information by designing uncertainty management schemes with the current information available. The aim is to enhance the FSP's ability to optimize revenue stacking strategies, taking into account uncertainty factors such as renewable energy generation variability, market price fluctuations, and strategic actions of competitors. By achieving this objective, the FSP will be able to make informed and robust decisions, effectively integrate diverse resources, and maximize revenue potential in a competitive market environment.

1.3 Contributions

The main contributions of this thesis are listed below and are divided into two main categories: local flexibility markets and revenue stacking of the flexibility of DERs.

C1 *Market-clearing procedures for horizontally coordinated local markets*. The challenge of a joint market-clearing across different local markets is addressed by formulating and solving market-clearing problems for several types of products that could be procured. These market-clearing problems take into account the specific characteristics and requirements of the different actors involved, ensuring efficient allocation of resources. Then, a novel methodology is proposed to coordinate and decentralize these market-clearing protocols, addressing the privacy concerns associated with the exchange of sensitive information among market participants. This methodology utilizes Alternating Direction Method of Multipliers (ADMM)-based algorithms to enable secure and privacy-preserving transactions in local markets, fostering trust and facilitating effective market interactions while providing the same economic results as centralized markets. Besides, uncertainty factors are also analysed and flexibility envelopes are characterised in this context as is explained in the following points.

C1.1 *A clear and concise definition of different flexibility products that can be procured in the context of local markets*. This thesis provides a clear and concise definition of various flexibility products that can be procured within the context of local markets. These flexibility products are crucial for effectively managing the variability of distributed energy resources and addressing grid constraints in the local distribution network. The definition of these products serves as a valuable reference for market participants, regulators, and system operators, facilitating a common understanding of the available flexibility options and enabling informed decision-making.

C1.2 *A market-clearing procedure that handle energy flexibility products to reduce congestions and imbalances in distribution networks*. The designed market clearing procedure address the challenges of congestion and imbalance in distribution networks by enabling the DSO to procure flexibility products from DERs in the local market. This procedure is designed to be enhanced the DSO's ability to manage the DERs and to reduce the need for costly grid reinforcements.

C1.3 *A ADMM-based algorithm that can handle energy products in a decentralized and coordinated way.* Specifically, the algorithm incorporates a novel methodology based on dual decomposition of the economic signals associated with flexibility procurement. This approach allows for the disaggregation of the optimisation problem into smaller sub-problems that can be solved independently by DSOs while ensuring overall system coherence and coordination.

C1.4 *A market proposal that can accommodate capacity and energy products in a decentralized and coordinated way*. The introduction of the capacity products in the market framework as a different product to the energy products, is a novel contribution of this thesis. This capacity products hold back the capabilities of the DERs to provide flexibility, by incorporating them, the market gains enhanced liquidity as market participants have the opportunity to buy or sell the reserve capacity of DERs, thereby improving the overall efficiency and reliability of the system. The proposed market design considers the unique characteristics of DERs and ensures their active participation, fostering a more dynamic and responsive energy system. This contribution not only expands the range of available products but also encourages the optimal utilization of resources.

C1.5 *Analysis and integration of the uncertainty sources into the decentralized and coordinated market architectures*. By considering the inherent variability and unpredictability of RDERs, the proposed market architecture accounts for the uncertainty in the availability and generation of renewable resources. Additionally, a novel methodology is presented to capture and model the uncertainty in the activation of flexibility resources within the market. Enabling a more accurate representation of the uncertainty in the market, this methodology provides a more realistic approach to the procurement of flexibility products.

C1.6 *A linear and tractable optimisation problem for the assessment of the flexibility region in Multi-DSO LFMs. An analysis of the influence of the Transmission System Operator (TSO) in the flexibility procurement of multiple DSOs*. A novel methodology that assess the flexibility potential of these markets among them is proposed using a linear optimization problem. This analysis includes an exploration of the cost maps associated with the flexibility procurement process. By examining the interactions between the TSO and DSOs, and considering the varying cost factors involved, this research provides a comprehensive understanding of the financial implications of flexibility procurement. The resulting cost maps offer valuable insights into the economic aspects of flexibility provision, enabling more informed decision-making by both the TSO and DSOs in the optimisation of their respective flexibility portfolios.

C2 *Development of new bidding strategies and business cases for the FSP figure*. These innovative strategies go beyond traditional approaches and aim to create new business models that actively promote the integration of DERs into the distribution network. By leveraging the flexibility and capabilities of these resources, the proposed bidding strategies enable active actors in the distribution network to maximize their participation and revenue opportunities. These strategies take into account factors such as market conditions, resource availability, and system constraints, allowing the active actors to optimize their bidding decisions and enhance their economic viability. The resulting business cases provide a compelling value proposition for the active actors, encouraging their increased participation and contribution to the overall system flexibility.

C2.1 *A novel and tractable framework that supports the simultaneous participation of DERs in both national and local markets that are cleared sequentially*. To this aim, a tri-level optimisation problem is proposed and solved using an innovative algorithm that enables considering the sequential clearing of the markets. This methodology can also deal with the physical interface that appears between the national and local markets. Expected market prices are endogenously generated by the algorithm, which allows the FSP to make optimal bidding decisions based on much more accurate information.

C2.2 *Integration of multiple DERs technologies into the framework.* This inludes, Flexible Loads (FLs), DG, BESSs, EVs and HVACs systems, providing spatial and temporal flexibility coverage. This proposed framework can deal with multiple sources of energy, reserves and flexibility, providing services to both national and local markets.

C2.3 *Analysis and integration of diverse uncertainty sources into the framework*. A novel framework that integrates in a single problem the uncertainty of the RDERs, Rival Market Agents (RMAs) and the uncertainty in the dispatch is proposed. Currently, these uncertainty sources are considered independently, with the same uncertainty scheme. This framework provides a more realistic approach, where the uncertainty associated to the resources the FSP manages is considered using chance-constraints, the uncertainty of the RMAs is considered using a robust approach and the uncertainty in the dispatch is considered using a stochastic approach. This hybrid approach enables a trade-off between including a wide range of uncertainty sources and the robustness of the solution.

C2.4 *A risk analysis for the bidding strategies of the FSP*. The analysis takes into account the unique characteristics of the market environment, specifically the limited access to information. By considering the uncertainties and risks associated with this limited information, the thesis provides a more realistic understanding of the challenges faced by the FSP in determining optimal bidding strategies. The risk analysis offers insights into the potential risks involved in the FSP's participation and highlights the need for robust decision-making approaches that can effectively mitigate these risks.

1.4 Thesis Outline

The remainder of this thesis is organized as follows.

- *Chapter 2: Managing Flexibility in Energy Markets*. This chapter discusses the importance of flexibility in energy systems, addressing challenges in characterizing it and presenting two approaches: flexibility indexes and flexibility envelopes. It also introduces the concept of LFMs as a platform for trading energy-related commodities to support system operation and emphasizes the benefits and challenges of coordination among multiple LFMs, including revenue stacking for maximizing economic benefits.
- *Chapter 3: Market-Clearing Process for Multi-DSO Local Markets*. Several methodologies and frameworks to harvest the flexibility of the RDERs in the distribution network are presented. Special attention is paid to the decentralization and coordination of these markets, and in the market properties that are desirable to achieve.
- *Chapter 4: Stacking of Flexibility in Multiple Markets*. New business models are presented from the perspective of the FSP figure. These models are based on the participation of the FSP in multiple markets, both national and local, and the revenue stacking of the flexibility of the DERs. Uncertainty sources are also integrated in the framework in the second part of the chapter.
- *Chapter 5: Conclusion*. This chapter summarizes the works that support the thesis, draws the conclusions and presents the future lines of research.

1.5 List of Publications

The author was introduced to the research field of this thesis in the following publication, where a novel methodology to characterize and forecast the flexibility in distribution network based on flexibility indexes was conducted:

A J. Leiva, J. A. Aguado, **Á. Paredes**, and P. Arboleya, “Data-driven flexibility prediction in low voltage power networks,” *International Journal of Electrical Power & Energy Systems*, vol. 123. Elsevier, p. 106242, 2020. doi: 10.1016/j.ijepes.2020.106242.

After that, the author has been involved in the following publications, where the main contributions of this thesis are presented.

B **A. Paredes** and J. A. Aguado, “Capacity and Energy Local Flexibility Markets for Imbalance and Congestion Management,” *2021 IEEE International Smart Cities Conference (ISC2). IEEE*, 2021, pp. 1–7, ISBN: 978-1-6654-4919-9. doi: 10.1109/isc253183.2021.9562971.

C **A. Paredes** and J. A. Aguado, “Coordinated Trading of Capacity and Balancing Products in Multi-Area Local Flexibility Markets,” *2022 IEEE Electrical Power and Energy*

Conference (EPEC). IEEE, Dec. 05, 2022. doi: 10.1109/epec56903.2022.10000246.

D J. A. Aguado and **Á. Paredes**, “Coordinated and decentralized trading of flexibility products in Inter-DSO Local Electricity Markets via ADMM,” *Applied Energy*, vol. 337, no. May 2023, p. 120 893, 2023, ISSN: 03062619. doi: 10.1016/j.apenergy.2023.120893.

E **Á. Paredes**, J. A. Aguado, and P. Rodríguez, “Uncertainty-Aware Trading of Congestion and Imbalance Mitigation Services for Multi-DSO Local Flexibility Markets,” *IEEE Transactions on Sustainable Energy*, pp. 1–13, 2023, ISSN: 1949-3029doi: 10.1109/tste.2023.3257405.

F **A. Paredes** and J. A. Aguado, “On the Assessment of the Flexibility Region in Inter-DSO Local Markets,” accepted for publication in *IEEE PowerTech 2023*, Belgrade, Serbia.

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CHAPTER 2

Managing Flexibility in Energy Markets

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This chapter serves as a comprehensive guide, providing a holistic view of the proposals presented in this thesis and the interconnections between them. Its aim is to enhance the reader's understanding of the main contributions and their significance in the context of flexibility management and coordination of markets and DERs. The chapter is structured to facilitate the exploration of these concepts, with a strong emphasis on the coordination among markets and the vertical integration of revenue streams to boost the integration of DERs.

To lay the foundation, the chapter begins by introducing the essential concepts of flexibility and local markets, recognizing their dynamic and context-dependent nature. However, this thesis goes beyond conventional and standalone definitions of LFMs by considering the influence of the broader energy system and the interactions between different local markets. It emphasizes that achieving joint optimal solutions through coordination is fundamental, rather than settling for suboptimal non-coordinated solutions for each market.

A key contribution of this thesis lies in exploring coordination techniques for managing flexibility horizontally across different LFMs, which is denoted as Multi-DSO coordination. Conventionally operating in isolation, these markets hindered the efficient utilization of flexible resources when considering a broader energy system perspective. By integrating and coordinating these markets, synergies are unlocked, enabling effective sharing and trading of flexibility among various actors in the distribution network. This horizontal coordination empowers market participants to optimize their flexibility utilization, enhance system stability, and foster a more sustainable and customer-centric power system. The proposed horizontal coordination approach it is not limited to the proposed LFMs, but it can be extended to other types of architectures, such as, multiple local energy communities, multi-microgrids schemes, virtual power plants, and so on. To extend the operational analysis of Multi-DSO markets, the thesis employs flexibility envelopes to characterize it and assess the costs of the deployment. By understanding the flexibility envelope and associated flexibility procuring costs, a detailed analysis of the effects of the coordination of these markets can be done.

Building upon the foundation of flexibility characterization and horizontal coordination, the thesis delves into the vertical coordination of DERs within several market structures. Recognizing that DERs contribute to the diversification and decentralization of the energy system, this thesis proposes a management approach based on the stacking of flexibility revenues obtained from multi-scale energy markets.

The revenue stacking approach enables efficient utilization of DER flexibility by vertically coordinating revenue streams from different markets operating at various time scales and geographical areas. This includes a vertical integration of revenue streams from national markets to local markets, leveraging the unique capabilities of DERs to participate in multiple markets simultaneously if properly managed. The novelty of this approach lies in its ability to optimize flexibility utilization by considering interactions between different markets, creating optimal bidding strategies, and maximizing revenue streams. By optimizing revenue streams through stackable business models, the economic viability of DERs can be enhanced, attracting more investments and accelerating the transition to a sustainable energy future.

Furthermore, this thesis explores the integration of uncertainties associated with DERs, such as variability and forecast errors, as well as those associated to the participation of RMAs, within the proposed revenue stacking methodology. By jointly considering these uncertainties, the proposed framework ensures robust decision-making, enhancing the economic viability of FSP’s bidding program.

In this chapter, the flexibility is defined and examined through its characterization using indexes and envelopes, and its role in LFMs is explored. The coordination of these markets and the concept of revenue stacking across different markets are discussed, emphasizing the benefits, barriers, and opportunities associated with these approaches.

2.1 What is flexibility?

The Merrian-Wester dictionary defines flexibility as “*capable of being flexed: pliant*”, “*yielding to influence: tractable*” or “*characterized by a ready capability to adapt to new, different, or changing requirements*” [4]. The definition is broad, but it reflects the essence of the concept of flexibility. Today’s power systems need to be pliant, tractable and capable of adapting to changing requirements. Flexibility in the context of energy systems refers to the system efficient adaptation to the variability of the electricity demand and renewable generation. To do so, modern power systems are required to be able of accommodating a wide range of fluctuations and new actors, while ensuring grid stability and security of supply in the case of unforeseen events. Flexibility can be provided through diverse means, such as the use of energy storage systems, demand response, or the use of flexible DERs such as FLs, Flexible Generators (FGs), BESSs, EVs or HVACs systems.

The objective is twofold, to optimize the utilization of the existing infrastructure and to promote the integration of renewable energy sources to boost decarbonization.

The concept of flexibility is not new, but it has gained importance in recent years due to the increasing penetration of renewable energy sources and the electrification of the transport and heating sectors. The integration of renewable energy sources in the power system has been a key driver for the development of flexibility solutions, since the variability of renewable energy sources can cause imbalances between generation and demand, which can lead to grid instability and security of supply issues. In addition, efforts are being made towards a more user-oriented energy system, where the end-users are not only consumers but also producers and prosumers, and they can actively participate in the energy market. This new paradigm is based on the use of DER technologies and the active participation of the end-users in the energy market, which has the potential to provide the tools to solve the ever-increasing complexity and technical constraints of the modern power systems.

As the share of renewable energy sources increases, the need for flexibility also increases, specially in the distribution network, where the integration of DER is more challenging due to the lower voltage levels and the higher number of actors involved. Distribution networks were not designed to accommodate this new paradigm, and the traditional approach of reinforcing the network to solve the technical constraints is not sustainable in the long term. Therefore, new solutions are needed to solve the technical constraints of the network, and flexibility is one of the most promising framework to do so. The digitalization of this distribution systems is occurring at a fast pace, what is making these grids to move towards a more decentralized, autonomous and user-oriented energy system. A user-oriented energy system is the one where the needs and preferences of customers are at the forefront. This philosophy empowers the end-users to be more active, having greater control and choice over their energy consumption, production and storage, allowing them to make informed decisions about their energy use and to participate in energy markets. In addition, these systems enhance customer satisfaction fostering a win-win relationship between end-users and grid operators, retailers and other stakeholders.

This type of relationships are the basis to create new communities and local markets, which at the same time increase grid resilience because of the integration of DER and the use of local flexible resources to solve the operational constraints. Thus, it is clear that a user-centric energy system is the way forward, but what it is also clear is that the current distribution networks are not yet ready to accommodate this new paradigm. Local markets have the potential to solve the technical constraints that may arise in the distribution network in a resilient way because of the proximity to consumption and generation points. This proximity between the actors involved in the local markets enables a responsive and fast reaction to the technical constraints and the transactions of the DSOs and the end-users, which is not possible in the current centralized energy markets with several hours of anticipation. In addition, local markets can be used to coordinate the different actors involved across regions, which promotes cost-effectiveness. Therefore, local markets are a key element to solve the technical constraints of the distribution network in a resilient way, and they are the key element to create a user-oriented energy system.

Then, before trading with the flexibility, it is necessary to identify and quantify it. The concept of flexibility in this thesis is described in Figure 2.1. As shown in the figure, we need to take into account several aspects as we will see in the next sections. First, an introductory work to this thesis based on a data-driven approach is briefly described to introduce the first concepts of flexibility estimation. Then, the concept of flexibility is extended to calculate the flexibility envelopes of the different actors that appear in distribution networks.

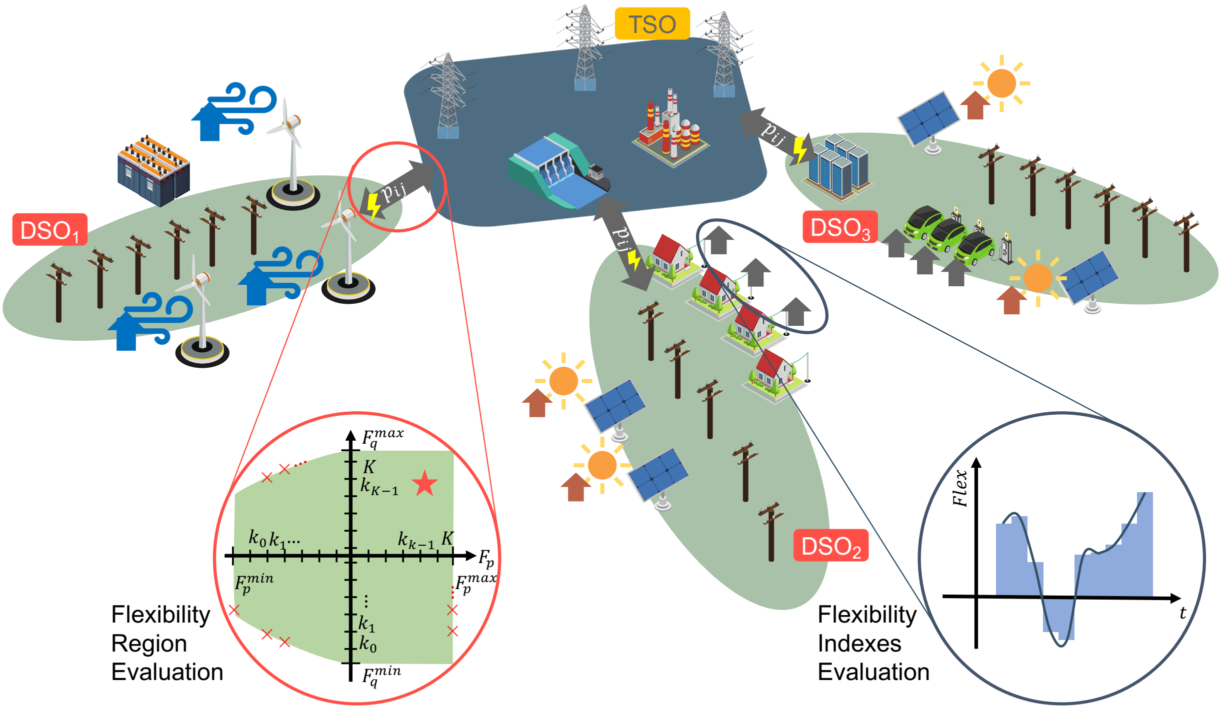

Figure 2.1: The concept of flexibility in the context of Multi-DSO energy coordinated systems. DERs provide flexibility to accommodate the variability of the renewable generation. Flexibility envelopes and indexes are used to evaluate the flexibility capabilities of these resources.

2.1.1 Data-driven Flexibility Characterization through Flexibility Indexes

The rapid evolution towards digitalization and decentralization of distribution networks has resulted in a greater complexity in their operation and maintenance strategies, particularly with regard to the wide-adoption of new uses of energy such as storage or active demand management. Consequently, there has been a growing interest in enabling flexible operation of MV and LV distribution networks through the use of massive data acquisition solutions, smart metering, sensorization, and data-driven and Artificial Intelligence (AI)-based algorithms.

Flexibility, however, has been defined in different dimensions in the literature depending on the object of study [31]–[33], and a proper approach must address the particularities and the constraints of the distribution network, such as congestion, imbalances and voltages deviations. Research up to date has taken a case-by-case approach or tackled flexibility of entire power systems at a glance, but these approaches have been deemed too partial or biased and do not reflect the dynamic, variable, and uncertain nature of power systems [31].

In this context, a previous work based on cost-effective current sensorization implemented on LV feeders and LV side of power transformers, were used to characterize flexibility in distribution networks [34]. This work redefined existing MV/LV flexibility indexes and defined new ones, considering demand status and DER operation possibilities at the end-user side. These indexes took part in a massive data-driven analysis and AI-based prediction in order to be determined 15 minutes and one hour ahead, and the predicted values were compared to a set of characteristic cluster curves previously determined to identify the operational scheme being experienced for any index and distribution network element of study.

This previous work [34] advanced the traditional approaches that addressed flexibility as a mathematical problem, especially in its application to distribution networks. Besides, it provided DSOs and stakeholders with an additional planning and operation tool about existing and future condition of the distribution network. This is particularly useful when operating their controllable resources or building alternatives to traditional planning strategies.

Overall, the importance of the flexibility characterization in distribution networks was highlighted, given the increasing complexity of energy use and the need for DSOs to play an active role in facilitating local energy markets and decarbonization policies. It also emphasizes the limitations of previous approaches that either focused too narrowly on individual cases or too broadly on power systems as a whole. Finally, this characterization of flexibility was carried out based on a model-agnostic approach, which is a key aspect for the reproducibility to other distribution networks and the scalability to other time horizons. Nevertheless, although this previous work obtain a good accuracy in the prediction and could characterize the decrease in the flexibility in the presence of imbalanced phases, it was not able to characterize the flexibility in the presence of voltage deviations. This is due to the fact that the only parameter that was used to characterize the flexibility was the current flowing through the lines, which cannot reflect well the flexibility in the reactive dimension.

Besides of that, the agnostic-model approach used in the previous work was based on the use of clustering techniques, which are not able to capture the temporal dependencies of the data. Although it helped to reduce the computational burden aggregating similar branches, it cannot precisely predict the flexibility in the future, since the flexibility is a dynamic parameter that changes over time. Most importantly, some of these indexes were divided by the flexibility amplitude to obtain a per unit value, which could cause high spikes in the event of low flexibility amplitude at some periods of the time.

2.1.2 Flexibility Envelopes

Given the limitations of the previous work, a model-based approach to characterize the flexibility is necessary. The characterization of the flexibility based on envelopes is a key aspect to comprehensive understand the capabilities of the distribution network when they are accommodating new actors and new uses of energy. Flexibility envelopes are a powerful tool to characterize the flexibility of the distribution network. They are dynamic operating boundaries that define the maximum possible change in the point of connection of a region of the distribution network, while respecting the operational constraints of the network. [35]. This flexibility envelopes have the potential of being used to coordinate a set of use cases where different renewable agents are integrated at the same time in a distribution network.

These approaches are based on the use of optimization techniques [36], which are able to capture the temporal dependencies of the data and the flexibility in the reactive dimension. Besides, it overcomes the limitations of the previous indexed based approach, focusing on the flexibility amplitude rather than indexes that might not able to capture the dependency on technical restrictions of the distribution network. Instead, it computes the bounds of the flexibility of a region of a distribution network as the maximum possible change in the point of connection of the region, while respecting the operational constraints of the network.

The flexibility envelopes provide a detailed and comprehensive representation of the flexibility capabilities of the DERs capturing also the environment in which they are located. They have numerous applications, such as setting dynamic limits for the DERs in the distribution network [37], or to quantify the flexibility that can be provided to the system operator [36]. In this sense, the flexibility envelopes can be used to coordinate the different actors in the distribution network by dynamically calculating the operational envelopes based on the current state of the network. This is a key aspect, as enables the solving of local issues with local resources. The main challenge of this type of approach is the computational burden, since the number of agents involved in the coordination is high, and the resolution of the optimization lies between 5 and 15 minutes. Besides of this, there are other challenges that need to be addressed. Currently, the flexibility envelopes that are being used does not account for the flexibility of BESSs, EVs or HVACs, which will play a fundamental role in the distribution of the future. Besides, in a context where multiple local markets are being deployed all over the network, considering them when computing this operational envelopes is a key aspect to ensure feasibility of the solutions.

Flexibility characterization is a crucial aspect of deploying LFMs. By accurately characterizing the flexibility capabilities of DERs through techniques like flexibility envelopes, it becomes possible to understand the dynamic operating boundaries of the distribution network. The use of flexibility envelopes enables the coordination of multiple actors in the distribution network, taking advantage of the proximity to consumption and generation points. This proximity facilitates a responsive and fast reaction to technical constraints, ensuring the efficient utilization of flexible resources. This responsiveness is a key aspect to ensure the stability of the distribution network, especially in the presence of high penetration of DERs. Besides, it supports the idea that local issues should be solved locally, since the proximity of the flexible resources to the point of connection enables a fast reaction to technical constraints. Furthermore, local markets leverage this coordination to promote cost-effectiveness by integrating and optimizing the utilization of flexibility across regions, as it will be discussed in the next section. This coordination among regions can be facilitated by local markets or other decentralized energy structures if properly designed. Then, the architecture of the LFMs for accommodating the different flexibility products is essential to ensure cost-effectiveness and feasibility of the solutions.

2.2 Local Flexibility Market definition and coordination scheme

A local flexibility market is a dynamic marketplace where a range of energy-related commodities are traded to support the operation of power energy systems. It serves as a platform that enables the exchange of a wide range of energy products among various stakeholders. The definition of local flexibility market is broader than what will be discussed in this thesis, since it is possible to trade a wide range of goods within these types of architectures. These markets can facilitate the exchange of electricity, demand response services, energy storage services, renewable energy generation, ancillary services, and even environmental attributes, such as carbon emissions. Nevertheless, in this thesis the focus will be on the trading of flexibility products to support the operation of the distribution network, that is, to unlock the flexibility potential of the resources connected to the distribution network, to ensure an efficient and reliable operation of it. Considering that the vast majority of the resources being deployed all over the grid uses renewable energy sources as their primary source of energy, the trading of flexibility products in local markets will be key to foster the energy transition.

Participants in these markets, such as energy consumers, producers, prosumers, aggregators and even DSOs can offer or ask for flexibility based on their specific needs, capabilities and availability. There will be another figure which will be responsible for coordinating this market activities, specially important in the case that several markets or jurisdictions are being coordinated. When designing schemes for LFMs, it is crucial to consider the different types of resources and products that will be traded in the market, as well as the different actors and the specific needs of the grid.

The market operates based on a set of rules, protocols, and market mechanisms that govern the trading process. These include bidding and pricing mechanisms, scheduling and dispatch procedures, and settlement arrangements. Market participants submit their offers and bids indicating the quantity, availability, and price of their flexibility products, and the market operator matches these offers with the asking requirements of the system. The market clearing process determines the optimal allocation and utilization of flexible resources based on the needs of the DSOs, system constraints, and resources dynamics.

Local flexibility markets are a form of transactive energy systems that enable the exchange of energy products among various stakeholders deployed in a specific region of the grid. They promote the integration of renewable energy sources by providing incentives for their deployment and utilization. These markets enhance grid resilience taking advantage of the proximity of flexible resources to the points of consumption and generation, minimizing the need for extensive grid reinforcements. Moreover, they empower end-users by allowing them to actively participate in the market, make informed decisions about their energy usage, and potentially monetize their flexibility capabilities.

The establishment of LFMs requires robust market frameworks, reliable communication infrastructures, advanced metering and monitoring systems, as well as appropriate regulatory and legal frameworks. It also relies on accurate and timely flexibility characterization, as well as effective market design and coordination mechanisms. On top of these aspects, the design of the LFMs should also consider the different market properties that any market could have: market efficiency, incentive compatibility, revenue adequacy, and cost recovery.

- *Market efficiency* is achieved when prices accurately reflect the underlying value of the traded commodities, ensuring that resources are allocated to their most economically beneficial uses. This promotes competition, incentivizes efficient behaviour, and ultimately leads to optimal resource utilization within the local energy system. In the context of local markets, market efficiency is aligned with social welfare, and it is achieved when the maximum social welfare is achieved.

- *Incentive compatibility* is another important aspect of local markets. Participants need to be incentivized to actively participate in the market and provide their energy-related services. Local markets should offer fair and transparent price signals that accurately reflect the costs and benefits associated with the provision of these services. When incentives align with the interests of market participants, they are encouraged to engage in the market and maximize their economic gains, leading to a more competitive marketplace. In short, incentive compatibility ensures that market participants are rewarded for acting in their true best interests, because their objective is aligned with the objective of the market and maximized.

- *Revenue adequacy* is a key consideration for the sustainability and viability of local markets. Market participants, specially those who invest in DERs or provide flexibility services, need assurance that the revenues generated from participating in the market are sufficient to cover their costs and provide a reasonable return on investment. Revenue adequacy ensures that market participants are adequately compensated for the value they provide to the energy system, thereby encouraging ongoing investment in renewable energy, energy storage, and other flexibility-enabling technologies. Thus, the revenue adequacy implies that there is a fair distribution of the benefits and no financial deficit for the market participants.

- *Cost recovery* is closely related to revenue adequacy and refers to the ability of market participants to recover their costs incurred in providing energy-related services, so that they can continue to operate in the market. In this context, the costs incurred by the market participants must be recovered through the incomes generated by the market. Benefits must be non-negative. This includes the costs associated with installing and operating DERs, managing flexible resources, and participating in market transactions. A well-designed local market should provide mechanisms that allow market participants to recover their costs in a transparent and fair manner, ensuring that the financial viability of their operations is maintained over the long term.

In practice, and due to the impossibility theorem of Hurwicz [38], it is not possible to achieve all these properties at the same time. Therefore, the design of the LFMs should consider the trade-off between these properties, and the specific needs of the grid, to ensure that the market is sustainable and viable in the long term. The market architectures and designs described in chapter 3 will be evaluated based on these properties, but as it will be seen, any marginalist market design will suffer from not being incentive compatible, as it is not possible to guarantee that all the participants will bid their true costs.

So, *when and why LFMs are needed?*. As it has been mentioned, local markets arise in response to the evolving needs and challenges of the energy sectors. Various are the factors that contribute to their emergence, such as the increasing penetration of renewable energy sources, the growing deployment of DERs, the proliferation of electric vehicles, and the need for net-zero carbon emissions systems by 2050. These factors are driving the transition towards a more decentralized, decarbonized, and digitalized energy system, where LFMs will play a key role in enabling the efficient utilization of proximity commodities. This proximity is the key aspect of the local markets as it allows solving operational local issues locally, avoiding the need of slow and bureaucratic coordination mechanisms with upper stream markets and agents. This thesis envisions a future where LFMs are the cornerstone of the energy system, providing the necessary flexibility services to ensure the safe and reliable operation of the grid, as can be seen in Fig. 2.2. The adoption of these markets will however require the development of new fair coordination mechanisms among them, since they are not isolated, but part of a broader energy system.

2.2.1 Coordinating Local Flexibility Markets

As it has been previously discussed, in a context of multiple and interconnected LFMs, coordination is a crucial aspect to ensure the efficient operation of the energy system. The complexity of managing a decentralized energy system with numerous DERs requires effective coordination mechanisms to ensure smooth integration and optimal utilization of flexible resources. Coordination, in this context, refers to the collaborative management of interdependencies between LFMs to achieve a common goal, such as solving a grid constraint or maximize the use of renewable energy. A similar reasoning can be applied to the coordination of other actors, such as multi-microgrids, peer-to-peer energy trading

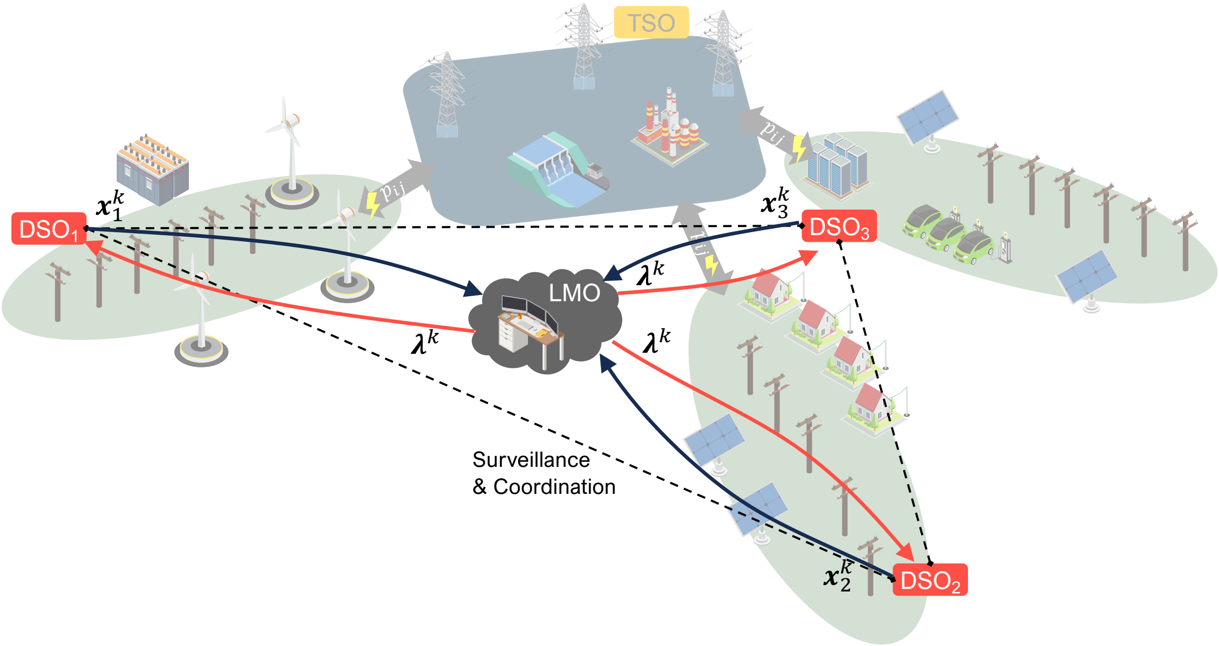

Figure 2.2: Coordination of multiple local flexibility markets among different DSOs under the supervision of the LMO. x_i^k and λ^k are the variables at the interface of the DSO i and the price of the flexibility at iteration k.

platforms, or even the coordination of the LFM with the upper stream markets. The coordination mechanisms investigated in this thesis are valid for any market design, and they are not limited to the ones proposed in this thesis.

Thus, to create wide useful coordination technique, it is necessary to align and standardize the actions of different participants, exchanging information among them in an efficient, timely and transparent manner, establishing common rules and procedures, and developing mechanisms to ensure fair and equitable outcomes for all parties involved. The harmonization and synchronization of the activities among stakeholders when procuring flexibility is crucial, as it allows to avoid the duplication of efforts and the inefficient use of resources.

Secondly, the exchange of information and data sharing among market actors must be carefully designed to ensure that the right information is shared with the right actors at the right time. All of this, inside an environment where the privacy concerns may arise due to the sensitive nature of the data that is being shared, and where the rapidness of the market operation is a key aspect to ensure the stability of the grid. There is need for a minimal level of information sharing that at the same time ensures a proper management of the markets that are interconnected.

Coordination requires the development and implementation of appropriate market mechanisms and frameworks. This includes defining clear market rules, standardized protocols, and transparent pricing structures that incentivize flexibility providers and consumers to actively participate in the local flexibility markets. In addition, these architectures must also consider the establishment of governance structures and regulatory frameworks that ensure fair and equitable outcomes for all market participants, and that in case of conflict, there are mechanisms to resolve them in a timely and efficient manner.

As it has been discussed, coordination is a multifaceted concept that encompasses the harmonization of activities, the exchange of information, the development of market mechanisms, and the establishment of governance structures. Besides this, there are some concerns regarding privacy and data sharing, and the rapidness of the market operation. Thus, a careful analysis on the conditions required to the deployment of these coordination mechanisms must be conducted.

The need for coordination arises from the recognition that LFMs are not isolated entities but are interconnected within a broader energy system. While it is important to address local issues through local solutions, it is equally crucial to coordinate these markets to effectively tackle global optimal solutions. Standalone LFMs are unlikely to be able to obtain the full benefits of flexibility, as they are limited in their scope and scale. Coordination allows pooling resources, expertise, and flexibility across multiple markets to solve complex problems that cannot be addressed by individual markets alone. The conditions for deploying coordination mechanisms in LFMs depend on several factors.

Firstly, coordination becomes necessary when there is a high degree of interdependence among LFMs. If the actions and outcomes of one market significantly affect or depend on the operations of another market, coordination becomes essential to ensure coherence and efficiency across the system. This interdependence can arise due to shared resources, overlapping geographic boundaries, or the need to optimize the utilization of flexibility across multiple markets.

Secondly, the need for coordination is influenced by the scale and scope of the operational problems that LFMs aim to solve. If the challenges faced by individual markets are limited in scope and can be adequately addressed within their local boundaries, coordination may not be a pressing concern. However, as the complexity and magnitude of the issues increase, coordination becomes vital to pool resources, and flexibility across markets for more effective and less expensive problem-solving.

This coordination is facilitated by the advances in digital technologies, which enable the seamless exchange of information and data sharing among market participants. The development of digital platforms and tools, such as blockchain, distributed ledgers, and smart contracts, can help to streamline the coordination process and ensure an optimal solution for all parties involved. In this sense, it is important to define a clear communication channels and data sharing protocols to facilitate coordination, standardizing the information that is being shared and the way it is being shared.

The way in which coordination is achieved depends on the nature of the problem and the degree of interdependence among LFMs. Generally, LFMs are interconnected by several tie-lines that allow the exchange of electricity. The coordination methodologies that this thesis presents builds on the idea that these power flows that join two areas or jurisdictions or DSOs can be used to coordinate the activities of the different LFMs. In standalone LFMs, the power that flows through the tie-lines remain fixed, however, in coordinated LFMs, the power flow through the tie-lines can be adjusted to optimize the utilization of flexibility across markets. This is achieved by establishing a common communication protocol that enable to exchange economic signals related to the change in these power flows among LFMs. This communication protocol can be implemented through a centralized or decentralized architecture, depending on the nature of the problem and the degree of interdependence among LFMs. In the case of a centralized architecture, a central entity is responsible for coordinating the activities of the different LFMs and ensuring that the actions of one market do not adversely affect the operations of another market. In the case of a decentralized architecture, the local market operator, or a third party, is responsible for coordinating the activities of the different LFMs, generally updating the economic signals in an iterative negotiation mechanism.

A timeline of the flexibility coordination is shown in Figure 2.3. The process starts with the identification of the need for coordination, which is allowed by the metering infrastructure of each DSO. Every time a DSO identifies a need for coordination, it sends a flexibility request to the LMO to start the LFM. Then, the LMO collects asks and bids from the flexibility service providers and consumers, and other DSOs that are willing to participate in the LFM. Then, the market is iteratively solved until the convergence of the market clearing price, and the LMO sends the economic signals to the DSOs to adjust the power flows through the tie-lines. After the market-clearing process is completed, the LMO sends a message of the bid acceptance to the interested parties and the DSOs. Finally, the DSOs adjust the power flows through the tie-lines according to the economic signals received from the LMO. The dispatch process is monitored by the LMO to ensure the proper operation of the LFM.

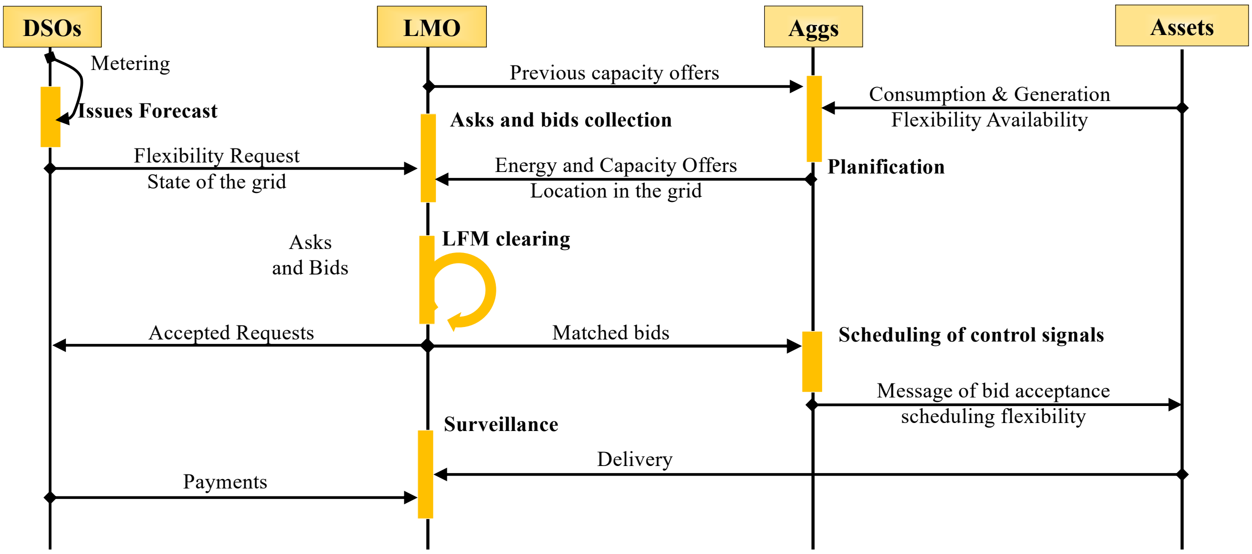

Figure 2.3: Timeline of the flexibility coordination

During this process, no private information is shared between the different DSOs that participate in the market, as the only information that is shared is the economic signals that are sent by the LMO to the DSOs. No information regarding intrinsic characteristics of the flexibility service providers and consumers is shared between the DSOs, whatsoever. This is achieved by a decentralized architecture based on Lagrangian relaxation, which will be further explained in Chapter 3. These architectures enable finding the global optimal solution to the problem, even with this high requirements regarding information privacy.

2.2.2 Barriers of coordination among LFMs

As discussed in the previous section, the coordination of LFMs brings several benefits when compared to standalone LFMs designs. The flexibility utilization is increased, the system stability and reliability is improved, and optimal solutions are achieved, even in an environment with high requirements regarding privacy and data protection. However, the coordination of LFMs is not exempt of barriers.

The introduction of the coordination among LFMs can face various barriers that hinder their implementation among existing local market structures. One significant barrier is the lack of adequate market designs and regulatory frameworks to enable the coordination of LFMs. If disparate markets are to be coordinated, the regulatory framework that governs each market must be compatible with adequately tailored to accommodate the coordination process. This can be achieved by defining clear rules regarding communication protocols and market operation procedures. Additionally, technical barriers also pose a challenge to the coordination of LFMs. Currently, the distribution system is facing a rapid digitalization process, which is enabling the deployment of these markets. However, that is not always the case, as the digitalization process is not homogeneous across the different DSOs. In addition, financial barriers can also hinder the coordination, as the need for a specialized market operator and several local optimizer algorithms that automatically compute the actions at each iteration of the procedure can be costly for the DSOs. Finally, conservative market practices and the lack of a clear business models can also hinder these coordination mechanisms. Markets must be trustfully and transparently designed to ensure that all parties involved are willing to participate in the coordination process.

As far as this context is concerned, the opportunities in the coordination of LFMs are numerous. Chapter 3 will further discuss the benefits of this coordination process by presenting several case studies and numerical results that demonstrate the economic and technical benefits of implementing such coordination mechanisms in the distribution system. The horizontal coordination of LFMs can be easily achieved by the implementation of a simple coordination process based on optimization algorithms.

2.3 Vertically stacking of flexibility across multi-scale markets

Until this moment, the focus of this chapter has been on the coordination of LFMs within the same market layer. Nevertheless, with the aim of maximizing the economic benefits of the flexible resources, the coordination of LFMs across different market layers is also a promising research topic. The vertical integration of the flexibility across different market structures boosts the economic viability of the flexible resources deployed in the distribution system, as will be discussed in the Chapter 4. In this section, the concept of revenue stacking is introduced, explaining how the flexibility is traded across markets and the benefits, barriers and opportunities of this concept.

2.3.1 Revenue stacking concept

The revenue stacking concept is based on the idea of streamlining DERs to provide multiple services in different markets, simultaneously. This concept is not new, as it has been applied in the past to other market actors participating in several electricity markets. The main difference with these market actors is that DERs are deployed all over the distribution grid, what usually makes them invisible to the majority of market operators, and therefore, they are not able to participate in upper level market structures. In this concept, the strategic management of flexibility products derived from DERs is emphasized to maximize the economic benefits of the flexible resources.

The revenue stacking of flexibility involves aggregating and bundling the flexibility capabilities of disparate DERs technologies to provide multiple services in different markets. The services provided by these products are diverse, and they can range from the energy balancing, frequency regulation, voltage control, capacity reserves, and others types of ancillary services. The multi-scale coordination of flexibility enables the participation in several markets with different time horizons and granularities. This aspect recognizes that the flexible resources can be used at different levels, ranging from local distributions grids to regional or national transmission grids and markets. However, these resources alone cannot provide all these services mainly due to coordination and regulation barriers.

2.3.2 How is flexibility traded across different markets?

The vertical coordination and aggregation needed to enable the revenue stacking of flexible resources is achieved by the implementation of a hierarchical architecture for market participation, where the decisions made in a higher level are used to inform the decisions made in a lower level. This hierarchical architecture is fundamental for the concepts explained in Chapter 4. In this thesis it is explored, not only the horizontal coordination of the flexibility across different local markets, but also this vertical coordination among multi-scale markets, as Fig 2.4 shows.

The flexibility management in this architecture is crucial to ensure optimal bidding strategies in the different markets. This requires sophisticated algorithms that are able to captures the dynamics of the flexible resources, the rival markets agents and the uncertainty associated to them. The flexibility management process involves an uncertainty aware forecasting process, a bidding strategy formulation and a scheduling procedure that match the operational requirements of all the markets where the flexibility is traded. In this sense, the flexibility can adopt very different facets, in the form of demand response, voltage regulation, imbalance management, congestion management and many others.

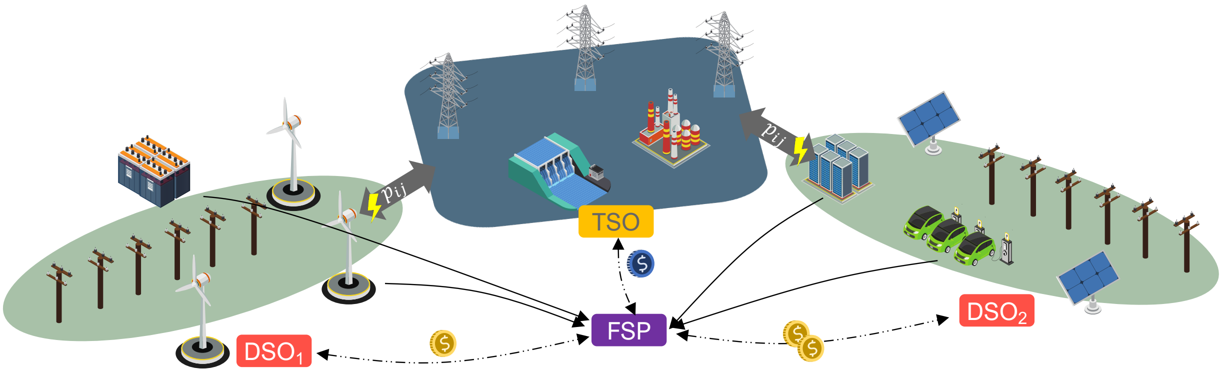

Figure 2.4: Conceptual visualization of the vertical provision of flexibility among DSOs and TSO, i.e. Local and National Level, through the figure of the FSP.

2.3.3 Revenue stacking benefits, barriers and opportunities

The vertical coordination of flexible resources enables the revenue stacking across different market structures and the increase of the economic viability of the DERs. By streamlining the different sources of flexibility into a single flexible entity able of providing different services in different markets, diverse revenue streams can be obtained increasing the value of the resources during the lifetime of the asset. New business models appear, incentivizing the deployment of DERs. If properly managed, these DERs can be conformed by renewable energy sources, complementing one another to provide the required flexibility. This would also help to achieve the decarbonization goals set by the European Union.

This integration and maximization of the usage of renewable sources can, in a way, help to control the uncertainty associated to these resources. The revenue stacking needs from advanced forecasting and management algorithms in order to proper set the bidding strategies in the different markets. So, by allowing these types of business cases, the development of new vertical coordination algorithms are incentivized, promoting the research of proper tools to control and manage the uncertainty associated to the renewable energy sources.

At the same time, this increase of flexibility utilization can help to reduce the investments in the grid, even with the incipient electrification of the economy. Those DER such as EVs or HVACs can be used to provide the required flexibility, accommodating the variability and indeterministic nature of the distributed renewable energy sources. This would, at the end, benefit to the end user by reducing the costs of the energy and the grid tariffs.

However, there are several barriers that need to be overcome in order to enable the revenue stacking of flexible resources, and therefore the vertical coordination of the flexibility across different market structures. These barriers can be categorized into regulatory, technical and market barriers.

Regulatory barriers represent a significant hurdle in realizing the benefits of revenue stacking. One key challenge is the lack of coordination between different markets. Often, national and local markets operate under separate regulatory frameworks, with different rules, requirements, and pricing structures. This lack of coordination can create inefficiencies, hinder market participation, and limit the ability to fully exploit the revenue potential of DERs. Additionally, the absence of coordination between different regulatory bodies adds complexity and uncertainty to the regulatory landscape, making it challenging for stakeholders to navigate through them and implement revenue stacking strategies effectively. This brings challenges to the coordination of the flexible resources across different markets, however it also creates opportunities for the FSP figure, which will be discussed in Chapter 4. To fully deploy the potential of the flexibility from DERs, it is necessary to overcome these regulatory barriers, which is not straightforward, but can be achieved through the proposed vertical coordination.

Technical barriers also impede the development of stacking revenue strategies. The successful management of flexibility across different markets requires advanced algorithms and tools. These tools need to be capable of accurately forecasting the availability of flexible resources, optimizing their dispatch across multiple markets, and assessing the influence of uncertainty associated with these resources. Currently, there is a research gap in the development of algorithms and tools that can effectively manage flexibility while accounting for the uncertainty associated to its operation. This gap needs to be addressed to promote the development of business cases that can fully exploit the revenue potential of DERs.

This absence of proper business models and market designs is another key barrier to revenue stacking. New business models that can capture, integrate and accommodate the value generated from participating in multiple markets are needed. In this context, the figure of the FSP can be a key player, as it can provide the necessary tools to integrate the different revenue streams. Additionally, the market design itself may not be optimized to accommodate the simultaneous participation of DERs in various markets, so new market designs may be also required, which is also a key aspect of this thesis when integrating new local market designs into the algorithm design. The lack of market structures that recognize and facilitate revenue stacking can limit the attractiveness and viability of participating in multiple markets, disincentivizing the deployment of DERs and hindering the realization of their full flexibility potential. However, this thesis tries to address this barrier by proposing new algorithms for the streamlining of the flexibility across traditional national and local markets, with the hope that early-adopters FSPs can help to develop new business models.

