UNIVERSITAT POLITÈCNICA DE VALÈNCIA

TESIS DOCTORAL

METODOLOGÍA PARA LA OPTIMIZACIÓN DEL BENEFICIO DE LA RESPUESTA DE LA DEMANDA EN CONSUMIDORES INDUSTRIALES: CARACTERIZACIÓN POR PROCESOS Y APLICACIÓN

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RESUMEN

En la actualidad, existe una creciente necesidad a nivel global de incrementar la producción de electricidad, elemento clave de las economías modernas, a partir de fuentes de energía renovable. Este fenómeno, conocido como “transición energética”, pretende cambiar el modelo actual basado en combustibles fósiles por un modelo cien por cien renovable. Para llevarlo a cabo, es importante tener en cuenta que la mayoría de los recursos de generación renovables no son gestionables y presentan una fuerte variabilidad en su producción de energía difícilmente predecible, lo que hace necesario que el sistema eléctrico tenga que ser más flexible para poder operarse de forma segura. Por otro lado, en los últimos años, las tecnologías de la información y la comunicación han experimentado una rápida evolución como consecuencia del proceso de digitalización y de los continuos desarrollos en este campo, lo que ha permitido a otros sectores, como el sector eléctrico, evolucionar hacia nuevos modelos de funcionamiento más avanzados como las denominadas “redes inteligentes”. Todos estos cambios hacen que la flexibilidad de la demanda, conocida como la capacidad de un consumidor de modificar su forma de consumir energía en función de una señal externa, pueda ofrecerse como un recurso valioso a los operadores del sistema eléctrico. De esta forma, los consumidores más activos tienen una oportunidad para reducir su coste energético, pudiendo ser más competitivos y ayudando a la vez a facilitar la transición energética.

La presente tesis doctoral tiene como objetivo general el desarrollo de una metodología y de las herramientas de apoyo necesarias que permitan fundamentalmente plantear soluciones destinadas a la resolución de las barreras más importantes en relación con la participación de los recursos de demanda en la operación del sistema eléctrico. Adicionalmente, permiten determinar la estrategia óptima de participación de grandes y medianos consumidores de energía eléctrica en productos y mercados en los que los recursos flexibles puedan ser económicamente competitivos y técnicamente fiables. Este objetivo general se ha abordado mediante el cumplimiento de cuatro objetivos específicos, los cuales se han traducido en la realización de un conjunto de modelos, metodologías y herramientas que dan cumplimiento a cada uno de ellos.

En este sentido, la tesis se ha dividido en cuatro desarrollos interrelacionados a partir de sus resultados. En primer lugar, se ha propuesto una novedosa arquitectura conceptual del sistema eléctrico para integrar los futuros mercados de electricidad, destinada a establecer un marco de referencia más adecuado para la explotación de los recursos energéticos distribuidos y de demanda. En segundo lugar, se ha elaborado una metodología para la estandarización y validación de los recursos flexibles que pueden ofrecer los consumidores, y que podría servir como base para la creación de un proceso de certificación de productos de demanda. En tercer lugar, se ha desarrollado una primera herramienta de planificación a medio plazo que, partiendo de la caracterización y evaluación técnico-económica de los recursos flexibles obtenida con la metodología anterior, permite ayudar a los propios consumidores a evaluar la rentabilidad asociada a las diferentes estrategias de participación en un mercado de operación específico utilizando sus procesos de consumo flexibles. Por último, se ha llevado a cabo una segunda herramienta destinada a optimizar la programación de la operación para el día siguiente de los recursos de demanda de un determinado consumidor participando en un mercado previamente seleccionado a partir de los resultados de la herramienta anterior y, por tanto, ofreciéndole en definitiva el apoyo técnico y las herramientas necesarias para maximizar el beneficio asociado a dicha participación.

Las metodologías y herramientas desarrolladas en esta tesis han sido validadas mediante su aplicación a un caso de estudio compuesto por tres consumidores industriales pertenecientes a segmentos con una elevada replicabilidad en Europa. Estos consumidores son una industria papelera, una industria del sector cárnico y un centro logístico de producto refrigerado y congelado.

Los resultados obtenidos en esta tesis permiten afirmar que se ha dado un paso relevante dentro de la investigación en este campo para ayudar a la implantación de sistemas de energía eléctrica sostenibles mediante una participación más activa y dinámica de los recursos de la demanda.

ABSTRACT

The ever-increasing need for electricity in our global and advanced society, along with the requirements to preserve the environment, have forced a fast growth of the use of primary renewable sources to produce it. The process of replacing the current fossil primary sources with renewable ones to produce electricity is known as the “Energy Transition”. This transition is conditioned for the highly volatile, intermittent, and unpredictable nature of renewable energy sources. In this sense, two options exist to ensure the security of supply in power systems with a high share of renewable generation: either very robust, redundant, and expensive electricity systems with overcapacity or an electricity system with new and enhanced flexibility resources. Fortunately, relevant and advanced parallel developments in the technology, mainly in the control, information and communication fields have allowed the digitalization of the electricity supply systems towards the “smart grid” paradigm. One of the pillars of smart grids is the opportunity that arises for energy consumers to reduce the cost of their energy bill by modifying the electricity consumption. According to external inputs (e.g. prices), consumers can provide to energy markets and system operators competitive “Demand Response Resources” (DRR) that will significantly enhance the required system flexibility to facilitate the transition to a decarbonized system.

The thesis’s main objective is to develop a new methodology as well as the necessary associated models and tools to overrun the main barriers that prevent the participation of large and medium electricity consumers in the electricity supply activities. Additionally, these tools allow determining the optimal strategy for the participation of large and medium electricity consumers in products and markets where flexible resources can be economically competitive and technically reliable.

Four complimentary and correlated sub-objectives have been fulfilled to address the main objective. First, the thesis proposes an original conceptual architecture for future Smart-Markets in order to establish a more suitable framework for DRR trading and implementation. Second, the research aims to solve the need to have “firm” DRR in the way that DRR can be considered reliable resources. This has been dealt with in the second sub-objective where a new methodology to standardize and validate the DRR offered by the customers has been developed and justified. This methodology can be used to regulate a “certification” process for DRR.

The two final sub-objectives are related to provide the customer with valuable knowledge and tools to make feasible the DRR offers generation in the long and short term. The third sub-objective is related to the need for the DRR provider to plan in the medium term (a few years ahead) the strategy for the demand participation and assess the necessary investments. A planning tool has been developed to meet that objective. Finally, the last sub-objective deals with the need of the customer to program the operation of their demand resources in the short term (one day ahead at most) by optimizing all the available resources and prices. Consequently, complementary to medium-term planning tool, a day-ahead optimization tool has been created for that purpose.

All methodologies and tools researched in this Ph.D. have been validated through its application to three different industrial environments and customers in sectors with high replicability all over Europe: a paper factory, a meat processing factory, and logistic centres with high freezing and refrigerating needs.