2.4 Summary

This chapter discusses the concept of flexibility in energy systems, focusing on its importance in accommodating renewable energy penetration and transitioning to a user-oriented energy system. Two approaches for flexibility characterization are presented: flexibility indexes and flexibility envelopes. While flexibility indexes highlight the complexity of energy use and the need for local energy markets, flexibility envelopes offer a comprehensive representation of DER flexibility capabilities. The concept of LFMs is introduced as a dynamic platform for trading energy-related commodities to support power system operation. Coordination among multiple LFMs is essential for efficient system operation, achieved through centralized or decentralized architectures. Revenue stacking, the leveraging of the same flexibility resource across different markets, enhances the economic viability of DERs. However, regulatory, technical, and market barriers hinder the implementation of revenue stacking strategies. Overcoming these barriers is crucial for realizing the potential of DERs, promoting renewable energy utilization, and achieving decarbonization goals while reducing grid investments.

CHAPTER 3

Market-Clearing Process for Multi-DSO Local Markets

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This chapter presents the first contribution of this thesis, which is the challenge of coordinating a several different local market structures in a multi-DSO environment. These problems consider the specific characteristics and requirements of different actors to ensure efficient resource allocation. Firstly, a novel methodology is proposed to coordinate and decentralize market-clearing protocols, addressing privacy concerns through the use of ADMM-based algorithms for secure and privacy-preserving transactions. Then, this chapter also analyzes uncertainty factors in these local market structures, proposing a novel methodology that consider, not only the uncertainty of the DERs but also the uncertainty of the activation of the energy events. Lastly, a flexibility characterization methodology is presented to assess the flexibility region of these local market structures, considering the influence of the TSO in the flexibility procurement. This research contributes to the understanding and optimization of flexibility provision, enabling informed decision-making in the management of flexibility portfolios.

3.1 Local Markets for Flexibility Procurement

Deployment of Renewable Energy (RE) has significantly increased over last years. Installed renewable capacity has increased an 89% in the last 10 years in Europe [5]. For instance, Spain has achieved a 50% of RE production share in 2020 [6]. Uncontrollability of Photovoltaic (PV) and wind energy is one of the main shortcomings when integrating RE. Part of this deployment is done at distribution level with DERs, usually, PV systems. Consequently, distribution grids face challenges such as imbalances, voltage deviations and line congestions. In this context, LFMs present a solution to the intermittent behaviour of DERs, using flexibility products to solve those issues.

In the literature, there exist a wide type of methods to clear local marketplaces. Focusing on market-based methods, those techniques includes: LFMs, Price-based control techniques and Transactive Energy approaches [8]. Market schemes are preferred over price based control techniques as its protect to end-customers, being also aligned with EU regulations [9]. Besides, offering high quality solutions with local resources, local communities running LFMs are emerging at organizational level [10].

For the purpose of this thesis, LFMs are defined as a type of marketplace where it is possible to trade electricity products in geographically limited areas, that is, small towns, neighbourhoods, communities or districts [11]. Therefore, they involve several agents who sell and buy electricity products, a market operator, and a clearing mechanism that match offers with asks [12].

The number of agents included in the market greatly varies depending on the LFM design. However, main actors are: DSOs, Balance Responsible Partys (BRPs), Aggregators and, LMOs [13]. These stakeholders are interested in participating in the market as DSOs solve congestion and voltage deviations, BRPs optimize their portfolios, and Aggregators obtain benefits from the management of their resources. Nevertheless, the role of each stakeholder differs among proposals. Reference [14], considers the Aggregator figure as the LMO, providing different services to DSO and BRPs. Market defined in [15], conversely, does not include BRP figure, enhancing Aggregators as the one who oversees the market, collecting bids and asks. Alternatively, reference [16] proposes a market structure where no Aggregator is presented, and flexibility is traded considering only end users. Moreover, authors of reference [17] acknowledge energy communities as a key player when defining market structure. Regardless of the approach considered, none of them clearly explain the relation between the prices of flexibility products and the wholesale market. From an operational viewpoint, several LFM pilot projects are being developed over the European Union. Some examples are: IREMEL [18], InterFlex [19], EMPOWER [14] and DREAM-GO [17]. The Spanish project IREMEL addresses three main mechanisms for DSO to obtain flexibility: Congestion Management, Local Flexibility Products and long-term contracts using Aggregators. The main objective of InterFlex project is to create a local energy markets consisting of Aggregators, Industrial Customers and Local Energy Communities. It focuses on both centralized and decentralized versions (P2P) of the market. EMPOWER and DREAM-GO situate Aggregators as the central actor of the LFM providing DSR services to DSO. Social welfare [20] or cost minimization for flexibility procurement are the usual objectives seek while defining the LFM. Costs op-

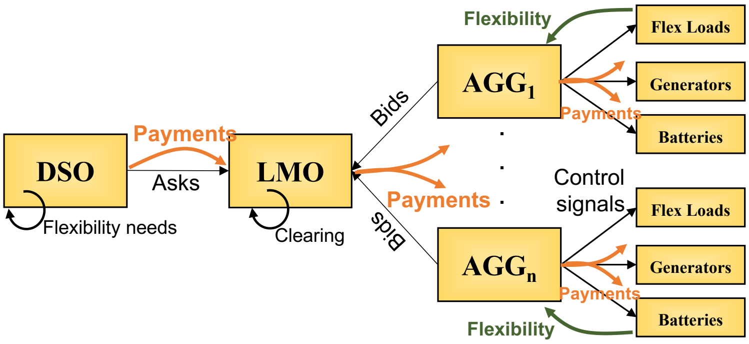


Figure 3.1: General taxonomy of local flexibility markets regarding its main actors, how bids are deployed and how control signals are scheduled.

timization, depending on the viewpoint considered, can be minimized for Aggregator [14], LMO [15] and, DSO [21]. All references work with complex mathematical problems using Mixed Integer Linear Programming or NLP techniques.

In terms of flexibility products, authors in [13] identifies three main energy products to be traded in distribution systems: Demand Side Response (DSR) from FLs, generation curtailment from FGs and storage from BESSs.

Before introducing the first contribution of this chapter, it is necessary to define the main concepts related to a traditional centralised clearing of the LFM. The centralised formulation described in this section is based on the work presented in [23], where the LMO is the central actor of the market, and DERs participates in the market through an Aggregator to solve DSO contingencies.

A deterministic framework of the problem is presented. Since market is cleared each 15 min during all day, uncertainties are considered negligible. For the sake of clarity, Figure 3.1 shows a general view of the taxonomy of local markets, and the involved actors.

Agents presented in these markets are aligned with the EU pilot projects mentioned, especially with EMPOWER and DREAM-GO, due to the Aggregators' role. Flexibility is obtained from prosumers organized in three main categories: FLs, FGs and BESSs.

Generally, LFMs are presented from a LMO perspective, the objective function ensures cost minimization of overall flexibility acquisition, leading to market efficiency where only the minimum possible quantity of products is traded to solve DSO contingency.

These centralised markets are cleared using a linear solver in a personal computer. Results demonstrante that local flexibility markets can effetive accommodate flexibility products to solve the operational constraints that DSO may face. Two key results can be highlighted from [23]. The first one is that the market formulation is linear, which besides of enabling solving the market in a reasoble amount of time, it guarantees the existence and uniqueness of the market solution, which is a desirable market property for the LFM. The second one is that the local markets are efficient mechanisms to solve both congestions and imbalances in the grid. This is the main reason why the LFM is a key enabler for the

DSO to face the challenges of the energy transition. These markets enables to trade the flexibility of the prosumers, in a way that the DSO can solve the congestions and imbalances in the grid, without the need of investing in grid reinforcements, and the prosumers can get a revenue from their flexibility. Nevertheless, a centralised market architecture might arise some privacy concerns among the users which will need to submit their full flexibility availability and their costs of operation to the LMO.

In this chapter two main contributions are presented, both of them related to the clearing of LFMs. After setting the grounds for centralised methodologies to solve local markets, attention is drawn to a decentralized energy-only architecture based on the ADMM , where several LFMs are coordinately and decentralized cleared by a LMO, ensuring the privacy of the market participants. Then, we investigate the influence of the uncertainty in the flexibility dispatch of these markets, proposed a chance-constrained-based formulation that can describe the uncertainty in the activation of the previously mentioned capacity products in a decentralised and coordinated environment.

3.2 Decentralised Local Energy Markets

In this section, the market-clearing investigated will be carried out in a decentralised and coordinate enviroment, this work has been published in [24]. Besides, assets will submit their flexibility offers directly to DSOs, which will be assumed to be a trusted party as will be the one interested in solving network issues that might appear. Then, several DSOs will iteratively interacting among each other to obtain the optimal schedule of the products. This process will be surveilled by a LMO which will update flexibility prices at each iteration. In the next sections, a brief introduction to this topic will be made. After that, the centralised problem will be reformulated and then it will be decentralised. Lastly, a case study presents the outcomes of this approach including also a brief analysis of the uncertainty that would affect to the market solution.

3.2.1 Motivation

Renewable energy sources operating at distribution grids are becoming increasingly common in modern smart grids. In this context, LEMs are being deployed as new layers of the traditional electricity markets [39], providing new business models for the renewable agents that in many cases did not have opportunities to participate in the conventional wholesale markets. Promoting LEMs among distribution networks is a strategic focus of global energy policies. Some examples can be found in the EU-funded pilot projects FLEXITRANSTORE [40]InterFlex [41], EMPOWER [11], and DREAM-GO [17].

The behaviour of market agents can lead to distribution line congestion [42], voltage magnitude deviations [43], or even power imbalances [44]. The adoption of LEMs allows the resolution of the distribution operational constraints through local agents connected to the same grid without involving upstream assets.

Trading of energy among LEMs to provide flexibility is an important challenge for modern distribution networks [45]. Interoperability of these markets offers a route to overcome this barrier [46] and motivates the study of Multi-DSO local market structures. This setting raises intrinsic concerns regarding the information privacy of the involved -DSO in the effort to achieve system-wide efficiency. Therefore, it is necessary to develop market designs for trading the flexibility products in Multi-DSO LEMs where -DSOs are allowed to trade among areas.

3.2.2 Literature Review

Several market structures have been studied for LEMs, including different combinations of agents. References [47] use the Aggregator as the central entity of the market, offering flexibility services to the DSO. Other approaches assume that the DSO is responsible for the energy balance of the market as well as for the grid operation [48]–[50]. LEMs can also be cleared on an auction basis; in this type of clearing, an auctioneer is responsible for the matching process between the asks and bids [51]. In reference [52], a transactive energy operator operates aggregated fleets of electric vehicles while providing peak-shaving services to the DSO. Traditional market structures have also been considered by [53] where energy from hydroelectric systems is traded in decentralized manner following a hierarchical structure. Additionally, another branch of research which considers LEMs without governance, i.e. with no market operator.

A bi-level peer-to-peer-to-grid market is proposed in [54], where the market is fully distributed among the participating agents. [55] investigates a methodology where the market is jointly hosted by community managers and peers. Blockchain technology was used in [56] to host a market for energy trading among households.

However, this feature may have profound implications for the transparency of the market. This work considers the DSO as the entity that receives offers from flexible agents within its network, but does not act as the market operator. The LEM is hosted by an independent LMO to promote transparency, as in [57]

In many cases, LEMs encompass several geographically restricted jurisdictions, such as energy communities, neighbourhoods, districts, or towns [11]. Thus, several DSOs can be involved in the participation of LEMs. This type of participation in pioneering flexibility market projects has been discussed in [12]. [58], the relevance of this type of coordination for congestion and imbalance management is assessed when organizing flexibility markets. DSOs cooperation is also highly important for flexibility providers operating assets across borders [59]. However, currently there is a gap in the knowledge about how such cross-border coordination can be facilitated. Only [60], [61] proposed a methodology to coordinate flexible power units using converted-coupled units that consider costs and potential flexibility procurement.

Multi-DSO coordination raises considerable concerns regarding the information privacy of the involved agents while trying to achieve system-wide cost-efficient solutions [62]. Privacy can be preserved using decentralized market protocols, e.g. peer-to-peer [54], agent-centric protocols [63], or hybrid approaches [64]. Nevertheless, little research has been conducted on the protection of privacy when several DSOs are cooperating in local market structures. The coordination of these DSOs while preserving confidential participant and network data is a noteworthy feature, which is one of the contributions of this paper. This paper offers a decentralized and coordinated market-clearing procedure for flexibility trading in Multi-DSO LEMs, achieving cost-effective system-wide solutions without compromising the market agents' data privacy.

Coordinated and decentralized solutions have been previously proposed. Coordination is attained by multi-bilateral trades between agents in peer-to-peer markets. The electrical distance of the peers in a distribution network drives the preference lists for coordinating a market solution in a peer-to-peer methodology [49]. [56] used an ant-colony optimization algorithm to coordinate the solution among peers. Nevertheless, since the algorithm is based on heuristics, this type of coordination may yield several solutions for the same input data. Consensus is used in [64] to coordinate a hybrid method for community formation and energy trading among peers, but this method may suffer from convergence difficulties when seeking to coordinate system-wide market properties. Grid usage prices are defined by the DSO in [16] to enforce network constraints in a peer-to-peer market. However, this approach does not guarantee the optimal solution of the market, hindering its efficient operation. Following an alternative research direction, several studies coordinate the solution of the market based on market signals. For example, [62] used only the variables associated with the energy transfer among peers. Other researchers also included market signals associated with the grid variables [62]. Following this approach, this paper proposes a coordination methodology based on market signals that can be applied to Multi-DSO LEM and ensures that an optimal solution will be achieved.

In the above-discussed works, several solution approaches have been proposed. In particular, Lagrangian relaxation has been applied to decentralize market-clearing procedures in distribution grids [53], [63]. Nevertheless, the ADMM algorithm [65] improves the Lagrangian relaxation decentralization process due to its convergence properties. Multiples methodologies have been proposed to decentralize the market-clearing using this algorithm atthe distribution level [16], [54]. However, little research has been performed regarding the coordination among the physically adjacent DSOs operating in the same LEMs.

A summary of the above literature review is shown in Table 3.1. Additionally, the limitations of the current approaches are described as follows:

L1. Coordination among DSOs when trading flexibility products for congestion and imbalance management has not been sufficiently addressed.

L2. Most of the current market-clearing methodologies have limited privacy protection of the participating users, and the decentralized methodologies that do provide such protection may obtain to suboptimal solutions.

L3. Little attention has been paid to coordination methodologies for the trading of flexibility products based on market signals while ensuring optimal market solution.

3.2.3 Contributions

The main contribution of this model is a decentralized and coordinated approach for flexibility products trading in Multi-DSO LEMs. The key features of the proposed model are:

C1. An operational framework that can handle flexibility needs an Multi-DSO LEM environment while preserving market privacy information.

C2. A decentralized solution approach based on the ADMM where optimal dual variables associated with the voltage magnitude and phase angle at the interconnecting DSOs nodes and system-wide imbalance equations, are the signals that properly drive the coordination mechanism to achieve system-wide efficiency.

3.3 Local Energy Market-Clearing Problem Formulation

This section describes the elements of the proposed LEM model. The market consists of several DSOs, demanding flexibility and different agents offering their products. The market mitigates the congestion and corrects balance deviations using a linear model of the distribution network. Moreover, the LEM is designed to be compatible with upward market-clearing solutions, such as those from wholesale markets. Power exchanged with upstream grid remains constant after the LEM market-clearing procedure. The centralized market clearing is based on [14], [15], [23].

3.3.1 LEM Architecture

Figure 3.2 presents the interactions among the different actors involved in the operation of LEMs. The LMO runs the market clearing for flexibility products, receiving asks and bids from DSOs. Each DSO manages the bids from the agents connected to its respective distribution network. In this paper, we assume that three different agents provide flexibility, namely FLs, FGs, and BESSs. It is also assumed that a unique flexibility product is traded regardless of its origin.

Figure 3.2: General diagram of the relationships between the stakeholders of the LEM formulation.

Table 3.1: Summary of the literature review

	DSO-DSO coord.	Type of products	Decentr. market	Market host	Privacy preserv.	Modelling Approach	Opt. granted	Grid	Math. Model
[11]	No	Flexibility	No	Aggregator	No	Optimization	Yes	None	MILP
[47]	No	Capacity	No	LMO	No	Optimization	Yes	Linear DistFlow	LP
[48]	No	Flexibility	No	DSO	No	Optimization	Yes	AC	LP
[49]	No	Energy	Yes	None	Yes	Peer-to-peer	No	None	-
[50]	No	Energy	No	DSO	No	Optimization	Yes	None	MILP
[51]	No	Energy	Yes	Auctioneer	Yes	Auction model	No	DC	-
[52]	No	Flexibility	No	Transactive Energy Operator	No	Optimization	Yes	DC	LP
[53]	No	Energy	Yes	Market operator	Yes	Lagrangian Relaxation	Yes	DC	MILP
[54]	No	Energy	Yes	None	Yes	Peer-to-peer	No	DistFlow	LP
[55]	No	Energy	Yes	None	Yes	Peer-to-peer	No	DC	QCP
[56]	No	Energy	Yes	None	Yes	Peer-to-peer	No	None	MINLP
[57]	No	Energy, Reserve	No	LMO	No	Optimization	Yes	None	MILP
[61]	Yes	Flexibility	No	-	No	Converter-coupled units	Yes	None	MILP
[62]	No	Energy	Yes	None	Yes	ADMM	Yes	DC	QCP
[63]	No	Energy	Yes	LMO	Yes	ADMM	Yes	None	QCP
[64]	No	Energy	Yes	None	Yes	Hybrid (Opt. and P2P)	No	PTDF	MILP
[16]	No	Energy	Yes	None	Yes	Peer-to-peer	No	DistFlow	MINLP
This paper	Yes	Flexibility	Yes	LMO	Yes	ADMM	Yes	Linear AC	QCP

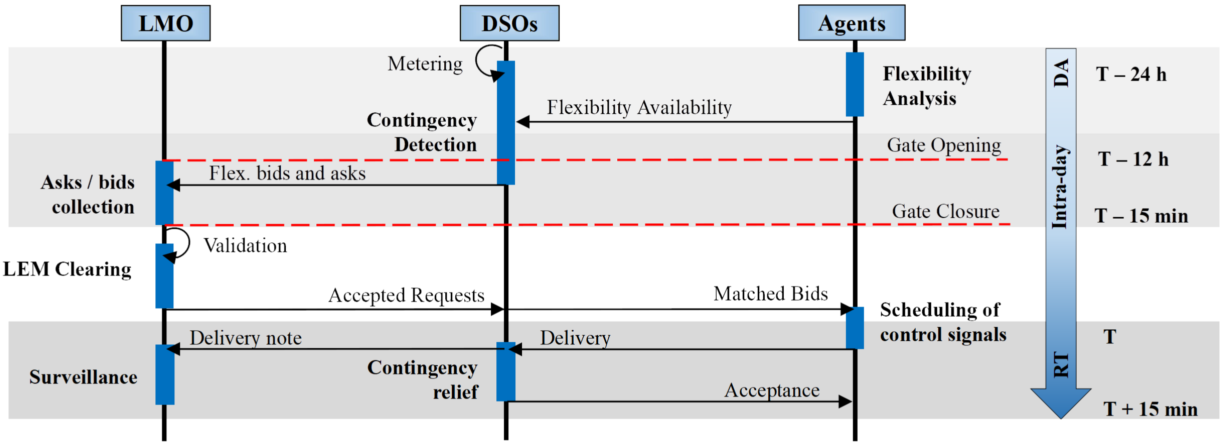


Figure 3.3: Sequence diagram of the LEM representing the interactions between the agents in the proposed framework [14], [15], [23].

More detailed information regarding the interactions between different agents is presented in Fig. 3.3 using a sequence diagram, where a visual representation of the communication protocols is shown. LEM is cleared on a near real-time basis, with a time frame of 15 minutes, assuming forecast values for wholesale market prices and demands. This market is cleared whenever an event occurs in the operation of the distribution network. The market-clearing results in the optimal scheduling of flexible assets for next 24 hours. If new congestions or imbalances appear as a result of forecast inaccuracies, the market clearing will be cleared again while incorporating the most updated information available.

The clearing process is as follows. First, DSOs predict their flexibility needs [66] and, if required, they ask the LMO to organize a LEM for providing flexibility. Each agent submits their flexibility availability to its respective DSO that interacts with the LMO submitting their bids. After collecting asks and bids, an iterative market-clearing protocol starts. Each DSO schedules the resources of its distribution network based on the costs and dual variables set by the LMO. After each iteration, coupling variables at the interface are shared with the LMO that updates the market signals. This process is repeated until convergence. Then, LMO sends accepted requests and matched bids to DSOs that finally inform the participating agents. As a result, agents schedule their internal control signals to deliver the flexibility products under surveillance of the LMO and DSO. Finally, the DSO leaves a delivery note of the products traded to the agents.

So far, it has been assumed that the optimal scheduling of the flexible resources is performed by the DSO. Nevertheless, the above-described protocol is compatible with the participation of flexibility aggregators and private entities. The only difference in the protocol in this case would be that the control signals will be determined by either the aggregator or the private owner.

3.3.2 Problem formulation for an Local energy-only Market

The LEM market-clearing problem is formulated in terms of the flexibility products offered, the market restrictions, the distribution network model and the objective function.

3.3.2.1 Flexibility product definition

In this section, the flexibility products offered by FLs, FGs and BESSs are defined. It is assumed that the energy traded by those flexible units will be collected in the wholesale market. Thus, the price of the energy should be considered in the costs functions to determine the real cost of obtaining flexibility. Then, the baseline of the flexible units or scheduled power arises from their participation in the wholesale market. For simplicity, this baseline is considered to be constant.

FLs can offer the flexibility product in two directions, either increasing or decreasing their scheduled consumption $P^{sch}_{f,t}$, because they are assumed to modify their demand within a given range. The associated costs for the provision of flexibility products are presented in (3.1a). The power demand of the FL f after the LEM clearing, at period t, $p^{am}_{f,t}$, is bounded by $\overline{P}_f$, $\underline{P}_f$ and is defined in (3.1b).

$$c_{f,t} = (S_t - S^u_{f,t})\omega^u_{f,t} + (S^d_{f,t} - S_t)\omega^d_{f,t} \qquad \forall f \in \Omega_f, \forall t \in \Omega_t \quad \text{(3.1a)}$$

$$p^{am}_{f,t} = P^{sch}_{f,t} + \frac{1}{\Delta t}(\omega^u_{f,t} - \omega^d_{f,t}) \qquad \forall f \in \Omega_f, \forall t \in \Omega_t \quad \text{(3.1b)}$$

To obtain profits, the upward flexibility product, $\omega^u_{f,t}$, is offered at a price, $S^u_{f,t}$, that is lower than the wholesale market price S_t. On the other hand, for the same reason the downward flexibility product, $\omega^d_{f,t}$, is offered at a price, $S^d_{f,t}$, that is higher than the previously settled wholesale market price.

FGs are assumed to be controllable in both directions (e.g. co-generation plants or PV with storage), providing upward and downward flexibility. Considering $P^{sch}_{g,t}$ as the scheduled power generation of FG g, at time t, the asset can provide upward, $\omega^u_{g,t}$, and downward, $\omega^d_{g,t}$, flexibility products at prices $S^u_{g,t} > S_t$ and $S^d_{g,t} < S_t$, respectively. Thus, the output power after market clearing must satisfy $\underline{P}_{g,t} \leq p^{am}_{g,t} \leq \overline{P}_{g,t}$ for all time periods $t \in \Omega_t$. Then, the cost of the flexibility product is defined in (3.1c) and the power generation output after LEM clearing in (3.1d).

$$c_{g,t} = (S^u_{g,t} - S_t)\omega^u_{g,t} + (S_t - S^d_{g,t})\omega^d_{g,t} \qquad \forall g \in \Omega_g, \forall t \in \Omega_t \quad \text{(3.1c)}$$

$$p^{am}_{g,t} = P^{sch}_{g,t} + \frac{1}{\Delta t}(\omega^u_{g,t} - \omega^d_{g,t}) \qquad \forall g \in \Omega_g, \forall t \in \Omega_t \quad \text{(3.1d)}$$

Lastly, BESSs constraints are described by (3.1e)-(3.1h). These agents can shift generation or consumption from one period to another. In this case, no baseline is considered for clarity. The agents are assumed to only participate in the proposed market clearing. BESSs provide both upward, $\omega^u_{s,t}$, and downward, $\omega^d_{s,t}$, flexibility, offered at the prices $S^u_{s,t} < S_t$ and $S^d_{s,t} > S_t$, respectively. The costs for BESS products are given by

$$c_{s,t} = (S_t - S^u_{s,t})\omega^u_{s,t} + (S^d_{s,t} - S_t)\omega^d_{s,t} \qquad \forall s \in \Omega_s, \forall t \in \Omega_t \quad \text{(3.1e)}$$

Operation limits for the BESSs are set by the battery converter rating P^{conv}_s and the SOC bounds. Let η^C_s and η^D_s be the charging and discharging efficiencies, then equation (3.1f) sets the SOC trajectories after LEM clearing while (3.1g) establishes the SOC bounds. For realistic modelling, it is considered that $soc_{s,0} = soc_{s,|\Omega_t|} = SOC0_s$. The power of the BESS s after market clearing is computed in (3.1h) considering that if $p^{am}_{s,t} \leq 0$, BESS is being discharged, else if $p^{am}_{s,t} \geq 0$, BESS is charged. This power is limited by the converter rating P^{conv}_s, setting the upper and lower bounds for $p^{am}_{s,t}$ according to (3.1i).

$$soc_{s,t} = soc_{s,t-1} + \eta^C_s \omega^u_{s,t} - \frac{\omega^d_{s,t}}{\eta^D_s} \qquad \forall s \in \Omega_s, \forall t \in \Omega_t \tag{3.1f}$$

$$\underline{SOC}_s \leq soc_{s,t} \leq \overline{SOC}_s \qquad \forall s \in \Omega_s, \forall t \in \Omega_t \tag{3.1g}$$

$$p^{am}_{s,t} = \frac{1}{\Delta t}(\omega^u_{s,t} - \omega^d_{s,t}) \qquad \forall s \in \Omega_s, \forall t \in \Omega_t \tag{3.1h}$$

$$-P^{conv}_s \leq p^{am}_{s,t} \leq P^{conv}_s \qquad \forall s \in \Omega_s, \forall t \in \Omega_t \tag{3.1i}$$

3.3.2.2 LEM Balancing Constraint

LEMs are organized to take advantage of local assets to fulfill local flexibility needs. The power exchanged with the upstream network $p_{i,t}$ does not change after market operation, alleviating congestion by a physical translation of the consumption from the high-load areas to other areas where thermal restrictions are not activated. Thus, the balance for all flexible upwards and downwards products must be zero as described by (3.1j). This equation guarantees that the clearing results do not affect to the upstream networks, ensuring the compatibility of the proposed framework with the current market structures. Associated with this equation, the dual variable λ^I_t represents the marginal cost of the traded flexibility products.

$$\sum_{l\in\Omega_l}(P^{sch}_{l,t} - P^{am}_{l,t}) + \sum_{f\in\Omega_f}(P^{sch}_{f,t} - p^{am}_{f,t}) - \sum_{g\in\Omega_g}(P^{sch}_{g,t} - p^{am}_{g,t}) - \sum_{s\in\Omega_s} p^{am}_{s,t} = 0 \;\; \lambda^I_t \qquad \forall t \in \Omega_t \tag{3.1j}$$

3.3.2.3 Network model

We consider a linear version of the AC network model to characterize the power balance and thermal limits [67]. Linear models of the grid are widely used in market studies [52], [55], [68] because such models eliminate the duality gaps that appear when using non-linear definitions. Thus, a robust economic interpretation of the dual variables can be provided. The power balance for all buses is given by (3.1k) and (3.1l). Active and reactive power flows are computed using (3.1m) and (3.1n). Equation (3.1o) sets the power flow limits $\overline{S}_{i,j}$.

$$\sum_{j\in\Omega_i}(G_{i,j}v_{j,t} - B_{i,j}\theta_{j,t}) = p_{i,t} + p^{am}_{g,t} - P^{am}_{l,t} - p^{am}_{f,t} - p^{am}_{s,t} \qquad \forall i \in \Omega_i, \forall t \in \Omega_t \tag{3.1k}$$

$$-\sum_{j\in\Omega_i}(B_{i,j}v_{j,t} + G_{i,j}\theta_{j,t}) = q_{i,t} + Q^{am}_{g,t} - Q^{am}_{l,t} \qquad \forall i \in \Omega_i, \forall t \in \Omega_t \tag{3.1l}$$

$$p_{i,j,t} = G_{i,j}(v_{i,t} - v_{j,t}) - B_{i,j}(\theta_{i,t} - \theta_{j,t}) \qquad \forall (i,j) \in \Omega_b, \forall t \in \Omega_t \tag{3.1m}$$

$$q_{i,j,t} = B_{i,j}(v_{j,t} - v_{i,t}) + G_{i,j}(\theta_{j,t} - \theta_{i,t}) \qquad \forall (i,j) \in \Omega_b, \forall t \in \Omega_t \tag{3.1n}$$

$$p^2_{i,j,t} + q^2_{i,j,t} \leq \overline{S}^2_{i,j} \qquad \forall (i,j) \in \Omega_b, \forall t \in \Omega_t \tag{3.1o}$$

3.3.2.4 Objective function

The LEM clearing problem objective function minimizes the total cost for the products offered by FLs, FGs and BESSs.

$$\min \sum_{t\in\Omega_t}\left[\sum_{f\in\Omega_f} c_{f,t} + \sum_{g\in\Omega_g} c_{g,t} + \sum_{s\in\Omega_s} c_{s,t}\right] \tag{3.1p}$$

3.3.3 Stochastic formulation

In this section, the stochasticity of the generation, the loads and the wholesale market prices prices is discussed. Loads and prices in distribution networks have an nondeterministic nature, which may influence the solution of the problem. Nevertheless, although DSOs have powerful prediction tools which are able to predict these variables, they may introduce an error in the parameters of the problem.

To characterize this behaviour, we assume that the probability density distribution of the forecast error of the loads and the prices is a normal distribution as in [69] with a standard deviation of 25% and mean value equal to the forecasted values. A scenario tree based approach is used to incorporate the uncertainty into the model as Fig. 3.4 shows. In order to avoid computational burden, a scenario reduction technique is used to include the most representative scenarios in the stochastic formulation [70]. Each scenario is simulated using the proposed ADMM algorithm.

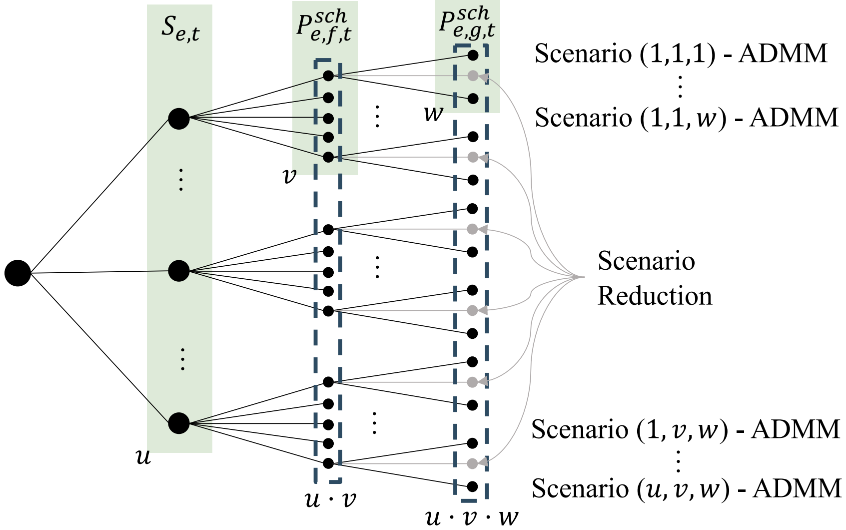


Figure 3.4: Scenario tree of the stochastic version of the Inter-DSO LEM with scenario reduction.

Let $\hat{X}$ be the mean of the parameter X and $\Delta\tilde{e}^X_e$ be the forecast error in the scenario e for the parameter X. The scheduled demand $P^{sch}_{e,f,t}$, the scheduled generation $P^{sch}_{e,g,t}$, and the wholesale market price $S_{e,t}$ in the scenario e are described as follows

$$P^{sch}_{e,f,t} = \hat{P}^{sch}_{f,t} + \Delta\tilde{e}^f_e \qquad \forall e\in\Omega_e, \forall f\in\Omega_f, \forall t\in\Omega_t \tag{3.2a}$$

$$P^{sch}_{e,g,t} = \hat{P}^{sch}_{g,t} + \Delta\tilde{e}^g_e \qquad \forall e\in\Omega_e, \forall g\in\Omega_g, \forall t\in\Omega_t \tag{3.2b}$$

$$S_{e,t} = \hat{S}_{e,t} + \Delta\tilde{e}^{S}_{e} \qquad \forall e \in \Omega_e, \forall t \in \Omega_t \quad \text{(3.2c)}$$

The expected value of the cost is minimized in the objective function for all scenario e in the set of possible realizations Ω_e. Let $\mathcal{P}_e$ be the probability of the scenario e, then, the market formulation stands as follows,

$$\min \sum_{e \in \Omega_e} \mathcal{P}_e \Bigg[\sum_{t \in \Omega_t} \Bigg[\sum_{f \in \Omega_f} c_{e,f,t} + \sum_{g \in \Omega_g} c_{e,g,t} + \sum_{s \in \Omega_s} c_{e,s,t} \Bigg] \Bigg] \quad \text{(3.2d)}$$

$$\text{s.t. (3.1a) – (3.1o)} \qquad \forall e \in \Omega_e$$

The output variables of (3.2d) are now variables with uncertainty with a determined probability density function.

3.3.4 Multi-DSO Local Energy Markets

Considering that LEMs are composed of a set of $|\Omega_p|$ DSOs, interconnected by tie-lines, the objective function is re-written as the cost minimization of the flexibility products offered by each independent DSO as given by (3.3a).

$$\min \sum_{p \in \Omega_p} \sum_{t \in \Omega_t} \Bigg[\sum_{f \in \Omega_f} c^{p}_{f,t} + \sum_{g \in \Omega_g} c^{p}_{g,t} + \sum_{s \in \Omega_s} c^{p}_{s,t} \Bigg] \quad \text{(3.3a)}$$

The balancing constraint (3.1j) is then re-defined as follows,

$$\sum_{p \in \Omega_p} I^{p}_{t} = 0 \;\; \lambda^{I}_{t} \qquad \forall t \in \Omega_t \quad \text{(3.3b)}$$

$$I^{p}_{t} = \sum_{l \in \Omega^{p}_{l}} (P^{sch}_{l,t} - P^{am}_{l,t}) + \sum_{f \in \Omega^{p}_{g}} (P^{sch}_{f,t} - p^{am}_{f,t}) - \sum_{g \in \Omega^{p}_{g}} (P^{sch}_{g,t} - p^{am}_{g,t}) - \sum_{s \in \Omega^{p}_{s}} p^{am}_{s,t} \qquad \forall t \in \Omega_t, \forall p \in \Omega_p \quad \text{(3.3c)}$$

where I^{p}_{t} is the imbalance of the DSO p at period t as defined in (3.3c). It is important to note that I^{p}_{t} is computed only considering the assets of DSO p. Node balance equations are also affected by this Multi-DSO setting. Let Ω^{p}_{i} be the set of nodes belonging to the DSO p, and Λ_p be the set of interconnecting nodes. Then, the node balance is given by

$$\sum_{j \in \Omega^{p}_{i}} (G_{i,j} v_{j,t} - B_{i,j} \theta_{j,t}) + \sum_{j \in \Lambda^{p}} (G_{i,j} v_{j,t} - B_{i,j} \theta_{j,t}) = p_{i,t} \qquad \forall i \in \Omega^{p}_{i}, \forall p \in \Omega_p, \forall t \in \Omega_t \quad \text{(3.3d)}$$

$$-\sum_{j \in \Omega^{p}_{i}} (B_{i,j} v_{j,t} + G_{i,j} \theta_{j,t}) - \sum_{j \in \Lambda^{p}} (B_{i,j} v_{j,t} + G_{i,j} \theta_{j,t}) = q_{i,t} \qquad \forall i \in \Omega^{p}_{i}, \forall p \in \Omega_p, \forall t \in \Omega_t \quad \text{(3.3e)}$$

The Multi-DSO LEM clearing problem can be formulated in compact form. Let $\boldsymbol{x}^{p}$ be the vector of the variables of the DSO p, $\tilde{\boldsymbol{v}}$ be the vector of the complicating variables, i.e. variables that belongs to different DSOs, $\boldsymbol{\lambda}$ be the vector of all Lagrange multipliers at complicating constraints. The Multi-DSO LEM is rewritten in (3.3i) considering the cost function $f^{p}(\boldsymbol{x}^{p}, \tilde{\boldsymbol{v}})$, subject to the DSO constraints $h(\boldsymbol{x}^{p}) = 0$, $g(\boldsymbol{x}^{p} \leq 0)$ and the complicating constraints $\tilde{m}(\boldsymbol{x}^{\mathcal{A}}, \boldsymbol{x}^{\mathcal{B}}, \ldots, \boldsymbol{x}^{|\Omega_p|}, \tilde{\boldsymbol{v}}) = 0$.

$$\min \sum_{p \in \Omega_p} f^p(\boldsymbol{x}^p, \tilde{\boldsymbol{v}}) \tag{3.3f}$$

Subject to

$$h(\boldsymbol{x}^p) = 0 \tag{3.3g}$$

$$g(\boldsymbol{x}^p) \leq 0 \tag{3.3h}$$

$$\tilde{m}(\boldsymbol{x}^{\mathcal{A}}, \boldsymbol{x}^{\mathcal{B}}, \ldots, \boldsymbol{x}^{|\Omega_p|}, \tilde{\boldsymbol{v}}) = 0 \; \boldsymbol{:} \boldsymbol{\lambda} \tag{3.3i}$$

3.4 Solution Approach to Inter-DSO Local Energy Markets

In this section, the solution approach to the Multi-DSO LEM clearing problem based on the ADMM is described. The decentralized coordination mechanism among the areas is activated when there is a request for flexibility. The market-clearing problem is iteratively solved where information is exchanged between the LMO and the involved DSOs. In this setting, information exchanges are reduced, attaining the same centralized solution sharing a reduced quantity of information.

3.4.1 Coordination Scheme

The coordination scheme is presented in Fig. 3.5, where the LMO acts as coordinator of the LEM clearing solution with the information provided by DSOs. Imbalance information is exchanged among DSOs to fulfil the flexibility requests without involving the upstream assets. Additionally, economic signals are also exchanged representing their offers to satisfy these flexibility requests.

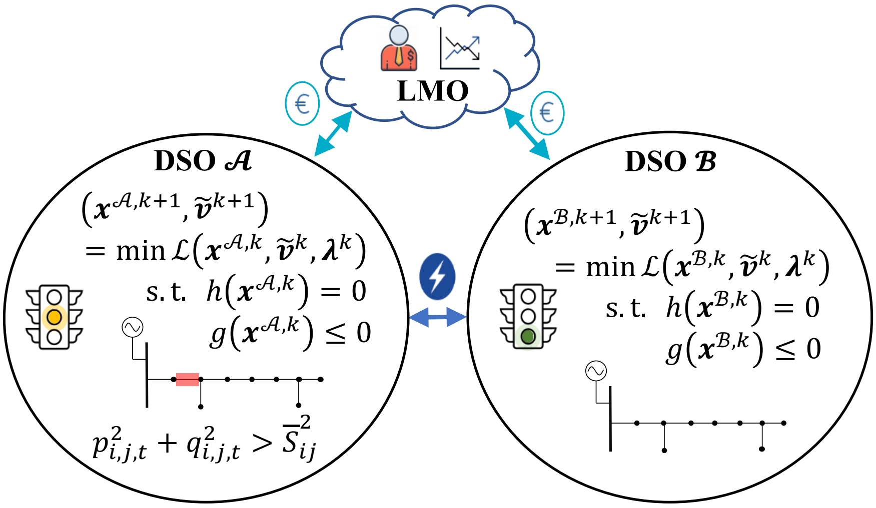
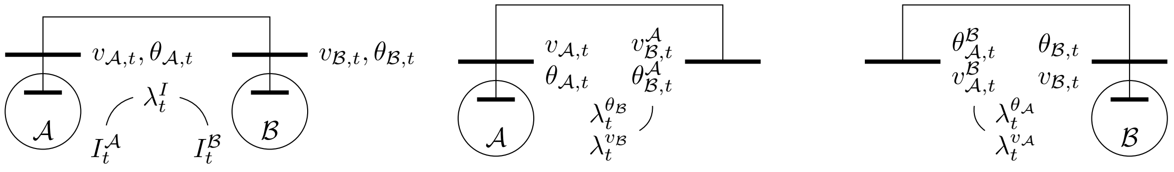


Figure 3.5: Coordination procedure among the agents in Multi-DSO LEM settings. Dark and light blue arrows represents flexibility requests and economical signals, respectively.

The objective of this approach is to find the overall optimal solution in a decentralized and coordinated manner. To achieve this goal, the coupling constraints (3.3b) and (3.3e) are coordinated. Information exchanges include the primal and dual variables at the interconnecting nodes ($v_{i,t}, \lambda_t^v, \theta_{i,t}, \lambda_t^\theta$) and flexibility products (I_t^p, λ_t^I). The first and second magnitudes are widely used in the literature as a method for coordination [16], [71]. Furthermore, this Multi-DSO LEM algorithm also considers area imbalances in the coordination procedure, using the Lagrange multiplier λ_t^I as the marginal cost for flexibility provision.

3.4.1.1 Coordination through the voltage magnitude and phase angle at interconnection

For readability, coordination is explained considering a LEM with two interconnected DSOs as shown in Fig. 3.6a. In this case, coordination is achieved by duplicating the DSO's node voltage magnitude and voltage phase angle $v_{\mathcal{A},t} = v_{\mathcal{A},t}^{\mathcal{B}}$, $\theta_{\mathcal{A},t} = \theta_{\mathcal{A},t}^{\mathcal{B}}$ and $v_{\mathcal{B},t} = v_{\mathcal{B},t}^{\mathcal{B}}$, $\theta_{\mathcal{B},t} = \theta_{\mathcal{B},t}^{\mathcal{A}}$, at the interconnection as depicted in figures 3.6b and 3.6c.



(a) **(b)** **(c)**

Figure 3.6: Representation of the coordination procedure between two different areas connected by a tie-line.

Those internal variables replace the complicating variables $v_{j,t}$, $\theta_{j,t}$ in (3.3e) for all $j \in \Lambda_p$, making the problem separable. Duplicated variables are coordinated using (3.4a) and (3.4b), ensuring that the node voltage obtained in DSO $\mathcal{B}$ in iteration k, $v_{\mathcal{B},t}^k$, $\theta_{\mathcal{B},t}^k$, is equal to the duplicated variables $v_{\mathcal{B},t}^{\mathcal{A}}$, $\theta_{\mathcal{B},t}^{\mathcal{A}}$ of DSO $\mathcal{A}$.

$$v_{\mathcal{B},t}^{\mathcal{A}} - v_{\mathcal{B},t}^k = 0 \ : \lambda_t^{v_{\mathcal{B}},k} \tag{3.4a}$$

$$\theta_{\mathcal{B},t}^{\mathcal{A}} - \theta_{\mathcal{B},t}^k = 0 \ : \lambda_t^{\theta_{\mathcal{B}},k} \tag{3.4b}$$

3.4.1.2 Coordination through the overall balance of the grid

The overall balance for all DSOs must be met. Following Fig 3.6, the sum of the imbalances from DSO $\mathcal{A}$ and $\mathcal{B}$ must be equal to zero,

$$I_t^{\mathcal{A}} + I_t^{\mathcal{B},k} = 0 \qquad \forall t \in \Omega_t \ : \lambda_t^{I,k} \tag{3.4c}$$

Through iterative exchange of information associated with (3.4a) – (3.4c), the centralized solution of the problem described by (3.3a) can be obtained without compromising the information privacy of the different DSOs and without solving a large economic dispatch.

3.4.2 DSO sub-problem

In this section, the DSO sub-problem is defined. At each iteration k, DSO information is shared with the LMO to coordinate the market-clearing solution. DSO $\mathcal{A}$ solves its sub-problem assuming known complicating variables of DSO $\mathcal{B}$, and complicating constraints (3.4a) – (3.4c) are relaxed and included in the objective function. For privacy reasons, the

DSO imbalance $I_t^{\mathcal{B},k}$ is computed inside the jurisdiction of DSO $\mathcal{B}$ and then, is shared.

$$\tilde{m}_t^{v,k,\mathcal{A}} = v_{\mathcal{B},t}^{\mathcal{A}} - v_{\mathcal{B},t}^{k} \qquad \forall t \in \Omega_t \tag{3.4d}$$

$$\tilde{m}_t^{\theta,k,\mathcal{A}} = \theta_{\mathcal{B},t}^{\mathcal{A}} - \theta_{\mathcal{B},t}^{k} \qquad \forall t \in \Omega_t \tag{3.4e}$$

$$\tilde{m}_t^{I,k,\mathcal{A}} = I_t^{\mathcal{A}} + I_t^{\mathcal{B},k} \qquad \forall t \in \Omega_t \tag{3.4f}$$

The DSO problem is described by (3.4g). Its objective function is composed of three terms. The first term involves the sum of flexible agent costs of the DSO $\mathcal{A}$. The second term relaxes the complicating constraints $\tilde{m}_t^{v,k,\mathcal{A}}$, $\tilde{m}_t^{\theta,\mathcal{A},k}$, $\tilde{m}_t^{I,\mathcal{A},k}$ multiplied by their associated dual variables $\lambda_t^{v,k}$, $\lambda_t^{\theta,k}$, $\lambda_t^{I,k}$. Lastly, a quadratic term of the sum of coupling constraints multiplied by the penalty factor γ is included. The last term is specific to the ADMM algorithm, enhancing the speed of the convergence to the optimal solution [65]. This DSO problem is subject to restrictions (3.1a) – (3.1o) for all assets connected to the network of the DSO.

$$\begin{aligned}\min \sum_{t\in\Omega_t} & \left[\sum_{f\in\Omega_f^{\mathcal{A}}} c_{f,t}^{\mathcal{A}} + \sum_{g\in\Omega_g^{\mathcal{A}}} c_{g,t}^{\mathcal{A}} + \sum_{s\in\Omega_s^{\mathcal{A}}} c_{s,t}^{\mathcal{A}} \right] + \sum_{t\in\Omega_t} \left[\lambda_t^{v,k} \tilde{m}_t^{v,\mathcal{A},k} + \lambda_t^{\theta,k} \tilde{m}_t^{\theta,\mathcal{A},k} + \lambda_t^{I,k} \tilde{m}_t^{I,\mathcal{A},k} \right] \\ & + \frac{\gamma}{2} \left[\sum_{t\in\Omega_t} \left(\tilde{m}_t^{I,\mathcal{A},k} \right)^2 + \sum_{t\in\Omega_t} \left(\tilde{m}_t^{v,\mathcal{A},k} \right)^2 + \sum_{t\in\Omega_t} \left(\tilde{m}_t^{\theta,\mathcal{A},k} \right)^2 \right] \end{aligned} \tag{3.4g}$$

Subject to

$$\begin{array}{ll} (3.1a), (3.1b) & \forall f \in \Omega_f^{\mathcal{A}} \\ (3.1c), (3.1d) & \forall g \in \Omega_g^{\mathcal{A}} \\ (3.1e) - (3.1h) & \forall s \in \Omega_s^{\mathcal{A}} \\ (3.1k) - (3.1o) & \forall (i,j) \in \Omega_i^{\mathcal{A}} \end{array}$$

3.4.3 Lagrange's multipliers update

The LMO updates the Lagrange multipliers once all DSOs have exchanged the information resulting from the solution of (3.4g).

$$\lambda_t^{v,k+1} = \lambda_t^{v,k} + \gamma \tilde{m}_t^{v,k} \qquad \forall t \in \Omega_t \tag{3.4h}$$

$$\lambda_t^{\theta,k+1} = \lambda_t^{\theta,k} + \gamma \tilde{m}_t^{\theta,k} \qquad \forall t \in \Omega_t \tag{3.4i}$$

$$\lambda_t^{I,k+1} = \lambda_t^{I,k} + \gamma \tilde{m}_t^{I,k} \qquad \forall t \in \Omega_t \tag{3.4j}$$

3.4.4 Convergence criterion: Primal and Dual Residuals

Primal residual $\left\| r^k \right\|_2$ is defined as $\left\| \tilde{m}(\boldsymbol{x}^{\mathcal{A}}, \boldsymbol{x}^{\mathcal{B}}, \dots, \boldsymbol{x}^{|\Omega_p|}, \tilde{\boldsymbol{v}}) \right\|_2$ while dual residual, $\left\| s^k \right\|_2$, is defined as $\gamma \left\| \tilde{\boldsymbol{v}}^{k+1} - \tilde{\boldsymbol{v}}^k \right\|_2$. In our case, they can be written as

$$\left\| r^k \right\|_2 = \left[\sum_{t\in\Omega_t} \left(\tilde{m}_t^{v,k} \right)^2 + \sum_{t\in\Omega_t} \left(\tilde{m}_t^{\theta,k} \right)^2 + \sum_{t\in\Omega_t} \left(\tilde{m}_t^{I,k} \right)^2 \right]^{1/2} \tag{3.4k}$$

$$\begin{aligned}\left\|s^k\right\|_2 = \gamma \Bigg[&\sum_{t\in\Omega_t}\left(v_{\mathcal{B},t}^{\mathcal{A},k+1} - v_{\mathcal{B},t}^{\mathcal{A},k}\right)^2 + \sum_{t\in\Omega_t}\left(v_{\mathcal{A},t}^{\mathcal{B},k+1} - v_{\mathcal{A},t}^{\mathcal{B},k}\right)^2 \\ &+ \sum_{t\in\Omega_t}\left(\theta_{\mathcal{B},t}^{\mathcal{A},k+1} - \theta_{\mathcal{B},t}^{\mathcal{A},k}\right)^2 + \sum_{t\in\Omega_t}\left(\theta_{\mathcal{A},t}^{\mathcal{B},k+1} - \theta_{\mathcal{A},t}^{\mathcal{B},k}\right)^2 \\ &+ \sum_{t\in\Omega_t}\left(I_{t}^{\mathcal{A},k+1} - I_{t}^{\mathcal{A},k}\right)^2 + \sum_{t\in\Omega_t}\left(I_{t}^{\mathcal{B},k+1} - I_{t}^{\mathcal{B},k}\right)^2 \Bigg]^{1/2}\end{aligned} \tag{3.4l}$$

The convergence criterion is selected as $\max\left\{\left\|r^k\right\|_2, \left\|s^k\right\|_2\right\} \leq \varepsilon$. For real case applications, this convergence criterion is set to $\varepsilon = 10^{-3}$ [72]. This accuracy is sufficient to obtain satisfactory solutions without incurring a large computational cost.

3.4.5 Solution algorithm for Multi-DSO LEM

The proposed solution approach is based on the ADMM decomposition algorithm [65]. Using this procedure, the Multi-DSO optimization problem presented in (3.4g) is solved in a coordinated and decentralized manner. This process allows LMOs to solve the market while having only partial access to the information. Thus, the principle of privacy among the agents is maintained [62].

The convergence is checked by calculating norm-2 of primal $\left\|r^k\right\|_2$ and dual residual $\left\|s^k\right\|_2$. Complicating constraints are relaxed and the objective function $f^p(\boldsymbol{x}^p, \tilde{\boldsymbol{v}})$ is replaced by its Lagrangian function $\mathcal{L}(\boldsymbol{x}^{p,k}, \tilde{\boldsymbol{v}}^k, \boldsymbol{\lambda}^k)$ at iteration k defined in (3.4g). The ADMM procedure for the LEM depicted in (3.3i) is presented in algorithm 1.