The results and justified conclusions allow stating that a relevant step in the research of the implementation of more sustainable energy systems has been produced by enhancing more committed and dynamic participation of the demand side resources.

RESUM

En l'actualitat, existeix una creixent necessitat a escala global d'incrementar la producció d'electricitat, element clau de les economies modernes, a partir de fonts d'energia renovable. Aquest fenomen, conegut com a transició energètica, pretén canviar el model actual basat en combustibles fòssils per un model cent per cent renovable. Per a dur-ho a terme, és important tindre en compte que la majoria dels recursos de generació renovables no són gestionables i presenten una forta variabilitat en la seua producció d'energia difícilment predictible, la qual cosa fa necessari que el sistema elèctric haja de ser més flexible per a poder operar-se de manera segura. D'altra banda, en els últims anys, les tecnologies de la informació i la comunicació han experimentat una ràpida evolució a conseqüència del procés de digitalització i dels continus desenvolupaments en aquest camp, la qual cosa ha permés a altres sectors, com el sector elèctric, evolucionar cap a nous models de funcionament més avançats com les xarxes intel·ligents. Tots aquests canvis fan que la flexibilitat de la demanda ,coneguda com la capacitat d'un consumidor de modificar la seua manera de consumir energia en funció d'un senyal extern, puga oferir-se com un recurs valuós als operadors del sistema elèctric. D'aquesta forma, els consumidors més actius tenen una oportunitat per a reduir el seu cost energètic, podent ser més competitius, i alhora ajudant a més a facilitar la transició energètica.

La present tesi doctoral té com a objectiu general el desenvolupament d'una metodologia i de les ferramentes de suport necessàries que permet fonamentalment plantejar solucions destinades a la resolució de les barreres més importants en relació amb la participació dels recursos de demanda en l'operació del sistema elèctric. Addicionalment, permeten determinar l'estratègia òptima de participació de grans i mitjans consumidors d'energia elèctrica en productes i mercats en els quals els recursos flexibles puguen ser econòmicament competitius i tècnicament fiables. Aquest objectiu general s'ha abordat mitjançant el compliment de quatre objectius específics, els quals s'han traduït en la realització d'un conjunt de models, metodologies i ferramentes que donen compliment a cadascun d'ells.

En aquest sentit, la tesi s'ha dividit en quatre desenvolupaments interrelacionats a partir dels seus resultats. En primer lloc, s'ha proposat una nova arquitectura conceptual del sistema elèctric per a integrar els futurs mercats d'electricitat, destinada a establir un marc de referència més adequat per a l'explotació dels recursos energètics distribuïts i de demanda. En segon lloc, s'ha elaborat una metodologia per a l'estandardització i validació dels recursos flexibles que poden oferir els consumidors, i que podria servir com a base per a la creació d'un procés de certificació de productes de demanda. En tercer lloc, s'ha desenvolupat una primera ferramenta de planificació a mitjà termini que, partint de la caracterització i avaluació tecnicoeconòmica dels recursos flexibles obtinguda amb la metodologia anterior, permet ajudar als mateixos consumidors a avaluar la rendibilitat associada a les diferents estratègies de participació en un mercat d'operació específic utilitzant els seus processos de consum flexibles. Finalment, s'ha dut a terme una segona ferramenta destinada a optimitzar la programació de l'operació per a l'endemà dels recursos de demanda d'un determinat consumidor participant en un mercat prèviament seleccionat a partir dels resultats de la ferramenta anterior i, per tant, oferint-li en definitiva el suport tècnic i les ferramentes necessàries per a maximitzar el benefici associat a aquesta participació.

Les metodologies i ferramentes desenvolupades en aquesta tesi han sigut validades mitjançant la seua aplicació a un cas d'estudi compost per tres consumidors industrials que pertanyen a segments amb una elevada replicabilitat a Europa. Aquests consumidors són una indústria paperera, una indústria del sector carni i un centre logístic de producte refrigerat i congelat.

Els resultats obtinguts en aquesta tesi permeten afirmar que s'ha realitzat un pas rellevant dins de la investigació en aquest camp per tal d'ajudar a la implantació de sistemes d'energia elèctrica sostenibles mitjançant una participació més activa i dinàmica dels recursos de la demanda.

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1.1. Motivación

En la actualidad, la humanidad se enfrenta a uno de los grandes problemas medioambientales de su historia, denominado el “Cambio Climático”. Durante los últimos setenta años, la actividad del ser humano ha provocado un desequilibrio importante en el ciclo rápido del carbono, fundamentalmente debido al incremento de las emisiones de gases de efecto invernadero” [1]. Este desequilibrio ha causado una serie de efectos negativos en el medioambiente y en el clima a nivel global: aumento de la temperatura media de la superficie de la tierra (conocido como el “calentamiento global”), reducción del volumen de hielo en los polos y nieve en glaciares, aumento del nivel del mar y de su temperatura, acidificación de los océanos, mayor frecuencia e intensidad de fenómenos meteorológicos extremos, cambio de los ecosistemas y peligro de extinción de numerosas especies vegetales y animales.

El crecimiento económico y de la población mundial han sido los principales motores de las emisiones antropogénicas de gases de efecto invernadero a nivel global durante los últimos años [2]. En 2016, según [3], casi el 73% de las emisiones fueron producidas por actividades relacionadas con el sector de la energía, de las cuales el 42% están relacionadas con la producción de electricidad y calor, debido fundamentalmente a la ignición de combustibles fósiles.

Actualmente, la electricidad es un elemento clave en las economías modernas. Debido a la electrificación del transporte y del calor, al incremento de las necesidades de aire acondicionado y al crecimiento del consumo asociado a los dispositivos digitales, las previsiones para las próximas décadas apuntan a un aumento en la demanda global de electricidad, tal y como refleja el informe de la Agencia Internacional de la Energía ("International Energy Agency", IEA) de 2019 [4]. En la Figura 1.1, se pueden observar dos previsiones de crecimiento diferentes para la demanda de electricidad a nivel global, en la parte de la izquierda se observa lo que sería el resultado de continuar con las políticas actuales, con un crecimiento de la demanda mundial de electricidad del 2,1% por año hasta 2040, mientras que a la derecha se ha planteado un escenario con una intensificación de las políticas energéticas, principalmente centradas en la integración de generación renovable, en la energía nuclear y las tecnologías de captura del carbón.