Algorithm 1 ADMM Multi-DSO LEM clearing procedure.

```
$\tilde{\boldsymbol{v}}^k, \boldsymbol{\lambda}^k \leftarrow 0$
procedure ADMM Loop
    while $\max\left\{\left\|r^k\right\|_2, \left\|s^k\right\|_2\right\} \geq \varepsilon$ do
        for $p \in \Omega_p$ do
            $\min\{\mathcal{L}(\boldsymbol{x}^{p,k}, \tilde{\boldsymbol{v}}^k, \boldsymbol{\lambda}^k) : h(\boldsymbol{x}^p) = 0, g(\boldsymbol{x}^p) \leq 0\}$.
            update $\tilde{\boldsymbol{v}}^k$.
            distribute $\tilde{\boldsymbol{v}}^k$ and $\boldsymbol{x}^{p,k}$ among DSOs.
        end for
        update $\boldsymbol{\lambda}^{k+1} = \boldsymbol{\lambda}^k + \gamma\tilde{m}(\boldsymbol{x}^{\mathcal{A}}, \boldsymbol{x}^{\mathcal{B}}, \ldots, \boldsymbol{x}^{|\Omega_p|}, \tilde{\boldsymbol{v}})$
        compute $\left\|r^k\right\|_2, \left\|s^k\right\|_2$
    end while
end procedure
```

This method is capable of solving the Multi-DSO LEM market-clearing problem among DSOs in a limited amount of iterations. However, in order to do so for a real bussiness implementation some other aspects must be considered. First, the communication overhead between DSOs and the LMO must be minimized. In this sense, this methodology offers a great advantage since the only information that must be exchanged are the dual variables associated with the coupling constraints. Nevertheless, especial care must be taken in order to set up the algorithm properly to minimise the number of iterations of the ADMM. Second, the robustness and the resiliance of the communication infraestructure must be ensured. In this sense, the communication between DSOs and LMO must be encrypted and the communication infrastructure must be robust enough to ensure the correct exchange of information. Thus, in a realistic implementation, all DSOs must be equipped with a compatible and protected data and communication infraestructure that enable a fast, secure and reliable exchange of information with the LMO. Lastly, this methodology must be integrated in the current infraestructure of the DSOs in order to be implemented in a real scenario. In this sense, the ADMM algorithm must be integrated in the current DSO's control centers using an minimal update of their computing capabilities, so the DSO sub-problem can be executed following an edge-computing approach. The following section presents a case study to illustrate the proposed approach, assuming that the aforementioned aspects are fulfilled.

3.5 Decentralised Case Study for Local Energy Markets

This section presents a case study to illustrate the proposed approach. The case study builds on three IEEE 123 bus test systems interconnected by tie-lines, as shown in Fig. 3.7. Each network is managed by an independent DSO that only exchanges the information of the interconnecting nodes and internal imbalances with the LMO. The LMO iteratively sends economic signals to each DSO for market coordination.

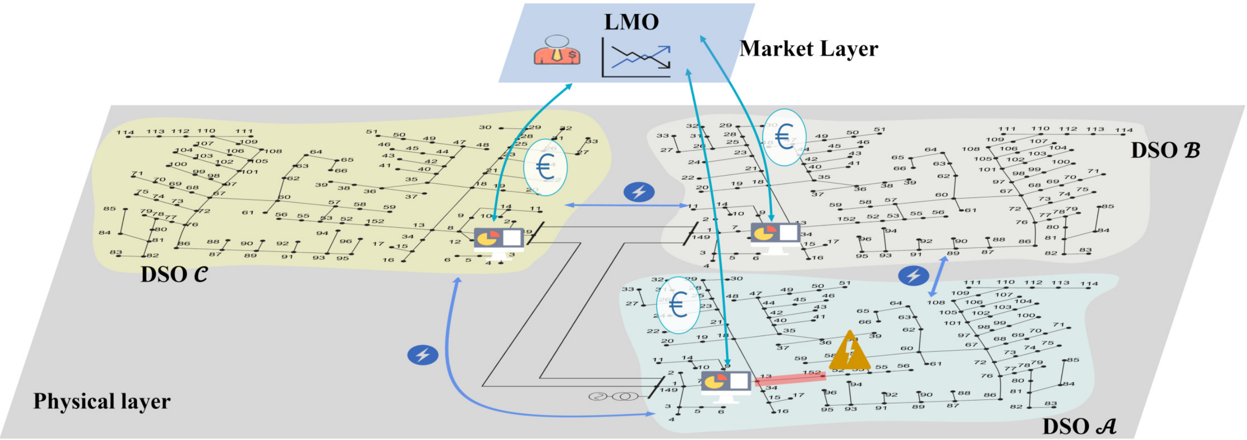


Figure 3.7: Illustration of the use case based on the IEEE 123 radial distribution system.

The total static load of the system is 8 MW shared among 229 Static Loads (SLs). Load profiles were synthetically generated considering three different types of end-users, namely residential, residential with PV and industrial clients. Regarding flexible assets, there are a total of 26 FLs, 42 FGs and 21 BESSs.

3.5.1 Operation limits of assets

We assume FLs can offer up to 20% of their average demand [73]. Therefore, upper and lower demand limits are given by $0.8P_{f,t}^{sch} \leq p_{f,t}^{am} \leq 1.2P_{f,t}^{sch}$. For FGs, only PV systems are considered for this case study. The upper bound is set by the scheduled power output $P_{g,t}^{sch}$, while the lower limit is 0 resulting in $0 \leq p_{g,t}^{am} \leq P_{g,t}^{sch}$. Additionally, charging and discharging efficiencies η_s^C, η_s^D are assumed to be constant and equal to 90% for all BESSs. For an effective provision of flexibility, $SOC0_s$ is set to 50%. Lastly, bounds for BESS s are set to $\underline{SOC}_s = 5\%$ and $\overline{SOC}_s = 95\%$.

3.5.2 Offers for flexibility products

Offers for flexibility products are randomly generated following Spanish balancing market average prices (5.261 €/MWh for upward products and 13.192 €/MWh for downward products). Prices for FGs are set considering that $S^d_{g,t} < S_t$, while for FLs and BESSs, $S^u_{f,t} < S_t$, $S^u_{s,t} < S_t$ and $S^d_{f,t} > S_t$, $S^d_{s,t} > S_t$. The upward flexibility product prices for FLs and BESSs are in the interval $[S_t - 5.261, S_t)$ €/MWh, while the downward flexibility product prices are in the interval $(S_t, S_t + 13.192]$ €/MWh. The downward flexibility product prices for FGs are in the interval $[S_t - 5.261, S_t)$ €/MWh.

3.5.3 Flexibility Trading at Multi-DSO LEMs: Centralized approach

To illustrate the trading of flexibility in Multi-DSO LEMs, we first start with the centralized approach. Given the input data described above, congestion appears at the distribution line 13 – 152 belonging to DSO $\mathcal{A}$. The thermal limit for this line is 1,750 kVA which is exceeded by the end of the day (blue line) as shown in Fig. 3.8. We assume that the DSO requests a volume of flexibility equal to the shaded area of the figure. Then, a LEM is organized with a time period granularity of 15 minutes for the operation horizon.

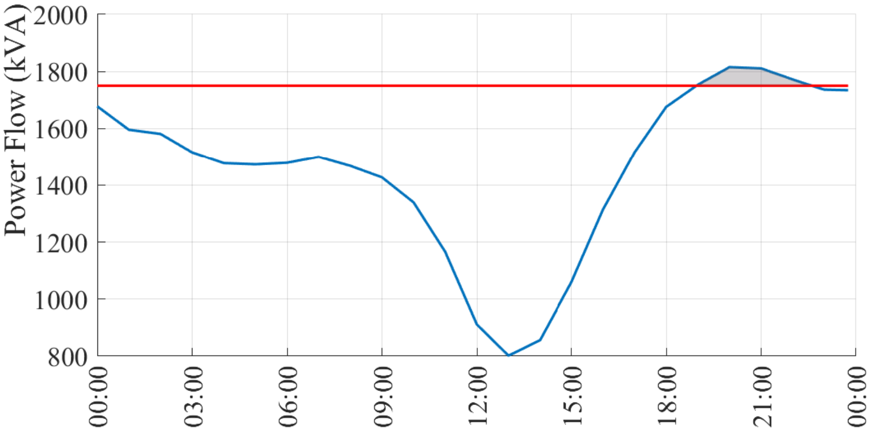


Figure 3.8: Power flow in line 13-152 of the DSO $\mathcal{A}$ before LEM clearing (blue line), thermal limit (red line) and flexibility needs (shaded area).

We first consider a solution to the LEM where only the agents of the DSO $\mathcal{A}$ (where the congestion is located) are involved in the flexibility provision and no DSO power exchange is allowed. The solution for this market is given in Fig. 3.9a, where the power flow through the previously congested line is shown (blue line) along with the traded flexibility (yellow bars). Not only is the power flow modified in the periods with congestion, but also in the previous time slots. This is due to the preparatory operations carried out to alleviate the congestion at the minimum cost considering the whole operation horizon.

Nevertheless, this cost can be further reduced if the rest of the interconnected DSOs are considered in the provision of flexibility through an Multi-DSO LEM. The market solution is modified as shown in Fig. 3.9b. In this case, the costs of flexibility procurement are

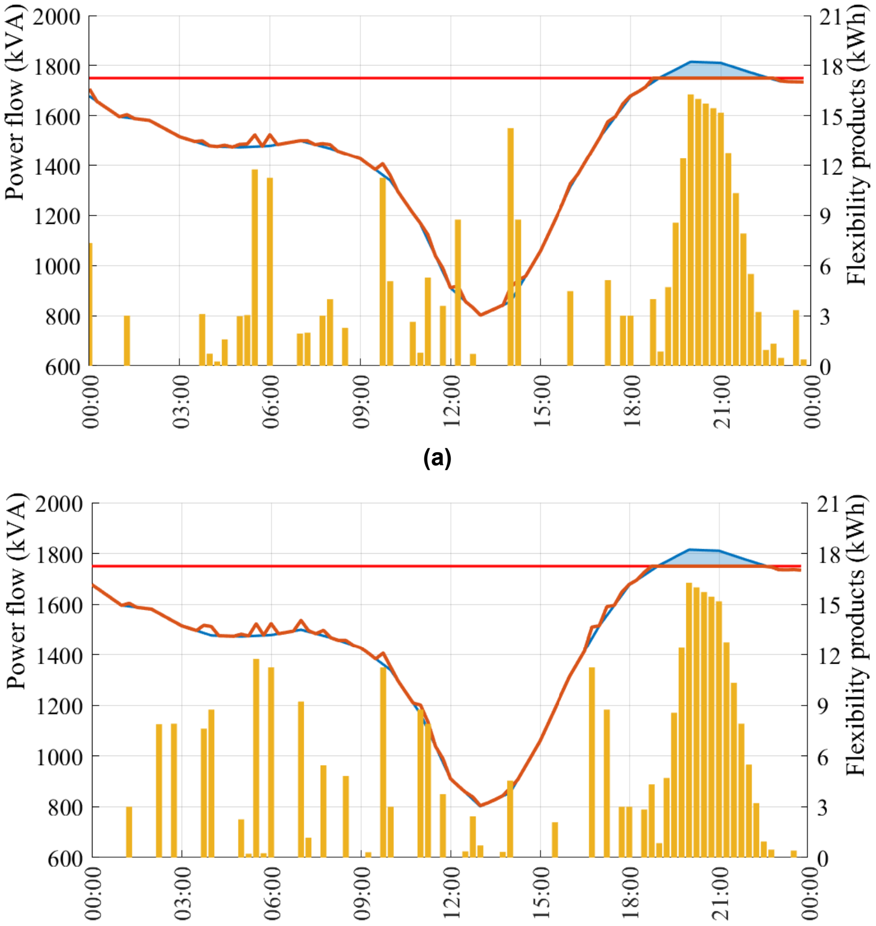


Figure 3.9: Power flow in line 13-152 belonging to DSO $\mathcal{A}$ after LEM clearing (blue line), thermal limit (red line) and flexibility products (bars) exchanged in the market. The solution considering only the assets from DSO $\mathcal{A}$ is presented in (a) while in (b) shows the solution considering all areas.

reduced. The cost savings are due to the participation of more competitive assets from the neighbouring DSOs.

Fig. 3.10 shows the distribution of the per unit total costs, considering the costs for DSO $\mathcal{A}$ as the basis. Most of the traded flexibility is concentrated in the periods with congestion (19:00 to 23:00), whereas the flexibility trading in other periods is due to preparatory operations. Since, in this case study, BESSs are the most competitive agents for flexibility products, they are responsible for the major part of the trading (yellow bars in Fig. 3.10).

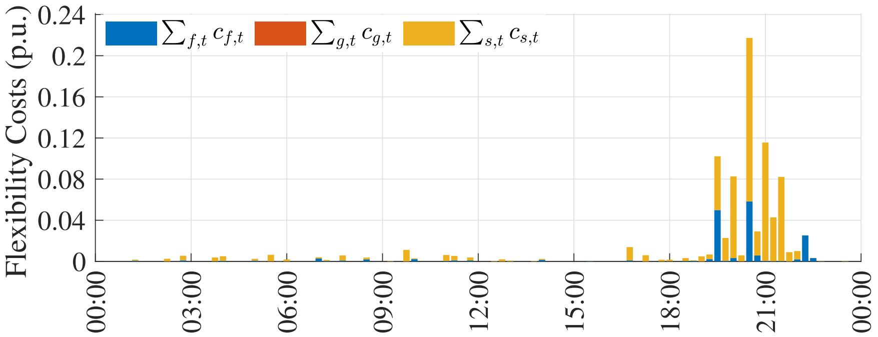
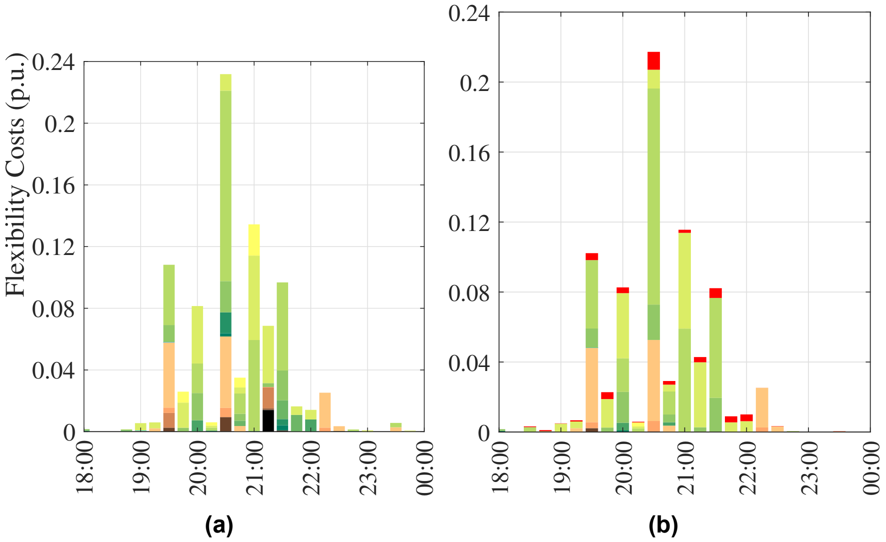


Figure 3.10: Distribution of the costs for the periods with market trading. Blue, orange and yellow lines represents the costs of the flexibility products of FLs, FGs and BESSs, respectively.

The flexibility costs allocated through the periods from 18:00 to 00:00 are shown in Fig. 3.11. Figure 3.11a displays the case where only the assets of the DSO $\mathcal{A}$ are included, while Fig. 3.11b presents the flexibility cost distribution when assets from all DSOs participate in the market. The total volume of the traded flexibility products is the same in both cases. In the second case, 11.39% of the traded flexibility is imported from DSOs $\mathcal{B}$ and $\mathcal{C}$, resulting in a cost reduction of 16.95%.



(a) **(b)**

Figure 3.11: Distribution of the costs for the periods with congestion considering (a) only flexibility assets from DSO $\mathcal{A}$ and (b) flexibility assets from all areas. Blue, orange, green and red represent the FLs, FGs, BESSs, and DSO $\mathcal{B}$ and $\mathcal{C}$ assets, respectively, included in case (b).

Finally, Fig 3.12 shows the Lagrange multiplier (λ_t^I) associated with the balance constraint (3.4c). Dual variable λ_t^I is $(S_t - S_t^u)$ of the marginal asset if the demand for flexibility is in the upward direction, or with $(S_t^d - S_t)$ of the marginal asset if the demand for flexibility is in the downward direction.

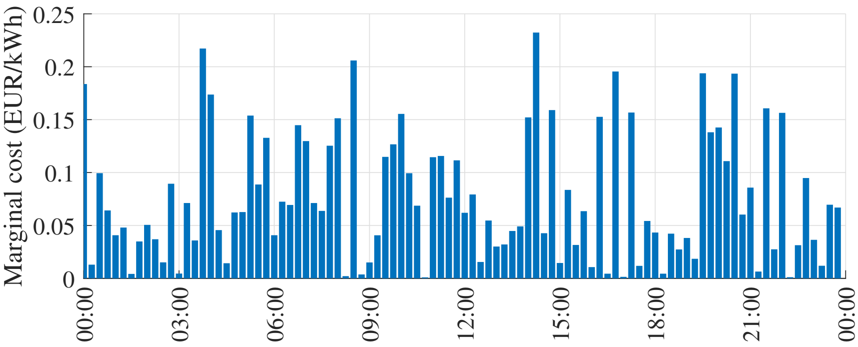


Figure 3.12: Representation of the marginal cost associated with the overall imbalance of the grid λ_t^I.

3.5.4 Flexibility Trading at Multi-DSO LEMs: Decentralized and Coordinated approach

The benefits of considering the interaction among the neighbouring DSOs are presented in subsection 4.3., where the total costs for solving the congestion in DSO $\mathcal{A}$ are reduced when assets from areas $\mathcal{B}$ and $\mathcal{C}$ are considered. Nevertheless, although profitable, this approach may raise privacy concerns. The proposed ADMM approach addresses this issue.

ADMM algorithm, as explained in section 3, is implemented sharing variables v_t^k, $\lambda_t^{v,k}$, θ_t^k, $\lambda_t^{\theta,k}$, $I_t^{p,k}$, $\lambda_t^{I,k}$ among DSOs and LMO, at each iteration k. The solution using this approach is found to be the same as that obtained in the centralized approach. Considering a penalty factor of $\gamma = 10^{-5}$ and $\varepsilon = 10^{-3}$, convergence is reached after 20 iterations. Moreover, both primal and dual residuals tend to decrease, as presented in Fig. 3.13. The presented results obtained with the ADMM algorithm are compared to the Lagrangian Relaxation (LR) algorithm in Fig. 3.13 [53]. Convergence is reached after 73 iterations of the LR algorithm. Additionally, both primal and dual residual curves are steeper for the ADMM algorithm. This feature enables this method to not only to reach convergence before LR, but also to obtain an order of magnitude higher level of precision after 100 iterations.

Figure 3.14 presents the evolution of the marginal costs associated with the overall imbalance restriction for each time period t. For simplicity, only 12 Lagrange multipliers are shown.

The evolution of the dual variable $\lambda_t^{v,k}$ associated with the voltage magnitude $v_{3149,t}$ is depicted in Fig. 3.15. The values of the multipliers tends to zero.

Evolution of the total costs and imbalance among DSOs is shown in Fig. 3.16, attaining the centralized solution. These iterations represent the interactions among DSOs and LMO prior to reaching convergence. During the initial iterations, DSOs $\mathcal{B}$ and $\mathcal{C}$ respond

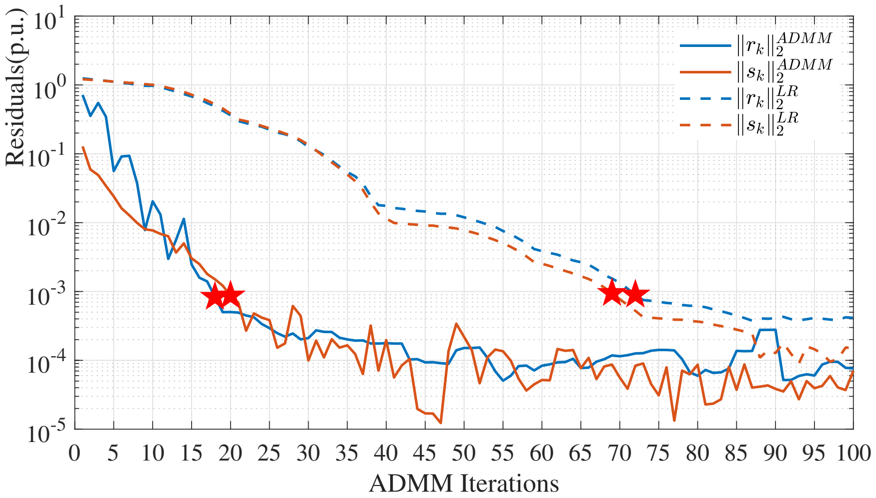


Figure 3.13: Evolution of the primal (blue) and dual (orange) residuals for the case study of the LEM using ADMM (solid line) and LR algorithm (dashed line).

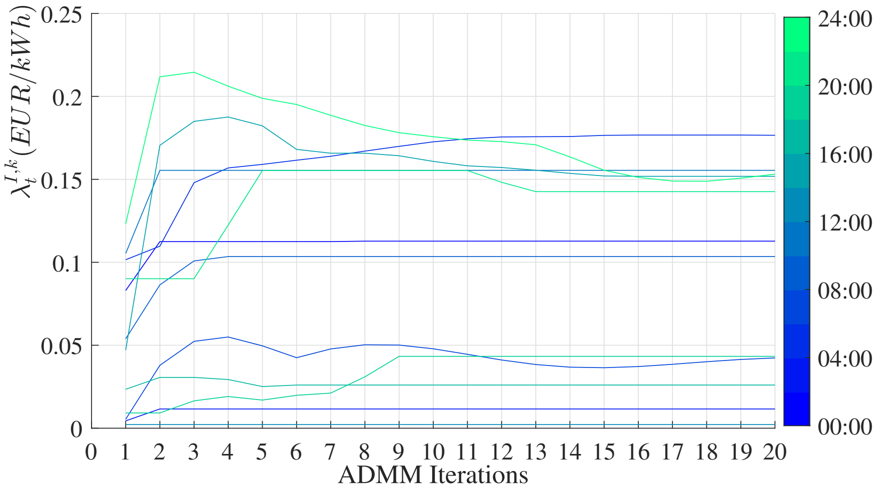


Figure 3.14: Evolution of the dual variable λ_t^I in the case study during the iterations of the ADMM algorithm.

to the LMO market signals with upward imbalance. Then, after some iterations, DSO $\mathcal{A}$ trades downward flexibility. Finally, the market is cleared, and complicating constraint (3.4c) is satisfied when the upward and downward imbalances reach convergence.

Comparing the centralized and decentralized solutions in terms of their hourly costs and the dual variable $\lambda_t^{I,k}$, the maximum differences are $1.17 \cdot 10^{-4}$ and $1.42 \cdot 10^{-4}$, respectively.

3.5.5 Impact of the uncertainty in the Multi-DSO LEMs clearing

In this section the impacts of the uncertainty of the forecast errors in the local market-clearing solution is analysed. The number of scenarios included in the formulation is 125 for random parameters $S_{e,t}$, $P^{sch}_{e,f,t}$, and $P^{sch}_{e,g,t}$, after a scenario reduction technique is used.

The results of the deterministic and the stochastic simulations are compared in Fig. 3.17, where the deterministic costs are compared with the expected costs of the stochastic formulation. The expected costs in the stochastic version are a 6% greater than those

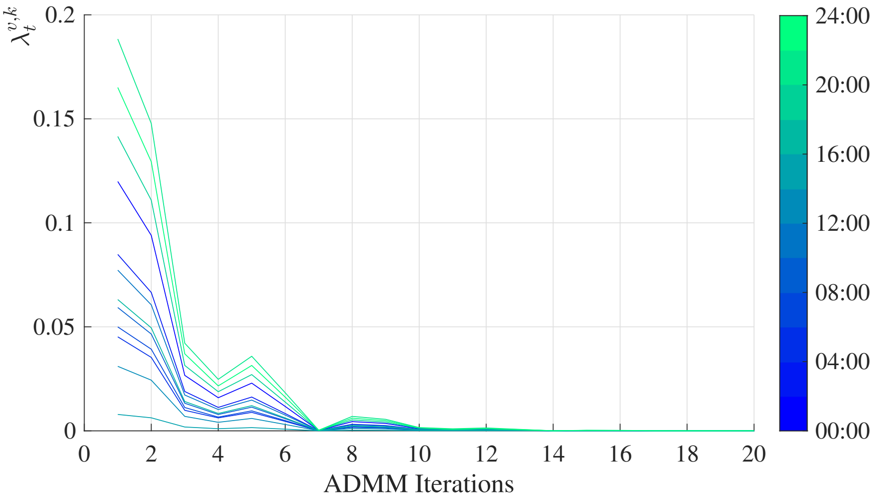


Figure 3.15: Evolution of the dual variable $\lambda_t^{v,k}$ associated with voltage magnitude $v_{3149,t}$ in the case study during the iterations of the ADMM algorithm.

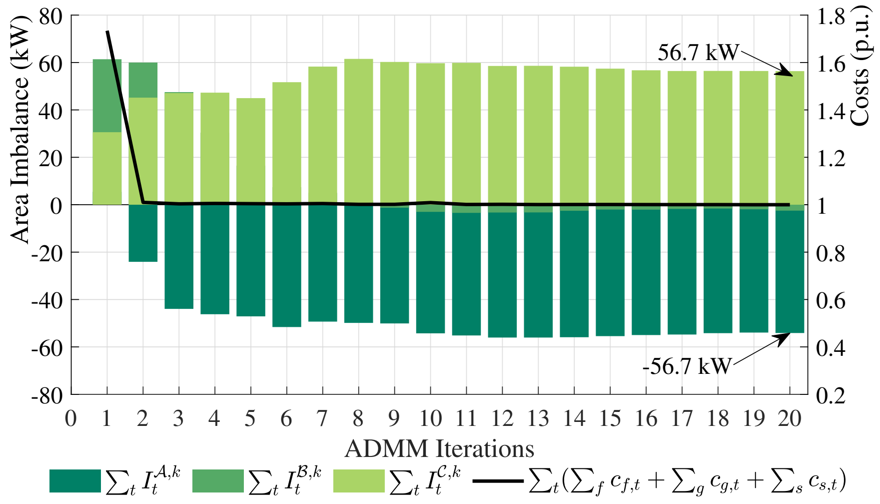


Figure 3.16: Evolution of the total costs (green line) and the imbalance variables in the case study during the iterations of the ADMM algorithm (bars).

obtained in the deterministic version. The flexibility products quantity also increases to 4.79% and it also increases flexibility mean price also to 2.51%. Nevertheless, these variables show a similar temporal distribution as Fig. 3.17 shows.

The stochastic version of the proposed formulation return values for the variables in each scenario. Thus, the probability density distributions of the flexibility magnitudes can be rebuilt. Figure 3.18 represents the probability density functions for the costs, products quantity and prices of the market for different time periods. As figure shows, there are some time periods where it is expected that the costs, the products quantity and the price are close to zero, i.e., when the grid is not congested. However, the time periods around 20:00, shows a displaced distribution function, which indicates that it is expected that flexibility is traded during these periods to solve the congestion.

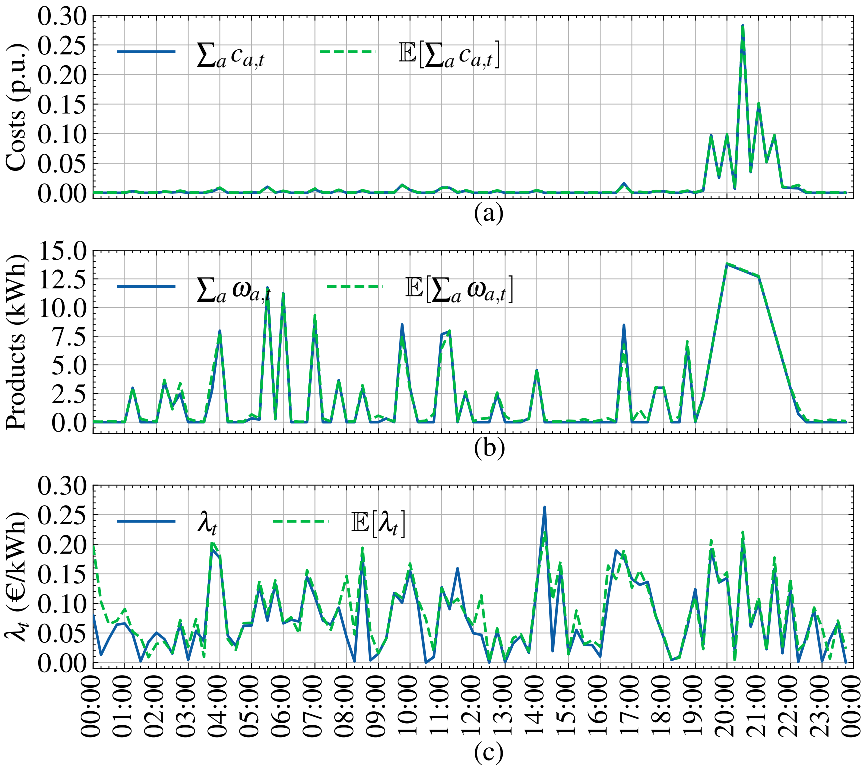


Figure 3.17: Comparison of the deterministic solution (blue) versus stochastic solution (green), regarding the market costs (a), the quantity of the products (b) and the marginal price of the flexibility (c).

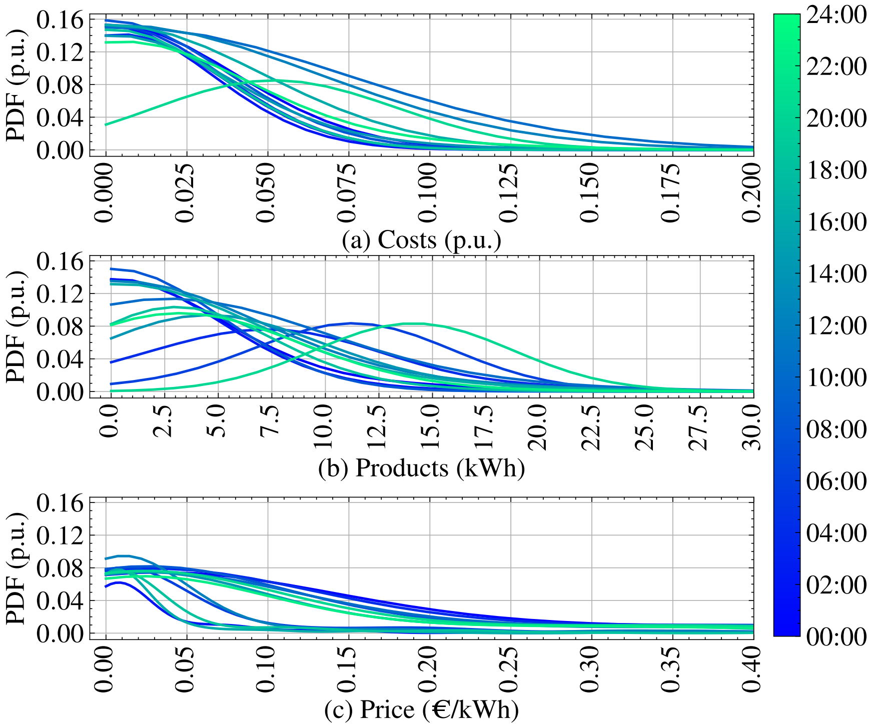


Figure 3.18: Probability density functions of the costs of the market solution (a), the quantity of the products (b) and the marginal price of the flexibility (c) for different time periods.

3.5.6 Computational and privacy issues

The decentralized Multi-DSO LEM clearing problem can be cast as a quadratic optimization problem with a set of linear constraints. This problem is solved using CPLEX in the GAMS software [74]. All simulations are performed on a personal computer with a quad-core Intel i7–4720 HQ 2.60 GHz with 16 GB of RAM. It takes approximately one second per iteration to solve the market clearing, using the ADMM algorithm, for a total time of 21.397 seconds. The total time spent using LR for the market clearing was 37.954 seconds. The stochastic version of the problem spent around 29.245 seconds per scenario to solve the market clearing. Thus, although the time spent per iteration is lower for LR, the high number of iterations needed to obtain the same level of precision makes this algorithm less favourable. The results for both algorithms are compared in Table 3.2.

	ADMM	**LR**	**SCH**
Number of its.	20	73	25
Seconds per it.	1.0699	0.5199	1.1698
Computational time	21.397	37.954	3655.63
Model type	QCP	LP	LP
Solver	CPLEX	CPLEX	CPLEX
Precision 100 its.	$\sim 10^{-4}$	$\sim 10^{-3}$	$\sim 10^{-4}$

Table 3.2: Comparison of the performance of the ADMM, LR and stochastic algorithms for solving the decentralized version of the LEM.

The performed simulations proved that the proposed market-clearing procedure can be solved within the market time frame. In the case of an increase in the number of participating DSOs or an increase in the complexity of the flexible assets, a parallelized version of the ADMM can be used [75] to streamline the algorithm. In the decentralized setting, the number of equations and variables are 231,651 and 216,963, respectively. Only 16 variables are exchanged among DSOs and LMO, accounting for 0.00691% of all problem variables. Privacy is preserved because the shared information does not contain any nominative data of the participants.

3.6 Multi-Area LFMs: Capacity and Energy Products

A coordinated and decentralised metodology for energy product-trading has been proposed for solving congestions and imbalances in an Multi-DSO LEMs hitherto. The previous methodology could solve the market-clearing problem using ADMM-based algorithms while preserving the privacy of the information associated with each DSO. The optimal dual variables associated with the node voltage magnitude and phase angle at the tie-lines and overall imbalance equation, were the signals that properly drive the coordination mechanism to achieve system-wide efficiency. This enables the methodology to achieve the same electrical and economic dispatch as the one obtained when DSOs are centrally operated, at the cost of strong and iterative coordination among the involved DSOs. The previous methodology was able to demonstrate their effectiveness achieving savings of 16.95 % compared to that of the non-coordinated solutions, requiring a reduced number of interactions to fully achieve convergence. Besides, an stochastic version of the problem showed less than 6% of deviation from the deterministic simulations, which demonstrate the robustness of the proposed approach.

Notwithstanding the foregoing and although the previous methodology was able to solve the market-clearing problem, the influence of the capacity products was not considered in the decentralised protocol. As it was demonstrated in our conference paper [23] capacity products are a straightforward tool to hold back the capabilities of the agents and increase the market liquidity. In addition to this, performing an scalability analysis is of interest to determine the feasibility of the Lagrangian based methodologies in larger systems, with plenty of distribution systems and actors included in the optimisation. To respond this concerns, a conference paper was presented in the EPEC 2022 [25]. In this paper a protocol based on the ADMM is proposed to solve the multi-area LFM problem in a decentralised setting considering the capacity products. The protocol is designed to address imbalances and congestion by utilizing the capacity and balancing products of distributed energy resources, while maintaining compatibility with existing regulatory frameworks. The contributions of the paper include a novel multi-area LFM platform that integrates with current market structures, a coordinated and decentralized market clearing protocol using adaptive ADMM that protects the privacy of participating agents, and a scalability analysis of the market clearing algorithm for different numbers of areas.

In this paper, a deterministic and decentralised Multi-Area LFM for congestion and imbalance mitigation was presented. The results of the simulations showed that capacity products are a straightforward tool to hold back the capabilities, and protect the power system from uncertainty, while the energy products are the ones that provide solution to operational constraints. Similarly to the energy-only model, the previous market clearing model was solved using an adaptative ADMM approach which preserves information privacy of the agents. Flexibility products quantity, overall imbalance, voltage phase angle at interconnection as well as dual variables are the signals that attain coordination in the market clearing protocol, achieving serviceable solutions for network operation. A case study based on the IEEE-34 bus system demonstrate the relevance of an adaptive ADMM algorithm for coordination, achieving better results than the standard version. Furthermore, from the scalability analysis performed, iterations are linearly related with then number of areas and the elapsed time is reasonable for local communities to operate near real time. Nevertheless, one key aspect remains to be addressed: the uncertainty in the activation of the capacity products, which will be addressed in the forthcoming sections and has been published in [26].

3.7 Activation of Capacity products: Uncertainty-aware LFMs

The ever-increasing penetration of RDERs is motivating a profound change in the operation of energy markets. With the long-term objective of becoming the first climate-neutral continent by 2050, Europe aspires to have 32% of its final energy consumption from REs by 2030 [76]. Medium and small scale DG can be pivotal in the decarbonisation of electrical energy systems. Nevertheless, those assets do not have easy access to traditional wholesale market structures. To fill this gap, LFMs promote the participation of these medium to small scale assets. At the same time, uncertainty associated to RDERs operation introduce further operational complexities. Deviations from forecast estimates, may lead to congestions and imbalances when the real time approaches [77], [78] . Traditionally, those contingencies are managed in intra-day and balancing markets, following the top-down approach. Despite that, as the adoption of the LEMs progresses [79], such local issues could be directly managed from a local perspective, without involving upstream resources and agents [46]. In this scenario, trading opportunities arise, especially when using RDERs flexibility [80].

LEMs have been object of wide discussion in the literature [8]. They serve as a tool for energy dispatch in local energy communities [81], microgrids [82], or even for creating a pool for scheduling the charging of electric vehicles [83]. Other works investigate hierarchical RDERs structures for balancing services [84] or transactive energy markets structures from a game-theoretic point of view [85]. The figure of the DSO oversees that the clearing of those LEMs dot not compromise the integrity of network elements [86]. Several market designs for RDERs have been examined in the literature. Incentive mechanisms for energy and reserve trading among areas [87] and peers [55] were proposed. Decentralised markets for energy communities [81] and microgrids [82] have been also investigated. Within this context, little attention has been paid to the provision of congestion and imbalance mitigation services among multiple DSOs. Flexibility trading among those market players is important as LFMs are an effective platform to boost the integration of RDERs while meeting the growing demand for energy of modern distribution systems

It is reasonable to assume that the provision of congestion and mitigation services needs both capacity and energy products to effectively accommodate RDERs. The integration of both products allows DSOs to hold back the flexibility of the participating agents in case of a foreseeable event, and activate it in the form of energy only when it is needed [23]. Capacity and energy products are linked through the duration of the event for secondary frequency regulation markets, where the capacity is firstly cleared and then agents are activated to respond against an energy event[88]. However, there are few works that acknowledge the importance of this link as those products are usually cleared in separated markets [89]. Nevertheless, this activation has been modelled through a hierarchical model in [90] for energy communities and in [91] for generators under uncertainty. Authors in [92] propose a formulation that ensures the availability of the reserve capacity offered by BESSs under uncertainty, investigating the impact of the activation of the products. Several methodologies are proposed to deal with the uncertainty of the activation, scenario generation [93], which came at a high computational cost, or even ensuring energy for all the activation for the worst-case scenario [94]. A detailed description of this link through the duration of the events is explained in [95] where the uncertainty distribution of the activation of the products is integrated in a framework for the operation of BESSs.

This fact, along with the integration of the uncertainties, allows DSOs to, not only protect themselves against contingencies, but also study how the reliability level impacts on the clearing solution. Those effects are barely described in the literature, and they play a fundamental role in the integration of DGs.

In order to do so, the uncertainty associated to RDERs must be further analysed and introduced in the problem formulation. To model those events, Monte-Carlo [96] and robust optimization [97], [98] techniques are proposed in the literature, but the output of the optimization problem may vary depending on the scenario selection. Other works study the Chance Constraints (CCs)' method to provide consistent solutions for a given level of reliability [55]. This approach is one of the most popular methodologies [99]–[101] when dealing with uncertainty of a wide set of actors due to the fact that their Probability Density Functions (PDFs) can be assimilated to well-established distributions functions[102]. Nevertheless, the above works formulate uncertainty only for energy and reserve dispatch of RDERs and do not take into account the integration of capacity products for congestion and imbalance mitigation services provision, nor the duration of energy events. The uncertainty modelling gives insights about the future outcomes and it also enables DSOs to study what could happen for a determined level of reliability. [81].

The regulatory design of local markets and its decentralisation are still an active research topic [103], [104]. Although, efforts were made in this sense over the last several years, further concerns about coordination may arise in a LFM that encompass several DSOs [16]. Several methodologies to coordinate coupling constraints among systems have been studied, which can be arranged in four categories as Table 3.3 shows: Augmented Lagrangian based, Karush-Kuhn-Tucker (KKT) conditions based, metaheuristics based and technique with no coordination technique. The authors in [105] simulated the behaviour of each agent by solving an individual optimization, while the authors in [51] present an auction where the energy is traded for small-scale consumers. These techniques can represent all market participants, but at a high computational cost and with the risk of auction price spikes. Metaheuristic methods such as Particle Swarm Optimization (PSO), are well suited for large-scale optimisation [106], while Reinforcement Learning (RL) techniques can even deal with partial observability of the data [107], but they cannot guarantee the optimal solution. To overcome this, optimisation-based techniques such as Augmented Lagrangian and KKTs condition decomposition can achieve the optimal dispatch of the market. Optimality Conditions Decomposition (OCD) has been used in [103] to solve cross-border electricity trading, but this technique is limited to one single subproblem. Analytical Target Cascading (ATC) is used if there are multiple subproblems[108], but it is limited to leader-follower problems. Then Proximal Message Passing (PMP) [109] can be used to coordinate the solution of distributed markets in a parallel fashion for any coordination problem but requires a higher number of iterations compared with ADMM technique. Standard ADMM coordinate power dispatch solutions among energy communities [81] and power plants with carbon markets [16]. Operation of networked microgrids

Table 3.3: Comparison of the coordination techniques among physically distributed agents.

Coord. methods		**Shared information**	**Opt.**	**Pros**	**Cons**
Augmented Lagrangian	**ADMM**	Coupling constraints and variables	Yes	High speed convergence, it can represent the negotiation among participants.	Sequential algorithm
	ATC	Coupling variables among hierarchical levels	Yes	Participants can have different objectives	Can only represent Leader-follower problems
	PMP	Coupling constraints and variables	Yes	Parallel algorithm	Higher number of iterations
KKTs	**OCD**	First and second order KKT conditions and coupling variables at interface	Yes	It does not need a coordinator, and can be used to solve non-convex problems.	It can only solve one regional level problem. Complex communication.
Metaheuristic	**PSO**	Coupling variables.	No	Well suited for large-scale optimisation	Can get stuck in local optima. High volume of historical data
	RL	Action of the agent is shared with the environment (LFM)	No	Can deal with partial observability of the information and multiple agents.	High volume of data needed, complicated hyperparameters set up
No coordination	**Auction**	No information	No	Scalable, Low computational cost	High price spikes if competition is excessive
	Sim.	No information	No	Represent all market participants	Computational burden

[44] and peer-to-peer markets [54], [55] have been coordinated based on consensus decomposition. Those decentralised methodologies are mostly oriented for energy dispatch applications. Coordination among DSOs has been barely studied in the literature when trading flexibility to mitigate congestions and imbalances. Authors in [58] highlight the importance of DSO-TSO coordination for congestion mitigation. Blockchain technology for coordination among DSOs is analysed in [110]. However, decentralisation of CCs among different DSOs has not been extensively studied.

This paper shows that an uncertainty-aware LFM which trades capacity and energy products can be cleared in a decentralised setting, reaching the same solution that the centralised clearing formulation achieves. In light of these gaps in knowledge, this paper builds its contributions as follows:

C1. Modelling of a Multi-DSO LFM for the trading of capacity and energy products. There are few works that address the modelling of LFM involving different jurisdictions while mitigating contingencies. Congestions and imbalances mitigation using Multi-DSO LFMs is a topic not well addressed that may arise concerns in future distribution networks.

C2. Analysis of the uncertainty ligated to RDERs and duration of energy events using CCs. Handling uncertainty of RDERs is of vital importance when considering the local market clearing in distribution networks.

CC modelling captures the knowledge DSOs have about the contingency, as well as, it enables to analyse the impact that different levels of uncertainty have on the market solution.

C3. Coordination and decentralisation of the uncertainty aware Multi-DSO LFM. On a context of increasing concerns about privacy, this work sheds light on the coordinated and decentralised trade of capacity and energy products among DSOs under uncertainty for contingency mitigation while preserving privacy of participating agents. CCs have been coordinated among areas using the Inverse Cumulative Density Function (ICDF) of real data. This setting enables to model the activation of energy products, which is a topic not well addressed in the literature.

In this work, a decentralised market clearing mechanism is proposed using an adaptive-ADMM algorithm. Forecast deviations are fitted to a Versatile distribution [102] and the duration of the energy events are fitted to an exponential distribution [88]. Results of the case study illustrate that the coordination of the decentralised clearing is driven by economic and electric signals that physically appear at interconnections.

The paper is organised as follows. Sections II and III present the context and the decentralised clearing problem formulation for the Multi-DSO LFM analysing the uncertainty associated to the problem. Results from a case study based on SimBench dataset and a realistic distribution network are depicted in Section IV. Lastly, Section V concludes the

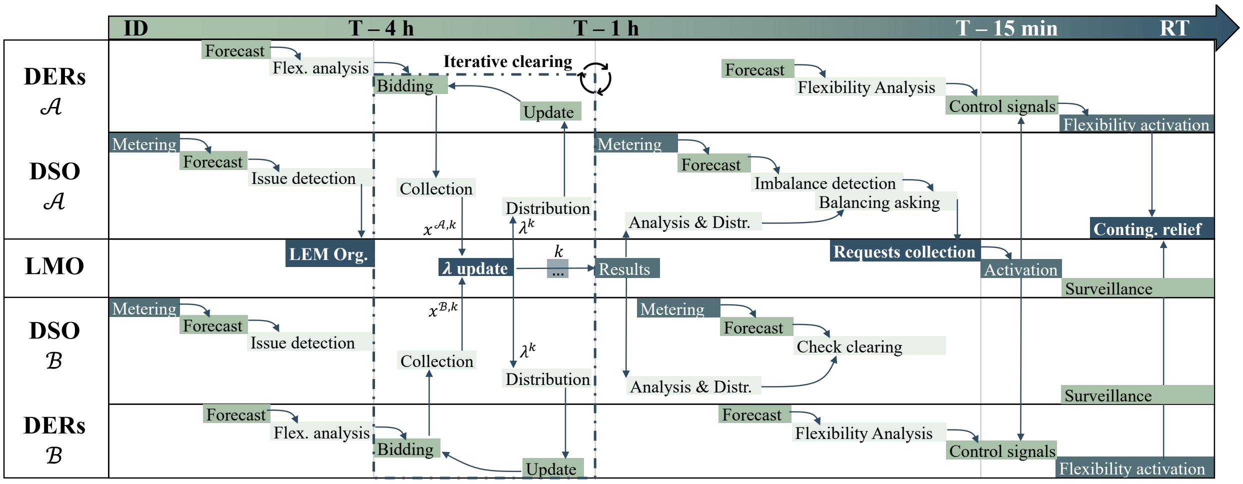


Figure 3.19: Overview of the LFM clearing procedure.

paper.

3.8 Uncertainty aware LFM-Clearing Problem

An overview of the different stages of a LFM clearing mechanism between two DSOs is depicted in Fig. 3.19. When the DSO $\mathcal{A}$ identifies a congestion or an imbalance, it asks the LMO to organise a LFM. Flexibility of the RDERs are obtained after a forecast and a subsequent analysis of those results. Then, each RDER submits its bid to the market through the DSO. The capacity market is then cleared using a iterative process, being the LMO responsible for market coordination. LMO receives asks and bids $x^{\mathcal{A},k}, x^{\mathcal{B},k}$ from both DSOs and it responds with an update of the price signals (λ^k) . When convergence is reached, results are disseminated among areas and energy products of RDERs are activated only in case they are needed. LMO and DSO $\mathcal{B}$ surveillance the market.

3.8.1 Modelling of RDERs agents

In this section, the market participants are modelled. Three different types of RDERs are included in the formulation: FLs, FGs and BESSs.

Let $P^{sch}_{f,t}$ be the forecast power demand of the FL f at time period t. These agents provide flexibility by means of varying its demand level after market clearing $p^c_{f,t}$, within a lower and upper bound $\underline{P}_f \leq p_{f,t} \leq \overline{P}_f$. Their participation in the capacity market with upward $\nu^u_{f,t}$ and downward $\nu^d_{f,t}$ products leads to,

$$p^c_{f,t} = P^{sch}_{f,t} + \nu^u_{f,t} - \nu^d_{f,t} \qquad \forall f, \forall t \quad (3.5a)$$

The power demand of the FLs after the energy products activation is,

$$p^e_{f,t} = P^{sch}_{f,t} + (\omega^u_{f,t} - \omega^d_{f,t})/\Delta t \qquad \forall f, \forall t \quad (3.5b)$$

Those flexibility products are constrained by upper and lower bounds of consumption. Then, $\nu^u_{f,t} \leq \overline{P}_f - P^{sch}_{f,t}$ and $\nu^d_{f,t} \leq P^{sch}_{f,t} - \underline{P}_f$ for all FL f and time period t. After the capacity clearing, the DSO may request a determined quantity of energy product $\omega^u_{f,t}, \omega^d_{f,t}$, which must satisfy that $\omega^u_{f,t} \leq \nu^u_{f,t}\Delta t$ and $\omega^d_{f,t} \leq \nu^d_{f,t}\Delta t$.

Flexibility bids are calculated as linear functions of the volume traded [104] in (3.5c) and (3.5d). Costs $S^{c,u}_{f,t}, S^{c,d}_{f,t}, S^{e,u}_{f,t}$, and $S^{e,d}_{f,t}$ differentiate each product and are defined unilaterally by agents. Thus, those bids internalise agent costs for providing flexibility. This approach is widely employed in literature when defining markets bids [8].

$$c^c_{f,t} = S^{c,u}_{f,t}\nu^u_{f,t} + S^{c,d}_{f,t}\nu^d_{f,t} \qquad \forall f, \forall t \quad (3.5c)$$
$$c^e_{f,t} = S^{e,u}_{f,t}\omega^u_{f,t} + S^{e,d}_{f,t}\omega^d_{f,t} \qquad \forall f, \forall t \quad (3.5d)$$

DG in distribution networks usually encompass technologies such as PV, wind, biomass or small-hydro [96]. Thus, FG g participates in the capacity market with upward $\nu^u_{g,t}$ and downward $\nu^d_{g,t}$ products. Let $P^{sch}_{g,t}$ be the forecast generation, which can be modified by the trading as,

$$p^c_{g,t} = P^{sch}_{g,t} + \nu^u_{g,t} - \nu^d_{g,t} \qquad \forall g, \forall t \quad (3.5e)$$

Moreover, the generated power of FG g after the activation of the energy products is,

$$p^e_{g,t} = P^{sch}_{g,t} + (\omega^u_{g,t} - \omega^d_{g,t})/\Delta t \qquad \forall g, \forall t \quad (3.5f)$$

Similarly, trading is restricted by upper and lower bounds of generation $\underline{P}_g \leq p^c_{g,t} \leq \overline{P}_g$. Thus, $\nu^u_{g,t} \leq \overline{P}_g - P^{sch}_{g,t}$ and $\nu^d_{g,t} \leq P^{sch}_{g,t} - \underline{P}_g$. Energy and capacity products are related considering that $\omega_{g,t} \leq \nu_{g,t}\Delta t$, for upward u and downward d products. Bids are calculated as linear functions of products traded [104] as follows,

$$c^c_{g,t} = S^{c,u}_{g,t}\nu^u_{g,t} + S^{c,d}_{g,t}\nu^d_{g,t} \qquad \forall g, \forall t \quad (3.5g)$$
$$c^e_{g,t} = S^{e,u}_{g,t}\omega^u_{g,t} + S^{e,d}_{g,t}\omega^d_{g,t} \qquad \forall g, \forall t \quad (3.5h)$$

BESSs in distribution systems are being operated for diverse purposes, such as energy arbitrage, surplus storage or peak-shaving [89], [111]. Let $P^{sch}_{s,t}$ be the power of the battery s in its daily operation. BESSs participate in the capacity market with upward $\nu^u_{s,t}$ and downward $\nu^d_{s,t}$ products, modifying scheduled power and their SOC, as (3.5i) and (3.5j) present, respectively.

$$p^c_{s,t} = P^{sch}_{s,t} + \nu^u_{s,t} - \nu^d_{s,t} \qquad \forall s, \forall t \quad (3.5i)$$
$$soc^c_{s,t} = soc^c_{s,t-1} + \eta^C_s\nu^u_{s,t} - \nu^d_{s,t}/\eta^D_s \qquad \forall s, \forall t \quad (3.5j)$$

Then, if the energy products are activated, the BESS variables are,

$$p^e_{s,t} = P^{sch}_{s,t} + (\omega^u_{s,t} - \omega^d_{s,t})/\Delta t \qquad \forall s, \forall t \quad (3.5k)$$
$$soc^e_{s,t} = soc^e_{s,t-1} + (\eta^C_s\omega^u_{s,t} - \omega^d_{s,t}/\eta^D_s)/\Delta t \qquad \forall s, \forall t \quad (3.5l)$$

Their participation is subject to the power rating of the converter $P^{conv}_{s,t}$ and SOC limits.

Then, after market power bounds are set by $-P^{conv}_s \leq p_{s,t} \leq P^{conv}_s$ and SOC bounds by $\underline{SOC}_s \leq soc_{s,t} \leq \overline{SOC}_s$ for all BESS s and time period t. These restrictions also affect the quantity of the capacity products that could be offered, so $\nu^u_{s,t} \leq P^{conv}_s - P^{sch}_{s,t}$ and $\nu^d_{s,t} \leq P^{sch}_{g,t} + P^{conv}_s$. Additionally, SOC restrictions (3.5m) and (3.5n) must be considered when offering capacity products. Energy and capacity products are related such as $\omega_{s,t} \leq \nu_{s,t}\Delta t$.

$$\nu^u_{s,t} = (\overline{SOC}_s - soc_{s,t-1})/(\Delta t \eta^C_s) \qquad \forall s, \forall t \tag{3.5m}$$

$$\nu^d_{s,t} = \eta^D_s (soc_{s,t-1} - \underline{SOC}_s)/\Delta t \qquad \forall s, \forall t \tag{3.5n}$$

Bids for BESSs products are linear functions [104] of the flexibility traded quantity as,

$$c^c_{s,t} = S^{c,u}_{s,t}\nu^u_{s,t} + S^{c,d}_{s,t}\nu^d_{s,t} \qquad \forall s, \forall t \tag{3.5o}$$

$$c^e_{s,t} = S^{e,u}_{s,t}\omega^u_{s,t} + S^{e,d}_{s,t}\omega^d_{s,t} \qquad \forall s, \forall t \tag{3.5p}$$

3.8.2 Network modelling

The power flow through distribution networks is governed by the difference in voltage magnitude and in voltage phase angle. Considering only active power flow to this matter could lead to optimistic estimations of the state of the branch, which could result in the market not being activated when the real thermal limit of the line is violated. To solve this, second order cone relaxation of the power flow of the grid are used [84], [97]. However, they are not valid if reverse power flows may appear due to a high share of distributed PV, as expected in future distribution networks [112]. Thus, the lineal and state-independent model is needed to model the power flow equations as in [67]. Active and reactive node balances are considered in (3.6a) and (3.6b)

$$p_{i,t} = \sum_j (G_{i,j}v_{j,t} - B_{i,j}\theta_{j,t}) \qquad \forall i, \forall t \tag{3.6a}$$

$$q_{i,t} = \sum_j (-B_{i,j}v_{j,t} - G_{i,j}\theta_{j,t}) \qquad \forall i, \forall t \tag{3.6b}$$

Power flow through branches and thermal branch limit are determined as follows,

$$p_{i,j,t} = G_{i,j}(v_{i,t} - v_{j,t}) - B_{i,j}(\theta_{i,t} - \theta_{j,t}) \qquad \forall (i,j), \forall t \tag{3.6c}$$

$$q_{i,j,t} = B_{i,j}(v_{j,t} - v_{i,t}) + G_{i,j}(\theta_{j,t} - \theta_{i,t}) \qquad \forall (i,j), \forall t \tag{3.6d}$$

$$p^2_{i,j,t} + q^2_{i,j,t} \leq \overline{S}^2_{i,j} \qquad \forall (i,j), \forall t \tag{3.6e}$$

3.8.3 Market constraints

Energy products are activated within shorter time windows than capacity products. Let φ_t be the duration of the energy event in time period t, so that $\varphi_t \in [0, \Delta t)$. Energy ene^u_t, ene^d_t and capacity cap^u_t, cap^d_t volumes are related so that,

$$ene^u_t \geq cap^u_t \varphi_t \qquad \forall t \tag{3.6f}$$

$$ene^d_t \geq cap^d_t \varphi_t \qquad \forall t \tag{3.6g}$$

Energy volume is computed as $ene^u_t = \sum_a \omega^u_a$, $ene^d_t = \sum_a \omega^d_a$ and capacity volume as $cap^u_t = \sum_a \nu^u_a$, $cap^d_t = \sum_a \nu^d_a$. In addition to that, in order to maintain the market working in a local environment, the imbalance imb_t is calculated as the overall difference before and after the market must remain zero, as

$$imb^c_t = \sum_a (P^{sch}_{a,t} - p^c_{a,t}) = 0 \; : \lambda^c_t \qquad \forall t \tag{3.6h}$$

$$imb^e_t = \sum_a (P^{sch}_{a,t} - p^e_{a,t}) = 0 \; : \lambda^e_t \qquad \forall t \tag{3.6i}$$

Prices of the energy λ^e_t and capacity λ^c_t are the dual variables of imbalance equations (3.6h) and (3.6i) [104].

3.8.4 Complex bids formats

Until this point, a linear bidding strategy is used to model the participation of the agent in the market. Although this assumption is extended, real world markets can also accept complex bidding formats which represent costs more precisely [43]. Let $R_{a,t}$ be the ratio which describes the willingness to change the power output of the agents. Then, the bids are described as follows for all agent a and time period t,

$$c^c_{a,t} = (S^{c,u}_{a,t} + R^{c,u}_{a,t}\nu^u_{a,t})\nu^u_{a,t} + (S^{c,d}_{a,t} + R^{c,d}_{a,t}\nu^d_{a,t})\nu^d_{a,t} \tag{3.7a}$$

$$c^e_{a,t} = (S^{e,u}_{a,t} + R^{e,u}_{a,t}\omega^u_{a,t})\omega^u_{a,t} + (S^{c,d}_{a,t} + R^{c,d}_{a,t}\omega^d_{a,t})\omega^d_{a,t} \tag{3.7b}$$

In addition to this, complex bidding formats may also include the degradation of the BESSs. The degradation of the battery is driven by non-linear physics laws. Nevertheless, the authors in [113] model the degradation phenomena as a semi-definite function of the SOC $soc_{s,t}$ and the power output $p_{s,t}$, as follows,

$$c^{deg}_{s,t} = K[b(soc_{s,t} - a \cdot B_s)^2 + c \cdot p_{s,t} + d \cdot p^2_{s,t}] \qquad \forall t \tag{3.7c}$$

where K is the degradation cost, B_s is the capacity of the BESS s and a, b, c and, d are per-unit costs scalars. These complex bidding formats are included in the objective function of the problem, maintaining the convexity of the problem. Thus, the existence and uniqueness of the solution is granted.

3.8.5 Objective of the market clearing mechanism

The objective of the market clearing mechanism is a joint minimization of the capacity and energy products bids traded, as follows,

$$\min \sum_t \sum_f (c^e_{f,t} + c^c_{f,t}) + \sum_t \sum_g (c^e_{g,t} + c^c_{g,t}) + \sum_t \sum_s (c^e_{s,t} + c^c_{s,t}) \tag{3.8}$$

Minimization of the costs for the bids of the participating agents would lead to minimum flexibility procuring costs [81].

3.9 Multi-DSO LFM-Clearing: Coordination of uncertain events

3.9.1 Modelling uncertainty of RE sources

The forehand LFM optimization problem has several uncertainty sources. The first one is associated to the forecast of RDERs. Inspired by [55], Versatile distribution is used to model the distribution of the forecast uncertainty. A pictorial example of this method is presented in Fig. 3.20. Uncertainty sets are generated using ARIMA models for FLs and FGs [114]. The ICDF is described as,

$$\phi^{-}(\xi) = \beta_3 - \frac{1}{\beta_1}\ln\left(\xi^{-1/\beta_2} - 1\right) \tag{3.9a}$$

where β_1, β_2, and β_3 are fitted to quantile functions using non-linear least-square fitting method. In order to set up the uncertainty model of the agents, forecasts are generated using a ARIMA modelling.

Let L_t be historical data of the agent, forecast for period $\hat{L}_{t+1}$ is calculated based on AR(N)-process coefficients ϕ_m, α and the prediction error ε_{t+1} in,

$$\hat{L}_{t+1} = \alpha + \sum_{m=1}^{N} \phi_m L_{t+1-m} + \varepsilon_{t+1} \tag{3.9b}$$

Data from SimBench dataset is used to set up the model. One ARIMA(d,p,q) is fitted for each FLs and FGs using auto_arima() method from PMDArima library in Python 3.10. Then, the distribution of the error is computed comparing forecast with test data from the dataset. A pictorial example of this method is shown in Fig. 3.20

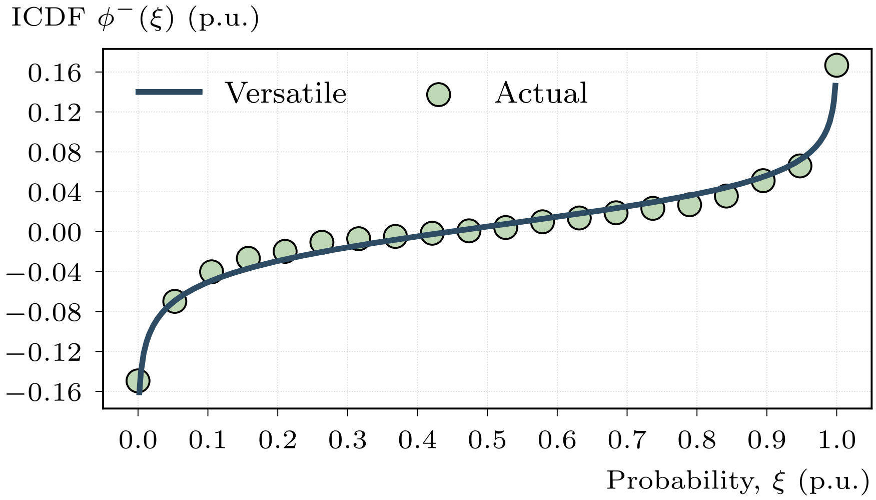


Figure 3.20: An example of the versatile distribution for uncertainty modelling of a FL.

3.9.2 Modelling uncertainty of energy events

The second uncertainty source is related with the duration of the balancing events φ_t. We assume that only one balancing event can occur in each time slot t, and that those events are independent of each other [90]. These system-wide events are strongly related with frequency, which duration follows an exponential distribution function $\varphi_t \sim \exp(\lambda)$, as depicted in Fig. 3.21 [88]. Notwithstanding the foregoing, this methodology is fully compatible with whichever distribution function is selected. The rate λ has been fitted using least squares method with real data from Portugal during 2021 [115]. An R^2 score of 98.52% was obtained using this method.

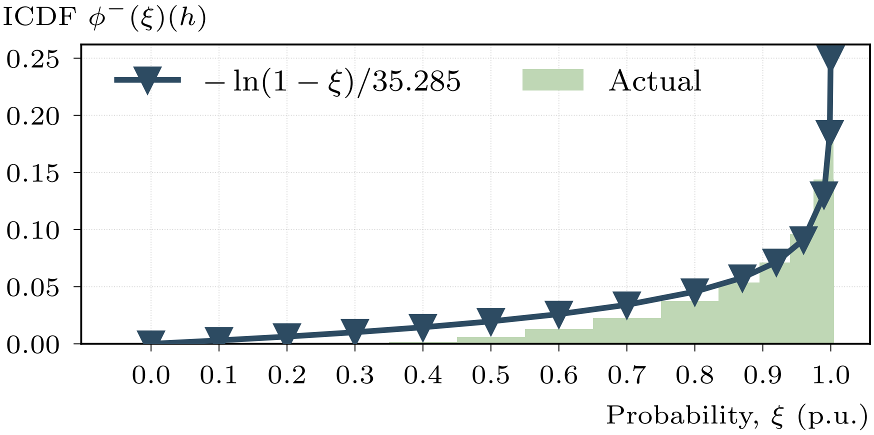


Figure 3.21: ICDF representation of the duration of energy events.

3.9.3 Chance Constraints formulation

Considering the previously described uncertainty sources, CCs are defined to introduce the uncertainty component into the market clearing formulation. In the case of the RDERs, once the forecast is determined, their uncertainty can be also obtained as the ICDF are analytical and known. The actual bounds of the after market power (3.5a) and (3.5e) are redefined using CCs,

$$\mathcal{P}\{\underline{P}_a \leq p^c_{a,t} \leq \overline{P}_a\} \geq 1-\alpha_a \quad \forall a, \forall t \tag{3.10a}$$

Equation (3.10a) ensure that each agent a is able to meet with its power limits when participating in the market, for a given value of the uncertainty level α_a. Following this reasoning, forecast uncertainty also affects to the bidding limits for the different products of the market. Then,

$$\mathcal{P}\{\nu^u_{a,t} \leq \overline{P}_a - P^{sch}_{a,t}\} \geq 1-\alpha_a \qquad \forall a, \forall t \tag{3.10b}$$

$$\mathcal{P}\{\nu^d_{a,t} \leq P^{sch}_{a,t} - \underline{P}_a\} \geq 1-\alpha_a \qquad \forall a, \forall t \tag{3.10c}$$

Similarly, equations (3.6f) and (3.6g), must consider the uncertain behaviour of the duration of energy events. They are reformulated as CCs as,

$$\mathcal{P}\{ene^u_t \geq cap^u_t \varphi_t\} \geq 1-\alpha^p \qquad \forall t \tag{3.10d}$$

$$\mathcal{P}\{ene^d_t \geq cap^d_t \varphi_t\} \geq 1-\alpha^p \qquad \forall t \tag{3.10e}$$

The uncertainty level α^p models the expected duration of the events, and the energy that is needed. Lower values of α^p lead to higher costs, but also higher level of reliability in the operation. In this case, the physical meaning of the uncertainty value α^p represents the knowledge DSO p has about the duration of the event. This fact enables the model to capture situations such as the DSO underestimating the duration of the event (α^p low), and needing to increase its capacity products acquisitions.

3.9.4 Chance Constraints resolution

Let $x \in \mathbb{R}^m$ be the vector of decision variables, $c \in \mathbb{R}^m$ the cost vector, $t_i \in \mathbb{R}^m$ the vector of technology coefficients for the chance constraint i and $\omega_i \in \Omega$ the vector of random variables in a random space Ω. For a given uncertainty level α, we define the stochastic programming with individual CCs,

$$\min_{x \in X}\{c^T x\} \text{ s.t. } \mathcal{P}\left\{t_i x \geq \omega_i\right\} \geq 1-\alpha \qquad \forall i \in \mathbb{R}^m \quad (3.11a)$$

Let $\phi_{\omega_i}(\xi) = \mathcal{P}\left\{\omega_i \leq \xi\right\}$ be the Cumulative Density Function (CDF) of the random variable ω_i for a given realization of uncertainty ξ such that $\phi_{\omega_i}(\xi) : \mathbb{R}^m \rightarrow [0,1]\ \forall \xi \in \mathbb{R}$, $\forall \omega_i \in \Omega$. Then, $\mathcal{P}\left\{\omega \leq t_i x\right\} \geq 1-\alpha$, so $\phi_\omega(t_i x) \geq 1-\alpha$, lastly each CC is solved as $t_i x \geq \phi^-_\omega(1-\alpha)$, where $\phi^-_\omega(1-\alpha)$ is the inverse CDF, such that $\phi^-_\omega(\eta) = \inf\left\{\xi : \phi_\omega(\xi) \geq \eta\right\}$. Then, the stochastic programming,

$$\min_{x \in X}\{c^T x\} \text{ s.t. } t_i x \geq \phi^-_\omega(1-\alpha) \qquad \forall i \in \mathbb{R}^m \quad (3.11b)$$

The following procedure is applied to solve the CCs of the market clearing problem. Let use equation (3.10a) as an example. Let $\phi_{P^{sch}_{a,t}}$ be the CDF of the scheduled power for the agent a, then

$$\begin{aligned}
&\mathcal{P}\{\underline{P}_a \leq p^e_{a,t}\} \geq 1-\alpha \\
&\mathcal{P}\left\{\underline{P}_a \leq P^{sch}_{a,t} + \nu^u_{a,t} - \nu^d_{a,t}\right\} \geq 1-\alpha \\
&\mathcal{P}\left\{P^{sch}_{a,t} \geq \underline{P}_a - \nu^u_{a,t} + \nu^d_{a,t}\right\} \geq 1-\alpha \\
&1-\mathcal{P}\left\{P^{sch}_{a,t} \leq \underline{P}_a - \nu^u_{a,t} + \nu^d_{a,t}\right\} \geq 1-\alpha \\
&\phi_{P^{sch}_{a,t}}\left(\underline{P}_a - \nu^u_{a,t} + \nu^d_{a,t}\right) \leq \alpha
\end{aligned} \qquad (3.11c)$$

Considering that the ICDF $\phi^-_{P^{sch}_{a,t}}$ for a given forecast $P^{sch}_{a,t}$ can be expressed as,

$$\phi^-_{P^{sch}_{a,t}}(\xi) = P^{sch}_{a,t} + \phi^-_e(\xi) \qquad (3.11d)$$

where $\phi^-_e(\xi)$ is the distribution of the forecast error. Both distributions have the same shape, but they are displaced with respect of each other [102]. Then assuming that $\phi^-_{P^{sch}_{a,t}}$ is known and analytical,

$$\begin{aligned}
&\underline{P}_a - \nu^u_{a,t} + \nu^d_{a,t} \leq \phi^-_{P^{sch}_{a,t}}(\alpha) \\
&\underline{P}_a - \nu^u_{a,t} + \nu^d_{a,t} \leq P^{sch}_{a,t} + \phi^-_{e_a}(\alpha) \\
&\underline{P}_a - \phi^-_{e_a}(\alpha) \leq p^c_{a,t}
\end{aligned} \qquad (3.11e)$$

which solves the CC as the Versatile and Exponential distributions used in this work are known and analytical. Following similar reasoning, CCs (3.10b) – (3.10e) are solved. CCs (3.10a) is solved as,

$$\underline{P}_a - \phi^-_{e_a}(\alpha_a) \le p^c_{a,t} \le \overline{P}_a - \phi^-_{e_a}(1-\alpha_a) \qquad \forall a, \forall t \tag{3.11f}$$

Similarly, CCs (3.10b) to (3.10c) are,

$$\nu^u_{a,t} \le \overline{P}_a - P^{sch}_{a,t} - \phi^-_{e_a}(1-\alpha_a) \qquad \forall a, \forall t \tag{3.11g}$$

$$\nu^d_{a,t} \le P^{sch}_{a,t} - \underline{P}_a + \phi^-_{e_a}(\alpha_a) \qquad \forall a, \forall t \tag{3.11h}$$

The physical meaning of the uncertainty value α_a represents how confident are RDERs in the forecast output when they participate in the LFM. Higher values of α_a would lead to wider bounds of operation, maximizing flexibility at the cost of assuming higher risk. Then, CCs (3.10d) and (3.10e) are,

$$ene^u_t \ge \phi^-_{\varphi_t}(1-\alpha^p)cap^u_t \qquad \forall t \tag{3.11i}$$

$$ene^d_t \ge \phi^-_{\varphi_t}(1-\alpha^p)cap^d_t \qquad \forall t \tag{3.11j}$$

Following the same procedure for the upper bound, it can be obtained that, $p^c_{a,t} \le \overline{P}_a - \phi^-_{e_a}(1-\alpha)$. Then, bounds are modified as,

$$\underline{P}_a - \phi^-_{e_a}(\alpha) \le p^c_{a,t} \le \overline{P}_a - \phi^-_{e_a}(1-\alpha) \tag{3.11k}$$

On the other hand, CC associated to upper bounds of the capacity constraint (3.10b) is solved as follows,

$$\begin{aligned}
&\mathcal{P}\left\{P^{sch}_{a,t} \le \overline{P}_a - \nu^u_{a,t}\right\} \ge 1-\alpha \\
&\overline{P}_a - \nu^u_{a,t} \ge \phi^-_{P^{sch}_{a,t}}(1-\alpha) \\
&\overline{P}_a - \nu^u_{a,t} \ge P^{sch}_{a,t} + \phi^-_{e_a}(1-\alpha) \\
&\nu^u_{a,t} \le \overline{P}_a - P^{sch}_{a,t} - \phi^-_{e_a}(1-\alpha)
\end{aligned} \tag{3.11l}$$

Following the same procedure for (3.10c),

$$\nu^u_{a,t} \le P^{sch}_{a,t} - \underline{P}_a + \phi^-_{e_a}(\alpha) \tag{3.11m}$$

Lastly, CCs (3.10d), is solved using a similar procedure, as

$$\mathcal{P}\left\{\varphi_t \le \frac{ene^u_t}{cap^u_t}\right\} \ge 1-\alpha,\ \ ene^u_t \ge \phi^-_{\varphi_t}(1-\alpha)cap^u_t \tag{3.11n}$$

Similarly, for downward products of (3.10e) $ene^d_t \ge \phi^-_{\varphi_t}(1-\alpha)cap^d_t$.

3.9.5 Decentralised Negotiation Mechanism

The Multi-DSO LFM is cleared in a decentralised setting using an adaptive ADMM technique [65].The coordination scheme for a three-DSO setting is depicted in Fig. 3.22.

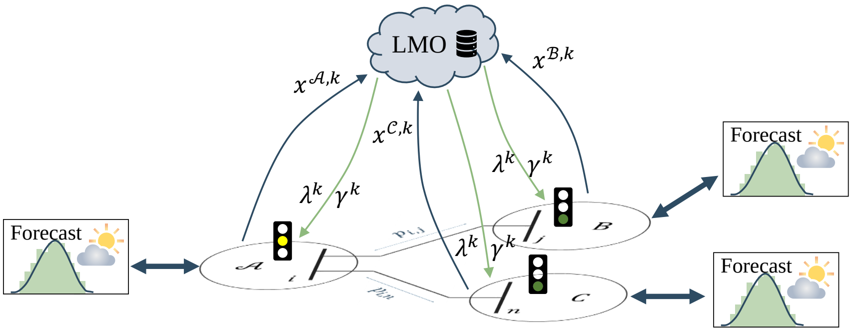
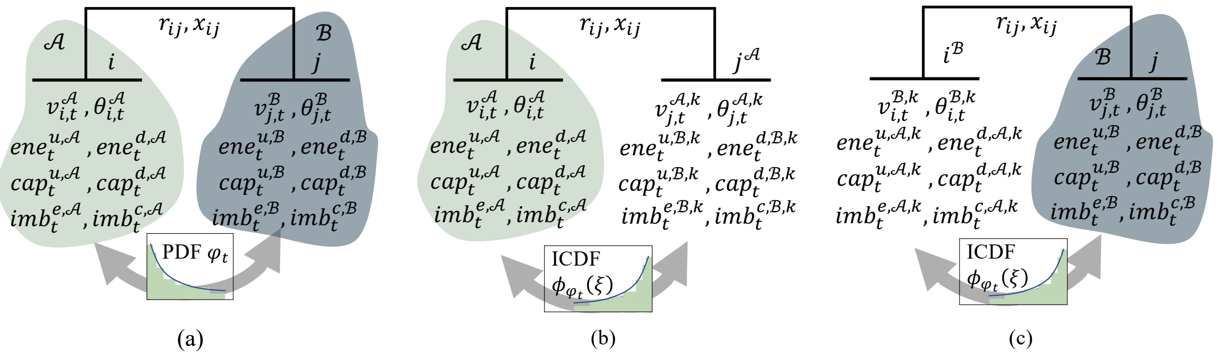


Figure 3.22: Representation of the coordination scheme for a LFM with three DSOs interconnected.

After solving their respective sub-problems, each DSO sends an update of the complicating variables ($x^{p,k}$) to the LMO. Vector $x^{p,k}$ contains information about volume of products traded in each area p at iteration k, i.e., $ene_t^{u,p,k}$, $cap_t^{d,p,k}$, $cap_t^{u,p,k}$, $cap_t^{d,p,k}$, imbalance those products generates $imb_t^{u,p,k}, imb_t^{d,p,k}$ and voltage magnitude and phase angle at interface $v_{i,t}^{p,k}$, $\theta_{i,t}^{p,k}$. Then, the LMO sends back an updated value of the dual variables (λ^k) and the penalty factor (γ^k). The algorithm continues iterating until an agreement in prices is reached, when the residuals of the solution are lower than a threshold level ε. To solve the problem in a decentralised setting, coupling constraints must be separated and decomposed. This separation of the coupling constraints is based on the network and market magnitudes that appear at the interface.

Let $p \in \Omega_p$ be the set of DSOs participating in the market. Fig. 3.23 depicts how coordination is done at the interface. Coupling constraint (3.11i) is decomposed as follows,



(a) (b) (c)

Figure 3.23: Coordination scheme between two DSOs for the proposed LFM.

$$\sum_p ene_t^{u,p} \geq \phi^{-}_{\varphi_t}(1-\alpha) \sum_p cap_t^{u,p} \qquad \forall t \quad (3.12a)$$

$$g_t^{u,\mathcal{A},k} = ene_t^{u,\mathcal{A}} + \sum_{p \neq \mathcal{A}} ene_t^{u,p,k} \geq \phi^{-}_{\varphi_t}(1-\alpha) \left[cap_t^{u,\mathcal{A}} + \sum_{p \neq \mathcal{A}} cap_t^{u,p,k} \right] \; : \lambda_t^{u,k} \qquad \forall t \quad (3.12b)$$

Same procedure can be applied for (3.11i). Imbalance constraints (3.6h) and (3.6i) are decomposed computing the imbalance internally within each area. Then,

$$h_t^{c,\mathcal{A},k} = imb_t^{c,\mathcal{A}} + \sum_{p\neq\mathcal{A}} imb_t^{c,p,k} = 0 : \lambda_t^{c,k} \qquad \forall t \quad (3.12c)$$

$$h_t^{e,\mathcal{A},k} = imb_t^{e,\mathcal{A}} + \sum_{p\neq\mathcal{A}} imb_t^{e,p,k} = 0 : \lambda_t^{e,k} \qquad \forall t \quad (3.12d)$$

Network model also define coupling constraints among DSOs. Let branch (i, j) be the power branch connecting the two DSOs as Fig. 3.23a shows, each area duplicates the other's node variables as Fig. 3.23b and 3.23c shows. Coupling variables related to power flow are duplicated at the interface. Voltage magnitude $v_{i,t}$ and $v_{j,t}$ and voltage phase angle $\theta_{i,t}$ and $\theta_{j,t}$ are duplicated. Thus,

$$h_{i,t}^{v,\mathcal{A},k} = v_{i,t}^{\mathcal{A}} - v_{i,t}^{\mathcal{B},k} = 0 : \; \lambda_{i,t}^{v,k} \qquad \forall t \quad (3.12e)$$

$$h_{i,t}^{\theta,\mathcal{A},k} = \theta_{i,t}^{\mathcal{A}} - \theta_{i,t}^{\mathcal{B},k} = 0 : \; \lambda_{i,t}^{\theta,k} \qquad \forall t \quad (3.12f)$$

$$h_{j,t}^{v,\mathcal{B},k} = v_{j,t}^{\mathcal{B},k} - v_{j,t}^{\mathcal{A}} = 0 : \; \lambda_{j,t}^{v,k} \qquad \forall t \quad (3.12g)$$

$$h_{j,t}^{\theta,\mathcal{B},k} = \theta_{j,t}^{\mathcal{B},k} - \theta_{j,t}^{\mathcal{A}} = 0 : \; \lambda_{j,t}^{\theta,k} \qquad \forall t \quad (3.12h)$$

After this coordination protocol, the problem became separable, and can be decomposed into several sub-problems, one for each DSO, using the Augmented Lagrangian as objective. The sub-problem for a single DSO is,

$$\begin{aligned} \min \sum_t \sum_a & \left(c_{a,t}^{\mathcal{A}} + \lambda_t^k m_t^{\mathcal{A},k} + \frac{\gamma^k}{2} \| m_t^{\mathcal{A},k} \|_2^2 \right) \\ & \text{s.t. } (3.5a) - (3.6e), (3.11f) - (3.11h) \quad \forall (a,i) \in \Omega^{\mathcal{A}}, \forall t \end{aligned} \qquad (3.12i)$$

where vectors λ_t^k, $m_t^{\mathcal{A},k}$ are defined as follows for every time period t in Ω_t,

$$m_t^{\mathcal{A},k} = [h_{i,t}^{v,\mathcal{A},k}, h_{i,t}^{\theta,\mathcal{A},k}, h_t^{c,\mathcal{A},k}, h_t^{e,\mathcal{A},k}, g_t^{u,\mathcal{A},k}, g_t^{d,\mathcal{A},k}] \qquad (3.12j)$$

$$\lambda_t^k = [\lambda_{i,t}^{v,k}, \lambda_{i,t}^{\theta,k}, \lambda_{i,t}^{c,k}, \lambda_{i,t}^{e,k}, \lambda_{i,t}^{u,k}, \lambda_{i,t}^{d,k}]^T \qquad (3.12k)$$

After all DSOs complete their inner iteration, primal $\|r^k\|_2$ and dual $\|s^k\|_2$ residuals are updated. Convergence is achieved if and only if $\max\{\|r^k\|_2, \|s^k\|_2\} < \varepsilon$. If that is not the case, multipliers λ_t^k and the penalty factor γ^k are updated for the next iteration. This is done by approximating the dual problem using the subgradient rule.

3.9.6 Desirable Market Properties

When developing LFM algorithms, it is of major importance to analyse the four desirable properties that a market could have: market efficiency, revenue adequacy, incentive compatibility and cost recovery.

1. Market efficiency is ensured when the final outcome of the decentralised algorithm ensures the optimality of the clearing solution. After convergence, residuals of each sub-problem falls below ε. Thus, $m_t^{p,k} \to 0$ and the optimal cost of the agent a of each

area p, ${c^p_{a,t}}^*$ is defined by,

$$ {c^p_{a,t}}^* = \arg\min \sum_{a \in \Omega^p_a} \sum_{t \in \Omega_t} c^p_{a,t} \tag{3.13} $$

Then, total costs of all areas $p \in \Omega_p$ is equal to the result of the centralised clearing problem as follows,

$$ \sum_{p \in \Omega_p} {c^p_{a,t}}^* = \arg\min \sum_{a \in \Omega_a} \sum_{t \in \Omega_t} c_{a,t} \tag{3.14} $$

Which proves the optimality of the decentralised solution. Thus, market efficiency is ensured.

2. Incentive compatibility is granted when the dominant strategy is to bid according to the true preferences of the agents. However, in marginalism markets strategic behaviour of the agents may affect the solution. This could be controlled with policies that ensure if any participant is unable to offer what has been previously settled in the market, and obtained an unfair revenue for this behaviour, it will be penalised.

3. Revenue adequacy refers to the condition of the LMO never incurring into financial deficit. Two different products are traded in this market at marginal prices λ^e_t and λ^c_t. As they are linked to equations (3.6h) and (3.6i), exporting DSOs with $imb^p_t \leq 0$ will receive revenues at prices λ_t while importing DSOs with $imb^p_t \geq 0$ will issue payments. Then, due to the fact that, $\sum_{p \in \Omega_p} imb^p_t = 0$, the market is budget balanced and the LMO does not incur into financial deficit nor profit.

4. Cost recovery of the operational costs of the participation in the market is granted as no DSO is forced to participate in the market at a loss. Cost functions of the agents are linear functions crossing the origin of the products $c_{a,t} = f(\omega_{a,t}, \nu_{a,t})$ which ensure that $f(0,0) = 0$. Then, negative profits are avoidable, and cost recovery is granted.

The market hereby proposed fulfills three out of four market properties. However, due to the impossibility theorem of Hurwicz [38], no market mechanism is capable of ensuring all properties at the same time.

3.10 Case Study: Activation of the capacity products

This case study is based on the radial network 201_3 [116]. Data of consumption and generation of different agents are obtained from SimBench dataset [117]. Fig. 3.24 depicts the network used for this case study. 42 SLs, 15 FLs, 42 FGs and 12 BESSs are connected to the grid distributed over three DSOs. Only FLs, FGs, and BESSs offer in the LFM. Simulations are carried out using GAMS with an Apple M1, 3.2 GHz processor and 16 GB of RAM. The problem has 292,753 equations and 290,305 variables distributed in three areas.

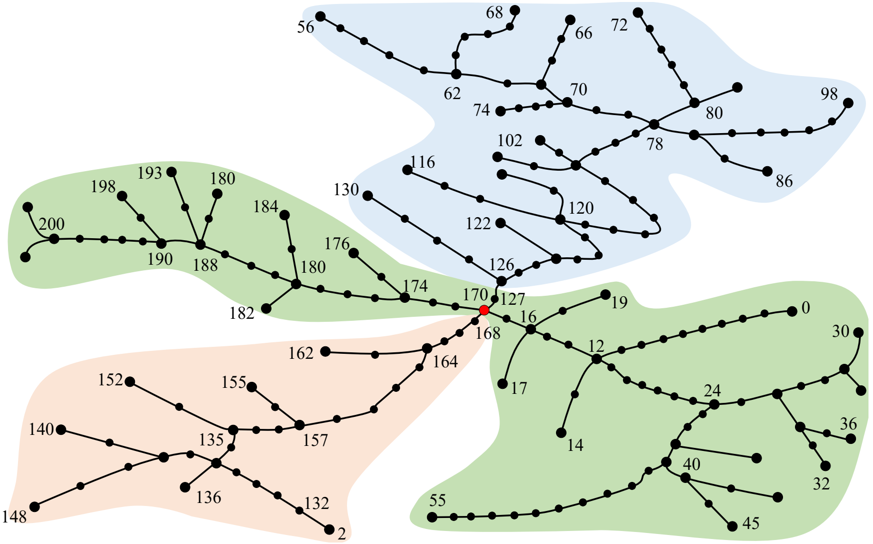


Figure 3.24: Representation of the Bus 201_3 network in radial configuration. DSO $\mathcal{A}$: orange, DSO $\mathcal{B}$: blue, DSO $\mathcal{C}$: green.

3.10.1 Impact of the reactive power modelling in the market solution

Voltage magnitude and voltage phase angle plays a fundamental role in distribution systems when computing the power flow. DC modelling of the grid neglects voltage magnitude, which can lead to an underestimation of the power flow. For that reason, the model proposed in [67] is used. In this point, it is possible to run the LFM without considering the reactive power flow. However, it has great influence in determining if a line is congested or not due to (3.6e). An example of the different estimations of the power flow through branch 126–127 in the case study is depicted in Fig. 3.25.

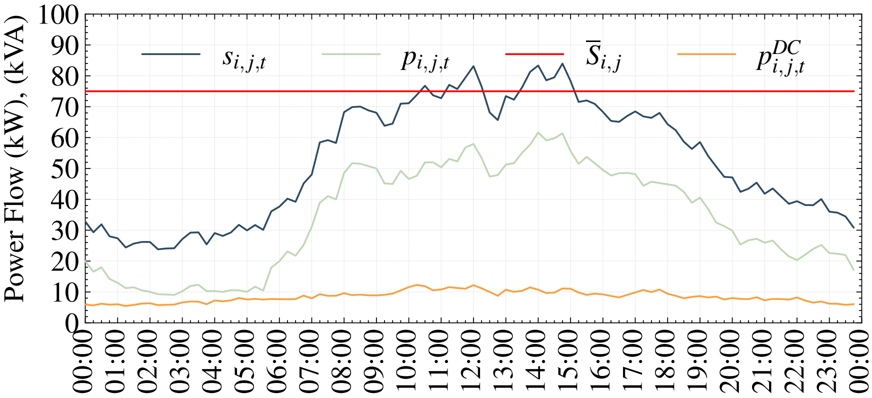


Figure 3.25: Comparison of the power flows considering active and reactive power (blue), only reactive power (green) and DC model (orange), and branch thermal limit (red).

As Fig. 3.25 shows, both the reactive power flow and the voltage magnitude modelling are of overly importance to determine if a congestion occurs, and thus, if the market is activated.

Table 3.4: Comparison of the costs and the parameters of the versatile distribution of each DSO for the case study.

		$\max S_{a,t}^{e,u}$ (€/kWh)	$\min S_{a,t}^{e,u}$ (€/kWh)	$\max S_{a,t}^{e,d}$ (€/kWh)	$\min S_{a,t}^{e,d}$ (€/kWh)	$\max S_{a,t}^{c,u}$ (€/kW)	$\min S_{a,t}^{c,u}$ (€/kW)	$\max S_{a,t}^{c,d}$ (€/kW)	$\min S_{a,t}^{c,d}$ (€/kW)	$\max \beta_1$	$\min \beta_1$	$\max \beta_2$	$\min \beta_2$	$\max \beta_3$ $\times 10^{-3}$	$\min \beta_3$ $\times 10^{-3}$
$\mathcal{A}$	FLs	8.767	0.009	13.577	5.451	0.865	0.002	1.352	0.554	160.429	19.116	1.535	0.870	5.169	-8.324
	FGs	11.437	0.012	13.577	1.960	1.138	0.002	1.352	0.199	4896.95	52.054	2.456	0.770	1.238	-4.081
	SSs	37.449	0.002	31.687	1.500	3.686	0.000	3.027	0.259	-	-	-	-	-	-
$\mathcal{B}$	FLs	77.631	0.005	95.061	37.797	6.905	0.001	9.081	4.048	1530.74	169.55	1.423	0.934	0.977	-7.923
	FGs	93.072	0.001	120.297	21.015	9.303	0.000	12.025	2.177	7148.69	296.73	2.115	0.590	1.526	-3.900
	SSs	31.912	0.036	40.731	18.681	3.179	0.005	4.055	1.914	-	-	-	-	-	-
$\mathcal{C}$	FLs	9.933	0.000	11.690	0.467	0.987	0.000	1.137	0.049	155.651	19.269	1.623	0.926	-0.164	-8.764
	FGs	9.259	0.171	15.131	0.089	0.910	0.043	1.506	0.009	1666.92	76.694	1.342	0.769	2.017	-1.838
	SSs	22.994	0.002	26.552	13.204	2.277	0.000	2.597	1.327	-	-	-	-	-	-

3.10.2 Comparison of the linear and complex bid models

To model the willingness of the agent a to change their power output, the ratio $R_{a,t}$ is introduced as a quadratic term in (3.7a) and (3.7b). This ratio is a thousand times lower than the bid cost $S_{a,t}$ [43]. Besides, degradation costs are described following (3.7c), considering the degradation cost K as 400 €/kWh, and scalars $a = 0.37, b = 0.42(kW)^{-2}, c = 0.0065(kW)^{-1}, d = 0.006(kW)^{-2}$ [113]. The solution of the LFM under both bid models are compared in Table 3.5

Table 3.5: Comparison of the linear bidding strategy versus the quadratic bidding strategy. Costs are in (€), Energy and capacity products in kWh and kW, respectively.

		Linear Bidding		Quadratic Bidding	
		Energy	**Capacity**	**Energy**	**Capacity**
Costs	**FLs**	1415.9	414.84	1450.67	424.1
	FGs	2458.76	389.77	2491.83	396.73
	BESSs	95.99	33.87	96.93	34.44
Prods	**FLs**	1.08	8.95	1.07	8.9
	FGs	0.31	4.3	0.31	4.21
	BESSs	40.26	284.85	40.08	283.87

Costs for the flexibility procurement increase between 0.98% and 2.46% depending on the type of agent. On the other hand, products quantities are reduced between 2.11% and 0.64%.

3.10.3 Incentivizing RE DG participation

To verify that the LFM design fulfils the previously settled objectives, several simulations are considered. Simulations are carried out assuming uncertainty levels α_p of 10%, 5% and 2% and with DG share of 45%, 60%, 75% and 85%, when solving a congestion of 75 kVA in the beginning of the feeder (line 126-127). Uncertainty level α^a is equal to 5% for all agents. Branch selection responds to the worst-case scenario for the participation of RDERs. Area $\mathcal{B}$ is forced to reduce its demand or increase its generation to solve the issue. This congestion forces FGs to provide upward flexibility products which is difficult for RDERs.

Results are shown in Table 3.6, analysing the impact of the DG in the reliability of the solution, the total costs, the volume of the products traded and the mean duration of the events. Reliability is calculated as the joint probability that all CCs are fulfilled for a given time period t. DG share has positive impact on the minimum reliability of the stochastic solution due to a reduction in the duration and the magnitudes of the events, as the last row of Table 3.6 shows. Volume of energy and capacity products traded in the market give a sense of the magnitude of the congestions that appears in the grid for a given DG share. The magnitude of those events and costs for solving them are reduced as the DG share increase, but if the share is over 75%, volume and costs of products traded start increasing again, because of the impact of the stochasticity in the clearing. Nevertheless, the expected duration of those events is reduced as the DG share increases no matter the knowledge DSO has of the contingency, i.e., α^p is 10% or 2%.

Table 3.6: Behaviour of the market for different DG share and uncertainty level (α^p).

α^p	10 %				5%				2%			
DG Share	**45%**	**60%**	**75%**	**85%**	**45%**	**60%**	**75%**	**85%**	**45%**	**60%**	**75%**	**85%**
Minimum Reliability (%)	86.76	89.90	89.95	89.96	91.56	94.70	94.83	94.87	94.45	96.00	97.33	97.88
Total Costs (€)	46060	4651.41	84.21	437.89	47592	5552.55	385.38	605.19	52757	7015.68	410.70	415.93
Volume Energy Products (kWh)	232.90	40.56	0.65	2.77	236.21	51.76	2.72	4.28	259.26	45.22	3.52	3.55
Volume Capacity Products (kW)	1213.32	289.53	4.71	20.78	1159.69	310.15	16.22	25.50	1154.72	203.65	16.49	16.61
Event duration (h)	0.1920	0.1401	0.1377	0.1335	0.2037	0.1669	0.1675	0.1680	0.2245	0.2220	0.2136	0.2136

3.10.4 Impact of the uncertainty level

Following the same case study of a congestion of 75 kVA in line 126-127, the impact the uncertainty has on the solution is analysed in this section. Figure 3.26 presents the power flow through that line in each case. However, power flow scheduled after energy trading varies depending on the level of uncertainty α^p . Power flow scheduled after capacity market do not get affected by the change in uncertainty level, however, it does affect to the volume of flexibility products and their costs.

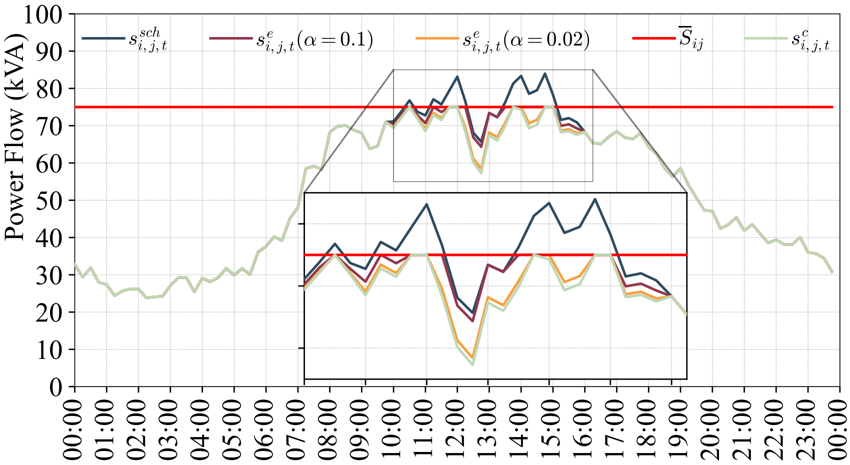


Figure 3.26: Summary of the results of the LFM for different values of uncertainty levels α^p.

Volume of products traded in the market also changes with the uncertainty level α^p as Fig. 3.27 shows. For a DG share of 60%, the volume of capacity products decreases from 289.53 kW ($\alpha^p = 10\%$) to 203.65 kW ($\alpha^p = 2\%$). As the magnitude of the congestion is the same no matter the uncertainty level α^p, energy products volume is around the same value, 40.56 kWh for $\alpha^p = 10\%$ and 45.22 kWh for $\alpha^p = 2\%$. The reason behind such behaviour lies in the physical meaning of α^p. Higher values of α^p exemplify the situation where the DSO assummed that the duration of the event would be low, but ended up being bigger than expected, needing a higher amount capacity products at the end, as Fig. 3.27 (a) depicts. On the other hand, if α^p is maintained low, as Fig. 3.27 (b) presents, the amount of capacity products is reduced, but energy products slightly increases. This is illustrated in Table 3.6.

Total costs for flexibility procuring increases with the level of uncertainty as Table 3.6 presents. This is due to the fact that the reliability of the solution also increases, and the solution is nearer to the worst-case scenario.

3.10.5 Decentralisation of the solution

In a context with intrinsic concerns about privacy, the decentralisation of the market clearing enables a full market integration in areas of the grid operated by several DSOs. This section presents a case study that mitigates a congestion of 36 kVA in branch 78–80 of the DSO $\mathcal{B}$. It is assumed that assets from DSO $\mathcal{B}$ have higher operational costs

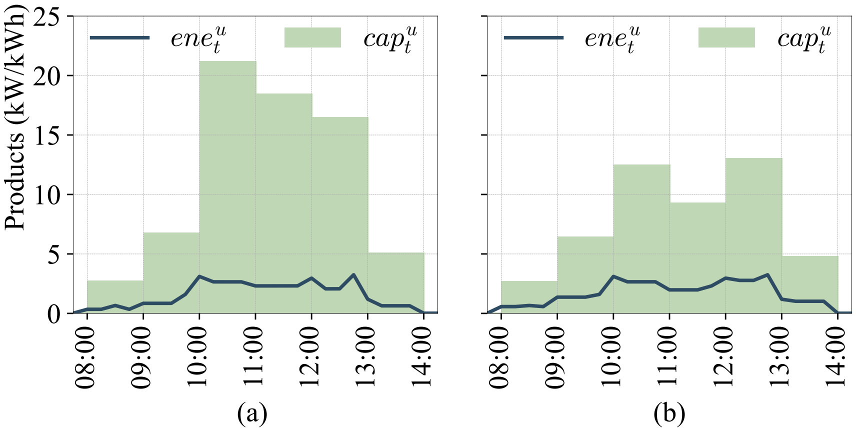


Figure 3.27: Total volume of energy and capacity products for uncertainty levels (a) $\alpha^p = 0.10$ and (b) $\alpha^p = 0.02$ for a DG share of 60%.

as the uncertainty of their forecast is lower compared to assets from DSOs $\mathcal{A}$ and $\mathcal{C}$ as Fig. 3.28 and Table 3.4 present. Selected branch is located in the middle of the feeder to allow DSO $\mathcal{B}$ to mitigate the congestion with the assets connected to its jurisdiction. In this sense, downward flexibility needed downstream the congestion can be balanced with assets from DSO $\mathcal{B}$, connected upstream the congestion, trading upward flexibility. Simulations are performed considering $\alpha^p = \alpha_a = 10\%$.

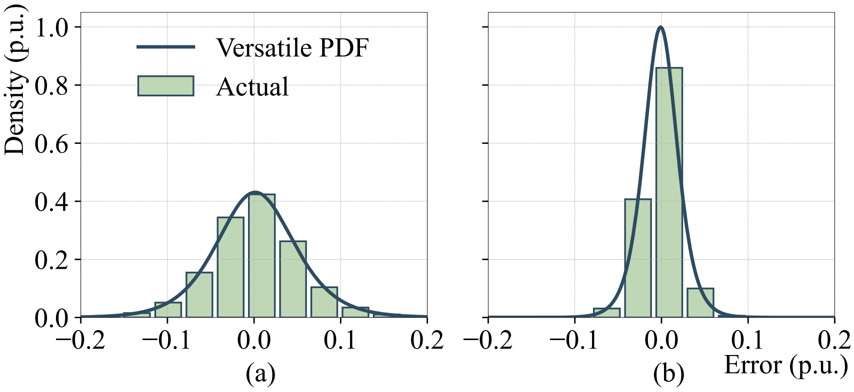


Figure 3.28: Comparison of the PDF of FL from DSO (a) $\mathcal{A}, \mathcal{C}$ and (b) $\mathcal{B}$.

Then, the results of this case study are depicted in Fig. 3.29 and Table 3.7. Market efficiency is enhanced when all DSOs participate in the market, as the cost of the solution is reduced a 44.65% and the power flow through branch 78-80 is closer to the thermal limit, as Fig. 3.29 shows. The volume of products, as well as the flexibility per agent increases when all areas participate in the market . Thus, the clearing solution when assets from all DSOs participate in the market can face shorter balancing events compared with the solution of only DSO $\mathcal{B}$. Nevertheless, the reliability of the solution is enhanced from a 3.80% to 89.44%. Costs of energy and capacity flexibility products also are reduced an 80.15% and 82.14%, respectively, as more economical assets participate in the market clearing.

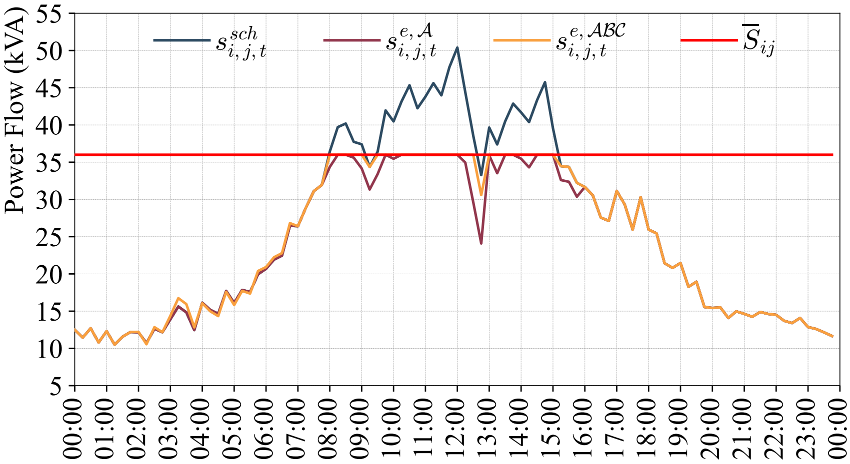


Figure 3.29: Power flow through branch 78–80 when solving the congestion using only area $\mathcal{B}$ assets, and assets from all areas.