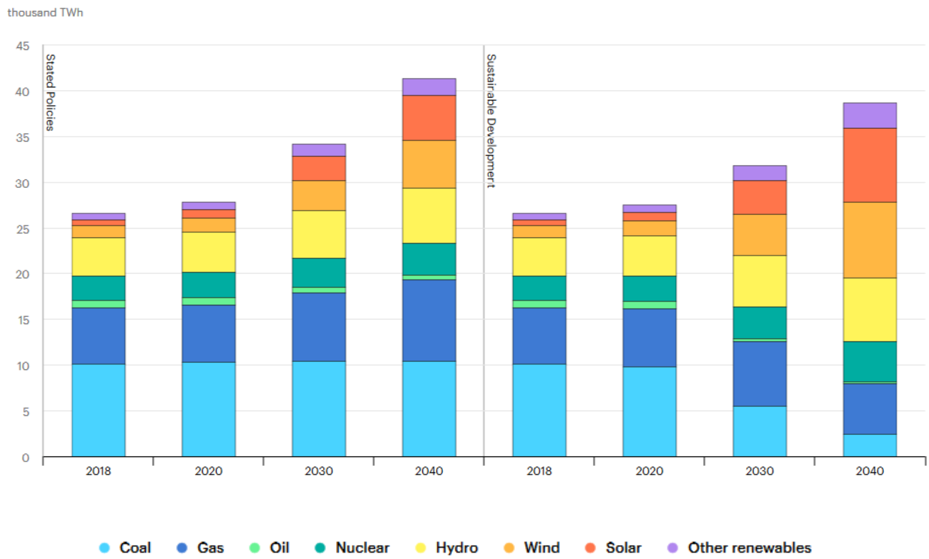

Figura 1.1. Escenarios asociados a la previsión de la demanda global de electricidad según IEA [4].

Atendiendo a los resultados de los escenarios planteados, se puede concluir que es necesario que las políticas energéticas a nivel global impulsen la transición energética desde un modelo basado en combustibles fósiles hacia un modelo descarbonizado mediante el aprovechamiento intensivo de las fuentes de energía renovable y la electrificación de la economía. Pero para llevar a cabo esta transición, es necesario tener en cuenta que las centrales de producción de generación renovable, principalmente la eólica y la solar, suelen ser de pequeña potencia y se encuentran mucho más distribuidas en la red, no son gestionables y presentan una fuerte variabilidad en su producción a lo largo del tiempo difícil de predecir.

Estas características de la generación renovable hacen necesario que los sistemas eléctricos sean cada vez más flexibles, para poder garantizar el equilibrio entre la demanda y la generación de forma segura. En este sentido, los avances tecnológicos de los últimos años, especialmente en las áreas del almacenamiento de energía, de las tecnologías de la información y la comunicación, de la automatización y el control, y del procesamiento de datos, permiten disponer de nuevas oportunidades para mejorar los sistemas eléctricos actuales, haciéndolos más flexibles, eficientes, fiables y seguros.

Asimismo, el consumidor ha evolucionado, pasando de ser un elemento pasivo en el sistema que solo consume energía a ser un elemento mucho más activo con capacidad de generar su propia energía y de ofrecer servicios a la red. Este consumidor activo requiere una mayor versatilidad en la compra y venta de electricidad y servicios, en un marco económico más competitivo y que pueda ajustarse a sus necesidades y flexibilidad.

Por tanto, la transición energética requiere la evolución de las redes eléctricas tradicionales, donde se transporta la energía desde los grandes centros de producción de forma unidireccional hasta los consumidores finales, a redes inteligentes, donde la generación de energía está más distribuida y los consumidores son más activos (con capacidad de generar y proporcionar servicios a la red), lo que requiere que sean más flexibles y seguras, permitiendo que la energía pueda fluir de forma bidireccional. Estas nuevas redes inteligentes ("Smart Grids"), deben habilitar y facilitar el desarrollo de nuevos mercados y nuevas formas de transar energía y servicios.

En este sentido, las redes inteligentes nacieron con esta visión estratégica [5], resumida en la Figura 1.2, y con objeto de intentar dar solución a todos estos retos planteados: la integración masiva de generación eólica y solar, la electrificación del transporte, la conservación del medio ambiente, el empoderamiento del consumidor a través de la información y conocimiento, y el desarrollo de nuevas relaciones comerciales que se ajusten a la realidad física y económica de cada transacción.

Figura 1.2. Visión estratégica de las redes inteligentes [5].

Pero el nuevo paradigma energético necesita, además de las redes inteligentes, que el consumidor deje de ser un agente pasivo, y que evolucione a un consumidor activo y con capacidad de producir su propia energía en muchos casos. Este nuevo consumidor (prosumidor) ha de ser más responsable del uso que hace de la energía, más eficiente, capaz de responder a precios de los productos y servicios energéticos, y con capacidad de ofrecer servicios a la red. Pero esta activación de la demanda no se produce de forma natural, ya que normalmente el consumidor no conoce sus posibilidades, sino que es necesaria la ayuda de terceros agentes, como empresas de servicios energéticos o consultorías avanzadas.

Además, en las redes inteligentes, los recursos de demanda están mucho más distribuidos y son muy diferentes desde el punto de vista técnico, por lo que se hace necesario el desarrollo de nuevas tecnologías y sistemas que faciliten su explotación. También son necesarios nuevos agentes, como el "agregador" o las "plantas de generación virtual" que pueden jugar un papel muy importante en esta activación, pero que deben evolucionar para poder aprovechar todo el potencial disponible de la respuesta de la demanda. Todo esto resulta en una serie de barreras en todos los ámbitos (regulatorias, técnicas, económicas, falta de estándares, falta de conocimiento, etc.), que deben ser superadas a través de estudios e investigación en este campo, como el desarrollado en el presente trabajo de investigación.

Esta tesis doctoral ha sido desarrollada como miembro del grupo de investigación del **Área de Sistemas y Mercados de la Energía** del **I.U. de investigación de Ingeniería Energética** de la "**Universitat Politècnica de València**". Este grupo de trabajo cuenta con una amplia experiencia de participación en proyectos de investigación dentro del sector público y privado a nivel nacional e internacional en el campo de la gestión de la demanda, dentro de los cuales destacan los siguientes:

- "**Demand Response Opportunity Pilot**" (DROP), programa piloto para evaluar las oportunidades de la gestión de la demanda en diferentes tipos de consumidores en colaboración con la empresa eléctrica "Progress Energy of Florida" (EE. UU.).
- "**The birth of a EUropean Distributed EnErgy Partnership**" (**EU-DEEP**), centrado en el desarrollo de herramientas de análisis y de estrategias de operación para la implantación masiva de recursos energéticos distribuidos (generación renovable, gestión de la demanda y almacenamiento) [6].
- "**Estudios y gestión energética en la UPV**" (**DERD**), centrado en el desarrollo de un sistema de monitorización y control para la mejora de la gestión energética de los diferentes usos finales del Campus de Vera de la "Universitat Politècnica de València" (UPV).
- "**Demand Response in Industrial Production**" (**DRIP**), proyecto de demostración de la viabilidad técnico-económica de la participación de la respuesta de la demanda en consumidores industriales en mercados de operación en Europa [7].
- "**Análisis para la implementación de redes inteligentes en Ecuador: Diseño conceptual y aplicación a plan piloto**", en el cual se analizó el entorno y se diseñó una solución técnica de redes inteligentes, incluyendo el diseño de la estructura del mercado eléctrico con nuevos agentes y servicios.

La experiencia adquirida en el desarrollo de todos estos proyectos ha servido como base para la elaboración de la presente tesis, centrada en la optimización del beneficio de la respuesta de la demanda en consumidores industriales.

1.2. Antecedentes

El principal aspecto del consumidor que se va a tratar en esta tesis es su "capacidad de respuesta de la energía consumida/producida a los precios de la energía (Respuesta de la Demanda)". Existen varias definiciones de la respuesta de la demanda, mientras para la "Federal Energy Regulatory Commission" (FERC) [8] y el "U.S. Department fo Energy" (DOE) [9], en base a una estructura del sector eléctrico más vertical, definen la "respuesta de la demanda" como "los cambios en el uso de la electricidad por parte de los consumidores finales respecto a su patrones de consumo normales en respuesta a cambios en el precio de la electricidad, o al pago de incentivos diseñados para inducir una reducción en el uso de la electricidad en momentos de precios altos en el mercado mayorista o cuando está en peligro la fiabilidad del sistema", la Comisión Europea en [10] utiliza en su definición conceptos más vinculados a los mercados liberalizados, definiéndola como "el cambio de consumo de electricidad por parte de los consumidores finales, respecto de sus pautas de consumo normales o actuales, como respuesta a las señales del mercado, incluidos aquellos en respuesta a los precios de la electricidad o los pagos de incentivos, o como respuesta a la aceptación de la oferta de los clientes finales para vender una reducción o un incremento de la demanda a un precio en un mercado organizado bien individualmente o mediante agregación".

En este apartado se pretende dar una visión general de lo que es la respuesta de la demanda mediante la revisión de las opciones que tiene el consumidor para participar en la planificación y operación del sistema eléctrico, así como conocer su potencial beneficio. Por otro lado, se va a resumir el estado actual de la respuesta de la demanda en Estados Unidos y Europa, en el primer caso debido a su larga trayectoria en la explotación de este tipo de recurso y en el segundo por el interés específico de describir el marco de referencia en el cual se han desarrollado los trabajos de investigación.

1.2.1. Clasificación de las opciones del lado de la demanda

El **"**Electric Power Research Institute**"** (EPRI) desarrolló en 2009 una clasificación de los tipos de acciones que se pueden implementar desde el lado de la demanda, basándose en la propuesta inicial de la "North American Electric Reliability Corporation**"** (NERC) y el "North American Energy Standards Board**"** (NAESB) [11], a la cual se añadieron las estructuras de precios de las comercializadoras.

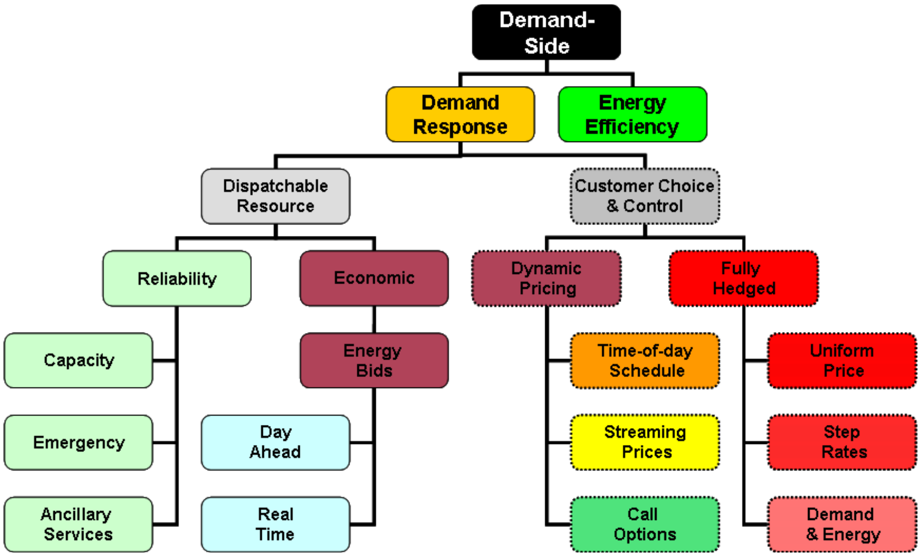

Figura 1.3 Árbol de clasificación de las principales opciones del lado de la demanda según EPRI (2009).

En la Figura 1.3 se muestra dicha clasificación, cuya primera división se corresponde con la separación entre las acciones de **Eficiencia Energética** (“Energy Efficiency”), que están vinculadas a la reducción del consumo de forma permanente como resultado de la implementación de una medida de mejora en las instalaciones, y las acciones de **Respuesta de la demanda** (“Demand Response”), que son variaciones puntuales en la demanda de un consumidor como respuesta a un estímulo económico que pretende ayudar a resolver una situación específica producida en el sistema eléctrico (precios elevados de la energía, emergencia en el sistema, etc.).

Los recursos de respuesta de la demanda han sido clasificados en dos grandes grupos en función de cómo estos pueden ser utilizados. Por un lado, los recursos que pueden ser controlados desde un centro de control (“**Dispatchable Resources**”), pudiendo ser un control físico o administrativo de dicho recurso. Por otro lado, están los recursos asociados a una respuesta voluntaria del consumidor a una señal de precios (“**Customer Choice & Control**”).

Dentro de este último grupo, existen opciones de bajo riesgo para el consumidor (“**Fully Hedged**”) con precios de la electricidad fijos a lo largo del tiempo, pudiendo ser el mismo para toda la energía consumida (“**Uniform Price**”) o estar definidos por escalones (“**Step Rates**”). También hay opciones en las que se tiene en cuenta no solo la energía consumida sino también la máxima potencia demandada (“**Demand & Energy**”).

Respecto al grupo de respuesta a precios, existen otras opciones que suponen un mayor riesgo para el consumidor, pero a la vez pueden derivar en una oportunidad si responde de forma adecuada a las variaciones de los precios en cada momento (“**Dynamic Pricing**”). Dentro de este grupo estarían todos los **Programas Basados en Precios** [11], que ofrecen al consumidor la posibilidad de cambiar su patrón de consumo mediante precios diferentes de la electricidad en diferentes instantes de tiempo, de forma que este puede obtener un beneficio económico simplemente trasladando consumo de periodos de más caros a otros más baratos. Dentro de este concepto, se incluyen los programas de discriminación horaria (“**Time-of-Day Schedule**”), como el programa “**Time-Of-Use**” (TOU), que consiste en una estructura con diferentes precios unitarios para el uso de la electricidad en los diferentes periodos definidos.