Table 3.7: Comparison of the results of the market when solving a congestion of 36 kVA in line 78-80 using resources of area $\mathcal{B}$ only and all areas ($\alpha_a = \alpha^p = 0.10$).

	Area $\mathcal{B}$	**All areas**	**Difference**
Total Costs (€)	42,923.74	23,760.17	-44.65%
Minimum Reliability (%)	3.80%	89.44%	2,253.68%
Volume Energy Prods. (kWh)	78.84	144.20	82.91%
Volume Capacity Prods. (kW)	473.34	1,063.71	124.73%
Duration of events (h)	0.169	0.136	-19.53%
Avg. Volume Energy Prods by ag (kWh/ag)	15.96	28.84	80.64%
Avg. Volume Capacity Prods by ag (kW/ag)	23.67	53.18	124.72%
Max. Energy Price (€/kWh)	0.3169	0.0629	-80.15%
Max. Capacity Price (€/kW)	0.4966	0.0887	-82.14%

The evolution of the dual and primal solutions of the Multi-DSO LFM using standard and adaptive version of the ADMM is also analysed. Fig. 3.30 shows the evolution of the primal ($\|r_k\|_2$), dual ($\|s_k\|_2$) residuals and the penalty factor (γ^k) during the decentralised market clearing process. ADMM parameters are fixed to $\gamma_0 = 10^{-1}$, $\tau = 25$, $\mu = 10$.

As Fig. 3.30 shows, the standard version of the ADMM algorithm is unable to obtain enough precision when clearing the market. This justifies the use of the adaptive version of the algorithm which obtains primal and dual convergence within 140 iterations for a precision level of $\varepsilon = 10^{-3}$. The solver spends 280.252 seconds to solve the decentralized version of the problem, which results in 2.0018 seconds per iteration.

3.11 Flexibility Envelopes at Multi-DSO Local Flexibility Markets

Despite the fact the the previously presented methodologies are effective and efficient methodologies to solve the decentralised Local Flexibility Market among adjacent DSOs, another techniques can be used to this aim. In this sense, one idea is to coordinate adjacent markets through the use of their flexibility envelopes and associated costs maps. This idea is under development and will be object of future research. Nevertheless, this section presents a preliminary research to this idea regarding the estimation of these flex-

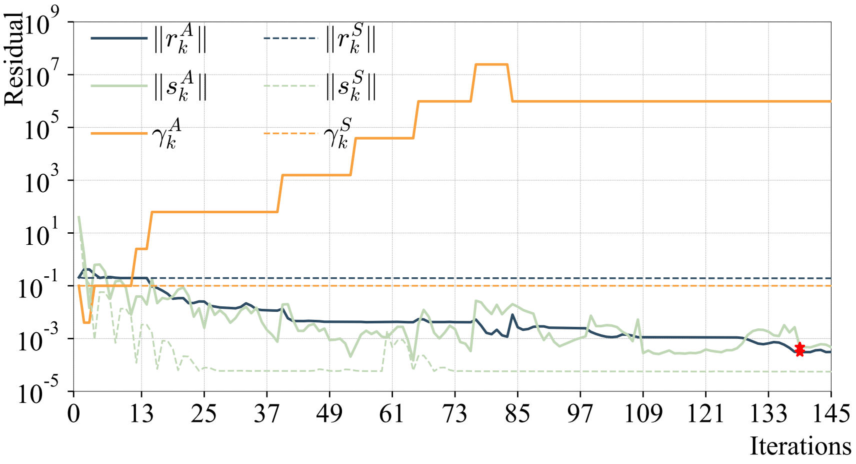


Figure 3.30: Comparison of the evolution of the residuals in the adaptive ADMM (dashed lines), versus its standard version (solid lines).

ibility envelopes in the context of Multi-DSO LFMs in the presence of RDERs. This work has been presented for the IEEE PES PowerTech 2023 conference in Belgrade, Serbia [27].

When assessing the flexibility region of distribution systems, various search methodologies have been proposed. Monte-Carlo simulation is used in [36] and [118] for flexibility and feasibility assessment. This method generates a random point cloud and obtains the flexibility region as the convex hull of the feasible points. However, the outcome depends on sampling and initial point selection, requiring complex methods for precise evaluation. It can also be computationally intensive, necessitating a large number of points for reliable results. Another approach searches for the boundary of the flexibility region using optimization problems. Linear search algorithms [119], [120] determine the region limits in active and reactive dimensions. A rotational angle method [121] uses a reference point to compute the limits by changing the search direction. An interactive algorithm [122] sequentially obtains boundary points until the output area difference reaches a threshold. Multi-objective optimization [123], [124] maximizes flexibility procurement, and a method based on Minkowsky addition [125] combines the flexibility of all RDERs. This non-linear method can be computationally expensive though, and its optimality is not guaranteed. Modelling of RDERs varies, including FLs and FGs at the TSO/DSO interface [119], controllable loads and fuel-based generation at the upstream network [121], and FLs and FGs with Monte-Carlo simulation [126]. Nevertheless, the impact of distributed BESSs is often not considered, underestimating grid capabilities. Some studies evaluate flexibility of virtual power plants with temporal constraints but do not integrate the network or BESS [127]. A gap in the knowledge exists in analyzing the flexibility region at the DSO/DSO interface, particularly in Multi-DSO LFMs participation.

This section presents a linear approach for determining the flexibility region of the DSO in Multi-DSO LFMs, incorporating BESSs into the assessment. The methodology utilizes

McCormick envelopes and a polygonal inner approximation to linearize the problem. The key contribution of this section is a linear approach to assess the flexibility envelopes of each DSO, effectively linerising non-linear constraints of BESSs. The proposed method is able to determine this flexibility region even with congested and several interconnections with the upstream network, which enable to assess the TSO's infuence on the flexibility dispatch.

3.11.1 Flexibility Estimation

In this section, the constraints and the objectives functions needed to determine the flexibility region of RDERs in Multi-DSO LFM are explained. Flexibility resources, network and flexibility market are adopted from [24]. The simultaneous activations of upward and downward flexibility directions must be prevented, as they are not feasible in practice. To this aim and following what was done in [23], a variable change and a linearisation based on the McCormick Envelopes are used to linearise the non-linear constraints that enforce this condition.

Then, in order to estimate the flexible region where the assets connected to a DSO multiple simulations are carried out. Figure 3.31 shows how the simulations are performed to determine the flexible region of DSO n.

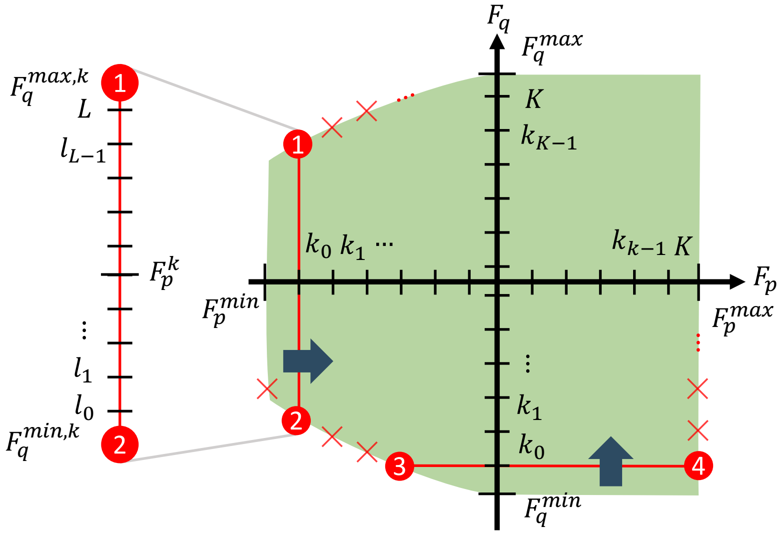


Figure 3.31: Methodology for the estimation of the feasible region in Multi-DSO LFM.

First, maximum and minimum values of active $F_p^{n,\max}$, $F_p^{n,\min}$ and reactive $F_q^{n,\max}$, $F_q^{n,\min}$ flexibility are computed using (3.15a) - (3.15d) for all $t \in \Omega_t$ and DSOs $p \in \Omega_p$.

$$\min -\sum_{t\in\Omega_t} F_{p,t}^{n} + \sum_{t\in\Omega_t}\sum_{s\in\Omega_s}(u_{s,t}^{n} + r_{s,t}^{n}) \qquad \forall n \in \Omega_n \quad (3.15a)$$

$$\min \sum_{t\in\Omega_t} F_{p,t}^{n} + \sum_{t\in\Omega_t}\sum_{s\in\Omega_s}(u_{s,t}^{n} + r_{s,t}^{n}) \qquad \forall n \in \Omega_n \quad (3.15b)$$

$$\min -\sum_{t\in\Omega_t} F_{q,t}^{n} + \sum_{t\in\Omega_t}\sum_{s\in\Omega_s}(u_{s,t}^{n} + r_{s,t}^{n}) \qquad \forall n \in \Omega_n \quad (3.15c)$$

$$\min \sum_{t\in\Omega_t} F_{q,t}^{n} + \sum_{t\in\Omega_t}\sum_{s\in\Omega_s}(u_{s,t}^{n} + r_{s,t}^{n}) \qquad \forall n \in \Omega_n \tag{3.15d}$$

$$\min \sum_{t\in\Omega_t}\sum_{s\in\Omega_s}(u_{s,t}^{n} + r_{s,t}^{n}) \qquad \forall n \in \Omega_n \tag{3.15e}$$

After that, those dimensions are discretized K times as Fig. 3.31 shows. Points 1 and 2 are computed using objectives (3.15c) and (3.15d), respectively while fixing active flexibility using (3.15f). Points 3 and 4 are calculated using (3.15a) and (3.15b), respectively while fixing reactive flexibility using (3.15g). Additionally, costs associated to each point of the flexible region are obtained as the flexibility dispatch costs of the DERs.

$$F_{p,t}^{n} = F_{p,t}^{n,\min} + k(F_{p,t}^{n,\max} - F_{p,t}^{n,\min})/K \qquad \forall t \in \Omega_t \tag{3.15f}$$

$$F_{q,t}^{n} = F_{q,t}^{n,\min} + k(F_{q,t}^{n,\max} - F_{q,t}^{n,\min})/K \qquad \forall t \in \Omega_t \tag{3.15g}$$

Then, reactive dimension is discretized L times between points 1 and 2, as Fig. 3.31 shows. In these simulations, both the reactive and active flexibility are fixed, and the costs are the only output of the optimization problem. The methodology for estimating the Flexibility Region in Multi-DSO LFM is summarised in algorithm 2.

Algorithm 2 Estimating Multi-DSO Flexibility Region

```
for $n \in \Omega_n$ do
    $F_{p,t}^{n,\max} \leftarrow \arg\min\{$(3.15a) s.t. Market Restrictions$\}$
    $F_{p,t}^{n,\min} \leftarrow \arg\min\{$(3.15b) s.t. Market Restrictions$\}$
    $F_{q,t}^{n,\max} \leftarrow \arg\min\{$(3.15c) s.t. Market Restrictions$\}$
    $F_{q,t}^{n,\min} \leftarrow \arg\min\{$(3.15d) s.t. Market Restrictions$\}$
    for $k = 1, 2, \ldots, K$ do                                        ▷ Parallelized Loop
        $C_t^{n,k}, F_{p,t}^{n,\max,k} \leftarrow \arg\min\{$(3.15a) s.t. Market Restrictions, (3.15g)$\}$,
        $C_t^{n,k}, F_{p,t}^{n,\min,k} \leftarrow \arg\min\{$(3.15b) s.t. Market Restrictions, (3.15g)$\}$,
        $C_t^{n,k}, F_{q,t}^{n,\max,k} \leftarrow \arg\min\{$(3.15c) s.t. Market Restrictions, (3.15f)$\}$,
        $C_t^{n,k}, F_{q,t}^{n,\min,k} \leftarrow \arg\min\{$(3.15d) s.t. Market Restrictions, (3.15f)$\}$
        for $l = 1, 2, \ldots, L$ do                                    ▷ Parallelized Loop
            $C_t^{k,l} \leftarrow \arg\min\{$(3.15e) s.t. Market Restrictions, (3.15f), (3.15g)$\}$
        end for
    end for
end for
```

3.11.2 Case Study

Figure 3.32 lays out a case study based on the IEEE-34 test network. Without loss of generality, LFM is solved for periods of $\Delta t = 15$ minutes. Data used in this case study is available in [128]. Total static load of the case study is 611.84 kVA with 18 SLs, 8 FLs, 5 FGs and 3 BESSs distributed among two DSOs. The interface with the TSO is modelled using a generator connected to node 100. Flexible region is computed considering two situations; the first one where the TSO is in green state and can modify the power flow through the interface and, the second, where the interface is congested, and the flexibility should be exclusively exchanged among DSOs. Simulations were performed using GAMS 24.2.2 and CPLEX 12.6.3. on a cluster with 80 TB of RAM memory and 160 nodes of 2 x AMD EPYC 7H12 CPUs at 2.60 GHz, running Suse Leap 42 Linux distribution.

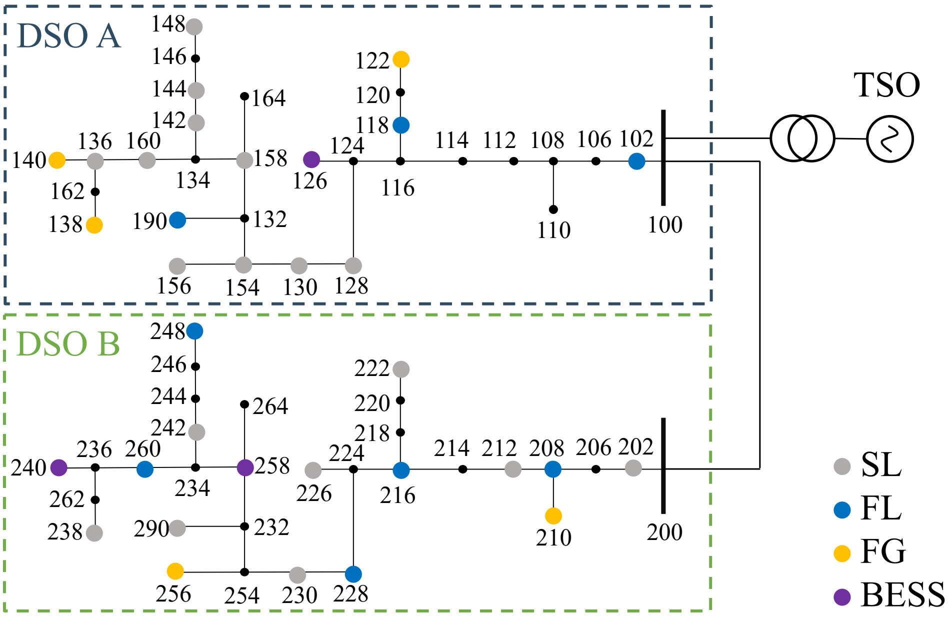


Figure 3.32: Case study based on two IEEE 34 bus networks representing the DSOs. Grey, blue, orange and purple dots represent SLs, FLs, FGs and BESSs, respectively.

3.11.2.1 Estimation of Flexibility Region for isolated Multi-DSO LFMs

The evolution of the flexibility region and its associated costs when the TSO cannot procure flexibility in the interconnection is depicted in Fig. 3.33.

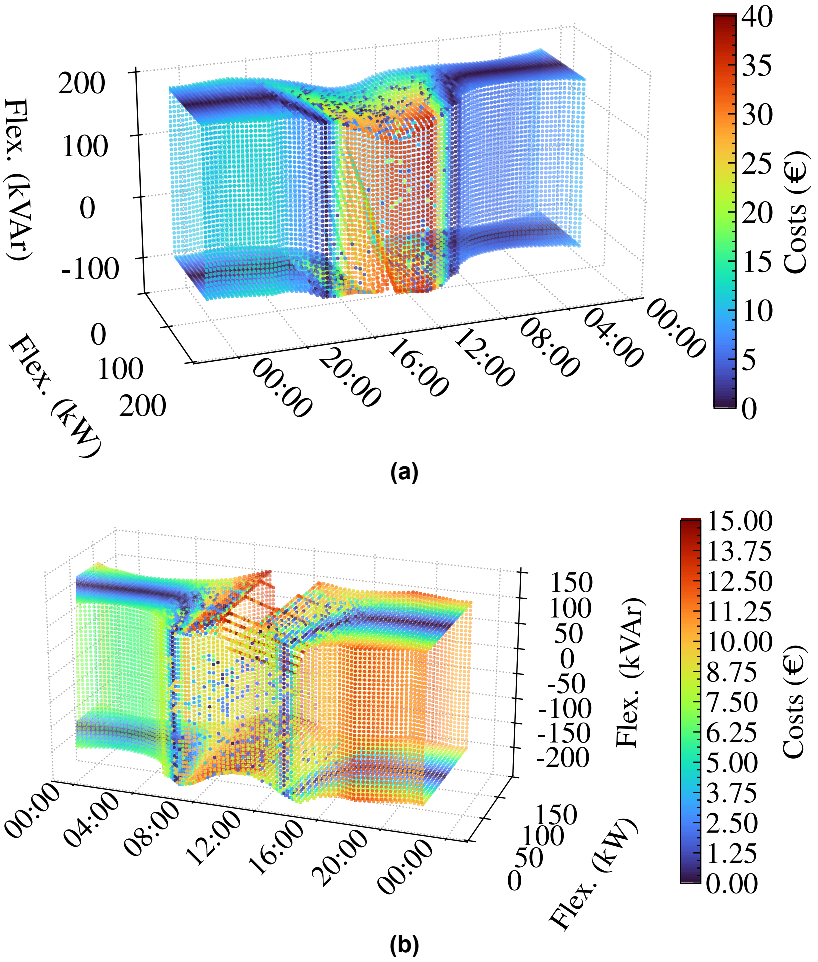
Flexible region limits are compared in Table 3.8. In this situation, DSO A can produce a 44% and 17% more of upward active and downward reactive flexibility, respectively. On the other hand, DSO B obtains a 30% and 15% more of downward active and upward reactive flexibility, respectively. Overall costs are reduces, however, DSO A still has nearly two times bigger costs than DSO B.

Table 3.8: Flexible region limits for DSO A and B with TSO in emergency state.

	DSO A (TSO in emergency state)			
	Active Flex. (kW)		**Reactive Flex. (kVAr)**	
	Upward	Downward	Upward	Downward
Value	114.37	-79.52	140.23	-164.05
Time	11:00	20:00	00:00	12:00
Costs (€)	3.09	12.45	9.66	26.48
	DSO B (TSO in emergency state)			
	Active Flex. (kW)		**Reactive Flex. (kVAr)**	
	Upward	Downward	Upward	Downward
Value	79.52	-114.37	164.05	-140.23
Time	20:00	11:00	12:00	00:00
Costs (€)	12.45	6.08	13.21	9.08

3.11.2.2 Associated costs of Flexibility Regions

Costs associated to the operation of the flexibility region are depicted in Fig. 3.34 for DSO A and in Fig. 3.35 for DSO B at different times of the day. Flexibility costs at nighttime are lower than costs at daylight, when they can reach 34 € for DSO A and 15 € for DSO B. The non-linearity of the problem appear in the non-uniform contour plots of the costs



(a)

(b)

Figure 3.33: Flexible Region of DSO A (a) and DSO B (b) when the interface with TSO is congested.

associated to each operation point.

3.12 Summary

In this chapter, several LFMs market design has been proposed to solve operational and congestion problems in distribution networks. In first place, a centralised LFM for capacity and energy products trading was presented in [23] from the perspective of the LMO. In addition, it was shown that the pre-allocation of the capacity products can increase market liquidity, incentiving to participate in the market. This market formulation relied on a linearisation technique for finding an approximation of the global minimum of the objective function. The uniqueness and existence of the solution was granted using this technique, demonstrating that an accuracy of 0.01% can be obtained within a reasoble amount of time for the market clearing.

Nevertheless, this approach neglected the issue of the sharing of privacy information with a central entity, which is a major concern for DSOs and market participants. Owing to this, a second market clearing design was proposed in [24]. The second market-clearing design was based on the ADMM algorithm, which is a decentralised algorithm that allows

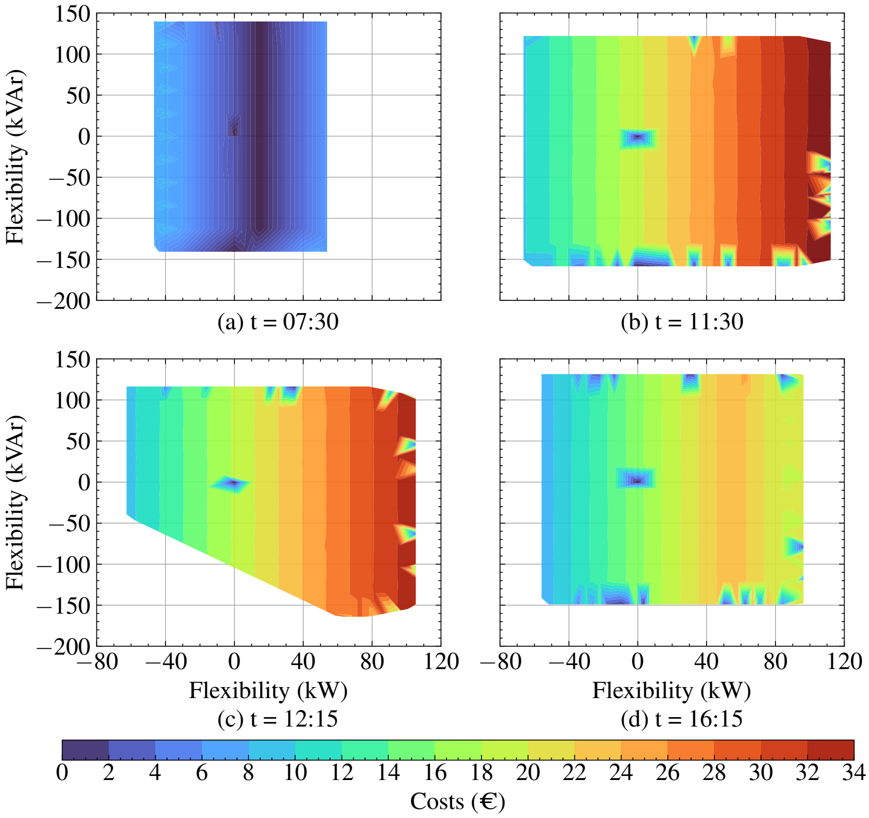


Figure 3.34: Contour plots of the costs associated to the flexible region of DSO A.

to solve the market clearing problem without the need of sharing information of private DSOs. The Multi-DSO market-clearing problem solved operational problems in the distribution network by only means of energy products. It was found that the optimal dual variables associated with the node voltage magnitude and phase angle at the tie-lines as well as the overall imbalance equation, are the signals that properly drive the coordination mechanism to achieve system-wide efficiency. In addition, the signal of the overall imbalance equation is the one which fix prices in the market, which is a key result for the design of the market. The coordination mechanism was able to achieve the same electrical and economic operating points as those where DSOs are centrally operated, at the cost of strong and iterative coordination among the involved DSOs. However, a case study based on the IEEE 123 bus system demonstrated the feasibility of this approach, achieving savings of 16.95% compared to the non-coordinated solutions. Requiring also a reduced number of iterations among DSOs and LMO to converge. A stochastic version of the market clearing showed less than 6% deviation from the deterministic simulations, demonstrating robustness of the proposed approach.

Thirdly, the ADMM algorithm was adapted to solve the market clearing problem of the LFM with capacity and energy products in [25], which requires new coordination schemes among DSOs. In this market-clearing design, an adaptative version of the ADMM protocol was used to preserve the privacy of the DSOs and to achieve a faster convergence of the algorithm. Flexibility products quantity, overall imbalance, voltage phase angle at inter-

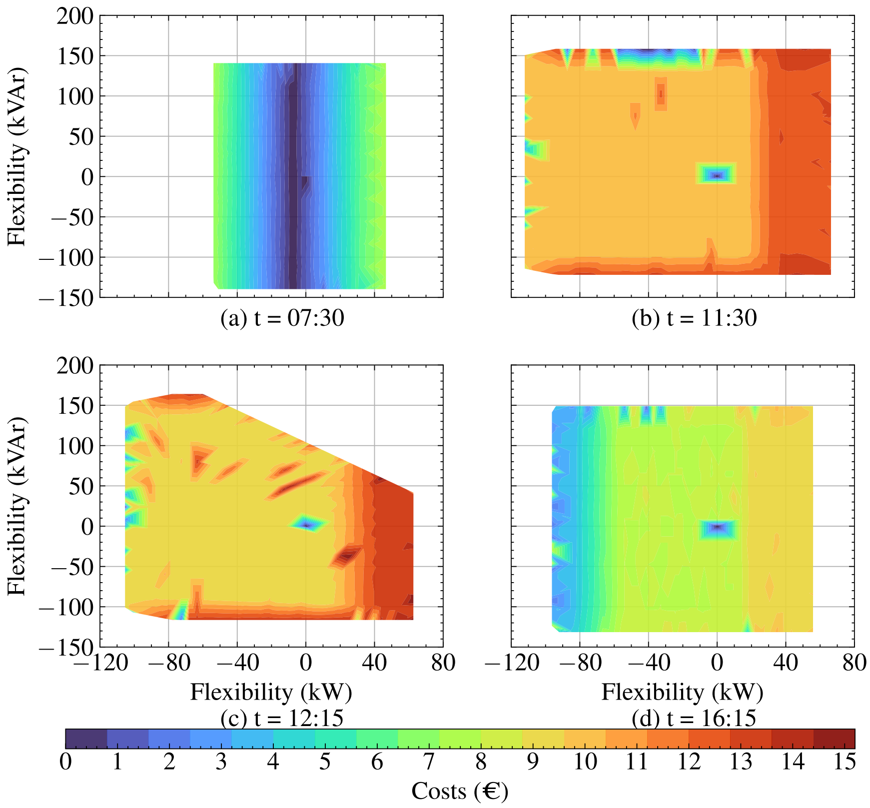


Figure 3.35: Contour plots of the costs associated to the flexible region of DSO B.

connection as well as dual variables are the signals that attain coordination in the market clearing protocol, achieving serviceable solutions for network operation. The case study based on the IEEE 34 bus system demonstrated the feasibility of the approach, achieving better results than the standard version. Furthermore, from the scalability analysis performed, iterations are linearly related with then number of areas and the elapsed time is reasonable for local communities to operate near real time.

Then, a decentralised procotol for the capacity and energy products trading that intrinsically captures the uncertainty in the activation of the energy events was proposed in [26]. This market-clearing design captures the non-deterministic nature of the energy events, that can be discreationary activated by the DSOs at any time and the uncertainty of the different RDERs that participates in the market. Besides, it also analyses the associated costs of hedging against events of a determined duration. This LFM clearing design helps to integrate RDERs across several DSO jurisdictions while maintaining their operational independence, obtaining the same solution that the centralised setting, which is one of the main contributions of this thesis. This decentralisation process is also driven by economical and physical constraints that appear at the interface, i.e., the prices of the products exchanged in the market, and node voltage magnitude and phase angle, using also an adaptative version of the ADMM algorithm for the sake of a faster convergence. A case of study based on radial network 201_3 and realistic data from SimBench dataset demonstrates the feasibility of the proposed approach to solve operational problems in distribution networks. The non-linearities associated to the operation of the RDERs can also be included into the model using a convex approximation of them. Reduced operational costs are obtained when the DG share increases, what incentives the DSOs to deploy them. Moreover, enhanced reliable solutions are obtained when integrating multiple DSOs in the market clearing protocol, even if the assets included have high uncertainty.

Finally, a proposal for the determination of the flexibility envelopes of the DSOs was presented. The proposed methodology is a valid tool for DSOs aiming to analyse their flexibility and the associated costs, no matter the situation of the upstream transmission network. Results based on the IEEE 34 bus network demonstrate the feasibility of the proposed approach to approximate the non-linearities of the model, while assessing the flexibility of DSOs, under high RDER penetration, when participating in LFMs.

CHAPTER 4

Stacking of Flexibility in Multiple Markets

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This chapter focuses on the development of new bidding strategies and business cases for the FSP figure to actively manage DERs into the distribution network while vertically integrating their flexibility into multi-scale market structures. The proposed framework enables the calculation of innovative strategies for the FSP to maximize the profitability of DERs by stacking revenues from the provision of flexibility services simultaneously in multiple markets. Multiple DER technologies are integrated into the framework, providing spatial and temporal flexibility coverage. Firstly, a deterministic approach is presented, where the FSP is assumed to have perfect knowledge of the system. Then, a stochastic approach is developed, where the FSP is assumed to have limited access to information and the behaviour of rival market agents is analysed.

4.1 Stacking of Flexibility Revenues in National and Local Markets

The ever-increasing penetration of DERs, the decarbonisation, sustainability and electrification of mobility and heating are motivating a profound change in the power landscape [129]. The proliferation of clean DERs is mainly driven by the Net Zero emissions objectives, which increases the penetration of technologies such as household and factory energy arbitrage systems, utility scale batteries, EVs and PV systems [75].

Distribution systems will be characterized by a strong renewable and uncontrollable foundation, which eventually would lead load to follow generation. [130] In this context, DSOs will face new challenges concerning those new consumption and generation patterns. Flexibility and LEMs are key elements of modern renewable energy systems that enable DSOs to deal with this change of paradigm [13].

Timescale is of paramount importance as generation and demands must remain in equilibrium at every instant. Moreover, given the intrinsic uncertainty associated to renewable generation and its hurried deployment, the number of contingencies increases [131]. In this context, energy and flexibility markets offer resilient and cost-effective solutions at a national and local level to system operators, which previously could only resort to grid reinforcements to meet these challenges.

Extensive research has been conducted regarding the design of these short-term LFMs [8], and numerous innovative industry-lead projects have been developed to test them [12]. Moreover, system operators could capitalise on the particular suitability of DERs for providing multiple types of services simultaneously at national and local scale[132]. Despite of this, individual DERs are limited in size to directly participate in national markets [97]. Then, although aggregation allows their participation in individual markets at a national scale, the determination of the optimal stacking of revenue across multiple scales remains a major challenge.

Concurrent participation in several markets enables adding worth to management techniques of DERs by stacking revenues. However, being too small, their participation is limited when they are operated independently. FSP figure naturally arises as a market facilitator for DERs aiming to maximise their profitability. Thus, there is a desire of improving the business cases for those resources as they provide low-cost solutions and promotes energy independent societies while accelerating transition to sustainable energy systems [133]. In this context, there is a strong motivation to study a business model for DERs with revenue stacking from the provision of flexibility services in multiple markets.

Various methodologies have been studied to manage DERs. Markov Decision Process was used in [91] to stack revenues from energy arbitrage and frequency regulation in PV -BESS systems. Deep-Learning was used in [85] to accelerate the solution of the energy management problem of a community of DERs under uncertainty. Those techniques only address the problem of DERs providing transmission or local services, but not both at the same time.

Optimization techniques were also used to manage simple business cases. Scalar indices are used in [134] and [135] to manage the participation of BESSs in national markets. Authors in [136] use Particle Swarm Optimization to co-optimize BESS size along wind systems to maximise profits. Reference [137] stacks revenues streams for BESSs in microgrids, with the aim of making them financially viable using linear programming. Long term BESSs bidding strategy in day-ahead and frequency markets is investigated at national scale by [138]. Energy, capacity and ancillary services were stacked in [139] considering different DER technologies over a monthly planning horizon for national energy and capacity markets.

Nevertheless, hierarchical structures cannot be modelled by these single-level approaches. Multi-level optimization is a well-suited method for the modelling of leader-follower problems, in which the results of the lower level problem depends on the variables upper level problem. In this sense, multiple time scales were considered in [140], stacking revenues from energy arbitrage and residuals unit commitments. Virtual Power Plant services were co-optimized in [97] using a multi-level framework. Multi-level optimization also captures strategic decisions made by a profit maximising operator.

Bi-level optimization was used in [141], [142] to model the maximisation of revenues of BESSs in day-ahead and reserve markets. Microgrids bidding strategy in national day-ahead and real-time markets were investigated in [143], also considering their possible reconfiguration [144]. Besides of these assets, clusters of buildings with BESSs were used for the stacking of flexibility benefits in national markets [145]. Clusters of BESSs were used at national [146] and local markets [89] to stack flexibility revenues using two-stage programming. However, the main limitation of these proposals is that they do not address the sequential market clearing as all of them includes market with different timescales in the same level of the problem. To overcome this, Stackelberg games were used in [147] and [148] for multi-time scale allocation of energy and reserves. Equilibrium models were proposed in [149] and [150] to determine the optimal bidding strategy of virtual power plants participating in national day-ahead and real-time markets.

Both Multi-Level and Equilibrium Problems are usually recast into single-level optimization using KKTs conditions. These MINLP suffer from tractability issues, which hinders the proliferation of new business cases. To address this issue, authors in [151] proposed a bi-level approach that address the sequential market clearing of heat and electricity markets. Nevertheless, in this proposal short-term decision-making were placed over day-ahead decisions, which is unrealistic. Reference [152] overcome this issue using a tri-level optimization model for sequential clearing of heat and electricity markets. However, how to deal with the sequential market clearing of national and future local electricity markets inside a revenues-maximization strategy has not been addressed.

A summary of the conducted literature review is shown in Table 4.1, where the number of markets, DER technologies, time and spatial scales and type of problem are compared. In light of the above, the identified gaps in knowledge are,

G1 The sequential clearing of national and local markets has not been well addressed by literature. Research to date has not yet determined how to strategically manage DERs participating in national and local markets that are cleared sequentially.

G2 Aggregation of disparate DER technologies, considering the expected grow in HVAC systems and the electrification of the mobility, when they participate in national and local markets, is not properly addressed. Future local flexibility markets will be another source of incomes to DERs, which could unlock new business studies and boost their

Table 4.1: Summary of the literature review.

Reference	**Markets**	**Agents**	**Time Scale**	**Spatial Scale**	**Problem**
[138]	Energy arbitrage, Frequency regulation	BESS	Monthly	National	QCP
[134]	Energy arbitrage, Fast Frequency Response	BESS	Monthly	National	Scalar
[135]	Energy arbitrage	BESS	Monthly	National	MILP
[137]	Energy arbitrage	BESS, PV	Hourly	Local	NLP
[136]	Energy arbitrage	BESS, Wind	Monthly	National	MINLP
[91]	Energy arbitrage, Frequency regulation	BESS, PV	Monthly	National	Heuristics
[97]	Energy arbitrage, Fast Frequency Response, Ancillary Services	Virtual Power Plant	Multiple	National	MILP
[140]	Energy arbitrage, Reserve provision, Residual unit-commitment	CHP, BESS	Multiple	National	MILP
[147]	Energy arbitrage, Reserve provision	EV	Hourly	National	MIQCP
[139]	Energy arbitrage, Reserve provision	PV, BESS, EV, Wind	Monthly	National	MILP
[149]	Energy arbitrage, Real-time markets	Virtual Power Plant	Hourly	National	MPEC
[150]	Energy arbitrage, Real-time markets	Virtual Power Plant	Hourly	National	MPEC
[143]	Energy arbitrage, Reserve provision, Real-time markets	Microgrids	Hourly	National	MILP
[144]	Energy arbitrage, Reserve provision, Real-time markets	Microgrids	Hourly	National	MINLP
[145]	Energy arbitrage, Reserve provision, Regulation services	Buildings with BESS	Hourly	National	MILP
[146]	Energy arbitrage, Reserve provision, Real-time markets	BESS	Hourly	National	MINLP
[89]	Energy arbitrage, Reserve provision, LFM	BESS	Hourly	National, Local	MINLP
This paper	DAM, RM, LEM, LFM	BESSs, HVACs, FLs, FGs	Multiple	National, Local	NLP

deployment.

G3 Few studies have investigated the need of considering the influence of strategic decisions made by a FSP. This requires a multi-level optimisation approach, and the number of methodologies to address it is scarce.

To fill these gaps, this section proposes a tri-level optimization problem for the maximisation of stacked revenues from flexible DERs. Disparate DERs technologies are managed to provide both national and local services, taking into account that markets are cleared sequentially. A tri-level optimization problem is recast into a single-level NLP using the methodology based on duality proposed in [152]. Contributions of the proposed work are,

C1 A novel framework that supports simultaneous participation of DERs in local and national markets, providing both energy and capacity services. This methodology can deal with the physical interface of national and local markets and with their sequential clearance.

C2 Integration of multiple DER technologies including EVs and electric HVACs providing spatial and temporal flexibility coverage. The proposed framework can deal with multiple sources of flexibility providing several services to national and local markets.

C3 A tri-level optimization problem that models the stacking of flexibility revenues of DERs participating in sequential national and local markets. This tri-level problem is then converted into a tractable single-level problem which captures strategic decisions made by a FSP when dealing with temporal and spatial scales.

To achieve the above contributions, the first part of the chapter is organised as follows. After the introduction, the problem formulation will be described. Then, the proposed methodology for solving the resulting tri-level problem that maximises stacked revenues is presented. Results of a case study based on a combination of a transmission and distribution network are depicted.

4.2 Determinisitic problem formulation

In this section, the national and local market problems, the agent constraints and the profit maximiser objective are described. The scheme of the problem formulation is depicted in Fig. 4.2. A FSP manages DERs connected to the distribution grid. Those assets participate in two markets at national level, i.e., the Day-Ahead Market (DAM) and Reserve Market (RM), and other two at local level LEM and LFM. Those markets are linked by power flows $p_{i,j,t}$ between transmission and distribution networks. Besides, the deployment of the FSP's bids in national and local market scales are mutually affected by each other. This setting provides a new framework for strategic decision-making, using a tri-level optimisation problem. This methodology captures both the sequential market clearing of national and local markets and the strategic behaviour of the FSP, which is reflected in the modification of the bids when the FSP is participating in multiple markets. Then, we use duality theory and the method proposed by [152] to find an equivalent single-level optimisation problem.

The FSP aims to stack flexibility revenues from all markets. National markets are cleared first on an hourly basis, then, local markets are run with a timescale of 15 minutes. Clearing price of DAM is λ_t^{DA}, RM are μ_t^{ru} and μ_t^{rd}, LFM is λ_t^{LFM} and LEM is λ_t^{LEM}. FSP decides the price of the bids $\boldsymbol{\pi}_t$ and the limits of the bids of energy $\overline{\boldsymbol{\omega}}_t$, and capacity $\overline{\boldsymbol{\nu}}_t$ products for each time period t.

The timeline of the market is presented in Fig. 4.1. The DAM, which is managed by the TSO, is the market for clearing energy trading at transmission level. Market Operator (MO) receives asks and bids from agents at transmission level and the FSP, and network information from the TSO. Then, the DAM is cleared and agents are dispatched. After that, RM is cleared on an hourly timescale. In this market, TSO asks for reserves to the MO, which receives bids from agents connected to the transmission network. Before local markets are cleared, network constraints at the interface are sent to the DSO.

Each distribution network has its own LEM and LFM running in parallel with a 15 min timescale. The LEM supplies the local energy mismatch between DAM clearing and real scheduling of the assets. Energy bids are submitted to the LMO and the market is cleared maximizing the social welfare of participants. Then, a LFM is cleared in case any congestion or imbalance appears near real-time operation in the distribution network. Flexibility bids are sent by independent DERs and by the FSP.

The proposed approach aims to maximize revenue stacking from DERs in the market layer, the FSP serves as an interface between the network and control layers, leveraging historical data and sending control signals to ensure efficient market participation $\boldsymbol{\pi}_t, \overline{\boldsymbol{\omega}}_t, \overline{\boldsymbol{\nu}}_t$. FSP collects information about past results to forecast future market states,

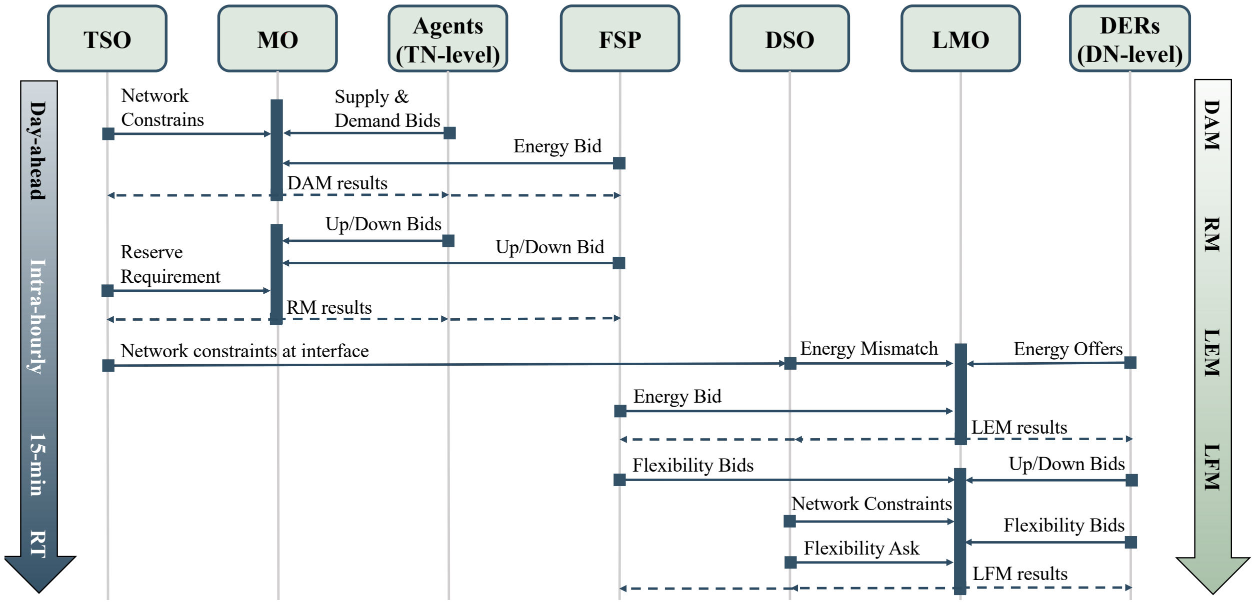


Figure 4.1: Timeline diagram of the market interactions among participants.

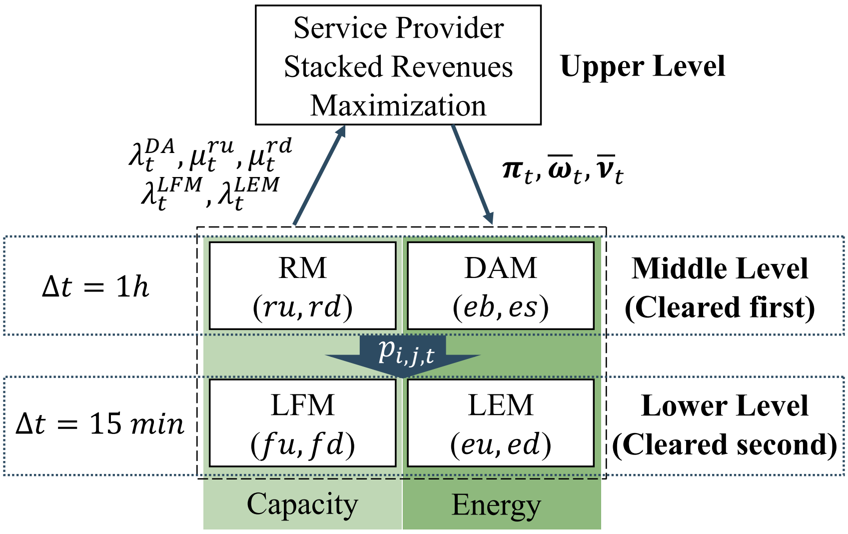


Figure 4.2: General scheme of the proposed structure. FSP sets bids prices π_t and limits for energy $\overline{\omega}_t$ and capacity $\overline{\nu}_t$ products, for the participation in national DAM and RM, and LEM and LFM, which set prices for energy λ_t^{DA}, upward μ_t^{ru} and downward μ_t^{rd} reserve, and local energy λ_t^{LEM} and flexibility λ_t^{LFM} products.

and the flexibility availability of its DERs. Figure 4.3 shows how the FSP manages this data to compute the optimal bid strategy and the control signals $p_{a,t}$ it sends to the DERs once the markets are cleared and the products ω, ν are dispatched. Note that no sensitive information about the DERs leaves the domains of the FSP. Thus, privacy is ensured.

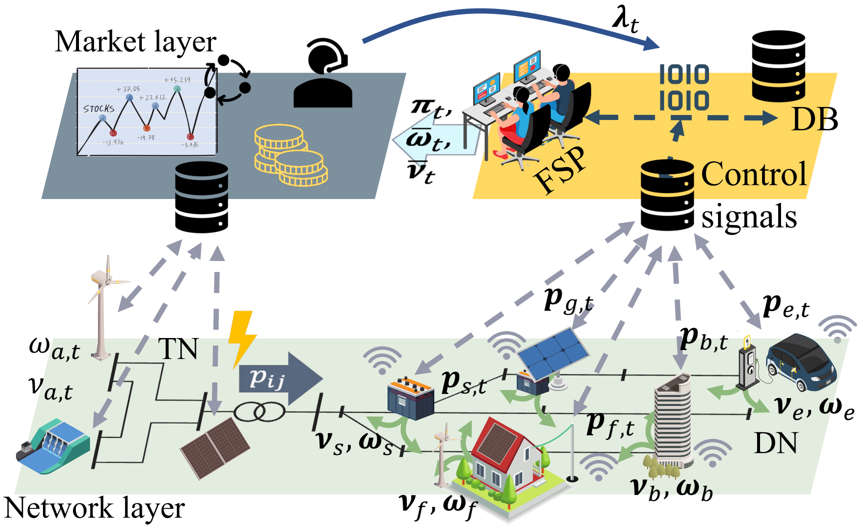


Figure 4.3: Conceptual diagram of the data exchanged in the proposed approach within the market/network layer and the FSP. Control signals are represented by grey dashed arrows while products dispatched are presented by green arrows

4.2.1 Day-Ahead Market

Problem (4.1) represents the DAM problem, where the social welfare of the participating agents is maximised. Let $\pi_{a,t}^{eb}$ and $\pi_{a,t}^{es}$ be the offer prices and $\omega_{a,t}^{eb}$ and $\omega_{a,t}^{es}$ be the quantity of the energy bought eb and energy sold es of the agent a in time period t in the DAM.

$$\max_{\omega^{eb}_{a,t},\omega^{es}_{a,t},\theta^{TN}_{i,t}} \sum_{t\in\Omega_t}\sum_{a\in\Omega_a}(\pi^{eb}_{a,t}\omega^{eb}_{a,t} - \pi^{es}_{a,t}\omega^{es}_{a,t}) \tag{4.1a}$$

Subject to,

$$\underline{\omega}^{eb}_{a,t} \leq \omega^{eb}_{a,t} \leq \overline{\omega}^{eb}_{a,t} \qquad \forall a\in\Omega_a, \forall t\in\Omega_t \tag{4.1b}$$

$$\underline{\omega}^{es}_{a,t} \leq \omega^{es}_{a,t} \leq \overline{\omega}^{es}_{a,t} \qquad \forall a\in\Omega_a, \forall t\in\Omega_t \tag{4.1c}$$

$$\sum_{a\in\Omega_a}\omega^{eb}_{a,t} = \sum_{a\in\Omega_a}\omega^{es}_{a,t} : \ \lambda^{DA}_t \qquad \forall t\in\Omega_t \tag{4.1d}$$

$$\sum_{j\in\Omega^{TN}_n} B^{TN}_{i,j}(\theta^{TN}_{i,t} - \theta^{TN}_{j,t}) = p^{TN}_{i,t} \qquad \forall i\in\Omega_n, \forall t\in\Omega_t \tag{4.1e}$$

$$\|B^{TN}_{i,j}(\theta^{TN}_{i,t} - \theta^{TN}_{j,t})\| \leq \overline{P}_{i,j} \qquad \forall (i,j)\in\Omega_l, \forall t\in\Omega_t \tag{4.1f}$$

$$-\pi \leq \theta^{TN}_{i,t} \leq \pi \qquad \forall i\in\Omega_n, \forall t\in\Omega_t \tag{4.1g}$$

Equations (4.1b) and (4.1c) represent the limit of the offers for the products traded in DAM. Demand is matched with generation through (4.1d). A DC power flow model is considered in (4.1e) – (4.1g) to characterize the node power balance as the DAM takes place in the transmission network. $p^{TN}_{i,t}$ represents the nodal injections of the agents connected to the grid. The prices of the products traded in the market are settled on a marginal basis using dual variables λ^{DA}_t associated with (4.1d).

4.2.2 Reserve Market

The RM is described by (4.2), where the cost of acquiring upward ru and downward rd reserves are minimised.

$$\min_{\nu^{ru}_{a,t},\nu^{rd}_{a,t}} \sum_{t\in\Omega_t}\sum_{a\in\Omega_a}(\pi^{ru}_{a,t}\nu^{ru}_{a,t} + \pi^{rd}_{a,t}\nu^{rd}_{a,t}) \tag{4.2a}$$

Subject to,

$$\nu^{ru}_{a,t} \leq \overline{\nu}^{ru}_{a,t} \qquad \forall a\in\Omega_a, \forall t\in\Omega_t \tag{4.2b}$$

$$\nu^{rd}_{a,t} \leq \overline{\nu}^{rd}_{a,t} \qquad \forall a\in\Omega_a, \forall t\in\Omega_t \tag{4.2c}$$

$$\sum_{a\in\Omega_a}\nu^{ru}_{a,t} \geq R^u_t : \ \mu^{ru}_t \qquad \forall t\in\Omega_t \tag{4.2d}$$

$$\sum_{a\in\Omega_a}\nu^{ru}_{a,t} \geq R^d_t : \ \mu^{rd}_t \qquad \forall t\in\Omega_t \tag{4.2e}$$

Upward ru and downward rd offer blocks are described by (4.2b) and (4.2c). TSO asks for upward R^u_t and downward R^d_t reserves in the market in prevision of future eventualities in the grid. The price of the upward and downward products are settled by dual variables μ^{ru}_t and μ^{rd}_t, respectively.