Otro concepto es el de los programas donde los precios se envían a los clientes con un cierto tiempo de antelación para que este pueda planificar su demanda “**Streaming Prices**”. Como ejemplo de este tipo destacan programas como “**Real-Time-Pricing**”, en el cual el precio de la electricidad normalmente fluctúa para reflejar los cambios en el mercado mayorista de electricidad y es notificado a los consumidores durante el día o la hora anterior, o como “**Critical-Peak-Pricing**”, que es un híbrido de los dos anteriores basándose en una estructura de precios como los programas de discriminación horaria, pero con la posibilidad de fijar un precio alto durante ciertos momentos críticos para el sistema eléctrico (limitados a un número máximo de horas al día y al año) en función de la previsión de contingencias o de precios altos en el mercado mayorista. Para terminar de revisar las opciones asociadas al concepto de precios dinámicos, faltarían las “**Call options**” que le permiten al consumidor reducir el riesgo asociado a la compra de electricidad teniendo en cuenta la volatilidad de los precios del mercado mayorista, mediante la posibilidad de adquirir con anterioridad paquetes de energía a un precio fijo, permitiéndole al final no usarlos si le resulta más interesante el precio del mercado, a cambio de un pequeño pago compensatorio.

Respecto a las opciones para los recursos que pueden ser gestionados directamente por un operador de forma física o administrativa (“Dispatchable Resource”), señalar que la utilización de este tipo de recursos está centrada fundamentalmente en la resolución de problemas de seguridad, para balancear el sistema o resolver las restricciones técnicas de la red. Dentro de este grupo estarían todos los **Programas de Operación**, que pueden ser los tradicionales **programas de incentivos** [11], donde el consumidor recibe un descuento o reducción en su factura eléctrica a cambio de participar, o los **programas de mercado**, en los cuales el consumidor participa en el mercado recibiendo un pago que depende de la cantidad de potencia reducida durante la contingencia, pasando el consumidor a ser un proveedor de servicios de respuesta de la demanda para el sistema eléctrico.

En este último grupo se incluye dos conceptos muy diferentes, el primero asociado a los recursos gestionables directamente que se activan para ayudar a resolver posibles problemas en el sistema eléctrico de fiabilidad del suministro (“**Reliability**”), y el segundo vinculado a los recursos gestionados de forma administrativa mediante un despacho económico (”**Economic**”). En este último caso, los consumidores presentan ofertas en el mercado mayorista por una determinada variación de su potencia demandada para un determinado instante (“**Energy Bids**”), bien durante el día anterior (“**Day Ahead**”) o un poco antes de que se produzca el tiempo de implementación (“**Real Time**”). Dentro de este grupo se encuentra programas como **Oferta de demanda y recompra** (“**Demand Bidding & Buy-Back**”), que puede funcionar o como ya se ha descrito, pero teniendo en cuenta que el consumidor es penalizado si no responde adecuadamente, o bien identificando cuanta potencia el consumidor está dispuesto a reducir en función de un precio específico.

En relación con el grupo de recursos utilizados para resolver problemas de seguridad en la red (“**Reliability**”), estos se dividen en tres tipos fundamentalmente, atendiendo al uso que se pretende del recurso: Capacidad (“**Capacity**”), Emergencia (“**Emergency**”) y Servicios Complementarios (“**Ancillary Services**”).

Los programas de **Capacidad** utilizan los recursos de demanda para aumentar o sustituir la capacidad proporcionada por los recursos de generación, y se dividen en programas tradicionales y de mercado. En los **programas tradicionales**, como se ha comentado anteriormente, los consumidores que participan reciben un descuento o reducción en su factura eléctrica a cambio de dicha participación, este es el caso de programas como el programa de **Control Directo de Cargas** (“**Direct Load Control**”), donde es el operador del programa el encargado de gestionar remotamente los recursos del consumidor mediante señales de control sin preaviso o con uno muy reducido, o el programa de **Interrumpibilidad de la Demanda** (“Interruptible Demand”), en el cual son los propios consumidores los que gestionan los recursos de demanda para conseguir reducir su potencia durante un intervalo de tiempo definido por debajo de un límite preestablecido, pero en el caso de no implementar la reducción adecuadamente recibirían una penalización por parte del operador. En relación con los **programas de mercado**, los consumidores realizan una oferta de su disponibilidad para reducir su demanda dentro de un periodo determinado de cara a proveer al sistema con una capacidad adicional a la que proporcionan los recursos de generación. El consumidor recibe normalmente una notificación el día anterior al evento y un pago por adelantado, pero si no cumplen es penalizado económicamente.

Otra de las opciones de participación relacionadas con la seguridad del sistema, son los programas de **Emergencia** (“Emergency”), en los cuales los consumidores que participan reciben un incentivo para dejar de consumir cuando la red se encuentra en situación de emergencia y no se disponen de suficientes recursos de generación a nivel de sistema y/o local.

El último tipo dentro de este grupo son los **Servicios Complementarios** (“Ancillary Services”), donde se sustituye o complementa a los generadores empleados normalmente como reservas de operación y/o regulación. Estos se dividen en tres servicios diferentes, las reservas rodantes (“**Spinning reserves**”), las reservas no rodantes (“**Non-Spinning Reserves**”) y la regulación (“**Regulation**”). En los programas de Servicios Complementarios, los consumidores pueden ofertar una reducción de su demanda en los diferentes mercados de reserva (siempre que cumplan con los requisitos técnicos exigidos por el operador), y en caso de ser aceptada son remunerados al precio del mercado por dicha capacidad. En caso de ser necesario el uso del recurso, el operador le solicita al consumidor que implemente la reducción de potencia, recibiendo este último un pago adicional al precio del mercado correspondiente.

1.2.2. Situación de la respuesta de la demanda en Estados Unidos

Antes de comenzar a describir el estado actual de la respuesta de la demanda en EE. UU., se va a describir brevemente los principales agentes del sistema eléctrico y la situación actual de los mercados de electricidad.

1.2.2.1. Situación actual del sector eléctrico en EE. UU.

En la actualidad, la “Federal Energy Regulatory Commission” (FERC) es la agencia independiente dentro del “U.S. Department of Energy” responsable de regular el transporte y el funcionamiento de los mercados mayoristas de electricidad [12]. Por otro lado, la “North American Electric Reliability Corporation” (NERC) es la autoridad reguladora internacional sin ánimo de lucro cuyo objetivo principal es asegurar la fiabilidad y seguridad del suministro de energía en América del Norte (parte continental de EE. UU., Canadá, y la parte norte de Baja California, Méjico). Esta organización está supervisada por la FERC y las autoridades gubernamentales en Canadá.

Tal y como se muestra en la Figura 1.4, el sistema eléctrico de Norteamérica está formado por cuatro interconexiones diferentes: la interconexión de Quebec, del Oeste, del Este y de ERCOT. Dentro de las tres principales interconexiones de los EE. UU. se encuentran las organizaciones de transporte regional (“Regional Transmission Organization”, RTO) y los operadores de sistema independientes (“Independent System Operators”, ISO).