4.2.3 Local Energy Market

LEM is organized at the local level to adjust for the lack of demand or generation (i.e. ΔE_t) considering what has been previously settled up in the DAM. This market aims to maximise social welfare of participants as (4.3) states.

$$\max_{\omega^{eu}_{a,t},\omega^{ed}_{a,t}} \sum_{t\in\Omega_t}\sum_{a\in\Omega_a}(\pi^{eu}_{a,t}\omega^{eu}_{a,t} - \pi^{ed}_{a,t}\omega^{ed}_{a,t}) \tag{4.3a}$$

Subject to

$$\omega^{eu}_{a,t} \leq \overline{\omega}^{eu}_{a,t} \qquad \forall a \in \Omega_a, \forall t \in \Omega_t \tag{4.3b}$$

$$\omega^{ed}_{a,t} \leq \overline{\omega}^{ed}_{a,t} \qquad \forall a \in \Omega_a, \forall t \in \Omega_t \tag{4.3c}$$

$$\sum_{a\in\Omega_a}(\omega^{eu}_{a,t} - \omega^{ed}_{a,t}) = \Delta E_t : \;\; \lambda^{LEM}_t \qquad \forall t \in \Omega_t \tag{4.3d}$$

Equations (4.3b) and (4.3c) represent the upward eu and downward ed energy offer limits. Then, the mismatch is compensated by those energy products in (4.3d). Dual variable λ^{LEM}_t associated to (4.3d) represents the price of the products traded.

4.2.4 Local Flexibility Market

LFM is organized to mitigate congestions in the distribution grid. DSO minimizes the cost of acquiring flexibility in (4.4).

$$\min_{\substack{\nu^{fu}_{a,t},\nu^{fd}_{a,t},\theta^{DN}_{i,t},\\ v^{DN}_{i,t},p_{i,j,t},q_{i,j,t}}} \sum_{t\in\Omega_t}\sum_{a\in\Omega_a}(\pi^{fu}_{a,t}\nu^{fu}_{a,t} + \pi^{fd}_{a,t}\nu^{fd}_{a,t}) \tag{4.4a}$$

Subject to

$$\nu^{fu}_{a,t} \leq \overline{\nu}^{fu}_{a,t} \qquad \forall a \in \Omega_a, \forall t \in \Omega_t \tag{4.4b}$$

$$\nu^{fd}_{a,t} \leq \overline{\nu}^{fd}_{a,t} \qquad \forall a \in \Omega_a, \forall t \in \Omega_t \tag{4.4c}$$

$$\sum_{j\in\Omega_n}[G^{DN}_{i,j}v^{DN}_{j,t} - B_{i,j}\theta^{DN}_{j,t}] = p^{DN}_{i,t} \qquad \forall i \in \Omega_n, \forall t \in \Omega_t \tag{4.4d}$$

$$\sum_{j\in\Omega_n}[-B^{DN}_{i,j}v^{DN}_{j,t} - G_{i,j}\theta^{DN}_{j,t}] = q^{DN}_{i,t} \qquad \forall i \in \Omega_n, \forall t \in \Omega_t \tag{4.4e}$$

$$p_{i,j,t} = G_{i,j}v_{i,j,t} - B_{i,j}\theta_{i,j,t} \qquad \forall (i,j) \in \Omega_l, \forall t \in \Omega_t \tag{4.4f}$$

$$q_{i,j,t} = -B_{i,j}v_{i,j,t} - G_{i,j}\theta_{i,j,t} \qquad \forall (i,j) \in \Omega_l, \forall t \in \Omega_t \tag{4.4g}$$

$$p^2_{i,j,t} + q^2_{i,j,t} \leq \overline{S}^2_{i,j} \qquad \forall (i,j) \in \Omega_l, \forall t \in \Omega_t \tag{4.4h}$$

$$\sum_{a\in\Omega_a}\nu^{fu}_{a,t} = \sum_{a\in\Omega_a}\nu^{fd}_{a,t} : \;\; \lambda^{LFM}_t \qquad \forall t \in \Omega_t \tag{4.4i}$$

$$-\pi \leq \theta^{DN}_{i,t} \leq \pi \qquad \forall i \in \Omega_n, \forall t \in \Omega_t \tag{4.4j}$$

$$\underline{V}^{DN}_i \leq v^{DN}_{i,t} \leq \overline{V}^{DN}_i \qquad \forall i \in \Omega_n, \forall t \in \Omega_t \tag{4.4k}$$

Upward fu and downward fd limits are represented by (4.4b) and (4.4c), respectively.

Let $p_{i,t}^{DN}$ and $q_{i,t}^{DN}$ be nodal injections at node i and time period t in the distribution network. Let $v_{i,j,t}$ and $\theta_{i,j,t}$ be the voltage magnitude and phase angle difference between nodes i and j in time period t. We consider a linear approximation of the active and reactive node balance of the distribution grid in (4.4d) and (4.4e) as in [67]. Then, power flows are computed in (4.4f) and (4.4g). Thermal limit of the branch is computed in conic constraint (4.4h). Equation (4.4i) ensures that the total amount of upward and downward products are the same, so the solution of the LFM market is compatible with previously settled markets. Lastly, voltage phase angle and magnitude limits are described by (4.4j) and (4.4k). Price of the products are settled by dual variable λ_t^{LFM} associated to (4.4i).

4.2.5 FSP objective

The FSP seeks the maximization of the revenues obtained from all the markets previously described, as (4.5) presents.

$$\max_{\boldsymbol{\pi}_t,\overline{\boldsymbol{\omega}}_t,\overline{\boldsymbol{\nu}}_t} \sum_{t\in\Omega_t} \left[\lambda_t^{DA}(\omega_t^{es}-\omega_t^{eb}) + \mu_t^{u}\nu_t^{ru} + \mu_t^{d}\nu_t^{rd} + \lambda_t^{LEM}(\omega_t^{ed}-\omega_t^{eu}) + \sum_{a\in\Omega_a}\lambda_t^{LFM}(\nu_{a,t}^{fu}+\nu_{a,t}^{fd})\right] \tag{4.5a}$$

Subject to

$$\pi_t^{eb},\pi_t^{es},\pi_t^{ru},\pi_t^{rd},\pi_t^{eu},\pi_t^{ed},\overline{\omega}_t^{eb},\overline{\omega}_t^{es},\overline{\nu}_t^{ru},\overline{\nu}_t^{rd},\overline{\omega}_t^{eu},\overline{\omega}_t^{ed},\geq 0 \ \forall t\in\Omega_t \tag{4.5b}$$

$$\pi_{a,t}^{fu},\pi_{a,t}^{fd},\overline{\nu}_{a,t}^{fu},\overline{\nu}_{a,t}^{fd}\geq 0 \qquad \forall a\in\Omega_a,\forall t\in\Omega_t \tag{4.5c}$$

$$\omega_t^{es}=\sum_{a\in\Omega_a}\omega_{a,t}^{es},\ \ \omega_t^{eb}=\sum_{a\in\Omega_a}\omega_{a,t}^{eb} \qquad \forall t\in\Omega_t \tag{4.5d}$$

$$\nu_t^{ru}=\sum_{a\in\Omega_a}\nu_{a,t}^{ru},\ \ \nu_t^{rd}=\sum_{a\in\Omega_a}\nu_{a,t}^{rd} \qquad \forall t\in\Omega_t \tag{4.5e}$$

$$\omega_t^{eu}=\sum_{a\in\Omega_a}\omega_{a,t}^{eu},\ \ \omega_t^{ed}=\sum_{a\in\Omega_a}\omega_{a,t}^{ed} \qquad \forall t\in\Omega_t \tag{4.5f}$$

$$(4.6)-(4.10) \tag{4.5g}$$

FSP stacks revenues from the markets it participates in by defining the optimal bid, i.e., price and quantity. The objective described in (4.5a) maximises the revenues obtained from the DAM, RM, LEM and LFM. Prices and offers are positive as (4.5b) and (4.5c) defines. Aggregation of the bids for the DAM is described in (4.5d), for RM in (4.5e) and for LEM in (4.5f). The agents constraints for FLs, FGs, BESSs, EVs and HVACs systems are explained in Appendix A and included in the model in (4.5g).

4.2.6 Agent modelling

With the aim of modelling disparate DER technologies, constraints of FLs, FGs, BESSs, EVs and HVACs are described in this appendix. FLs are modelled as elastic demands which can modify their consumption $p_{d,t}$ between an upper and lower bound $\underline{P}_d \leq p_{d,t} \leq \overline{P}_d$ [104]. Let $P_{d,t}^{ref}$ be the static consumption of the FL d in time period t, it can offer upward

$\omega^{u}_{d,t}$ and downward $\omega^{d}_{d,t}$ products following,

$$p_{d,t} = P^{ref}_{d,t} + (\omega^{u}_{d,t} - \omega^{d}_{d,t})/\Delta t \qquad \forall d \in \Omega_d, \forall t \in \Omega_t \quad (4.6)$$

In addition, FLs can also offer upward $\nu^{u}_{d,t}$ and downward $\nu^{d}_{d,t}$ capacity products restricting their limits of demand, as $\underline{P}_d + \nu^{d}_{d,t} \leq p_{d,t} \leq \overline{P}_d - \nu^{u}_{d,t}$. Similarly, FGs can modify their energy production $p_{g,t}$ between an upper and lower bound while providing upward and downward capacity products $\underline{P}_g + \nu^{d}_{g,t} \leq p_{g,t} \leq \overline{P}_g - \nu^{u}_{g,t}$. Then, considering $P^{ref}_{g,t}$ its generation,

$$p_{g,t} = P^{ref}_{g,t} + (\omega^{u}_{g,t} - \omega^{d}_{g,t})/\Delta t \qquad \forall g \in \Omega_g, \forall t \in \Omega_t \quad (4.7)$$

Let s be a storage system with a SOC $soc_{s,t}$ that could charge at power $p^{ch}_{s,t} \geq 0$ and discharge at power $p^{dis}_{s,t} \geq 0$, with efficiencies charging η^{ch}_{s} and discharging η^{dis}_{s} [104]. The internal constraints that model storage agents are the following,

$$soc_{s,t+1} = soc_{s,t} + \Delta t \left(\eta^{ch}_{s} p^{ch}_{s,t} - \frac{p^{dis}_{s,t}}{\eta^{dis}_{s}} \right) \qquad \forall s \in \Omega_s, \forall t \in \Omega_t \quad (4.8a)$$

$$\underline{SOC}_s \leq soc_{s,t} \leq \overline{SOC}_s \qquad \forall s \in \Omega_s, \forall t \in \Omega_t \quad (4.8b)$$

$$0 \leq p^{ch}_{s,t} \leq \overline{P}_{s,t}, \;\; 0 \leq p^{dis}_{s,t} \leq \overline{P}_{s,t} \qquad \forall s \in \Omega_s, \forall t \in \Omega_t \quad (4.8c)$$

Using this model, is possible to include the behaviour of EVs. Let t^{arr}_{e}, t^{dep}_{e} be arrival and departure times of the EV e, considering it must leave at departure time with SOC^{OBJ}_{e}, two additional constraints must be added [153],

$$\overline{P}_{e,t} = \begin{cases} 0, & \forall t \notin [t^{arr}_{e}, t^{dep}_{e}] \\ p^{EV}_{e} & \forall t \in [t^{arr}, t^{dep}] \end{cases} \qquad \forall e \in \Omega_e, \forall t \in \Omega_t \quad (4.9a)$$

$$soc_{e,t^{dep}_{e}} = SOC^{OBJ}_{e} \qquad \forall e \in \Omega_e \quad (4.9b)$$

Thermal characteristics of the HVAC systems are modelled by a first order discrete temperature model in (4.10). Let $\tau_{b,t}$ be the temperature of the building, $\tau^{out}_{b,t}$ be the ambient temperature, $p^{he}_{b,t}, p^{co}_{b,t}$ be the heating and cooling power, R_b, C_b, be thermal constants and $\eta^{he}_{b}, \eta^{co}_{b}$ are efficiencies of the heating and cooling [154]. Then, the HVAC system is modelled by,

$$\tau_{b,t+1} = \tau_{b,t} + \frac{\Delta t}{R_b C_b}\left[\tau^{out}_{b,t} - \tau_{b,t}\right] + \frac{\Delta t}{C_b}\left[\eta^{he}_{b} p^{he}_{b,t} - \eta^{co}_{b} p^{co}_{b,t}\right] \qquad \forall b \in \Omega_b, \forall t \in \Omega_t \quad (4.10a)$$

$$\underline{\tau}_{b,t} \leq \tau_{b,t} \leq \overline{\tau}_{b,t} \qquad \forall b \in \Omega_b, \forall t \in \Omega_t \quad (4.10b)$$

$$0 \leq p^{he}_{b,t} \leq \overline{P}^{he}_{b}, \;\; 0 \leq p^{co}_{b,t} \leq \overline{P}^{co}_{b} \qquad \forall b \in \Omega_b, \forall t \in \Omega_t \quad (4.10c)$$

4.3 Tri-level Optimization for revenues maximization

The maximization problem of the FSP is subject to the sequential market clearing of the DAM, RM, LEM and LFM. We propose a tri-level optimization problem for stacking revenues of DERs managed by a FSP in those markets.

The sequential clearing of the national and local markets is represented by the mid and lower-level problem, respectively, following [152].

4.3.1 Sequential problem formulation

We use matrix notation to represent the tri-level optimization problem. Let $\boldsymbol{x}_m$, $\boldsymbol{\lambda}_m$ be the vector of primal and dual decision variables for a given market m. Constraints of the markets are represented without loss of generality with inequalities for the sake of readability. Let $\boldsymbol{A}_m$ and $\boldsymbol{B}_m$ be the matrices of coefficients and $\boldsymbol{b}_m$ the vector of independent terms for market m. $\boldsymbol{B}_m$ is the matrix associated to FSP agents, and $\boldsymbol{A}_m$ is the matrix of the rest of agents. Lastly, vector $\boldsymbol{c}_m$ represents the price of the offers in the market m. Thus, the full tri-level optimization is presented in (4.11).

$$\min -\boldsymbol{\lambda}_{DA}^{T}\boldsymbol{x}_{DA}^{FSP} - \boldsymbol{\lambda}_{RM}^{T}\boldsymbol{x}_{RM}^{FSP} - \boldsymbol{\lambda}_{LEM}^{T}\boldsymbol{x}_{LEM}^{FSP} - \boldsymbol{\lambda}_{LFM}^{T}\boldsymbol{x}_{LFM}^{FSP} \tag{4.11a}$$

Subject to

$$\boldsymbol{A}^{FSP}\boldsymbol{x}^{FSP} \leq \boldsymbol{b}^{FSP} \tag{4.11b}$$

$$\min -\boldsymbol{c}_{DA}^{T}\boldsymbol{x}_{DA} - \boldsymbol{c}_{DA}^{FSP^{T}}\boldsymbol{x}_{DA}^{FSP} + \boldsymbol{c}_{RM}^{T}\boldsymbol{x}_{RM} + \boldsymbol{c}_{RM}^{FSP^{T}}\boldsymbol{x}_{RM}^{FSP} \tag{4.11c}$$

Subject to

$$\boldsymbol{A}_{DA}\boldsymbol{x}_{DA} + \boldsymbol{B}_{DA}\boldsymbol{x}_{DA}^{FSP} \leq \boldsymbol{b}_{DA} \;\; : \boldsymbol{\lambda}_{DA} \tag{4.11d}$$

$$\boldsymbol{A}_{RM}\boldsymbol{x}_{RM} + \boldsymbol{B}_{RM}\boldsymbol{x}_{RM}^{FSP} \leq \boldsymbol{b}_{RM} \; : \boldsymbol{\lambda}_{RM} \tag{4.11e}$$

$$\min \boldsymbol{c}_{LEM}^{T}\boldsymbol{x}_{LEM} + \boldsymbol{c}_{LEM}^{FSP^{T}}\boldsymbol{x}_{LEM}^{FSP} + \boldsymbol{c}_{LFM}^{T}\boldsymbol{x}_{LFM} + \boldsymbol{c}_{LFM}^{FSP^{T}}\boldsymbol{x}_{LFM}^{FSP} \tag{4.11f}$$

Subject to

$$\boldsymbol{A}_{LEM}\boldsymbol{x}_{LEM} + \boldsymbol{B}_{LEM}\boldsymbol{x}_{LEM}^{FSP} \leq \boldsymbol{b}_{LEM} : \boldsymbol{\lambda}_{LEM} \tag{4.11g}$$

$$\boldsymbol{A}_{LFM}\boldsymbol{x}_{LFM} + \boldsymbol{B}_{LFM}\boldsymbol{x}_{LFM}^{FSP} \leq \boldsymbol{b}_{LFM} : \boldsymbol{\lambda}_{LFM} \tag{4.11h}$$

Equation (4.11a) and (4.11b) represents the maximization problem of the FSP, which is subject to the mid and lower level problems. Mid-level problem objective (4.11c) represents the joint clearing of the DAM and RM. Equations (4.11d) and (4.11e) represents the

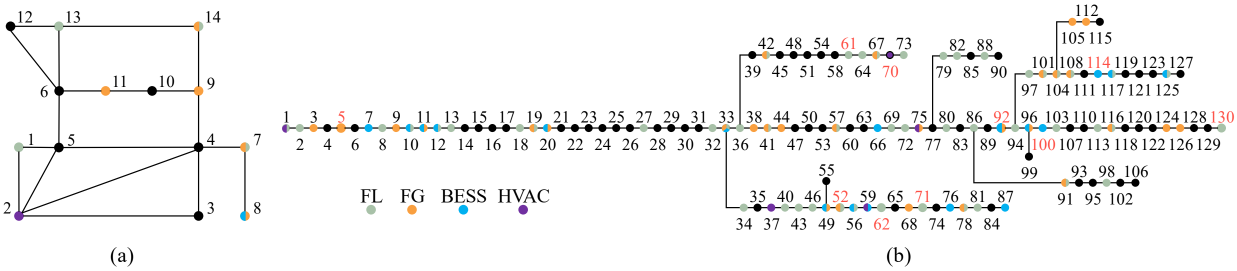


Figure 4.4: (a) IEEE 14 network (b) N5_1_DSS network. Assets managed by the FSP are noted in red.

DAM and RM constraints. Lower level problem (4.11f) jointly minimize costs for LEM and LFM, which constraints are represented by (4.11g) and (4.11h).

4.3.2 Equivalent problem

In this section, the tri-level problem in (4.11) is converted into a single-level problem using lexicographic optimization and duality theory. Note that variables from the mid-level problem (4.11c) – (4.11e) do not depend on the variables of the low-level problem (4.11f) – (4.11h). This enables to reformulate (4.11c) – (4.11h) as a single-level problem using the following lexicographic function [155].

$$\min \begin{pmatrix} -\boldsymbol{c}_{DA}^{T}\boldsymbol{x}_{DA} - \boldsymbol{c}_{DA}^{FSP^T}\boldsymbol{x}_{DA}^{FSP} + \boldsymbol{c}_{RM}^{T}\boldsymbol{x}_{RM} + \boldsymbol{c}_{RM}^{FSP^T}\boldsymbol{x}_{RM}^{FSP} \\ \boldsymbol{c}_{LEM}^{T}\boldsymbol{x}_{LEM} + \boldsymbol{c}_{LEM}^{FSP^T}\boldsymbol{x}_{LEM}^{FSP} + \boldsymbol{c}_{LFM}^{T}\boldsymbol{x}_{LFM} + \boldsymbol{c}_{LFM}^{FSP^T}\boldsymbol{x}_{LFM}^{FSP} \end{pmatrix} \tag{4.12a}$$

$$\tag{4.12b}$$

Subject to

$$\boldsymbol{A}_{DA}\boldsymbol{x}_{DA} + \boldsymbol{B}_{DA}\boldsymbol{x}_{DA}^{FSP} \leq \boldsymbol{b}_{DA} \;\; : \boldsymbol{\lambda}_{DA} \tag{4.12c}$$

$$\boldsymbol{A}_{RM}\boldsymbol{x}_{RM} + \boldsymbol{B}_{RM}\boldsymbol{x}_{RM}^{FSP} \leq \boldsymbol{b}_{RM} \; : \boldsymbol{\lambda}_{RM} \tag{4.12d}$$

$$\boldsymbol{A}_{LEM}\boldsymbol{x}_{LEM} + \boldsymbol{B}_{LEM}\boldsymbol{x}_{LEM}^{FSP} \leq \boldsymbol{b}_{LEM} : \boldsymbol{\lambda}_{LEM} \tag{4.12e}$$

$$\boldsymbol{A}_{LFM}\boldsymbol{x}_{LFM} + \boldsymbol{B}_{LFM}\boldsymbol{x}_{LFM}^{FSP} \leq \boldsymbol{b}_{LFM} : \boldsymbol{\lambda}_{LFM} \tag{4.12f}$$

This lexicographic problem can be asymptotically approximated by the linear problem (4.13) when $\gamma \to 1$ [152]. Let $f(y)$ and $g(z)$ be the objective of the mid and lower level problems. The resulting lexicographic function is $l(y, z) = \gamma f(y) + (1 - \gamma)g(z)$. The term $(1 - \gamma)g(z)$ becomes negligible when $\gamma \to 1$, so the objective first find the optimal value of y that minimises $f(y)$, and then optimises $g(z)$, approximating the sequential clearing behaviour.

The sequential clearing is then approximated by,

$$\begin{aligned} \min \gamma[&-\boldsymbol{c}_{DA}^{T}\boldsymbol{x}_{DA} - \boldsymbol{c}_{DA}^{FSP^T}\boldsymbol{x}_{DA}^{FSP} + \boldsymbol{c}_{RM}^{T}\boldsymbol{x}_{RM} + \boldsymbol{c}_{RM}^{FSP^T}\boldsymbol{x}_{RM}^{FSP}]+ \\ &+ (1-\gamma)[\boldsymbol{c}_{LEM}^{T}\boldsymbol{x}_{LEM} + \boldsymbol{c}_{LEM}^{FSP^T}\boldsymbol{x}_{LEM}^{FSP} + \boldsymbol{c}_{LFM}^{T}\boldsymbol{x}_{LFM} + \boldsymbol{c}_{LFM}^{FSP^T}\boldsymbol{x}_{LFM}^{FSP}] \end{aligned} \tag{4.13a}$$

s.t. (4.12c) - (4.12f) (4.13b)

At this point, the tri-level problem has been converted into a bi-level problem. To tackle this, the lower-level problem will be replaced by its set of primal and dual constraint.

After that, the resulting bi-level optimization is solved by replacing the inner problem for its set of primal (4.14c) – (4.14f), dual (4.14g) – (4.14n) and strong duality constraint (4.14o). The optimality of this problem will be guaranteed by also including the strong duality condition into the single-level problem [156].

Strong duality condition guarantees that any feasible solution of the proposed single level problem is an optimal solution of the lower level problem. The objective function is composed by two terms: FSP profit maximisation in national and local markets. However, the previous approximation affects to the scale of the dual variables of the inner problem. Thus, the original scale of the dual variables of the inner problem should be recovered by dividing mid-level dual variables by γ and lower-level dual variables by $(1-\gamma)$ in the final objective function (4.14a). The final result is presented in (4.14).

$$\min -\frac{1}{\gamma}\left[\boldsymbol{\lambda}_{DA}^{T}\boldsymbol{x}_{DA}^{FSP}+\boldsymbol{\lambda}_{RM}^{T}\boldsymbol{x}_{RM}^{FSP}\right]-\frac{1}{1-\gamma}\left[\boldsymbol{\lambda}_{LEM}^{T}\boldsymbol{x}_{LEM}^{FSP}+\boldsymbol{\lambda}_{LFM}^{T}\boldsymbol{x}_{LFM}^{FSP}\right] \tag{4.14a}$$

Subject to,

$$\boldsymbol{A}^{FSP}\boldsymbol{x}^{FSP} \leq \boldsymbol{b}^{FSP} \tag{4.14b}$$

$$\boldsymbol{A}_{DA}\boldsymbol{x}_{DA}+\boldsymbol{B}_{DA}\boldsymbol{x}_{DA}^{FSP} \leq \boldsymbol{b}_{DA} \tag{4.14c}$$

$$\boldsymbol{A}_{RM}\boldsymbol{x}_{RM}+\boldsymbol{B}_{RM}\boldsymbol{x}_{RM}^{FSP} \leq \boldsymbol{b}_{RM} \tag{4.14d}$$

$$\boldsymbol{A}_{LEM}\boldsymbol{x}_{LEM}+\boldsymbol{B}_{LEM}\boldsymbol{x}_{LEM}^{FSP} \leq \boldsymbol{b}_{LEM} \tag{4.14e}$$

$$\boldsymbol{A}_{LFM}\boldsymbol{x}_{LFM}+\boldsymbol{B}_{LFM}\boldsymbol{x}_{LFM}^{FSP} \leq \boldsymbol{b}_{LFM} \tag{4.14f}$$

$$\boldsymbol{\lambda}_{DA}^{T}\boldsymbol{A}_{DA} \leq -\gamma\boldsymbol{c}_{DA}^{T} \tag{4.14g}$$

$$\boldsymbol{\lambda}_{DA}^{T}\boldsymbol{B}_{DA} \leq -\gamma\boldsymbol{c}_{DA}^{FSP^{T}} \tag{4.14h}$$

$$\boldsymbol{\lambda}_{RM}^{T}\boldsymbol{A}_{RM} \leq \gamma\boldsymbol{c}_{RM}^{T} \tag{4.14i}$$

$$\boldsymbol{\lambda}_{RM}^{T}\boldsymbol{B}_{RM} \leq \gamma\boldsymbol{c}_{RM}^{FSP^{T}} \tag{4.14j}$$

$$\boldsymbol{\lambda}_{LEM}^{T}\boldsymbol{A}_{LEM} \leq -(1-\gamma)\boldsymbol{c}_{LEM}^{T} \tag{4.14k}$$

$$\boldsymbol{\lambda}_{LEM}^{T}\boldsymbol{B}_{LEM} \leq -(1-\gamma)\boldsymbol{c}_{LEM}^{FSP^{T}} \tag{4.14l}$$

$$\boldsymbol{\lambda}_{LFM}^{T}\boldsymbol{A}_{LFM} \leq (1-\gamma)\boldsymbol{c}_{LFM}^{T} \tag{4.14m}$$

$$\boldsymbol{\lambda}_{LFM}^{T}\boldsymbol{B}_{LFM} \leq (1-\gamma)\boldsymbol{c}_{LFM}^{FSP^{T}} \tag{4.14n}$$

$$\begin{aligned}&\gamma\left[-\boldsymbol{c}_{DA}^{T}\boldsymbol{x}_{DA}-\boldsymbol{c}_{DA}^{FSP^{T}}\boldsymbol{x}_{DA}^{FSP}+\boldsymbol{c}_{RM}^{T}\boldsymbol{x}_{RM}+\boldsymbol{c}_{RM}^{FSP^{T}}\boldsymbol{x}_{RM}^{FSP}\right]\\&+(1-\gamma)\left[-\boldsymbol{c}_{LEM}^{T}\boldsymbol{x}_{LEM}-\boldsymbol{c}_{LEM}^{FSP^{T}}\boldsymbol{x}_{LEM}^{FSP}+\boldsymbol{c}_{LFM}^{T}\boldsymbol{x}_{LFM}+\boldsymbol{c}_{LFM}^{FSP^{T}}\boldsymbol{x}_{LFM}^{FSP}\right]=\\&\boldsymbol{b}_{DA}\boldsymbol{\lambda}_{DA}^{T}+\boldsymbol{b}_{RM}\boldsymbol{\lambda}_{RM}^{T}+\boldsymbol{b}_{LEM}\boldsymbol{\lambda}_{LEM}^{T}+\boldsymbol{b}_{LFM}\boldsymbol{\lambda}_{LFM}^{T}\end{aligned} \tag{4.14o}$$

Equation (4.14b) represents FSP constraints, primal constraints of each market are depicted from (4.14c) to (4.14f). Equations (4.14g) - (4.14n) represent dual constraints of the sequential markets clearing considering the previously lexicographic function. Lastly, (4.14o) ensures that strong duality condition of the sequential markets clearing is satisfied.

4.3.3 Stochastic formulation

In this section, a stochastic formulation of the problem is described using a scenario tree, as Fig. 4.5 depicts. We assume that the FSP have access to historical data of previous market clearing results. This enable the FSP to build forecast tools which can predict the future values of the bids $\pi_{e,a,t}$, the quantities $\overline{\omega}_{e,a,t}$, $\overline{\nu}_{e,a,t}$ for all agent $a \in \Omega_a$, and time period $t \in \Omega_t$ for a set of scenarios $e \in \Omega_e$. Following authors in [69], the errors of the forecasting tools are characterized using a normal distribution, with a standard deviation of 25% and a mean value equal to the forecast value. To avoid computational burden, we use a scenario reduction technique to include the most representative scenarios into the final problem [70].

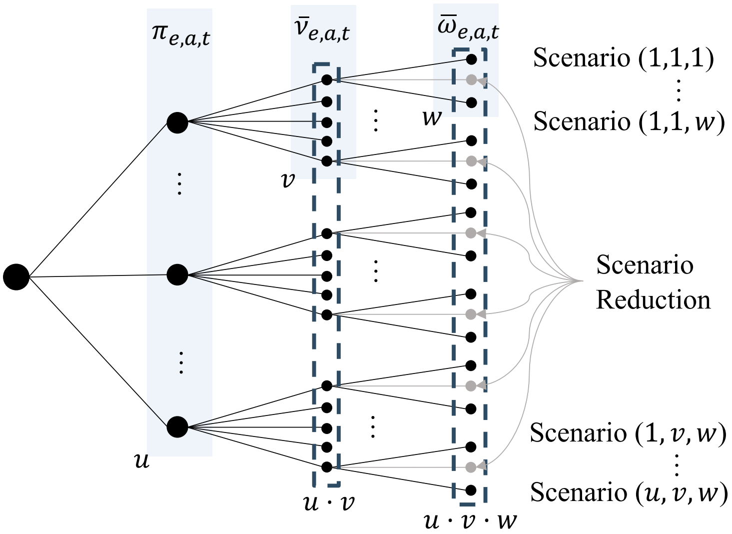


Figure 4.5: Scenario tree of the stochastic version of the problem. Unrepresentative scenarios are deleted using a scenario reduction technique.

The stochastic version is described as follows. Let $\hat{X}$ be the mean of the uncertain parameter X and $\Delta\tilde{e}_e^X$ be the forecast error in the scenario e for the parameter X. Thus, the bids $\pi_{e,a,t}$ and their quantities $\overline{\omega}_{e,a,t}$, $\overline{\nu}_{e,a,t}$ are decomposed as follows,

$$\pi_{e,a,t} = \hat{\pi}_{a,t} + \Delta\tilde{e}_e^{\pi_{a,t}} \qquad \forall e \in \Omega_e, \forall a \in \Omega_a, \forall t \in \Omega_t \tag{4.15a}$$

$$\overline{\omega}_{e,a,t} = \hat{\overline{\omega}}_{a,t} + \Delta\tilde{e}_e^{\overline{\omega}_{a,t}} \qquad \forall e \in \Omega_e, \forall a \in \Omega_a, \forall t \in \Omega_t \tag{4.15b}$$

$$\overline{\nu}_{e,a,t} = \hat{\overline{\nu}}_{a,t} + \Delta\tilde{e}_e^{\overline{\nu}_{a,t}} \qquad \forall e \in \Omega_e, \forall a \in \Omega_a, \forall t \in \Omega_t \tag{4.15c}$$

Then, the expected value of the profits is maximised for all scenario e in the set of possible realizations Ω_e. Let $\mathcal{P}_e$ the probability of the scenario e, the stochastic formulation of the problem stand as follows,

$$\min \sum_{e\in\Omega_e} \mathcal{P}_e \Bigg[-\frac{1}{\gamma}\Big[\boldsymbol{\lambda}_{e,DA}^T \boldsymbol{x}_{e,DA}^{FSP} + \boldsymbol{\lambda}_{e,RM}^T \boldsymbol{x}_{e,RM}^{FSP}\Big] - \frac{1}{1-\gamma}\Big[\boldsymbol{\lambda}_{e,LEM}^T \boldsymbol{x}_{e,LEM}^{FSP} + \boldsymbol{\lambda}_{e,LFM}^T \boldsymbol{x}_{e,LFM}^{FSP}\Big]\Bigg] \tag{4.16a}$$

$$\text{s.t. } (4.14\text{b}) - (4.14\text{o}) \qquad \forall e \in \Omega_e \tag{4.16b}$$

4.4 Case Study and Simulation Results

In this section, results based on a case study that builds on IEEE 14 bus network, acting as transmission network, and N5_1_DSS [157], acting as distribution network, are shown. Transmission and distribution networks are depicted in Fig. 4.4 (a) and (b), respectively.

Bus 1 of the distribution network is connected to bus 14 of the transmission network. A realistic dataset for generation and load profiles is used from [117]. Bids of the different market participants are randomly generated following Spanish markets average prices. 11 agents are connected to the transmission network as depicted in Fig. 4.4 (a), with a power of 3,85 MW. There are 105 agents connected to the distribution network as Fig. 4.4 (b) shows, with a power of 1,26 MW. FSP manages 4 FLs, 3 FGs, 2 BESSs and 1 HVACs connected to the distribution grid, they are noted with red text in Fig. 4.4 (b). National markets, i.e., DAM and RM are cleared at transmission level, while local markets, i.e., LEM and LFM, are cleared at distribution level. Simulations are carried out using PYOMO [158] and large-scale non-linear solver CONOPT v3.17A using an Apple M1, 3.2 GHz processor with 16 GB of RAM. CONOPT solver was used as it outperforms heuristics techniques to solve NLP problems, obtaining consistent solutions and computational times more than 30 times lower [159]. The optimization problem has 557,437 variables and 100,608 constraints. Time until convergence was 323.9165 seconds, which is compliant with the clearing timeframe of the short-term markets. The number of internal solver iterations until convergence was 3,769.

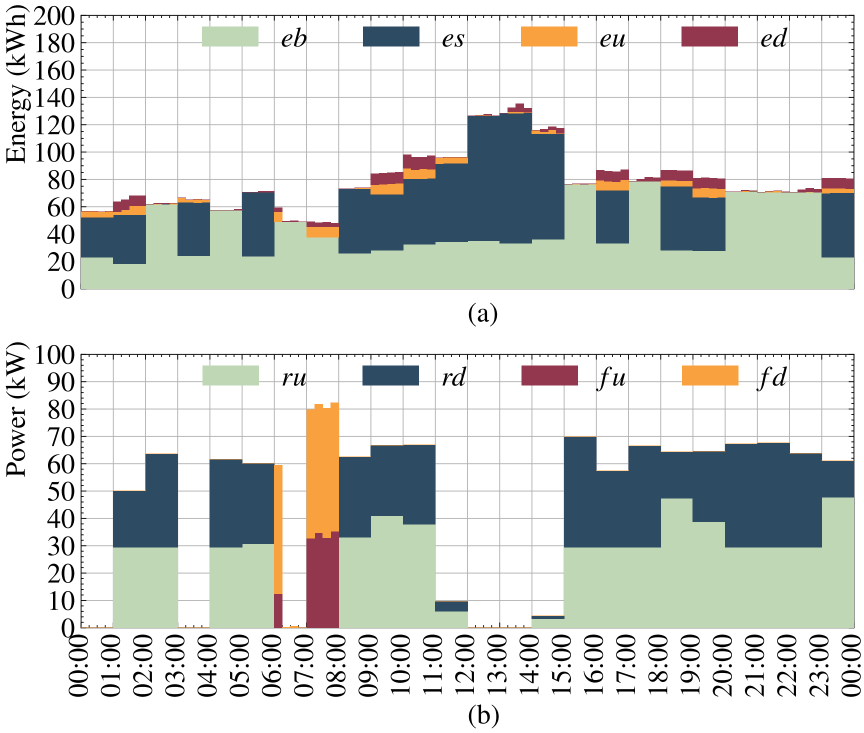
4.4.1 Stacked revenues from market participation

In this section, simulation results are presented for the case study to show how the FSP stacks profits by participating in different markets simultaneously. Figure 4.6 presents the products traded in the markets. Energy products eb, es, eu and eb are depicted in Fig. 4.6 (a), while capacity products ru, rd, fu and fd are depicted in Fig. 4.6 (b). What stands out in this figure is the multi-temporal scale of the products. Local products are traded with 15 min time granularity, while national products are traded on an hourly basis.

Energy products are traded in the DAM to maximise profits. Minimum demand is ensured for FLs and HVAC systems, while maximising the injection of the FGs. A summary of the traded products can be found in Table 4.2. Trading in the DAM represents a 45.7% of the total trades of the case study. Then, national reserve trading accounts for a 28.6% while LEM and LFM have a 15.2% and 10.5%, respectively. Trading shares among agents are 34.4% for FLs, 37.4% for FGs, 20.2% for BESSs and 8% for HVAC systems.

Temporal distribution of the profits obtained in each market is depicted in Fig. 4.7. 86.22% of the energy profits obtained in Fig. 4.7 (a) are due to energy sold es in the DAM. Revenues obtained from the participation in capacity markets are shown in Fig. 4.7 (b), where benefits from RM and LFM obtained. Total profits for this case study add up to 336.04 € for one day of operation. A summary of the revenues obtained by product, and by technology, is presented in Table 4.2. Energy trade in the DAM is specially profitable for BESSs, obtaining 72.46 € of profits. In the case of the HVAC system, its participation in RM and LFM allows it to recover a part of its energy costs.

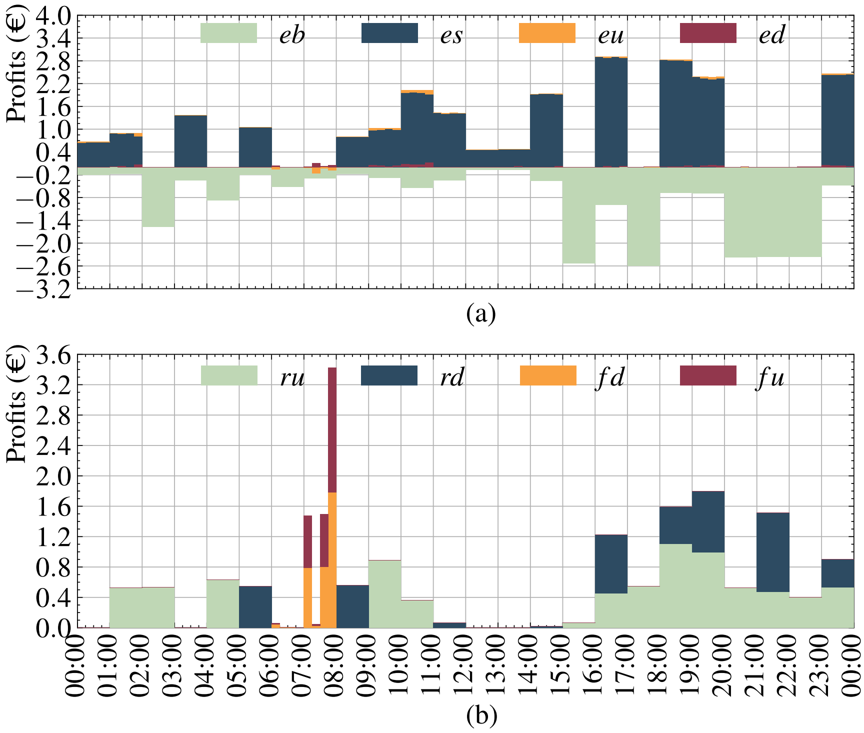
Figure 4.8 represents the evolution of the variables of the HVAC system controlled by the FSP. It buys energy from the DAM and LEM, and takes advantage of its thermal inertia to obtain profits from RM and LFM. Evolution of the temperature is depicted in Fig. 4.8 (b),



(a)

(b)

Figure 4.6: Stacked energy (a) and capacity (b) products traded by FSP when it participates in national and local markets.



(a)

(b)

Figure 4.7: Stacking energy (a) and capacity (b) revenues for the products traded by the FSP.

which is maintained inside of the comfort limits. Figure 4.9 represents the evolution of the variables of one of the BESS systems controlled by the FSP. Energy profits are obtained in the short term, for example, energy is bought before 03:00 to sell it in the following period

Table 4.2: Summary of the products quantities and profits obtained by DER technology.

		FLs	**FGs**	**BESSs**	**HVACs**	**Total**
Profits	**eb (€)**	-64.11	-	-13.76	-6.62	-84.50
	es (€)	-	277.30	86.22	-	363.52
	eu (€)	-0.43	-0.19	-0.28	-0.19	-1.09
	ed (€)	0.18	0.74	0.00	0.06	0.98
	ru (€)	0.05	27.67	4.43	-	32.15
	rd (€)	7.42	4.79	3.07	3.41	18.70
	fu (€)	1.16	-	1.25	0.58	2.99
	fd (€)	0.01	2.05	1.24	-	3.29
Products	**eb (kWh)**	857.640	-	141.184	74.052	1,072.88
	es (kWh)	-	615.064	165.220	-	780.284
	eu (kWh)	135.863	37.247	88.844	61.440	323.393
	ed (kWh)	40.518	239.180	-	11.960	291.659
	ru (kW)	38.586	415.061	96.526	18.793	568.967
	rd (kW)	244.465	63.686	170.092	115.191	593.434
	fu (kW)	77.603	-	70.592	41.140	189.335
	fd (kW)	0.387	148.124	88.240	-	236.751

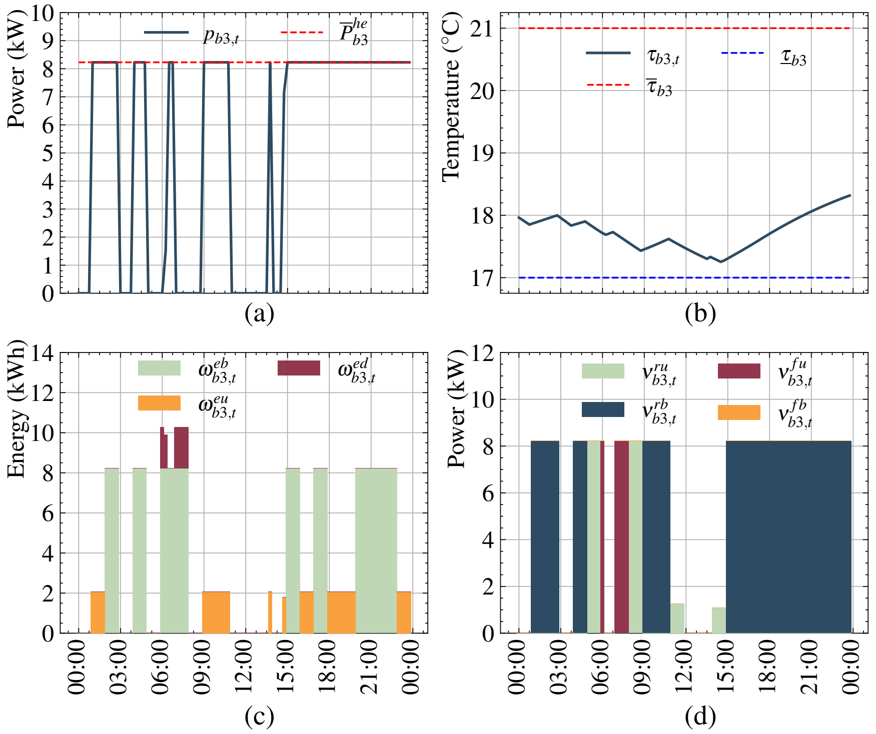
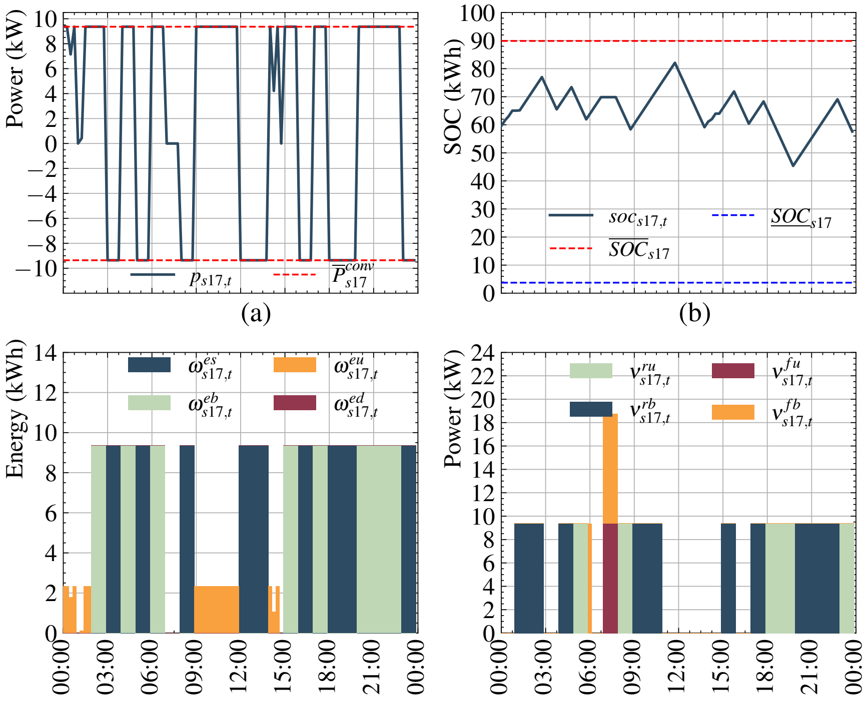


Figure 4.8: Evolution of the variables of the HVAC system managed by FSP, Power (a) temperature (b) energy products (c) capacity products (d).

of time when energy price increases. Moreover, it also participates in the LEM by selling energy that was bought in the DAM. Trading of reserve and flexibility services increase profits, as Fig. 4.9 (d) shows.

4.4.2 Profitability comparison with baseline scenarios

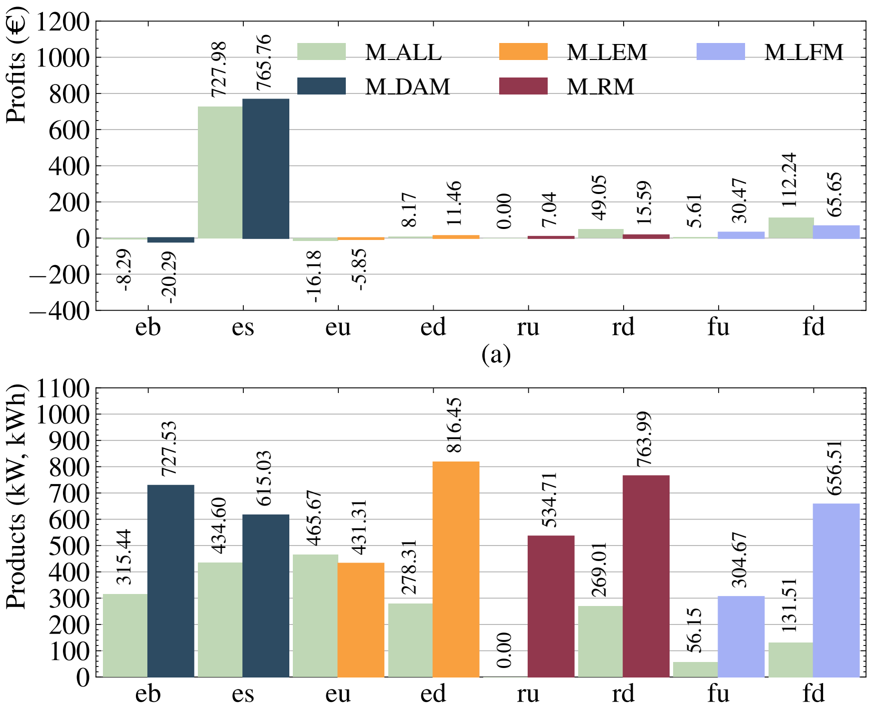
In this section, the proposed approach is compared with four different baselines where the FSP maximise profits in one single market at a time. The baselines are computed as a bi-level program where the FSP problem is subject to the market clearing. These bi-level



(a) (b)

(c) (d)

Figure 4.9: Evolution of the variables of the BESS managed by FSP, Power (a) SOC (b) energy and (c) capacity products (d).



(a)

(b)

Figure 4.10: Comparison of the profits (a) and products (b) traded by the FSP in the baselines and using the proposed strategy.

problems are converted into a single-level problem by incorporating the lower-level primal, dual, and strong-duality equations into the upper-level problem [156].

The quantity of the products traded, and the profits obtained are compared in Fig. 4.10. The total profits obtained by the proposed strategy are 878.59 €. This supposes an increase of in profits compared with the individual baselines, as Fig. 4.10 (a) presents. The quantity of products exchanged are compared in Fig. 4.10 (b). Products exchanged over the markets are lower individually, as the proposed method calculate the optimal bidding strategy to maximise profits, as the flexibility managed by the FSP is limited.

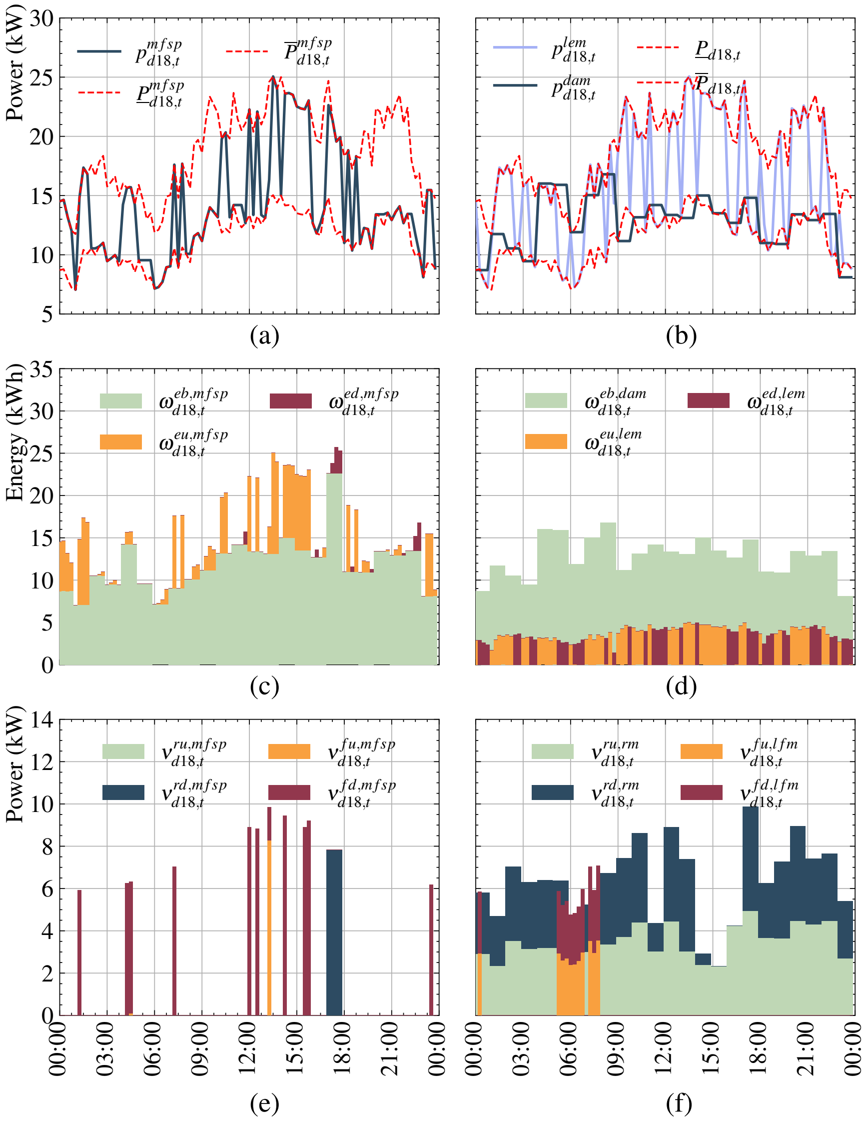
Figure 4.11 presents a comparison of one of the FLs managed by the FSP under the baselines (right column) and the proposed strategy (left column). The demand in the DAM strategy is displayed in Fig. 4.11 (a) for the DAM baseline, where the consumption is at minimum level for most of the day. In the LEM baseline (depicted in lilac) the strategy tries to obtain short term profits for its participation in the market, taking advantage of short variations in price. Lastly, the baselines for the RM and LFM are depicted in Fig. 4.11 (f), where the participation of the FL is maximised for the sake of benefits. Meanwhile, the profit maximiser strategy identifies the most profitable strategy. In this sense, it combines the short-term profit strategy of the LEM with the minimization of participation of consumption from DAM, while also providing products in the RM and LFM. Note that the products showed in the right column of the figure are not stacked together, while those of the left column are.