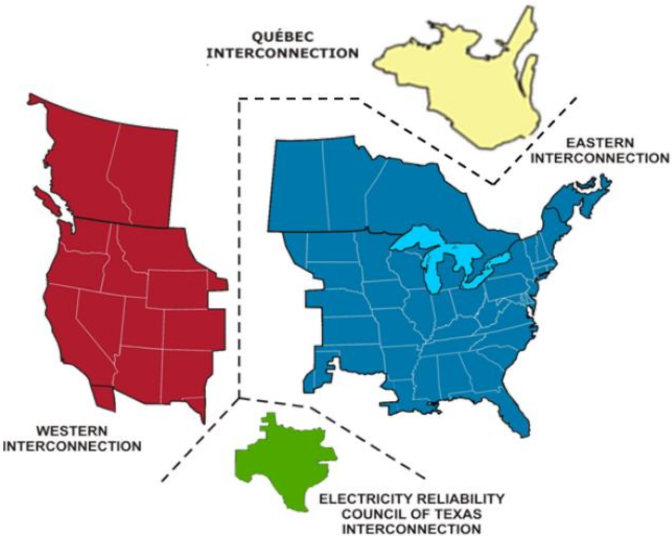

Figura 1.4. Interconexiones del sistema eléctrico en Norteamérica [13].

El papel que desempeñan ambos tipos de entidades es muy similar. Los ISO operan la red eléctrica de una región, gestionan su mercado mayorista de electricidad y son responsables de la planificación de la generación en dicha región para garantizar el suministro, mientras que las RTO tienen una mayor responsabilidad sobre las redes de transporte de su región, según lo define la FERC en [12]. Actualmente existen en América del Norte unos 7 operadores de sistema independientes (CAISO, NYISO, ERCOT, MISO, ISO-NE, AESO) y 4 organizaciones de transporte regional (PJM, MISO, SPP, ISONE). La Figura 1.5 muestra la región en la que opera cada una de estas entidades:

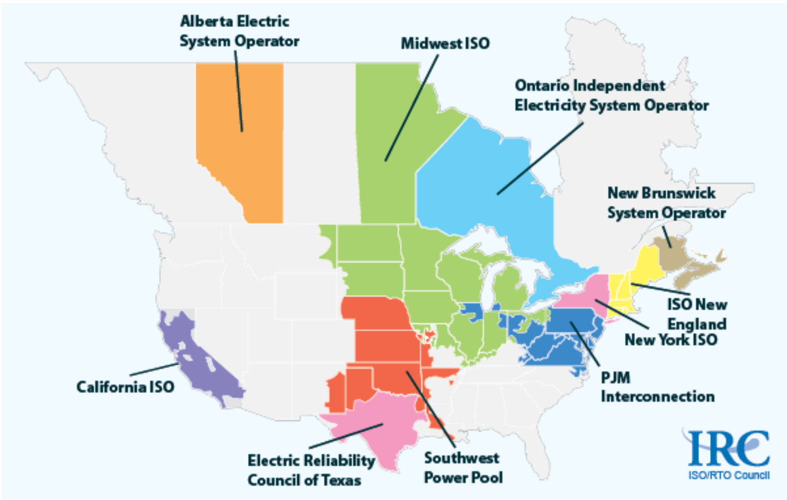

Figura 1.5. Miembros del "ISO/RTE Council" [14].

No todas las regiones de EE. UU. disponen de ISO o RTO como se puede ver en la Figura 1.5 (áreas de color gris). En estas regiones, son las empresas eléctricas las responsables de realizar las funciones de los citados operadores de sistema, aunque teóricamente siguiendo las mismas reglas impuestas por el regulador (FERC). Existen más de 3.200 empresas eléctricas que suministran electricidad a más de 145 millones de consumidores en los EE. UU., y son responsables de generar, transportar y distribuir electricidad para vendérsela al consumidor, normalmente con un modelo de empresa eléctrica verticalmente integrado, aunque puede haber casos en los cuales no realizan estas tres funciones.

En la Figura 1.6 se muestran las 10 regiones asociadas a los diferentes mercados de electricidad en EE. UU., de las cuales siete están siendo operados por alguna RTO o ISO y se corresponden con los mercados mayoristas de electricidad existentes. Las otras tres regiones restantes aún disponen de un mercado tradicional gestionado por empresas eléctricas (“Northwest”, “Southwest” y “Southeast”), normalmente verticalmente integradas, donde las propias empresas eléctricas son propietarias de los activos de generación, transporte y distribución, y son normalmente las responsables de la operación del sistema y su gestión, teniendo como objetivo final el suministro de energía a los consumidores minoristas. Estos mercados suelen estar basados en transacciones bilaterales y acuerdos entre empresas eléctricas (“Power pool agreements”).

Figura 1.6. Mercados de electricidad en EE. UU. [40].

Desde que comenzó la desregularización del sector eléctrico de EE. UU. en 1990, se han ido creando diferentes mercados mayoristas de electricidad, que como ya se ha comentado son gestionados por las RTO o los ISO de la región, donde los productores venden los paquetes de energía que producen a otros agentes, como las “Load Serving Entities” (LSE) o las comercializadoras, para que estos posteriormente se los vendan a los consumidores finales. Estos mercados están casi todos regulados por la FERC, a excepción del asociado a la región de ERCOT. Las RTO/ISO normalmente gestionan tres tipos de mercados que determinan el precio final del mercado mayorista: **mercados de energía**, **mercados de capacidad** y **mercados de servicios complementarios**.

Los **mercados de energía** están basados en subastas que sirven para coordinar la producción de electricidad diariamente. En estos mercados, los productores realizan ofertas de precio de venta para producir la electricidad en los diferentes intervalos del día, mientras que las empresas que sirven a los consumidores realizan ofertas de comprar para abastecer la demanda de sus consumidores. Con esta información se realiza la casación con objeto de determinar el precio final que percibirán los generadores por producir la electricidad. Normalmente, suelen haber dos mercados de energía diferentes: el **mercado diario** (“day-ahead market”), en el cual se realiza el 95% de las transacciones de energía y está basado en la previsión de la demanda del día siguiente, y el **mercado en tiempo real** (“real-time market”), que se ejecuta al menos una vez cada hora con objeto de reajustar la energía generada para compensar las desviaciones de la demanda y mantener el equilibrio en el sistema en todo momento.

Por otro lado, en relación con los mercados de capacidad, la NERC exige a las comercializadoras que estas dispongan de suficiente capacidad de generación para garantizar el abastecimiento de la demanda prevista más un determinado margen, con objeto de aumentar la fiabilidad del sistema. Algunas RTO operan **mercados de capacidad** (“Capacity markets”), donde las comercializadoras pueden adquirir la capacidad requerida, mientras que los generadores pueden recuperar parte de sus costes fijos, aunque actualmente **está capacidad también puede ser suministrada por recursos de demanda**. Estos mercados normalmente están basados en subastas, como los mercados de energía, donde los recursos de generación realizan ofertas de precios por mantener sus plantas disponibles para operar si es necesario. Estas ofertas se ordenan en sentido ascendente, y la última oferta de venta que permite cubrir la demanda de capacidad solicitada por las comercializadoras, es la que fija el precio final para todos los generadores. Si los generadores no están disponibles para operar cuando son requeridos a ello, estos pueden incurrir en una penalización. Las RTO que operan actualmente los mercados de capacidad de su región son ISONE, PJM, MISO y NYISO.

Por último, los **mercados de servicios complementarios** (“Ancillary Services Market”), que son gestionados por las RTO y los ISO en las diferentes regiones. Normalmente, existen al menos tres productos diferentes asociados a los principales servicios complementarios que se utilizan para operar la red: regulación, reserva rodante o sincronizada y reserva no rodante [15].

La **regulación y respuesta a frecuencia** (“Regulation”) es utilizada de forma constante para automáticamente compensar pequeñas fluctuaciones en el sistema eléctrico entre la generación y la demanda en tiempo real. Los generadores que proporcionan este servicio deben ser capaces de responder de forma automática a las señales AGC (“Automatic Generation

Control”) del operador del sistema en un corto periodo de tiempo (pocos segundos). En algunos mercados solo hay un producto, mientras que en otros separan la regulación a subir (“Regulation-up”) y a bajar (“Regulation-down”). En algunos mercados se han creado productos para regulación rápida, destinados normalmente a recursos de respuesta de la demanda o almacenamiento, ya que estos reaccionan más rápidamente que los generadores tradicionales. También pueden existir productos de regulación por uso (“Regulation Mileage”), con una señal de AGC que cambia cada 4 segundos (CAISO, NYISO y MISO), donde el generador recibe un pago por su respuesta a las señales de regulación y otro adicional por su disponibilidad.

La **reserva rodante o sincronizada** (“Spinning o Synchronized reserve”) se utiliza para responder a los cortes u otras contingencias del sistema rápidamente. Es proporcionada por los generadores que están ya en línea pero que no están utilizando toda su capacidad, por lo que pueden incrementar su potencia generada rápidamente para proveer al sistema con una capacidad adicional. Estas unidades de generación deben poder implementar su rampa de subida dentro de un periodo de 10-15 minutos (diferente en cada mercado) desde que reciben la orden de activación. Los recursos de demanda también pueden proporcionar este tipo de servicio, si son capaces de reducir su carga dentro del periodo de respuesta indicado.

La **reserva no rodante** (“Non-spinning reserve” o “Supplemental reserve”) se utiliza también para ayudar a estabilizar el sistema cuando ocurre alguna contingencia que no ha sido planificada. En este caso, pueden participar los generadores que están desconectados del sistema, si son capaces de llegar a la potencia objetivo en el tiempo definido, normalmente entre 10 y 30 minutos (diferente en cada mercado). En este producto también pueden participar los generadores que estaban activos, pero que disponían aún de capacidad sin utilizar.

Hay otros servicios complementarios que pueden proporcionar los generadores y los recursos de demanda al sistema eléctrico, como la generación de potencia reactiva para el control de tensiones, el arranque del sistema después de un apagón y la gestión de desvíos (“energy imbalance services”).

1.2.2.2. Estado actual de la respuesta de la demanda en EE. UU.

Los productos de respuesta de la demanda pueden ser ofrecidos por los operadores de red en los mercados mayorista de electricidad o por las empresas eléctricas. En primer lugar, se va a describir brevemente la situación actual de la respuesta de la demanda respecto a los programas ofrecidos por las empresas eléctricas, y posteriormente se describirá, con un poco más de detalle, los diferentes mercados mayoristas de electricidad y los productos existentes en cada uno de ellos.

1.2.2.2.1. Programas de DR en las empresas eléctricas

Respecto al potencial asociado a los programas de respuesta de la demanda ofrecidos por las empresas eléctricas, la capacidad estimada para reducir la demanda punta en 2018 fue de **30.895 MW**, según los datos publicados por la “U.S Energy Information Administration” (EIA) en [16]. La Figura 1.7 muestra la distribución por estado de esta capacidad, donde se puede observar una participación más elevada en estados como Florida (FL), Alabama (AL), California (CA) y Minnesota (MN), representando la suma de estos estados más del 30% del total de la participación de la respuesta de la demanda en programas de empresas eléctricas:

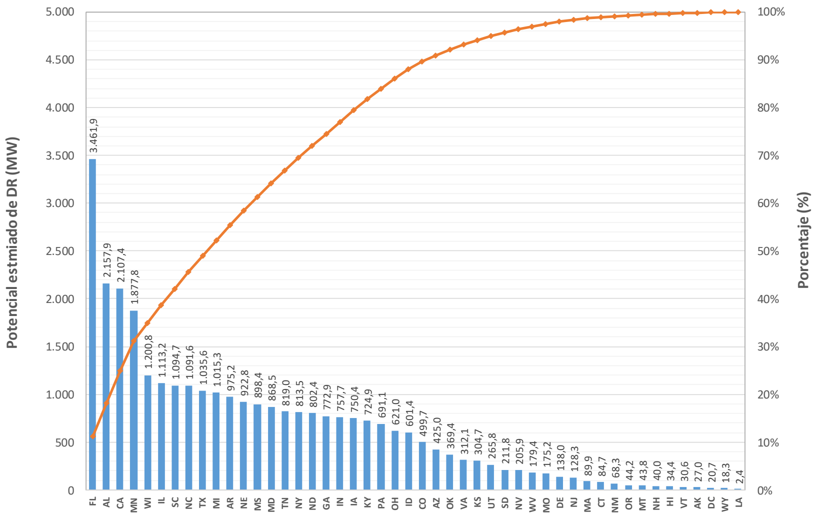

Figura 1.7. Participación de la respuesta de la demanda en programas de empresas eléctricas por estado (2018). Elaboración propia a partir de [16].

Si representamos esta capacidad por sectores se obtiene la Figura 1.8, donde se puede observar que casi la mitad de los recursos de respuesta de la demanda proviene del sector industrial (49,6%), mientras que la otra mitad se reparte entre el sector residencial (27,6%) y comercial (22,7%);

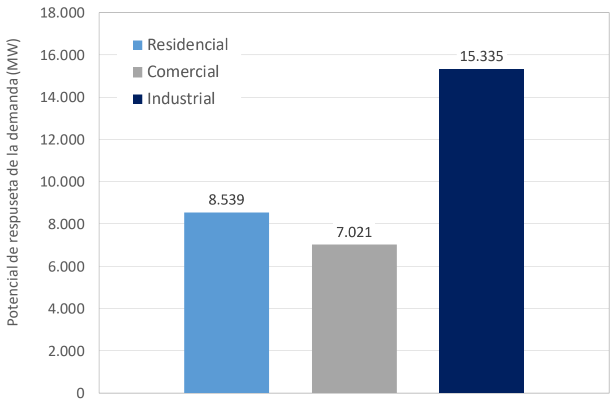

Figura 1.8. Potencial de la respuesta de la demanda ofrecido por las empresas eléctricas por sectores (2018). Elaboración propia a partir de [16].