Market clearing results are compared in Fig. 4.12. A closer inspection to the figure shows that the proposed strategy increases the price variability in the markets, however, it does lower mean prices in LEM and LFM markets. Energy cleared in the DAM and the LEM is lower, this is since if the energy price is low, generators do not get cleared in the market, and if it is high, demands are no longer willing to pay the price. Reserve quantities are the same in both cases, as it is assumed that the TSO will not modify its asking. Then, to maximize its participation, the FSP sends bids with lower prices to maximise its profits. Lastly, LFM market reduces its operation costs, spreading the products all over the day.

Following this comparison, Table 4.3 presents the results that the strategic behaviour of the FSP has in the markets. As shown, social welfare is reduced in the DAM, while increased in the LEM. In term of the costs of the reserve markets, RM costs increase, while LFM costs decrease. Then, although the DAM and LEM profits are reduced with the proposed approach, the overall balance is positive, as the net profits are 878.59€,

Table 4.3: Comparison of the market objectives and profits in the FSP maximization and the baselines.

	Baselines	**Profit max.**	**Diff. (%)**
DAM Social Welfare (€)	31.18	27.44	-13.62
RM Costs (€)	19.37	53.62	63.88
LEM Social Welfare (€)	14.16	63.66	77.75
LFM Costs (€)	13.65	10.27	-32.87
FSP DAM Profits (€)	745.47	719.69	-3.58
FSP RM Profits (€)	22.63	49.05	53.86
FSP LEM Profits (€)	5.62	-8.01	-170.16
FSP LFM Profits (€)	96.12	117.86	18.45



(a) (b)

(c) (d)

(e) (f)

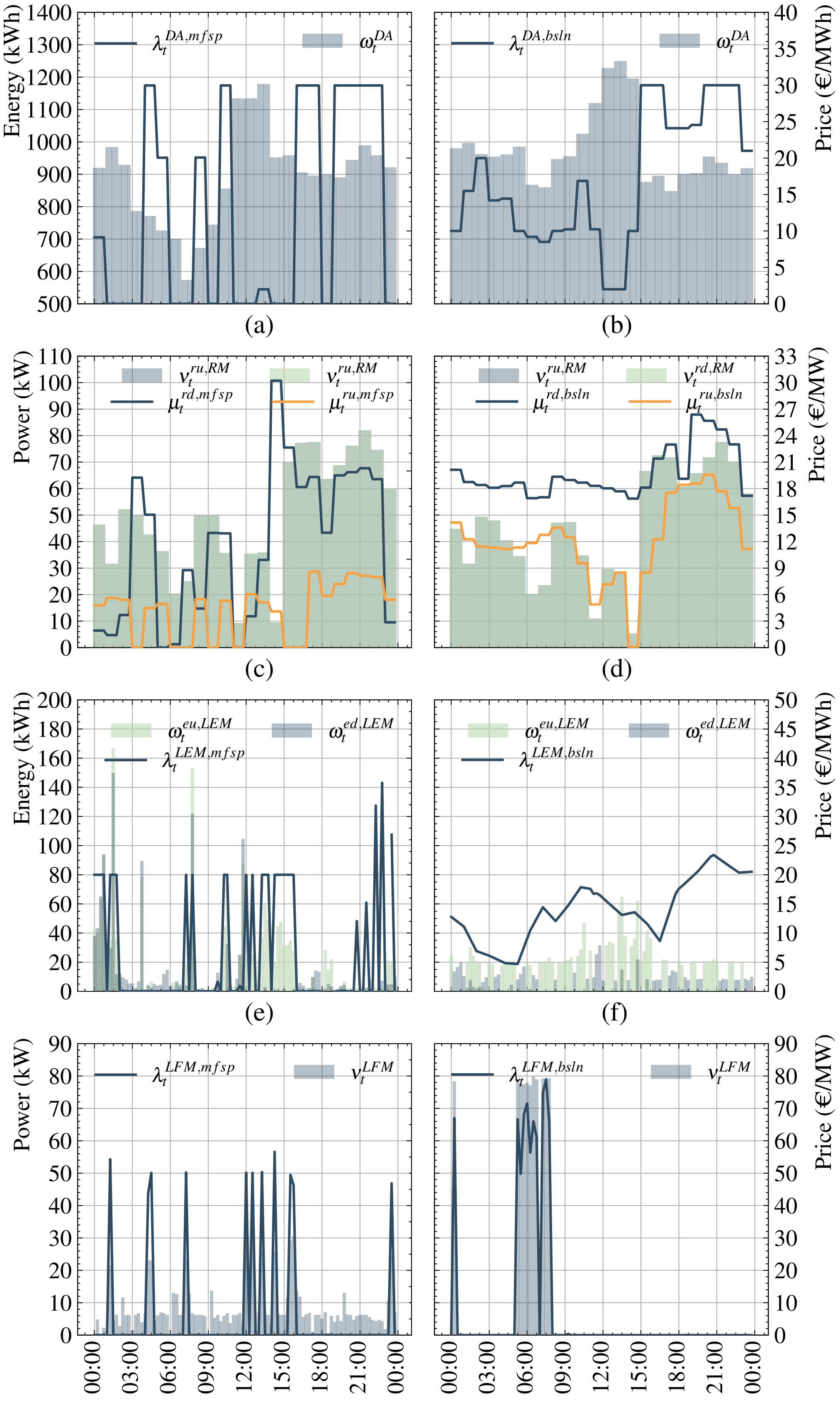
Figure 4.11: Comparison of the behaviour of a FL between profit maximiser strategy and the baselines (left and right column). Power: (a) and (b), energy products (c) and (d), capacity products (e) and (f).

a 17.86% more than the most profitable single-market strategy, i.e., DAM maximisation strategy with 745.47€.

4.4.3 Impact of the uncertainty in the stacking of revenues

In this section, the impact that the uncertainty in the prices and in the dispatch have in the stacking of revenues is assessed. Considering a normal distribution of the forecast error, 50 values per uncertain parameter are considered, originating 125,000 possible scenarios. Nevertheless, after the scenario reduction only the 125 most representative scenarios were simulated in parallel.

The probability density function of the products that the FSP exchange in the market is shown in Fig. 4.13. This representation extends what has been obtained in Fig. 4.10 (b), giving information to the FSP regarding the likelihood of its offers being matched in the market, and the possible outcomes of a determined strategy. The expected profits



(a) (b)

(c) (d)

(e) (f)

(g) (h)

Figure 4.12: Comparison of the market clearings between the FSP maximization (left column) and the baselines (right column). DAM: (a) and (b), RM: (c) and (d), LEM: (e) and (f), LFM: (g) and (h). Prices are shown in lines, and traded quantities in bars.

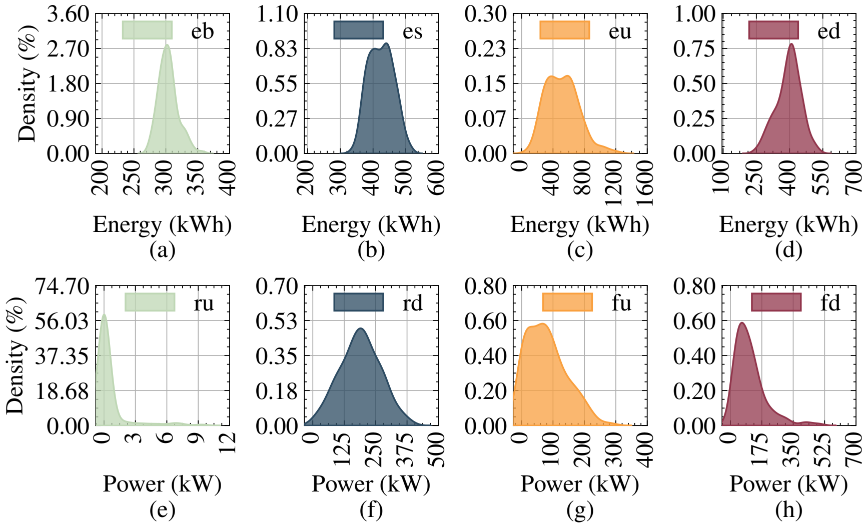


Figure 4.13: Probabilistic Density Function (%) of the total products quantities exchanged in the stochastic formulation.

are depicted in Fig. 4.14 along with the 95% Interval Confidence, which demonstrate the feasibility of the proposed approach to obtain benefits under uncertainty.

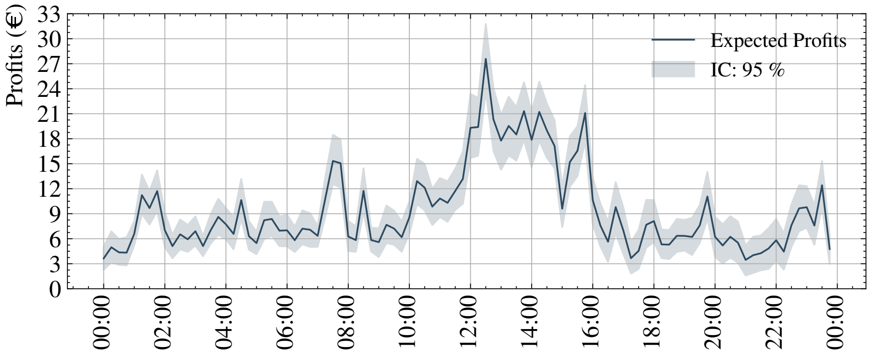


Figure 4.14: Expected FSP profits and 95% Interval Confidence for the stochastic formulation.

4.5 Stacking of revenues under uncertainty

Until this point, a tri-level optimization problem for the maximisation of the stacked revenues of DERs participating to multiple sequential markets has been proposed. This approach responded to the necessity of increasing the number of business cases for flexible distributed technologies such as FLs, BESSs, EVs and HVACs systems, with the aim of achieving long-term Net Zero Emissions objectives. Using duality theory and strong duality condition, the sequential tri-level optimization was recast into a tractable single-level problem, which maximised the profits of DERs for their participation in different markets through a FSP. A case study based on the IEEE-14 transmission network, N5_1_DSS distribution network and a realistic dataset demonstrated the feasibility of the approach. Profitability of flexibility procurement was enhanced when the FSP adopted the proposed strategy, compared with four different baselines, where profits were maximised for one market at a time. The proposed model increased the profits of the FSP as it took a holistic view of the market participation of the FSP. In the case study, profits where increased a 17.86% compared with the most profitable single-market strategy, while reducing 32.87% the costs in the LFM and increasing a 77.75% the social welfare of the LEM.

Nevertheless, although the impact of the uncertainty has been assessed in the stochastic version of the problem, the robustness of the proposed model will be extended in forthcoming research. The following sections will propose a stochastic version of the problem, which can deal with the partial information access of the FSP to the market and rival information, as well as the uncertainty in the prices and the dispatch.

The integration of DERs DERs into the grid is crucial for a sustainable future. By understanding how to effectively harness the power of renewable DERs, we can reduce our reliance on fossil fuels and mitigate climate change [160]. DERs offer decentralized power generation, minimizing transmission losses, improving grid efficiency and resilience, while empowering consumers to actively manage their energy usage and participate in energy markets [161]. With the objective of fostering the integration of DERs into the grid, the European Union has set ambitious targets, which can only be achieved if new and attractive business cases are created for these resources [162]. In this sense, there is a need to study the technical and economic implications of these new business cases where DERs participate in multiple markets. This leads to the development of new methodologies that maximise their profits and boost their deployment.

In addition, the future distribution grids will face several major challenges, including effectively integrating and coordinating diverse DERs, developing supportive market and policy frameworks while ensuring grid reliability and energy security [163]. Increasing the penetration of DERs conveys handling their intrinsic uncertainty and variability, which can lead to grid instability and reliability issues [164]. Nevertheless, these are key resources in the transition to a low-carbon economy, since if properly managed, they can provide flexibility to the grid. In this sense, demand response programs [165], along with active distribution network schemes [166] have been the classical approach of the DSO to effectively unlock the flexibility potential of the distribution network. Albeit effective, these approaches are not enough to manage active resources capable of scheduling their own operation (consumption, generation and storage), the so-called ‘prosugamers’ [167]. There are several proposals to handle them, among which it is possible to highlight the use of model-free reinforcement learning [168] able to learn the optimal strategy for the DER and organise a LFM for the sake of a resilient operation. Peer-to-peer strategies have also been proposed in this sense to manage consumption using cloud energy storage [169].

However, there is even more potential to unlock from these resources. Participating in multiple markets, their flexibility can be stacked and offered as a single entity, increasing the profits of the DERs. A first approach to this problem was conveyed by [140] where the authors propose a multi-layer representation of the different time-frames of the markets, but only one conventional combined heat and power unit is considered. Including into the analysis the renewable generation of wind farms, reference [136] analysed the impact of the deployment and revenue stacking of BESSs along the lifetime of the asset. In addition to this, a technology-agnostic model aggregating different technologies for the participation in capacity and energy markets is proposed by [139], but neglecting the uncertainty of the resources. Traditionally, the main uncertainty source considered when calculating a bidding strategy for FSPs is the price of the traded products. This price variability is generally represented through different scenarios. A Gaussian Mixture Model is used by [170] to generate them for PV and wind. Authors in [171] proposed an energy arbitrage model between the day-ahead and the intra-day market using a stochastic programming approach based on scenarios of the market prices. Nevertheless, assuming a normal distribution, these techniques are sensitive towards outliers. Besides, as demonstrated by [141], the endogenous price formation is a key aspect to be considered when developing a bidding strategy for the FSP, as it can accurately model the effects of other market participants.

Multi-scale markets were investigated in [97], managing the uncertainty of different DERs, but an analysis of the risks associated to the uncertainty representation for each bid strategy was not conducted. Authors in [172] propose a stochastic optimization approach capable of managing the risks associated with the participation in joint-energy and reserve markets using Conditional Value at Risk measure, but only for BESSs and neglecting the value added by the participation in LFMs. Then, reference [89] extends the previous approach including the FSP participation in the LFM and considering the distributed nature of the storage along the distribution network. Although the expected market prices for the developed strategy were endogenously created, the uncertainty of the RMAs was not considered in the formulation, which can lead to suboptimal strategies or even an inability to participate in the market, as their bids may get rejected or out of the market clearing. This is a key aspect, and the information available is scarce. There are several methodologies to model RMA's behaviour, inverse optimization was used in [173] to obtain the marginal costs for generators participating in the DAM, Bayesian inference approach was used in [174] and equilibrium models were used in [175]. Nevertheless, it is also possible to obtain meaningful RMA information based on the components of the locational marginal prices [176], which can be used to obtain information within a confidence interval.

In addition to this, previous approaches for computing FSP bidding strategies, model several sources of uncertainty using one single technique, which can lead to a misrepresentation of the information. Having fundamentally different characteristics, it is desirable that the uncertainty of the RMAs is modelled using a different technique than the uncertainty of the dispatch or the resources the FSP manages [177]. Robust optimisation can be used to model the uncertainty of those parameters with a limited amount of information, e.g. RMAs bidding strategies [178], stochastic optimisation is widely used to model the uncertainty of the dispatch [97] and chance-constraints can be used to model the uncertainty of the resources that provide flexibility [26]. The combination of these techniques in a single model has not been addressed in the literature.

In light of the previous literature review, the main research gap is identified as the joint-modelling of the different uncertainty sources that appear when participating in multiple markets. This includes the variability of the resources managed by the FSP, the behaviour of the RMAs and the uncertainty of the dispatch and generation. The joint-modelling of these uncertainty sources will need to be done using different techniques in a single framework, which has not been properly addressed in the literature.

In this paper, a bi-level optimization problem is proposed to determine the optimal participation of the FSP in sequentially-cleared national and local markets. The model relies on an innovative combination of robust and stochastic optimisation of the markets which is able to endogenously-estimate prices and account for the uncertainty of the RMAs and the variability of DERs. These are the features that enable the FSP to make robust bidding decisions in the markets. The main novel aspect of this methodology is the robust optimisation of the DERs managed by the FSP across different markets. The proposed approach has three core contributions:

C1 A model based on duality and Robust Stochastic Optimization (RSO) to maximise the profits of the FSP stacking revenues from DERs in sequential national and local markets. Energy, reserves and flexibility are vertically traded in the model to maximise revenues. The model relies on a combination of robust and stochastic optimisation. This allows for the inclusion of a wider range of variability while creating robust bidding strategies.

C2 In an environment of limited access to information, the proposed model deal with the uncertainty of the RMAs based on past market results. In addition, the variability of the DERs is managed using the concept of Wasserstein distance, K-Means clustering and chance-constraints.

C3 The methodology enables the FSP to evaluate the robustness against the RMAs in combination with the variability of the renewable DERs and the uncertainty of the dispatch.

In what follows, the methodology to maximise the stacked revenues of the DERs are firstly described, where the market representation and the general time frame of the proposed model are described. Then, the uncertainty of the resources by the FSP are modelled and the overall bi-level problem is formulated and solved. Finally, the case study is presented and the results are discussed.

4.6 Methodology to maximise the stacked revenues of DERs under uncertainty

A schematic of the timeline of the sequential market-clearing is shown in Fig. 4.15. The proposed problem is aimed to be solved while the gate for participating in national markets is open, commonly between 10:00 and 12:00 of the day before the market is cleared. Here, we assume the FSP participates in the national DAM and RM, and in a LFM at the distribution network. Following a similar approach to [152], we use a sequential optimization approach to represent the market clearing process of these three markets.

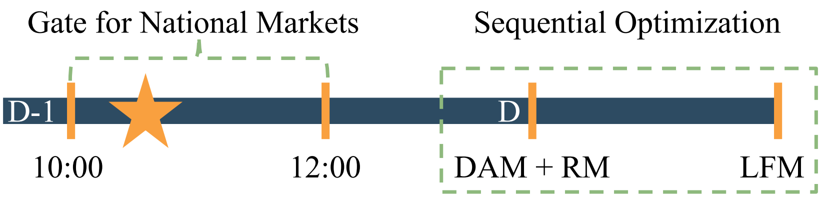


Figure 4.15: Timeline of the sequential market-clearing. The problem is solved when the gate is open (between 10:00 and 12:00 a.m.). Sequential optimization is used for the markets model.

An overview of the methodology used to solve this problem is shown in Fig. 4.16. The FSP is the decision maker of the problem, which submits bids π_i, $\overline{\boldsymbol{p}}_i$ to the markets. Markets are modelled using a sequential model which considers the uncertainty of the RMAs and the variability of the renewable DERs power output using RSO. Then, expected prices are obtained from this market representation $\boldsymbol{\lambda}$ and the FSP uses this information to send the set-points to the DERs, which has been characterised in the problem using chance constraints.

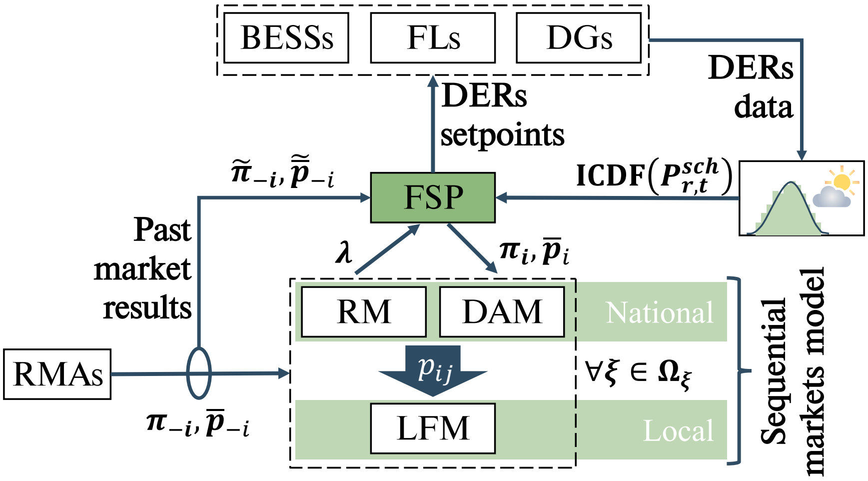


Figure 4.16: Overview of the approach to solve the problem. To make a decision, the FSP i) sends bids $\pi_i, \overline{\boldsymbol{p}}_i$ and receives prices $\boldsymbol{\lambda}$ from the market model considering the different scenarios $\xi \in \Omega_\xi$, ii) interacts with DERs $r \in \Omega_r$ based on the characterisation the ICDF and, iii) estimate the bidding strategy of RMA $-i$, $\tilde{\boldsymbol{\lambda}}_{-i}, \tilde{\overline{\boldsymbol{p}}}_{-i}$.

4.6.1 Sequential National and Local Market-Clearing model

The DAM and the RM are the national markets modelled in this paper. The RMAs' participation are noted by $-i$ while the FSP is noted by i, since it is assumed that each agent can be only connected to a single node in the Transmission Network (TN) $i \in \Omega_n^{TN}$. The RMA $-i$ submits a step-wise k supply function $\pi_{-i,t,k}^{es}$ at node i and time period t for the DAM, while the demand is considered inelastic, so $\pi_{-i,t}^{eb}$ can be considered a high value [173]. A simple offer is submitted by rival generators in the RM in the upward $\pi^{ru}_{g,t}$ and downward directions $\pi^{rd}_{g,t}$ for RM [89]. Then the market operator clears the market by setting the locational marginal prices $\lambda_{i,t}$ for the DAM and upward μ^{u}_{t} and downward μ^{d}_{t} reserve prices. The objective of the national market maximises the social welfare of the DAM and minimises the total procuring costs of the RM. The LFM is adapted from [89] using the concept of RMA, where the LFM solves congestions and imbalances that arise in the DN $(a, b) \in \Omega^{DN}_{n}$. Rival agents submit their flexibility offers in the upward $\pi^{fu}_{-a,t}$, and downward $\pi^{fd}_{-a,t}$ directions to the LFM operator as a single quantity and price bid. The FSP submits $\pi^{DAM}_{i,t,k}$, π^{ru}_{t}, π^{rd}_{t}, $\pi^{fu}_{a,t}$ and $\pi^{fd}_{a,t}$ bids to the markets. Note that the DAM offer can be submitted for demand or supply, depending on the available of the DERs.

These markets are cleared sequentially, and to reflect that in the modelling, lexicographic optimization is used. Let y and z be the vectors of the variables and $f(y)$ and $g(z)$ the objectives of the national and local markets, respectively. The problem is defined as $\{y, z\} = \arg\min\{\mathcal{L}(y, z) :$ (4.17b) – (4.17t)$\}$, where $\mathcal{L}(y, z)$ is the lexicographic objective function. This objective is asymptotically approximated by $\mathcal{L}(y, z) = \gamma f(y) + (1 - \gamma)g(z)$, when $\gamma \to 1$ [152]. The sequential market clearing is then approximated by solving the following problem:

$$\begin{aligned}
\min \gamma \Bigg[&\sum_{i,t,k} (\pi^{es}_{-i,t,k} p^{es}_{-i,t,k} - \pi^{eb}_{-i,t} p^{eb}_{-i,t} + \pi^{DAM}_{i,t,k} (p^{es}_{i,t,k} - p^{eb}_{i,t})) + \sum_{g,t} (\pi^{ru}_{g,t} p^{ru}_{g,t} + \pi^{rd}_{g,t} p^{rd}_{g,t}) + \\
&+ \sum_{t} (\pi^{ru}_{t} p^{ru}_{t} + \pi^{rd}_{t} p^{rd}_{t}) \Bigg] + (1 - \gamma) \Bigg[\sum_{a,t} \pi^{fu}_{-a,t} p^{fu}_{-a,t} - \pi^{fd}_{-a,t} p^{fd}_{-a,t} + \pi^{fu}_{a,t} p^{fu}_{a,t} - \pi^{fd}_{a,t} p^{fd}_{a,t} \Bigg]
\end{aligned} \tag{4.17a}$$

Subject to:

$$0 \le p^{es}_{-i,t,k} \le P^{es}_{-i,t,k} \qquad 0 \le p^{eb}_{-i,t} \le P^{eb}_{-i,t} \qquad \forall i, \forall k, \forall t \tag{4.17b}$$

$$0 \le p^{ru}_{g,t} \le P^{ru}_{g,t} \qquad 0 \le p^{rd}_{g,t} \le P^{rd}_{g,t} \qquad \forall g, \forall t \tag{4.17c}$$

$$0 \le p^{fu}_{-a,t} \le P^{fu}_{-a,t} \qquad 0 \le p^{fd}_{-a,t} \le P^{fd}_{-a,t} \qquad \forall i, \forall t \tag{4.17d}$$

$$\underline{P}^{DAM}_{i,t,k} \le p^{es}_{i,t,k} - p^{eb}_{i,t} \le \overline{P}^{DAM}_{i,t,k} \qquad \forall i, \forall b, \forall t \tag{4.17e}$$

$$0 \le p^{ru}_{t} \le P^{ru}_{t} \qquad 0 \le p^{rd}_{t} \le P^{rd}_{t} \qquad \forall t \tag{4.17f}$$

$$0 \le p^{fu}_{a,t} \le P^{fu}_{a,t} \qquad 0 \le p^{fd}_{a,t} \le P^{fd}_{a,t} \qquad \forall i, \forall t \tag{4.17g}$$

$$\sum_{j} B^{TN}_{i,j} \theta^{TN}_{i,j,t} = \sum_{k} [p^{es}_{-i,t,k} + p^{es}_{i,t,k}] - p^{eb}_{-i,t} - p^{eb}_{i,t} : \ \lambda^{DAM}_{i,t} \qquad \forall i, \forall t \tag{4.17h}$$

$$B^{TN}_{i,j} \theta^{TN}_{i,j,t} \le \overline{P}_{i,j} \qquad \forall (i, j), \forall t \tag{4.17i}$$

$$\begin{aligned}
\sum_{b} [G^{DN}_{a,b} v^{DN}_{b,t} - B^{DN}_{a,b} \theta^{DN}_{b,t}] = P^{SCH}_{-a,t} + p^{fu}_{-a,t} - p^{fd}_{-a,t} + \\
+ P^{SCH}_{a,t} + p^{fu}_{a,t} - p^{fd}_{a,t} : \ \lambda^{LFM}_{a,t} \qquad \forall a, \forall t
\end{aligned} \tag{4.17j}$$

$$\sum_{b} [-B^{DN}_{a,b} v^{DN}_{b,t} - G^{DN}_{a,b} \theta^{DN}_{b,t}] = Q_{a,t} \qquad \forall a, \forall t \tag{4.17k}$$

$$p^{DN}_{a,b,t} = G^{DN}_{a,b} v^{DN}_{a,b,t} - B^{DN}_{a,b} \theta^{DN}_{a,b,t} \qquad \forall (a, b), \forall t \tag{4.17l}$$

$$q^{DN}_{a,b,t} = -B^{DN}_{a,b} v^{DN}_{a,b,t} - G^{DN}_{a,b} \theta^{DN}_{a,b,t} \qquad \forall (a,b), \forall t \tag{4.17m}$$

$$A_m p^{DN}_{a,b,t} + B_m q^{DN}_{a,b,t} \leq \overline{S}^{DN}_{a,b} \cos(\pi/L) \qquad \forall m, \forall (a,b), \forall t \tag{4.17n}$$

$$-\pi \leq \theta^{TN}_{i,t} \leq \pi, \quad -\pi \leq \theta^{DN}_{a,t} \leq \pi \qquad \forall i, \forall a, \forall t \tag{4.17o}$$

$$0.95 \leq v^{DN}_{a,t} \leq 1.05 \qquad \forall a, \forall t \tag{4.17p}$$

$$\theta^{TN}_{i,t} = 0, \theta^{DN}_{i,t} = 0, v^{DN}_{i,t} = 1 \qquad i = \text{slack}, \forall t \tag{4.17q}$$

$$\sum_g p^{ru}_{g,t} + p^{ru}_t \geq R^u_t \; \lambda^{ru}_t \qquad \forall t \tag{4.17r}$$

$$\sum_g p^{rd}_{g,t} + p^{rd}_t \geq R^d_t \; \lambda^{rd}_t \qquad \forall t \tag{4.17s}$$

$$\sum_a (p^{fu}_{-a,t} + p^{fu}_{a,t}) = \sum_a (p^{fd}_{-a,t} + p^{fd}_{a,t}) \qquad \forall t \tag{4.17t}$$

RMA's bidding limits are defined from (4.17b) to (4.17d). Bidding limits for the DAM are set by (4.17b). Likewise, upward / downward reserve limits are defined by (4.17c) for RM and by (4.17d) for LFM. The FSP participation in the markets is stated from (4.17e) to (4.17g). We consider a DC modelling of the grid for the DAM, since it will be cleared in the TN. Nodal power flow is enforced by (4.17h) and branch thermal limit feasibility by (4.17i) based on the susceptance $B_{i,j}$ of the branch $(i,j) \in \Omega^{TN}_l$. Note that the voltage phase angle and magnitude difference between nodes i and j in time t is denoted by $\theta_{i,j,t}$ and $v_{i,j,t}$, respectively. The TSO asks for reserves R^u_t and R^d_t in the upward and downward direction, respectively. This is drawn in (4.17r) and (4.17s). We use a state-independent linear modelling of the DN [67] as it enables an accurate model of the active power flow events considering also the conductance $G_{a,b}$ of the branch $(a,b) \in \Omega^{DN}_l$. Constraints (4.17j) and (4.17k) define active and reactive power balance for the local market. Power flows between nodes a and b are defined by (4.17l) and (4.17m), branch thermal limit is secured using an inner circle approximation by (4.17n) [89]. The voltage and angle of the slack bus are defined by (4.17q), while (4.17o) and (4.17p) define the voltage magnitude and angle limits. The local market is balanced by (4.17t). The problem is linear and the market prices are endogenously generated by dual variables. The energy price for the DAM is defined on a locational marginal pricing scheme $\lambda^{DAM}_{i,t}$, as the shadow price of (4.17h). Similarly, a nodal pricing scheme is defined for the LFM by (4.17j) with $\lambda^{LFM}_{a,t}$ following reference [89]. On the other hand, prices for upward λ^{ru}_t and downward λ^{rd}_t reserves are defined by the dual variables of (4.17r) and (4.17s), respectively. Note that all the prices are endogenously generated in the problem.

4.6.2 RSO for Multi-Scale National and Local Markets

Two uncertainty sources can be identified, namely, the RMA's supply functions $\{\boldsymbol{\pi}_{-i,t}, \boldsymbol{P}_{-i,t}\}$ and the load $\{P^{sch}_{-i,t}, Q^{sch}_{-i,t}\}$ and reserves values $\{R^u_t, R^d_t\}$. The FSP aims to generate feasible bids for every realisation of the RMA's strategy, considering a given confidence interval, to ensure their participation in the market. However, at the same time, it would be useful to include a wider collection of possible load and reserves scenarios to capture a extensive variety of market outcomes. In this context, RSO is a suitable tool to deal with these uncertainties [53], as it can simultaneously hedge against interval and scenario uncertainties. Inferring the RMA's bidding strategies from the cost component of historical locational marginal prices, we can obtain a confidence interval of the bid price $\boldsymbol{\pi}_{-i,t}$ for each RMAs.

Thus, a linear RSO problem is formulated for the sequential market clearing model using the compact notation in (4.18). The robust parameters are included in the set of constraints as the nominal values $\hat{b}_k$ and, $\hat{c}_i$ with deviations, σ_k and ρ_i, respectively. Vector $\boldsymbol{b}$ represents uncertain parameters $P^{ru}_{g,t}$, $P^{rd}_{g,t}$, $P^{fu}_{-a,t}$ and $P^{fd}_{-a,t}$, while vector $\boldsymbol{c}$ represents uncertain parameters in the objective function $\pi^{es}_{-i,t,k}$, $\pi^{eb}_{-i,t}$, $\pi^{ru}_{g,t}$, $\pi^{rd}_{g,t}$, $\pi^{fu}_{-a,t}$ and, $\pi^{fd}_{-a,t}$. Stochastic parameters are $g_{\xi,l}$, with probabilities π_ξ. Deterministic parameters associated to the set of constraints are $a_{k,j}$, $f_{l,j}$ and d_i, Decisions variables are $x_{i,\xi}$, while auxiliary variables to obtain the robust counterparts of $\hat{b}_k$ are $\mu^b_{k,\xi}$, $\nu^b_{k,\xi}$, $y^b_{k,\xi}$, while for $\hat{c}_i$ are $\mu^c_{i,\xi}$, $\nu^c_{i,\xi}$. Variable τ_i is defined to move the uncertainty from the objective to the set of constraints. The parameters Γ^b_k and Γ^c_i control the level of robustness in the model against the parameters b_k and c_i, respectively. Further details on the derivation of the model using robust counterparts are provided in [179].

$$\min \sum_{\xi} \pi_\xi \sum_{i} (\tau_{\xi,i} + d_i x_{\xi,i}) \tag{4.18a}$$

Subject to:

$$\hat{c}_i x_{\xi,i} + \Gamma^c_i \nu^c_{\xi,i} + \mu^c_{\xi,i} - \tau_{\xi,i} \leq 0 \qquad \lambda_{\xi,i} \leq 0 \qquad \forall \xi, \forall i \tag{4.18b}$$

$$\nu^c_{\xi,i} + \mu^c_{\xi,i} \geq \rho_i x_{\xi,i} \qquad \lambda^r_{\xi,i} \geq 0 \qquad \forall \xi, \forall i \tag{4.18c}$$

$$\sum_j a_{k,j} x_{\xi,j} + \Gamma^b_k \nu^b_{\xi,k} + \mu^b_{\xi,k} \leq \hat{b}_k \qquad \lambda_{\xi,k} \leq 0 \qquad \forall \xi, \forall k \tag{4.18d}$$

$$\nu^b_{\xi,k} + \mu^b_{\xi,k} \geq \sigma_k y^b_{\xi,k} \qquad \lambda^r_{\xi,k} \geq 0 \qquad \forall \xi, \forall k \tag{4.18e}$$

$$y^b_{\xi,k} \geq 1 \qquad \lambda^y_{\xi,k} \geq 0 \qquad \forall \xi, \forall k \tag{4.18f}$$

$$\sum_j f_{l,j} x_{\xi,j} \leq g_{\xi,l} \qquad \lambda_{\xi,l} \leq 0 \qquad \forall \xi, \forall l \tag{4.18g}$$

$$x_{\xi,i}, \nu^c_{\xi,i}, \mu^c_{\xi,i}, \nu^b_{\xi,k}, \mu^b_{\xi,k}, y^b_{\xi,k} \geq 0 \tag{4.18h}$$

Equations (4.18b) and (4.18c) provides the robust counterparts for the uncertain parameters $\boldsymbol{c}$ of the objective, while (4.18d) to (4.18f) of the constraints. The rest of the constraints are represented in compact form by (4.18g). The approach balances computational efficiency and conservatism, leading to feasible solutions for most potential realizations of the uncertain parameters while considering a broader range of uncertainty.

4.7 Uncertainty and bi-level formulation

In this section, the uncertainty from Flexible DERs is managed and the bi-level problem is formulated and solved.

4.7.1 Flexible DERs

In this section we are describing the model of the FSP's resources when participating in national and local markets. It is assumed that the FSP has a portfolio of FLs, FGs and BESSs, which the former two are under uncertainty of the consumption and the generation, respectively. It is assumed that the FSP has a portfolio of FLs $f \in \Omega_f$, FGs $g \in \Omega_g$ and BESSs $s \in \Omega_s$, with the former two are under uncertainty of consumption and generation, respectively. A pictorial example of the flexibility of each asset is depicted in Fig. 4.17.

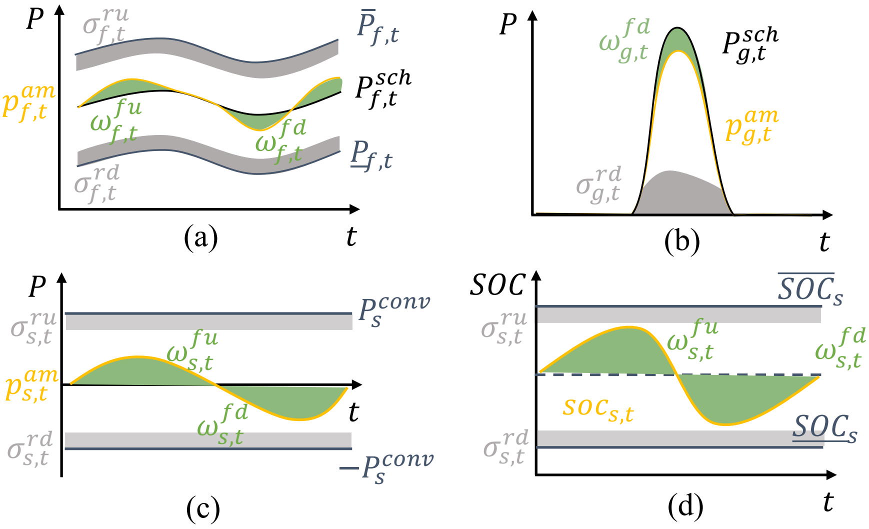


Figure 4.17: Pictorial example of the flexibility of each resource. (a) Flexible loads, (b) Flexible generation, (c) and (d) Battery energy storage system in power and energy dimensions respectively.

FLs are modelled as a baseline $P^{sch}_{f,t}$ with an upper $\overline{P}_{f,t}$ and lower $\underline{P}_{f,t}$ bounds. They participate in the market by buying $\omega^{eb}_{f,t,\xi}$ in the DAM, selling reserves $\sigma^{ru}_{f,t,\xi}$, $\sigma^{rd}_{f,t,\xi}$, and flexibility $\omega^{fu}_{f,t,\xi}$, $\omega^{fd}_{f,t,\xi}$ for every possible realisation of the uncertainty $\xi \in \Omega_\xi$. It is assumed that the FLs obtain their flexibility by re-scheduling their consumption during the day, so the total deviation in the upward direction must be the same as the total deviation in the downward direction. Their consumption can be modelled as follows,

$$\underline{P}_{f,t} + \sigma^{rd}_{f,t,\xi} \leq \omega^{eb}_{f,t} + (\omega^{fu}_{f,t,\xi} - \omega^{fd}_{f,t,\xi})/\Delta t \leq \overline{P}_{f,t,\xi} - \sigma^{ru}_{f,t,\xi} \qquad \forall f, \forall t, \forall \xi \quad (4.19a)$$

$$\sigma^{ru}_{f,t,\xi} \leq \overline{P}_{f,t} - \omega^{eb}_{f,t} \qquad \forall f, \forall t, \forall \xi \quad (4.19b)$$

$$\sigma^{rd}_{f,t,\xi} \leq \omega^{eb}_{f,t} - \underline{P}_{f,t} \qquad \forall f, \forall t, \forall \xi \quad (4.19c)$$

$$\sum_t (\omega^{eb}_{f,t} + (\omega^{fu}_{f,t,\xi} - \omega^{fd}_{f,t,\xi})/\Delta t) = \sum_t P^{sch}_{f,t} \qquad \forall f, \forall \xi \quad (4.19d)$$

For the aim of this model, the FGs are supposed to be PV panels, so the only flexibility they can offer is curtailing their generation. Their generation $\omega^{es}_{g,t,\xi}$, downward reserve $\sigma^{rd}_{g,t,\xi}$ and flexibility $\omega^{fd}_{g,t,\xi}$ products are sold in the DAM, RM and LFM, respectively. The model can easily be extended to other types of FGs that can offer flexibility in both directions. The forecast generation is sold in the DAM $\omega^{es}_{g,t}$, while the generator participate in the RM and LFM with products $\sigma^{rd}_{g,t,\xi}$ and $\omega^{fd}_{g,t,\xi}$, respectively. These products are described by the following equations

$$\sigma^{rd}_{g,t,\xi} \leq \omega^{es}_{g,t} \leq P^{sch}_{g,t} \qquad \forall g, \forall t, \forall \xi \tag{4.20a}$$
$$\sigma^{rd}_{g,t,\xi} \leq P^{sch}_{g,t} \qquad \forall g, \forall t, \forall \xi \tag{4.20b}$$
$$\omega^{fd}_{g,t,\xi} \leq (\omega^{es}_{g,t} - \sigma^{rd}_{g,t,\xi})\Delta t \qquad \forall g, \forall t, \forall \xi \tag{4.20c}$$

Lastly, BESSs can buy $\omega^{eb}_{s,t,\xi}$ and sell $\omega^{es}_{s,t,\xi}$ energy in the DAM and participate with upward $\sigma^{ru}_{s,t,\xi}$ and downward $\sigma^{rd}_{s,t,\xi}$ reserve and $\omega^{fu}_{s,t,\xi}$, $\omega^{fd}_{s,t,\xi}$ flexibility in RM and LFM. The BESS has a converter with a rated power P^{conv}_s, and efficiencies η^{ch}_s and η^{dis}_s for charging and discharging, respectively. These efficiencies are considered constant, and equal to 90%. The SOC of the BESS has an upper and lower bounds $\overline{SOC}_s$ and $\underline{SOC}_s$, respectively, which are defined as a 95 and 5% of the nominal capacity of storage. The SOC is the most versatile of the resources of the FSP, since it can be used to buy $\omega^{e,u}_{s,t,\xi}$ and sell energy $\omega^{e,d}_{s,t,\xi}$ in the DAM, provide upward $\sigma^{ru}_{s,t,\xi}$ and downward $\sigma^{rd}_{s,t,\xi}$ reserves in the RM, and upward $\omega^{fu}_{s,t,\xi}$ and downward $\omega^{fd}_{s,t,\xi}$ flexibility in the LFM. Battery degradation is modelled as a constant cost of use C^{DEG}_s, which can be computed as the cost of the battery divided by the energy throughput during its lifetime considering a maximum converter power P^c_s [180]. The battery is modelled by their power related constraints, where the different energy products are related among other, and limits for the converter are set

$$-P^{conv}_s + \sigma^{rd}_{s,t,\xi} \leq (\omega^{fu}_{s,t,\xi} - \omega^{fd}_{s,t,\xi})/\Delta t + \omega^{e,u}_{s,t,\xi} - \omega^{e,d}_{s,t,\xi} \leq P^{conv}_s - \sigma^{ru}_{s,t,\xi} \qquad \forall s, \forall t, \forall \xi \tag{4.21a}$$
$$\sigma^{ru}_{s,t,\xi} \leq P^{conv}_s \qquad \forall s, \forall t, \forall \xi \tag{4.21b}$$
$$\sigma^{rd}_{s,t,\xi} \leq P^{conv}_s \qquad \forall s, \forall t, \forall \xi \tag{4.21c}$$
$$\omega^{e,u}_{s,t,\xi} + \omega^{fu}_{s,t,\xi}/\Delta t \leq P^{conv}_s - \sigma^{ru}_{s,t,\xi} \qquad \forall s, \forall t, \forall \xi \tag{4.21d}$$
$$\omega^{e,d}_{s,t,\xi} + \omega^{fd}_{s,t,\xi}/\Delta t \leq P^{conv}_s - \sigma^{rd}_{s,t,\xi} \qquad \forall s, \forall t, \forall \xi \tag{4.21e}$$

And their energy related constraints, where the limits of the state of charge are enforced.

$$soc_{s,t,\xi} = soc_{s,t-1,\xi} + \eta^{ch}_s(\omega^{fu}_{s,t,\xi} + \omega^{eu}_{s,t,\xi}) - (\omega^{fd}_{s,t,\xi} + \omega^{ed}_{s,t,\xi})/\eta^{dis}_s \qquad \forall s, \forall t, \forall \xi \tag{4.21f}$$
$$soc_{s,0,\xi} = SOC0_s = soc_{s,\|\Omega_t\|,\xi} \qquad \forall s, \forall \xi \tag{4.21g}$$
$$\underline{SOC}_s \leq soc_{s,t,\xi} \leq \overline{SOC}_s \qquad \forall s, \forall t, \forall \xi \tag{4.21h}$$
$$\sigma^{u}_{s,t,\xi} \leq (\overline{SOC}_s - soc_{s,t-1,\xi})/\eta^{ch}_s \qquad \forall s, \forall t, \forall \xi \tag{4.21i}$$
$$\sigma^{d}_{s,t,\xi} \leq (soc_{s,t-1,\xi} - \underline{SOC}_s)\eta^{dis}_s \qquad \forall s, \forall t, \forall \xi \tag{4.21j}$$

FLs and FGs have uncertainty associated to their operation, as we cannot assume perfect knowledge about the outcome of the power demand of the FLs nor the generation of the renewable FGs. These future outcomes are forecast using a SARIMA model [181], which has an overall good results but still has an error associated to it. From historical dataset it is possible to characterize the error of the forecast variables, which is then fitted to a Versatile Distribution using a non-linear least squares method [55]. Then these PDFs are used to characterize the uncertainty of the forecast variables. This uncertainty can be introduced into the model using individual chance-constraints, as the FSP can ensure, in this way, that the constraints of their resources are satisfied with a certain confidence level. Then, equations from (4.19a) to (4.20c) are defined as CCs.

Let α be the confidence level of the chance-constraints, it is assumed that is the same for every individual chance-constraint, although it can be different to depend on the level of robustness that the FSP is willing to take. The chance-constraint associated to the left-hand-side of (4.19a) is,

$$\mathbb{P}\{\underline{P}_{f,t} + \sigma^{rd}_{f,t,\xi} \leq P^{sch}_{f,t} + (\omega^{fu}_{f,t,\xi} - \omega^{fd}_{f,t,\xi})/\Delta t\} \geq 1 - \alpha \tag{4.22a}$$

which can be rewritten as,

$$\mathbb{P}\{P^{sch}_{f,t} \geq \underline{P}_{f,t} + \sigma^{rd}_{f,t,\xi} - (\omega^{fu}_{f,t,\xi} - \omega^{fd}_{f,t,\xi})/\Delta t\} \geq 1 - \alpha \tag{4.22b}$$

and then, using the CDF $\phi_{P^{sch}_{f,t}}(x)$ associated to the uncertain parameter $P^{sch}_{f,t}$, it can be written as,

$$1 - \phi_{P^{sch}_{f,t}}(\underline{P}_{f,t} + \sigma^{rd}_{f,t,\xi} - (\omega^{fu}_{f,t,\xi} - \omega^{fd}_{f,t,\xi})/\Delta t) \geq 1 - \alpha \tag{4.22c}$$

$$\phi_{P^{sch}_{f,t}}(\underline{P}_{f,t} + \sigma^{rd}_{f,t,\xi} - (\omega^{fu}_{f,t,\xi} - \omega^{fd}_{f,t,\xi})/\Delta t) \leq \alpha \tag{4.22d}$$

and finally, using the inverse of the CDF $\phi^{-}_{P^{sch}_{f,t}}(p)$, it can be written as,

$$\underline{P}_{f,t} + \sigma^{rd}_{f,t,\xi} - (\omega^{fu}_{f,t,\xi} - \omega^{fd}_{f,t,\xi})/\Delta t \leq \phi^{-}_{P^{sch}_{f,t}}(\alpha) \tag{4.22e}$$

Then, we take advantage of the property of the ICDF that $\phi^{-}_{P^{sch}_{f,t}}(\alpha) = P^{sch}_{f,t} + \phi^{-}_{e_f}(\alpha)$, where $\phi^{-}_{e_f}(\alpha)$ is the ICDF of the error of the forecast variable $P^{sch}_{f,t}$, which is the distribution that will be fitted out of the SARIMA model. Then, the chance-constraint can be written as,

$$\underline{P}_{f,t} + \sigma^{rd}_{f,t,\xi} - (\omega^{fu}_{f,t,\xi} - \omega^{fd}_{f,t,\xi})/\Delta t \leq P^{sch}_{f,t} + \phi^{-}_{e_f}(\alpha) \tag{4.22f}$$

Following this procedure it is possible to write the chance-constraints associated to the FLs and FGs as follows,

$$\begin{aligned}
&\underline{P}_{f,t} + \sigma^{rd}_{f,t,\xi} - \phi^{-}_{e_f}(\alpha) \leq P^{sch}_{f,t} + (\omega^{fu}_{f,t,\xi} - \omega^{fd}_{f,t,\xi})/\Delta t \leq \\
&\qquad\qquad \leq \overline{P}_{f,t} - \sigma^{ru}_{f,t,\xi} - \phi^{-}_{e_f}(1-\alpha) && \forall f, \forall t, \forall \xi \quad (4.23a)\\
&\sigma^{ru}_{f,t,\xi} \leq \overline{P}_{f,t} - P^{sch}_{f,t} - \phi^{-}_{e_f}(1-\alpha) && \forall f, \forall t, \forall \xi \quad (4.23b)\\
&\sigma^{rd}_{f,t,\xi} \leq P^{sch}_{f,t} + \phi^{-}_{e_f}(\alpha) - \underline{P}_{f,t} && \forall f, \forall t, \forall \xi \quad (4.23c)\\
&\sigma_{g,t,\xi} \leq P^{sch}_{g,t} + \phi^{-}_{e_g}(\alpha) && \forall g, \forall t, \forall \xi \quad (4.23d)\\
&\omega_{g,t,\xi} \leq (P^{sch}_{g,t} + \phi^{-}_{e_g}(\alpha) - \sigma^{rd}_{g,t,\xi})\Delta t && \forall g, \forall t, \forall \xi \quad (4.23e)
\end{aligned}$$

4.7.2 FSP problem

Then, the FSP problem is defined as a bi-level optimization problem, where the benefits from its participation in the national and local markets are stacked together. Note that the $1/\gamma$ and $1/(1-\gamma)$ factors recover the dual variables values from the lexicographic optimization model of the markets.

$$\max \sum_{\xi} \pi_{\xi} \left[\frac{1}{\gamma} \left(\sum_{i,t,b} \lambda^{DAM}_{i,t,\xi} (p^{es}_{i,t,b,\xi} - p^{eb}_{i,t,\xi}) + \sum_{t} (\lambda^{ru}_{t,\xi} p^{ru}_{t,\xi} + \lambda^{rd}_{t,\xi} p^{rd}_{t,\xi}) \right) + \right.$$

$$\left. \frac{1}{1-\gamma} \sum_{i,t} \lambda^{LFM}_{i,t,\xi} (p^{fu}_{i,t,\xi} - p^{fd}_{i,t,\xi}) - \sum_{s,t} C^{DEG}_{s} p_{s,t} \right] \tag{4.24a}$$

Subject to,

$$\sum_{b} P^{es}_{i,t,b} = \sum_{g} P^{sch}_{g,t} + \sum_{s} \omega^{ed}_{s,t,\xi} \qquad \forall i, \forall t, \forall \xi \tag{4.24b}$$

$$p^{es}_{i,t,b,\xi} \leq \overline{P}_{block} \qquad \forall i, \forall t, \forall b \tag{4.24c}$$

$$\pi^{es}_{i,t,b-1} \leq \pi^{es}_{i,t,b} \qquad \forall i, \forall t, \forall b > 1 \tag{4.24d}$$

$$\sum_{b} P^{es}_{i,t,b} \leq \sum_{g} \omega^{es}_{g,t,\xi} + \sum_{s} P^{c}_{s} \qquad \forall i, \forall t, \forall b \tag{4.24e}$$

$$P^{eb}_{i,t} \leq \sum_{f} \overline{P}_{f,t} + \sum_{s} P^{c}_{s} \qquad \forall i, \forall t, \forall b \tag{4.24f}$$

$$P^{ru}_{i,t} \leq \sum_{f} (\overline{P}_{f,t} - \underline{P}_{f,t}) + \sum_{s} P^{c}_{s} \qquad \forall i, \forall t, \forall b \tag{4.24g}$$

$$P^{rd}_{i,t} \leq \sum_{f} (\overline{P}_{f,t} - \underline{P}_{f,t}) + \sum_{g} P^{sch}_{g,t} + \sum_{s} P^{c}_{s} \qquad \forall i, \forall t, \forall b \tag{4.24h}$$

$$P^{fu}_{i,t} \leq \sum_{f} (\overline{P}_{f,t} - \underline{P}_{f,t}) + \sum_{s} P^{c}_{s} \qquad \forall i, \forall t, \forall b \tag{4.24i}$$

$$P^{fd}_{i,t} \leq \sum_{f} (\overline{P}_{f,t} - \underline{P}_{f,t}) + \sum_{g} P^{sch}_{g,t} + \sum_{s} P^{c}_{s} \qquad \forall i, \forall t, \forall b \tag{4.24j}$$

$$p^{eb}_{i,t,\xi} = \sum_{f} \omega^{eb}_{f,t,\xi} + \sum_{s} \omega^{eu}_{s,t,\xi} \qquad \forall i, \forall t, \forall \xi \tag{4.24k}$$

$$p^{ru}_{t,\xi} = \sum_{f} \sigma^{rd}_{f,t,\xi} + \sum_{s} \sigma^{rd}_{s,t,\xi} \qquad \forall t, \forall \xi \tag{4.24l}$$

$$p^{rd}_{t,\xi} = \sum_{f} \sigma^{ru}_{f,t,\xi} + \sum_{g} \sigma^{rd}_{g,t,\xi} + \sum_{s} \sigma^{ru}_{s,t,\xi} \qquad \forall t, \forall \xi \tag{4.24m}$$

$$p^{fu}_{i,t,\xi} = \sum_{f} \omega^{fu}_{f,t,\xi} + \sum_{g} \omega^{fd}_{g,t,\xi} + \sum_{s} \omega^{fu}_{s,t,\xi} \qquad \forall i, \forall t, \forall \xi \tag{4.24n}$$

$$p^{fd}_{i,t,\xi} = \sum_{f} \omega^{fd}_{f,t,\xi} + \sum_{s} \omega^{fd}_{s,t,\xi} \qquad \forall i, \forall t, \forall \xi \tag{4.24o}$$

$$\text{(4.23a)} - \text{(4.23e)} \tag{4.24p}$$

$$\lambda^{DAM}_{i,t,\xi}, \lambda^{ru}_{t,\xi}, \lambda^{rd}_{t,\xi}, \lambda^{LFM}_{i,t,\xi} \in \arg\min \text{(4.18)} \tag{4.24q}$$

Equations (4.24b) to (4.24o) defines the aggregation constraints of the FSP problem. The energy sold in the DAM is defined by (4.24b) as the aggregated power generation of the FGs and the injection of BESSs. The size of each block b is then defined by (4.24c) and the price by (4.24d), as the offers must be increasing curves for the energy sold in the DAM. The limits of the quantities the FSP can bid are defined by (4.24e) and (4.24f) for DAM, by (4.24g) and (4.24h) for RM and by (4.24i) and (4.24j) for LFM. The amount of energy that is bought in the DAM is defined in (4.24k) as the aggregated power consumption of the FLs and the BESSs. The upward and downward reserves are defined in (4.24l) and (4.24m), respectively. These reserves are defined by all the resources managed by the FSP, although FGs only provide downward reserves. The participation in the LFM is defined by (4.24n) and (4.24o) for each node of the distribution network. Equations (4.24p) define the individual chance constraints of the FLs and FGs, BESSs constraints are also included. The market model is integrated in (4.24q) as a RSO.

Note that (4.24) is a bilevel optimization problem. The lower level problem endogenously set prices for the products in the DAM $\lambda_{i,t,\xi}^{DAM}$, the RM in the upward $\lambda_{t,\xi}^{ru}$, and downward $\lambda_{t,\xi}^{rd}$ directions, and for the LFM $\lambda_{i,t,\xi}^{LFM}$. The upper-level problem defines the quantity and prices of energy sold in the DAM $P_{i,b,t}^{es}, \pi_{i,b,t}^{es}$ and the amount and price of energy that will be bought in the DAM $P_{i,t}^{eb}, \pi_{i,t}^{eb}$, as well as the amount and price of upward $P_{i,t}^{ru}, \pi_{i,t}^{ru}$, $P_{i,t}^{fu}, \pi_{i,t}^{fu}$ and downward $P_{i,t}^{rd}, \pi_{i,t}^{rd}$, $P_{i,t}^{fd}, \pi_{i,t}^{fd}$ reserve and flexibility provided by the FSP. In other words, based on the uncertainty characterization of the RMA and the DERs, the FSP decides the quantity and prices for its participation in the different national and local markets. The lower level problem helps the FSP to model its participation in these markets. In this way, the FSP obtains the best possible outcome for the stacking of the different markets.

4.7.3 Solving the FSP bi-level optimization problem

For the sake of readability, we use a compact version of the previous formulation, where $\lambda_{\xi,n}$ and $\lambda_{\xi,l}$ are the prices of the national n and local l markets, respectively, for the realization ξ of the uncertainty, h_r, p_r are the parameters of the DERs and $z_{r,\xi}$ are its set of variables. Then, the FSP problem is formulated as follows:

$$\max \sum_{\xi} \pi_{\xi} \left[\sum_{n} \lambda_{\xi,n} x_n + \sum_{l} \lambda_{\xi,l} x_l \right] \tag{4.25a}$$

Subject to

$$\mathcal{P}\left\{ h_r z_{r,\xi} \leq p_r \right\} \geq 1 - \alpha \qquad \forall r, \forall \xi \tag{4.25b}$$

$$z_{r,\xi}, d_i, g_l \geq 0 \qquad \forall n, \forall \xi, \forall i, \forall l \tag{4.25c}$$

$$\lambda_{\xi,n}, \lambda_{\xi,l}, x_n, x_l \in \arg \text{(4.18)} \tag{4.25d}$$

The chance constraints associated to these DERs are defined in (4.25b) for all resources n and all possible realizations of the uncertainty ξ and a given confidence level α. Then, the price of the bids the FSP submit to the different markets are defined by d_i, and the limit of these bids by g_l. Note that these last two variables are not associated to the uncertainty ξ, as they are the bid outcome of the problem. They must be positive as defined by (4.25c). Lastly, this market participation is subject to the market clearing of the national and local markets defined by (4.25d) for all possible realizations of the uncertainty ξ. The objective of the FSP is to maximise the expected revenue from all the different markets, as defined by (4.25a).

To solve this bi-level optimization problem, we use duality theory [26] to replace the lower problem by its set of primal, dual and strong duality constraints. First, the dual problem of (4.18) in compact notation is computed as follows:

$$\max \sum_{k,\xi} (\hat{b}_k \lambda_{\xi,k} + \lambda^y_{\xi,k}) + \sum_{l,\xi} g_{\xi,l} \lambda_{\xi,l} \tag{4.26a}$$

Subject to

$$\hat{c}_i - \rho^c_i \lambda^r_{\xi,i} + \sum_k a_{k,i} \lambda_{\xi,k} + \sum_l f_{l,i} \lambda_{\xi,l} \leq \pi_\xi x_{\xi,i} \qquad \forall \xi, \forall i \tag{4.26b}$$

$$\Gamma^c_i \lambda_{xi,i} + \lambda^r_{\xi,i} \leq 0 \qquad \forall i, \forall \xi \tag{4.26c}$$

$$\lambda_{\xi,i} + \lambda^r_{\xi,i} \geq 0 \qquad \forall i, \forall \xi \tag{4.26d}$$

$$-\rho^b_k \lambda^r_{\xi,k} + \lambda^y_{\xi,k} \leq 0 \qquad \forall k, \forall \xi \tag{4.26e}$$

$$\Gamma^b_k \lambda_{\xi,k} + \lambda^r_{\xi,k} \leq 0 \qquad \forall k, \forall \xi \tag{4.26f}$$

$$\lambda_{\xi,k} + \lambda^r_{\xi,k} \geq 0 \qquad \forall k, \forall \xi \tag{4.26g}$$

$$\lambda_{\xi,i} = -\pi_\xi \qquad \forall i, \forall \xi \tag{4.26h}$$

Then, the FSP's problem (4.25) can be recast into the following bi-linear optimization problem,

$$\max \sum_\xi \pi_\xi \left[\sum_k \lambda_{\xi,k} x_k + \sum_l \lambda_{\xi,l} x_l \right] \tag{4.27a}$$

Subject to

$$\mathcal{P}\left\{ h_n z_{n,\xi} \leq p_n \right\} \geq 1 - \alpha \qquad \forall n, \forall \xi \tag{4.27b}$$

$$z_{n,\xi}, d_i, g_l \geq 0 \qquad \forall n, \forall \xi, \forall i, \forall l \tag{4.27c}$$

$$\hat{c}_i x_{\xi,i} + \Gamma^c_i \nu^c_{\xi,i} + \mu^c_{\xi,i} - \tau_{\xi,i} \leq 0 \qquad \forall \xi, \forall i \tag{4.27d}$$

$$\nu^c_{\xi,i} + \mu^c_{\xi,i} \geq \rho_i x_{\xi,i} \qquad \forall \xi, \forall i \tag{4.27e}$$

$$\sum_j a_{k,j} x_{\xi,j} + \Gamma^b_k \nu^b_{\xi,k} + \mu^b_{\xi,k} \leq \hat{b}_k \qquad \forall \xi, \forall k \tag{4.27f}$$

$$\nu^b_{\xi,k} + \mu^b_{\xi,k} \geq \sigma_k y^b_{\xi,k} \qquad \forall \xi, \forall k \tag{4.27g}$$

$$y^b_{\xi,k} \geq 1 \qquad \forall \xi, \forall k \tag{4.27h}$$

$$\sum_j f_{l,j} x_{\xi,j} \leq g_{\xi,l} \qquad \forall \xi, \forall l \tag{4.27i}$$

$$x_{\xi,i}, \nu^c_{\xi,i}, \mu^c_{\xi,i}, \nu^b_{\xi,k}, \mu^b_{\xi,k}, y^b_{\xi,k} \geq 0 \tag{4.27j}$$

(4.26b) – (4.26h) (4.27k)

(4.26a) = (4.18a) (4.27l)

Equations (4.27b) and (4.27c) represent the aggregation and scheduling constraints of the FSP. Note that the chance constraints are converted into deterministic constraints before solving the problem. Primal equations of the robust stochastic problem that models the behaviour of the markets are represented from (4.27d) to (4.27j). Dual equations are represented by (4.27k), while the strong duality condition is enforced by (4.27l). Both the objective (4.27a) and the strong duality condition (4.27l) introduce bi-linear terms in the problem, which make it challenging to solve. Following reference [182] the problem is solved based on a two-step approach. First, bi-linear terms are relaxed using McCormick's envelopes and then a NLP solver is used to obtain the final solution of the problem.

4.7.4 McCormick's envelopes

McCormick's envelopes are used to relax the bi-linear terms of the problem. The McCormick's envelopes of a bi-linear term x_1x_2 are defined as follows [183]. Let x_1 be in the interval $[\underline{x}_1, \overline{x}_1]$ and x_2 be in the interval $[\underline{x}_2, \overline{x}_2]$. Then, let $z = x_1x_2$, the McCormick's envelopes of z are defined as follows,

$$z \geq \underline{x}_1 x_2 + x_1 \underline{x}_2 - \underline{x}_1 \underline{x}_2 \tag{4.28a}$$

$$z \geq \overline{x}_1 x_2 + x_1 \overline{x}_2 - \overline{x}_1 \overline{x}_2 \tag{4.28b}$$

$$z \leq \underline{x}_1 x_2 + x_1 \overline{x}_2 - \underline{x}_1 \overline{x}_2 \tag{4.28c}$$

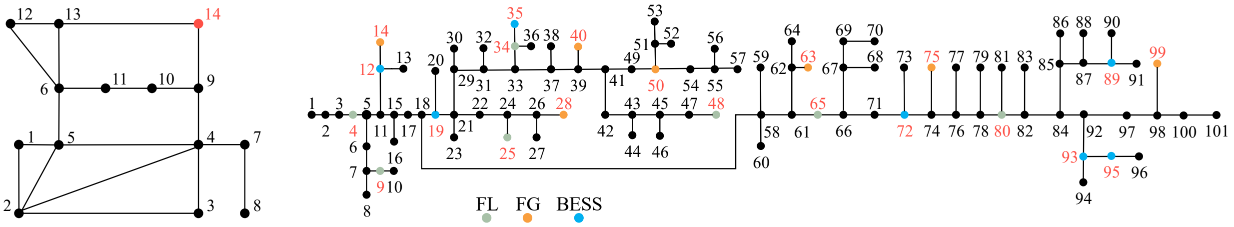
$$z \leq \overline{x}_1 x_2 + x_1 \underline{x}_2 - \overline{x}_1 \underline{x}_2 \tag{4.28d}$$

If proper lower and upper bounds are obtained, the feasible space is reduced, which will help to obtain a better initial solution for the problem. For every bi-linear term in the problem, the McCormick's envelopes are computed and added to the problem. Then, the linearised problem is solved using CPLEX. The solution of this problem is used as an initial point for the non-linear problem, which is solved using CONOPT v3.17A [159].

4.8 Case study: Stacking of revenues under uncertainty

The case study uses the IEEE-14 bus test system for the modelling of the transmission network, where the DAM and RM are cleared, and the 100-node grid of [184] for the distribution network, where the LFM is cleared. Both systems are connected through node 14 of the transmission network. A realistic dataset is used for the generation of the different baselines of the FLs and FGs [117]. The static load of the transmission network is 103.8 MW, while the static load of the distribution network is 12.9 MW. The FSP participates in the national markets through node 14 of the network, as it is shown in Figure 4.18. In the distribution network, the FSP controls 21 nodes, 7 FLs, 7 FGs and 7 BESSs, presented in green, orange and blue respectively. The rest of the nodes are controlled by different RMAs.

The case study is solved using CPLEX and CONOPT v3.17A [159] in an Apple M1 chip with 16 GB of RAM. The simulation is performed using Python 3.9.2 and the PYOMO



(a) TN

(b) DN

Figure 4.18: Transmission (a) and distribution (b) networks used in the case study. The RMAs are represented by black nodes and numbering, while the nodes controlled by the FSP are represented by red numbering and green nodes for FLs, orange nodes for FGs and blue nodes for BESSs. TN and DN are connected through node 14 of the TN.

package. The total simulation time is 1,023.6 s, where 164.3 s are used to solve the linear problem and 859.3 s are used to solve the non-linear problem.

4.8.1 System data and uncertainty characterization

For the RSO problem, the RMAs' supply functions are estimated using historical market results. Based on nodal pricing for the day-ahead market $\lambda_{i,t}^{DAM}$ and the local flexibility market $\lambda_{i,t}^{LFM}$ it is possible to estimate the supply function of the RMAs if enough time is considered, three months for this case study. Locational marginal prices are the marginal costs of the last unit of energy dispatched in the system, so they represent the marginal costs of the RMA in the market if they are the last unit of energy dispatched at a given node i. Based on this, the supply function is estimated as a step-wise increasing function of the form $\pi_i(p_{-i}^{es}) = \sum_{k=1}^{n} a_k \chi_{p_{-i}^{es}}$, where $\chi_{p_{-i}^{es}}$ is the indicator function of the power injected by the RMA at node i, a_k are the coefficients of the step-wise function, and n is the number of steps of the function. This estimation enables us to compute confidence intervals for the supply function, which are used in the RSO to characterize the uncertainty of the RMA in the market at each node of the transmission and distribution networks. Figure 4.19 shows an example of the estimation of the supply function of the RMA at node 1 of the transmission network.

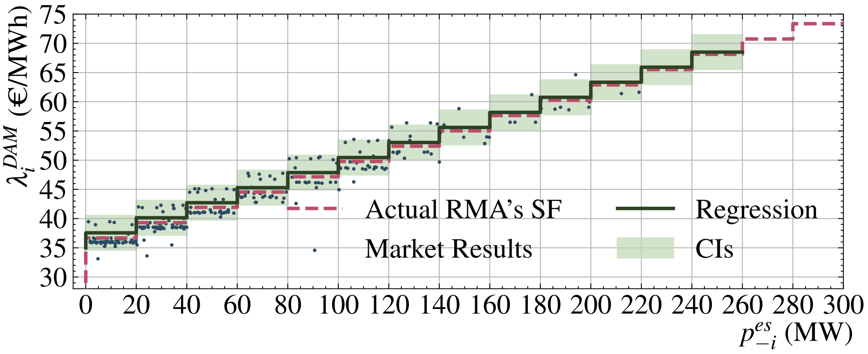


Figure 4.19: Estimation of the RMA's supply function. Blue points are from past market results, the pink dashed line is the real supply function, the green line is the estimated supply function with its CI.

For the aim of this model, we simulate three consecutive months of market results, simulating different congestions along the grid and different market prices to obtain a estimation of the stepwise supply function of the RMAs at each node of the transmission and distribution networks. Then, the uncertainty of the supply functions for the DAM $\pi^{es}_{-i,t,b}(P_{-i,t,b})$, the RM $\pi^{ru}_{g,t}(p^{ru}_{g,t})$, $\pi^{rd}_{g,t}(p^{rd}_{g,t})$ and the LFM $\pi^{fu}_{-i,t}(p^{fu}_{-i,t})$, $\pi^{fd}_{-i,t}(p^{fd}_{-i,t})$ are characterised using this method. Note that the supply function of the demand in the DAM can be assumed to be inelastic and set to a large enough constant, as considered by authors in [173].

Then, on the other hand, the uncertainty associated with demand in the distribution network $P^{sch}_{-i,t}$, $Q^{sch}_{-i,t}$ and reserves R^{u}_{t}, R^{d}_{t} are characterized using a scenario-based approach. Based on historical data, several scenarios are generated for demand and reserves throughout the day, as it is shown in Fig. 4.20 for the case of the demand, where the red lines are the generated scenarios and the grey lines are the input data. Sixteen scenarios are obtained using a clustering technique based on the K-means algorithm and the Wasserstein distance to calculate the dissimilarity between pairs of days. Probabilities associated with each scenario are computed as the fraction of the total days assigned to the corresponding cluster.

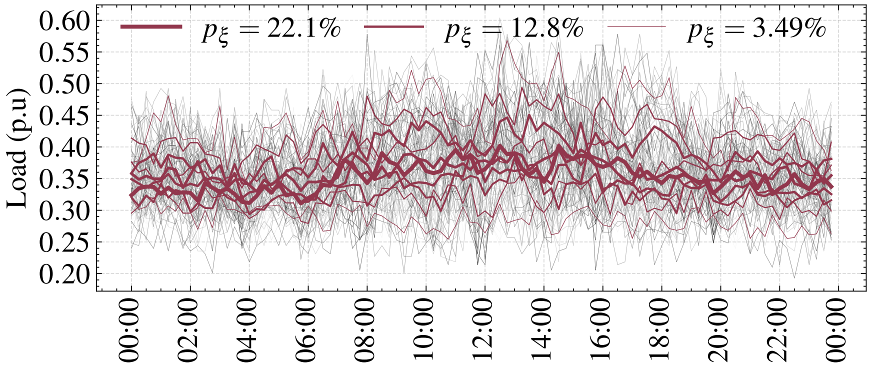


Figure 4.20: Load scenario generation based on K-Means algorithm and Wasserstein distance. Red lines represent the generated scenarios, grey lines the historical data. The thickness of red lines represents the probability of the scenario.

The uncertainty of the DERs that the FSP manages, is characterised based on a deterministic transformation of the chance constraints, following the approach presented by [26]. Then, based on historical data obtained from [117], the production of the renewable resources $P^{sch}_{g,t}$ and the consumption of the FLs $P^{sch}_{f,t}$ are forecast using an ARIMA model. Then, the distribution of the error of the forecast is fitted to a versatile distribution function [55] using a non-linear least squared method, which enables us to obtain an affine representation of the uncertainty and the corresponding ICDF. A pictorial example of this method is shown in Figure 4.21, where the PDF and the ICDF of the fitted distribution are shown. The coefficient of determination R^2 of the fitted ICDF is 0.962, which means that the fitted distribution is a good approximation of the actual data.

4.8.2 Stacking of revenues in Multi-Scale Markets

The results of the FSP for the day-ahead market are shown in Figure 4.22, where the stacked results of the FSP are shown for the DAM, the RM and the LFM. For this analysis $\Gamma^{b}_{k} = \Gamma^{c}_{i} = 1$, which corresponds to a conservative FSP bidding strategy.

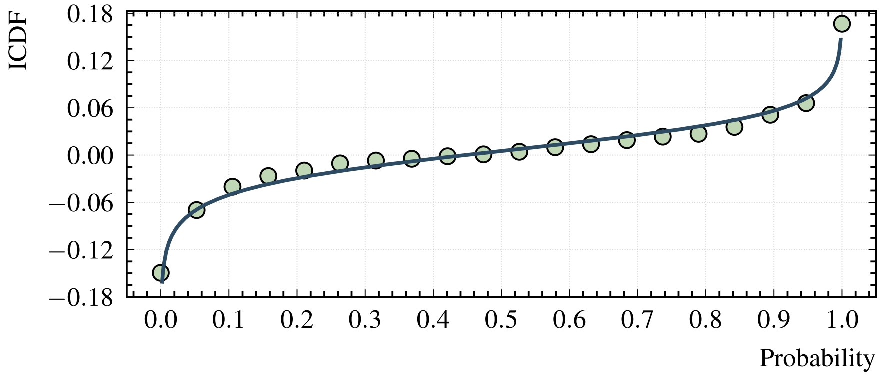


Figure 4.21: A pictorial example of the ICDF characterisation for the FLs resources that the FSP manages. Actual data is represented in green while versatile fitted distribution is in blue.

In this case, the dominant income stream is obtained from the RM, specially during the mid-hours of the day, where the FSP can offer flexibility to balance the grid. On the other hand, the DAM is the dominant expense stream. The generation of the FGs is used to cover part of the demand in the central hours of the day, as it can be seen for the decrease in the bought DAM energy in Fig 4.22 (b). Nevertheless, the FSP obtain revenues from its participation in the LFM, which adds value to the business model.

A detailed view of the stacked streams by type of DERs is shown in Table 4.4, where the income and the quantities of the DAM, the RM and the LFM are shown for each type of DER. In this case, the FLs are the main source of expense for the FSP as they need to cover their demand. However, the FSPs obtain revenues from their participation in the RM. More profitable are the FGs and BESSs which stack revenues from all the three markets. The 60.6% of the products traded correspond to BESSs, whose participation in the RM is the most profitable, followed by the DAM and the LFM.

The FSP distribution of the available resources among the different markets is shown in Figure 4.23. The main strategy to maximise benefits is to prioritise the participation in the RM over the DAM and the downward direction of the LFM. Using all the distributed generation of the FGs to cover part of the demand of the FLs. This leads the FSP to offer most of the available capacity of the FGs and BESS to this market.

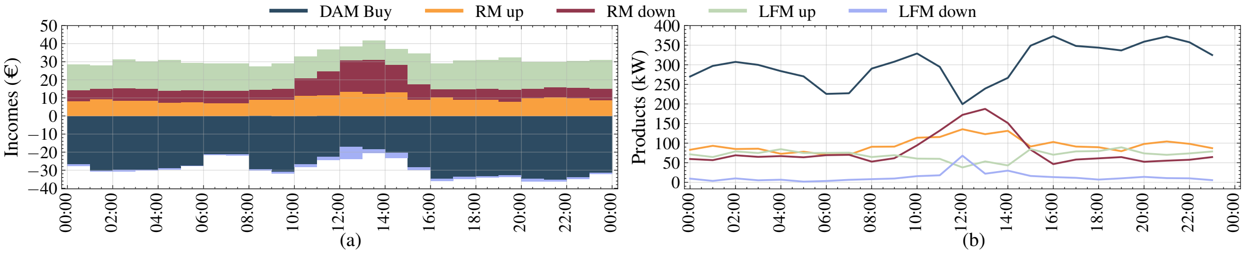


Figure 4.22: Stacked streams from the DAM, the RM, and the LFM. (a) Income streams and (b) Products exchanges.

Table 4.4: Stacked streams by type of DERs. Income and quantities are in € and kW or kWh, respectively.

	FL	FG	BESS	Total
DAM Demand (€)	-204.33	0.00	-0.76	-205.09
DAM Generation (€)	0.00	47.17	9.85	57.02
RM up (€)	24.12	0.00	114.11	138.23
RM down (€)	0.00	13.76	114.58	128.34
LFM up (€)	0.04	0.00	5.85	5.89
LFM down (€)	-83.66	86.48	-49.24	-46.42
Total (€)	-263.83	147.41	194.40	77.97
DAM Demand (kWh)	4,695.6	0.0	201.5	4,897.1
DAM Generation (kWh)	0.0	254.6	521.6	776.2
RM up (kW)	45.5	0.0	2,153.2	2,198.7
RM down (kW)	0.0	34.2	2,845.0	2,879.2
LFM up (kWh)	1.3	0.0	1,897.2	1,898.6
LFM down (kWh)	32.8	21.6	235.0	289.4
Total (kWh)	4,775.2	310.4	7,853.7	12,939.3

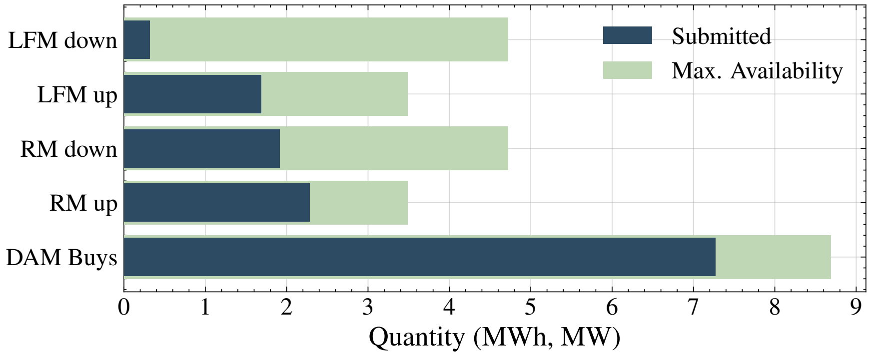


Figure 4.23: Distribution of the resources among the different markets. Blue bars represent the FSP offer and green bars the maximum available capacity.

4.8.3 Scheduling of DERs managed by the FSP

In this section, the scheduling of the DERs managed by the FSP is analysed. Figure 4.24 shows the schedule of one FL of the case study and the products exchanged with the FSP. The FL is scheduled to cover its demand, based on energy obtained from the DAM, while provide reserves in the RM and flexibility in the LFM. FLs takes advantage of its ability to reschedule theirselves to cover their demand and provide flexibility services.

Secondly, Fig. 4.25 shows the schedule of one of the FG of the case study that is injecting to one congested part of the distribution grid. Even in this case, the FG injects as much energy as possible to the node, while providing downward reserves, as shown in Fig. 4.25 (b).

Finally, Fig. 4.26 shows the schedule of one BESS of the case study. The battery degradation costs considered in the problem formulation disincentive the continuous charging and discharging of the BESS. Although reserves are provided in both directions, the BESS is not constantly charging and discharging during the day, and a smooth change of the state of charge is observed. Under these conditions, the BESS is scheduled to provide reserves in the RM and the LFM, while participating in DAM for benefits.

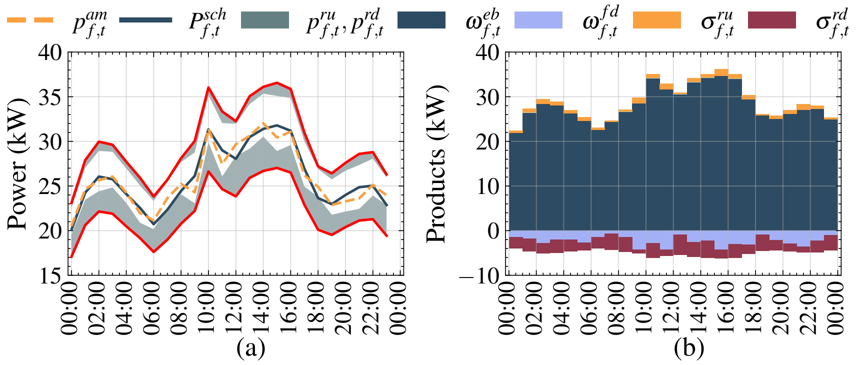


Figure 4.24: Schedule of one FL of the case study. (a) Power demand, reserves and limits. (b) Products exchanged with the FSP.

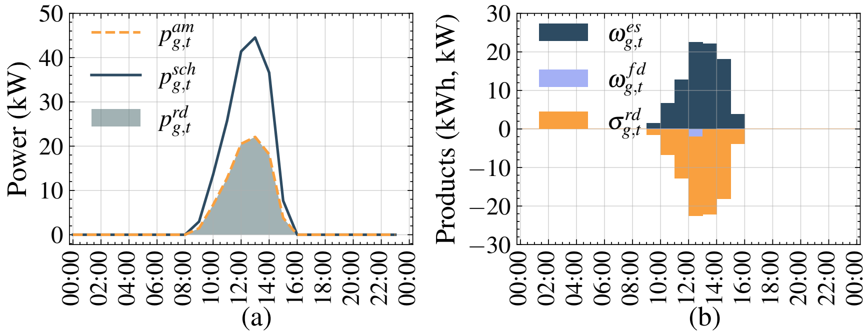


Figure 4.25: Schedule of one FG of the case study. (a) Power demand, reserves and limits. (b) Products exchanged with the FSP.

4.8.4 Out-of-sample and robustness analysis

The robust optimisation approach used in this work gives a solution that might be conservative, and the FSP might be interested in knowing how the solution changes for different realisations of the uncertainty. This is done by varying the value of the uncertainty parameters Γ^b_k, Γ^c_i and solving the problem for each value. Non-negative values of these parameters control the robustness of the problem against a subset of the uncertainty. For the sake of simplicity, the same value is considered for all the uncertainty parameters.

The process followed to perform the out-of-sample analysis is shown in Fig. 4.27. In the out-of-sample analysis, the input data used to characterise the uncertainty is divided into two sets: the in-sample (80%) and the out-of-sample (20%) dataset. The in-sample is used to characterise the uncertainty of the problem and solve the robust stochastic problem (4.27) for different values of Γ. Then, the out-of-sample dataset is used to evaluate the solution of the robust stochastic problem for each value of Γ.

The results of the out-of-sample analysis are shown in Fig. 4.28, where the results of the in-sample analysis (solid lines) are compared with the results of the out-of-sample analysis (shadow bounds). The solutions obtained are feasible for all the realisations of the uncertainty considered in the problem. The degree of conservatism of the solution can be seen in the results obtained from the participation in the DAM and the LFM. The

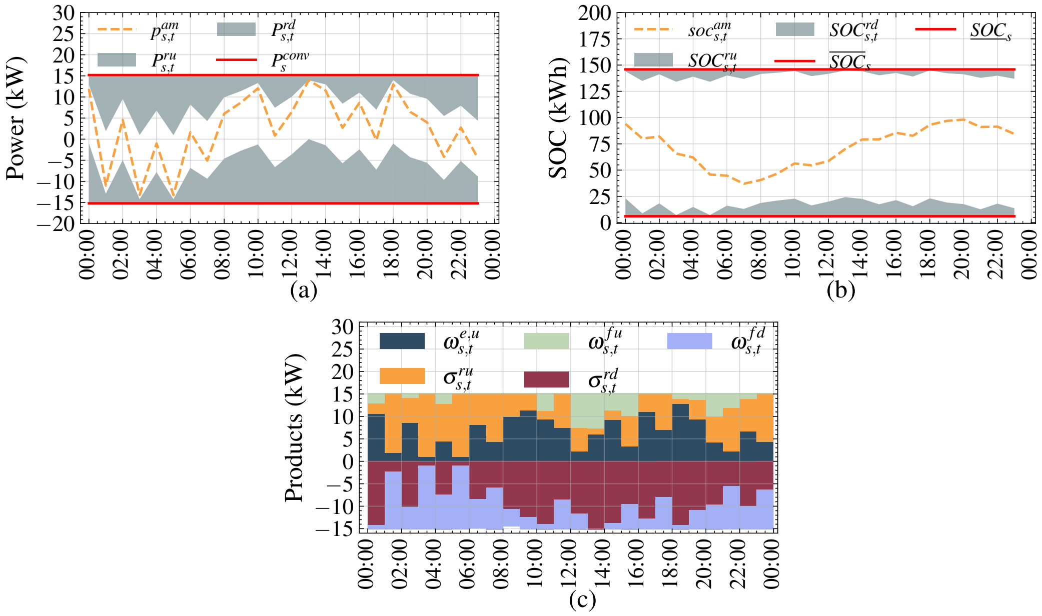


Figure 4.26: Schedule of one BESS of the case study. (a) Power demand, reserves and limits. (b) State of charge, (c) Products exchanged with the FSP.

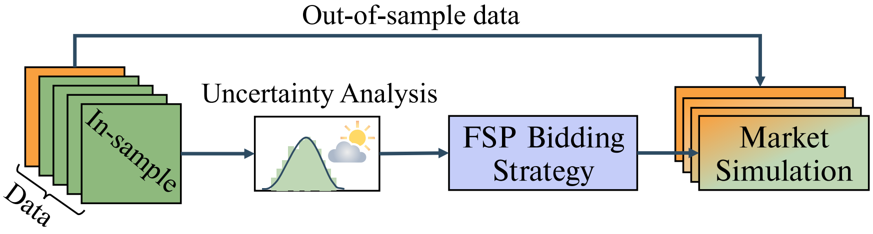


Figure 4.27: Scheme of the out-of-sample analysis performed.

more knowledge the FSP has about the uncertainty, i.e. for lower values of Γ, the more advantage it can take from its participation in the markets, which results in higher profits for the trading of upward flexibility in LFM and lower costs of energy in the DAM. This is because the FSP can anticipate the actions of the RMAs and schedule its DERs accordingly. If the FSP has no knowledge about the uncertainty, i.e. for higher values of Γ, it has to be more conservative and schedule its DERs without the certainty of a maximum profit for its participation in the markets.

This drives us to another important aspect of the approach used in this work, which is the possibility of quantifying the value of information as the difference between the profits obtained in conservative and non-conservative scenarios. With perfect information about the rivals' actions, the FSP would be able to increase its profits by 850€/day in this case study. This is even when similar quantities of products are traded, as shown in Fig. 4.28 (d), where 9 MWh of products provided 650€ of profits with $\Gamma = 0.33$, and 250€ of profits with $\Gamma = 0.66$ and 9.5 MWh of products. This puts in evidence the importance of bidding the right quantity at the right time and with the right bid price.

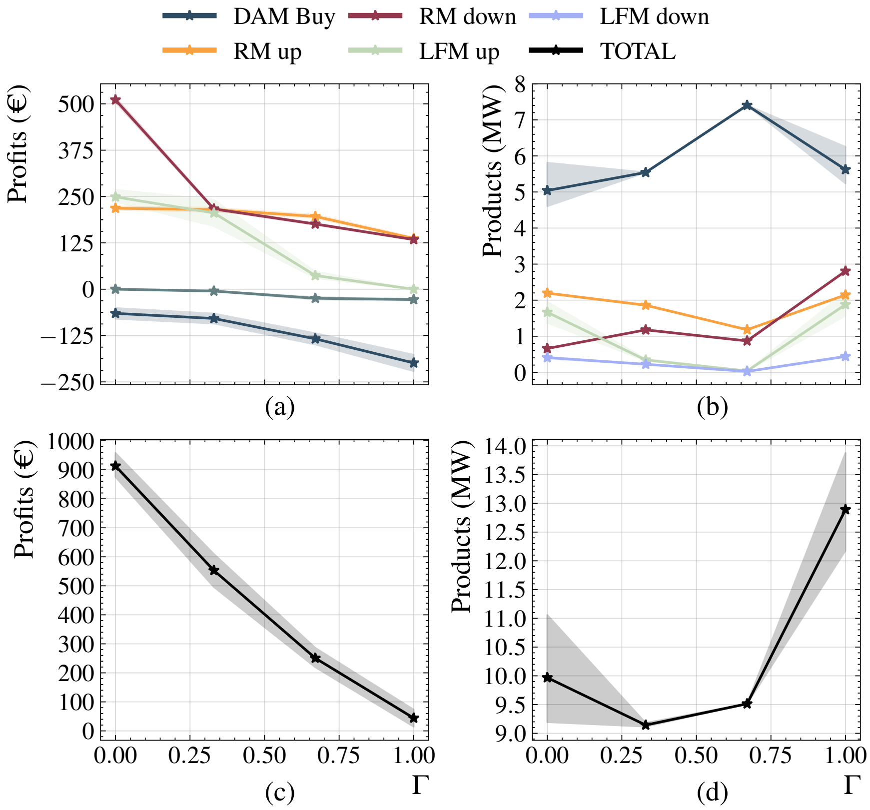


Figure 4.28: Out-of-sample analysis results varying Γ. (a) Profits and bounds for each product. (b) Quantity of products exchanged and bounds. (c) Total profits and bounds. (d) Total quantity of products and bounds.

4.9 Summary

In this chapter two different approaches for the participation of DERs in the electricity markets have been presented. The first approach is based on a tri-level optimization problem, where DERs such as FLs, FGs, BESSs, EVs and HVACs systems participate in multi-scale markets. The tri-level problem is recast into a single-level optimization problem using a an approximation of the sequential market-clearing process and duality theory. The first case study, which was based on IEEE-14 for the transmission network and N_5_1_DSS for the distribution network and a realistic dataset, demonstrated the feasibility of the approach, which was able to schedule the DERs among the different markets obtaining higher profits for the joint-participation in the markets than for the individual participation in each market.

Nevertheless, the main limitation of the first approach is the necessity of detailed information about the market and the rivals, which is difficult to obtain in practice. In this environment of partial information, the second approach presented in this chapter uses robust stochastic optimization to overcome this limitation. The sequential clearing of the multi-scale markets presented in the first version, is extended to a robust stochastic approach, where the uncertainty of the problem is characterized by a set of scenarios for the dispatch, and a set of robust parameters for the rivals' actions. Using a linear robust counterpart of the problem, the robust stochastic problem is recast into a deterministic lower-level problem, which is included into the upper-level problem using duality theory. This representation of the participation of the FSP in the multi-scale markets allows to obtain the optimal schedule of the DERs in an environment of limited access to information. The bidding strategies deployed by the FSP depending on the degree of conservatism of the solution are discussed in the case study, highlighting the importance of a good characterization of the problem for higher profits even with similar quantities of products traded. In addition, the out-of-sample analysis conducted shows the feasibility of the proposed uncertainty characterization, with less than 10% of variability in the profits of the FSP

CHAPTER 5

Conclusion

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In this chapter, a brief summary of the thesis is given, conclusions are drawn and the future works that will be developed after the completion of this thesis are explained.

5.1 Summary

Modern electrical energy systems are facing a profound transformation due to the increasing penetration of renewable energy sources and the development of new technologies. Changes in the pattern of consumption as well as the electrification of transport and heating sectors are also contributing to the transformation of the power system. In this context, the power system is becoming more complex and uncertain, which makes the operation of the system more challenging. In order to cope with these challenges, new tools and methods are needed to ensure the secure and reliable operation of the power system.

The main developments of this thesis can be depicted as a the two-pillar structure presented in Figure 5.1. The first pillar is built around the proposal of new architectures for local markets, which can be used to coordinate the operation among DSOs and multiple DERs. The second pillar is the proposal of new business cases for the FSP figure, which can be used to aggregate the flexibility of DERs and offer it to multiple national and local markets for the sake of benefits. Both pillars are supported by the same foundation, which is the of the potential of the new technologies deployed over the distribution networks, which will boost the decarbonization of the power system and contribute to create a more net-zero, reliable and secure energy system.

The contents of this thesis are included in the published papers [23], [24], [25], [26], [27], [28], and [29]. The main contributions of the thesis are summarized as follows:

- **Conference [23]**: introduces an efficient formulation for LFMs, where flexibility products are traded to address network problems in power systems. This paper proposes a centralized approach that considers both capacity and energy products, using linear programming optimization for the market-clearing. The study assumes

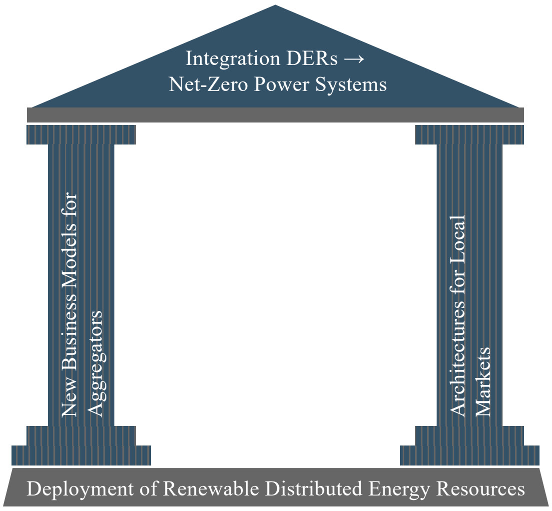

Figure 5.1: Two-pillar structure of the thesis

that Aggregators manage the flexibility assets in the distribution network. The results obtained from this centralized approach demonstrate the feasibility of the proposed method in effectively resolving network issues at the distribution level under various scenarios.

- **Journal [24]**: discusses the emergence of LEMs as new layers in current market designs, allowing for local trading of flexibility products. However, implementing LEMs that involve multiple DSOs raises concerns about information privacy while striving for system-wide efficiency. The paper proposes a market design for Multi-DSO LEMs where DSOs can trade among different areas under the coordination of a LMO. The coordination and decentralisation approach is based on the ADMM, with each DSO independently scheduling its assets in response to market signals to meet flexibility requests from itself or other DSOs. The proposed framework is tested using an illustrative case study based on the IEEE 123 bus test systems.
- **Conference [25]**: In this paper, an alternative solution for congestion and imbalance mitigation using capacity and balancing flexibility products is proposed. These products' prices are determined based on their relationship with traditional markets, ensuring compatibility and facilitating the implementation of LFMs. The paper also presents an adaptive ADMM algorithm that solves the market clearing problem in a Multi-Area setting while preserving information privacy. The feasibility of the proposed approach is demonstrated using the IEEE 34 bus system, where the solution for a two-area LFM is obtained in a few tens of iterations. Additionally, a scalability analysis reveals a linear relationship between the number of areas and convergence.
- **Journal [26]**: addresses the operational requirements related to congestion and imbalance mitigation services in a scenario with high penetration of RDERs across different DSOs jurisdictions. The proposed approach is an uncertainty-aware Multi-DSO LFM that utilizes flexibility products to manage congestions and imbalances

among DSOs. The market setting involves capacity products that hold back RDER flexibility in anticipation of contingencies, with energy products activated if the event occurs. The methodology is solved using the ADMM in a coordinated and decentralized manner, ensuring participant privacy. The uncertainty of RDERs and energy events duration is modeled through chance-constraint linear optimization. The proposed methodology is evaluated through a case study using realistic datasets and radial distribution systems.

- **Conference [27]**: addresses the operational challenges that arise in energy systems when DSOs tries to characterize the flexibility envelopes of the distribution network inside the LFM paradigm. This contribution introduced a novel linear approach for assessing the flexibility region and associated costs for DSOs in Multi-DSO LFMs, allowing the analysis of non-linear DERs such as batteries. The feasibility of this approach is demonstrated through a case study involving two IEEE 34 bus systems representing different DSOs participating in an Multi-DSO LFM. The results highlight the effective procurement of flexibility by RDERs in both active and congested interconnection scenarios, while accurately capturing the non-linear behavior of these resources.
- **Journal [28]**: discusses the challenges and opportunities presented by the growing number of flexible DERs in achieving Net-Zero Emissions goals. Currently, DERs face limitations in participating in multiple markets, which hampers their profitability. To address this issue, the paper proposes a tri-level optimization problem that focuses on maximizing revenues from DERs. The optimization problem takes into account the simultaneous participation of various flexible DERs, such as EVs, BESSs, and HVACs, in both national and local markets. By sequentially clearing the markets and using a dual formulation and strong duality condition, the proposed approach demonstrates its effectiveness in increasing profits compared to a baseline scenario, as evidenced by a case study conducted on realistic power system networks.
- **Working paper [29]**: extends the previous contribution in the revenue stacking for the figure of the FSP managing the uncertainty of the dispatch, the RDERs it manages and the RMAs in a scenario of limited information. The proposed method based its market model in a robust stochastic optimization problem and chance-constraints are used to capture the non-deterministic nature of the DERs of the FSP. The proposed approach is evaluated through a case study using realistic datasets and radial distribution systems. The results are validated using a out-of-sample analysis that helps to understand the risks associated to determined bidding strategies.

5.2 Conclusions

In conclusion, the presented works highlight the importance of local markets and decentralized trading in maximizing the benefits of flexibility resources in power systems. The methodologies proposed provide valuable insights and solutions for various aspects of flexibility trading and market participation.

The second chapter defined the concept of flexibility and its usage among local markets to solve operational constraints. It also highlighted the importance of the horizontal coordination and a clear and concise definition of the products among these new market frameworks to overcome the current barriers they face. In this way, the flexibility of the deployed DERs can be both horizontal and vertically integrated, unlocking new revenues streams that boost the transition to a net-zero energy system.

The third chapter presented a coordinated and decentralized methodology for flexibility products trading in Multi-DSO local energy markets in deterministic and uncertainty-aware versions. The use of ADMM-based algorithms preserves privacy while optimizing coordination among DSOs, finding specially fast convergence with the adaptive version of the algorithm, which could converge even with uncertainty and capacity products in the system. The coordination mechanism achieves system-wide efficiency by minimizing provision costs and yields the same operating points as centrally operated systems. The case study shows significant savings compared to non-coordinated solutions, highlighting the effectiveness of the proposed approach. These savings were 16.95% in the deterministic case study based on the IEEE 123 bus system and a 44.65% in the stochastic case study based on the network 201_3 and the SimBench dataset. A reduced number of iterations were needed to achieve convergence, 20 iterations in the deterministic case study and 140 iterations in the stochastic case study. Besides, the reliability of the stochastic solution is enhanced from 3.80% to 89.44% when integrating multiple DSOs in the market clearing protocol with capacity and energy products, even if the assets included have high uncertainty. In addition, a linear method to characterise the flexibility envelopes of the DSOs when participating in a Multi-DSO LFMs was proposed, showing that these market structures are effective tools to solve the operational constraints of the grid at low cost even when the TSO cannot provide any flexibility to the DN.

The fourth chapter proposes a vertical coordination mechanism for the participation of DERs in multiple national and local markets. The proposed approach is based on a deterministic tri-level optimization problem in first instance, and then extended to a stochastic version that incorporates robust stochastic optimization techniques and chance-constraints. The approach recasts the problem into a tractable single-level formulation using duality theory. The case study shows increased profitability, reduced costs in the locational flexibility market, and increased social welfare of the local energy market compared to single-market strategies. The deterministic model increases the profits of the FSP by 17.86% compared with the most profitable single-market strategy, while reducing 32.87% the costs in the LFM and increasing a 77.75% the social welfare of the LEM. The model proves robustness in the face of uncertainty, providing a holistic view of market participation.

Nevertheless, the main limitation of the first approach for revenue stacking is the necessity of detailed information about the market and the rivals, which is difficult to obtain in practice. In this environment of partial information, the second approach presented in this chapter uses robust stochastic optimization to overcome this limitation. The sequential clearing of the multi-scale markets presented in the first version, is extended to a robust stochastic approach, where the uncertainty of the problem is characterized by a set of scenarios for the dispatch, and a set of robust parameters for the rivals' actions. Using a linear robust counterpart of the problem, the robust stochastic problem is recast into a deterministic lower-level problem, which is included into the upper-level problem using duality theory. This representation of the participation of the FSP in the multi-scale markets allows to obtain the optimal schedule of the DERs in an environment of limited access to information. The bidding strategies deployed by the FSP depending on the degree of conservatism of the solution are discussed in the case study, highlighting the importance of a good characterization of the problem for higher profits even with similar quantities of products traded. The results show the value of the rival information in the calculation of the bidding strategies, adding up to 850 €/day to the profits of the FSP in the case study. In addition, the out-of-sample analysis conducted shows the feasibility of the proposed uncertainty characterization, with less than 10% of variability in the profits of the FSP.

Overall, these works emphasize the significance of local market trading, decentralized coordination, and optimization techniques in harnessing the full potential of flexibility resources. By enabling efficient utilization of resources, reducing costs, and enhancing grid reliability, the adoption of these methodologies contributes to the transition toward a more sustainable and efficient power system.

5.3 Future works

The following list of future works is proposed to continue the research line of this thesis:

- The development of bidding models for BESSs with a more realistic representation of the battery characteristics and the activation of the energy products, ensuring real-time availability of the energy in a multi-market revenue stacking scenario. These characteristics are not considered in the current version of the model, which could lead to unrealistic bidding strategies giving the degradation of the battery and the activation of the energy products.
- The development of bidding models for the incipient figure of the hydrogen electrolysers in a multi-market revenue stacking scenario. The deployment of this technology is expected to increase in the next years, which provide new opportunities for integrating the renewable energy in the power system. However, a detailed characterization of the technology is needed to develop the bidding models.
- The development of reinforcement learning algorithms to determine the optimal bidding strategy for DERs in a multi-market revenue stacking scenario. The use of these algorithms could provide another layer of privacy protection for the DERs while enabling them to learn the optimal bidding strategy in an environment of limited information.

- Investigation of the dissagregation of the flexibility revenues among clusters of DERs. During the development of the thesis, the aggregation of flexible elements has been demonstrated as beneficial. Nevertheless, the mechanims for dissagregating these benefits can be further investigated. To this aim, the use of cooperative game theory could provide a framework to determine the optimal dissagregation of the benefits. Further investigations will be needed to determine the fairest manner to dissamble what has been aggregated.
- The development of jointly coordination mechanisms between DSOs and TSO to ensure the efficient use of the flexibility. Until this point, the developed coordination mechanisms have been focused on the horizontal dimension. Nevertheless, it is important to consider the vertical dimension to provide flexibility services to the TSO.
- The forecasting of the flexibility envelopes of the DERs that helps the DSOs to determine the optimal operation of the distribution network.
- The development of coordination mechanisms based on the use of the flexibility and costs envelopes. The use of these envelopes could provide a model free approach to the coordination of the DSOs in the local energy markets. In this sense, these envelopes could be used to directly determine the optimal operation plan at the interface, and then, the optimal operation of each of the areas involved in the operation.

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