En la Figura 1.9 se puede ver el número de consumidores de cada sector que se inscribieron en un programa de respuesta de la demanda ofertado por una empresa eléctrica en 2018, se observa que el 89,2% eran del sector residencial, el 10,1% del sector comercial, y menos del 1% del sector industrial.

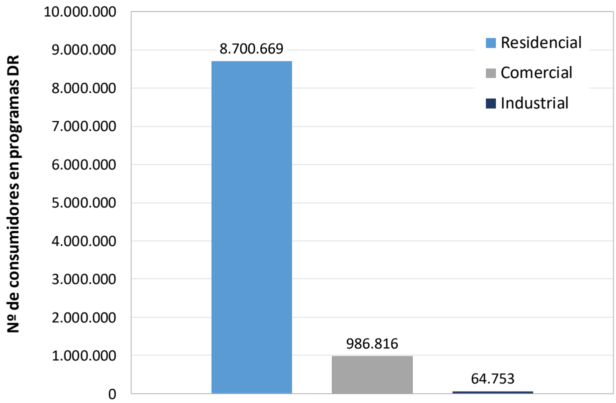

Figura 1.9. Número de consumidores inscritos a un programa de respuesta de la demanda de una empresa eléctrica (2018). Elaboración propia a partir de [16].

En general, como se observa en las gráficas anteriores, los programas de respuesta de la demanda ofertados por las empresas eléctricas en EE. UU. pueden clasificarse en dos tipos: los programas de residencial y pequeños comercios, que se caracterizan por un elevado número de participantes con una capacidad aportada muy reducida de forma individual, y programas para consumidores industriales y comerciales, con un número muy inferior de participantes pero con una capacidad muy superior por consumidor.

Según el estudio realizado por "Smart Electric Power Alliance" (SEPA) de 2019 [17], dentro de los programas para los consumidores más pequeños y con mayor número de participantes destacan por su contribución a la capacidad total los siguientes (ordenados de mayor a menor potencial de participación):

- **Interruptor del aire acondicionado**: es un programa que permite a un operador de la red desconectar la demanda de aire acondicionado de un consumidor o reducirla (controlar los ciclos de los compresores) mediante un interruptor que puede ser gestionado de forma remota.
- **Termostato**: es un programa que utiliza termostatos inteligentes para poder apagar y encender los equipos de aire acondicionado o calefacción de una casa o para ajustar las consignas de funcionamiento de estos equipos en ciertos momentos del día.
- **Calentador de agua:** en este programa se impide la conexión de los calentadores de agua en periodos específicos del día, por ejemplo, se puede aprovechar la inercia térmica de este proceso para traslada demanda de la punta del sistema al periodo valle.
- **Programas de comportamiento:** son programas, que pueden utilizar tecnología o no de apoyo, en los que se incentivan a los consumidores para reducir el consumo en los periodos de máxima demanda. Estos programas no tienen un pago directo asociado a la acción, sino que se basan en la variación de los precios de la energía, como por ejemplo las tarifas de discriminación horaria ("Time Of Use", TOU) o los programas con precios elevados en momentos de máxima demanda cuando se dan situaciones críticas para el sistema ("Critical Peak Pricing", CPP).
- **Otros programas para pequeños consumidores**: son el resto de programas no incluidos en los anteriores, como por ejemplo el almacenamiento de hielo, el control de las bombas de la piscina, la

recarga del vehículo eléctrico o el almacenamiento de energía eléctrica aguas abajo del contador de energía.

De acuerdo con el estudio anterior, los programas o acuerdos destinados a los consumidores comerciales e industriales medianos y grandes se pueden dividir fundamentalmente en tres grandes grupos (ordenados de mayor a menor potencial de participación):

- **Inicializados por el consumidor con notificación:** son programas que permiten a las empresas eléctricas enviar a los participantes una notificación para informarles de un evento próximo de respuesta de la demanda solicitándoles una reducción de su consumo o un incremento de la energía generada en los generadores o baterías conectados aguas abajo del contador de energía del consumidor.
- **Automatizado:** es un programa en el cual las empresas eléctricas pueden durante un evento de respuesta de la demanda implementar de forma remota y automática una reducción de la demanda o un incremento de la energía generada en los generadores o baterías conectados aguas abajo del contador de energía del consumidor.
- **Otros programas para medianos y grandes consumidores:** son el resto de programas que no se podrían incluir en los dos grupos anteriores, como por ejemplo los programas para el control de los sistemas de riego.

En la Figura 1.10 se muestra la distribución de la capacidad de los recursos de respuesta de la demanda en función de los tipos de programas ofertados por las empresas eléctricas en EE. UU. durante 2018, en la cual se representan en diferentes tonos del color verde todos los programas ofrecidos a los pequeños consumidores residenciales y comerciales, y en diferentes azules los programas para medianos y grandes consumidores comerciales e industriales:

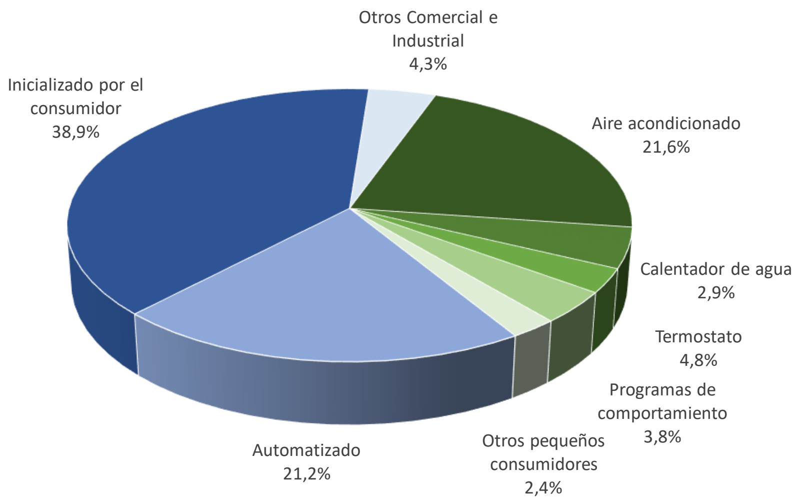

Figura 1.10. Porcentaje del potencial de DR por tipos de programas ofrecidos por empresas eléctricas (2018). Elaboración propia a partir de [17].

En la gráfica anterior, se puede observar que hay un mayor porcentaje de capacidad aportada por programas que están basados en soluciones tecnológicas que permiten una respuesta automática por parte de los recursos de demanda a los eventos, si se compara con el resto de programas implementados por los propios usuarios al recibir una notificación o señal de algún tipo.

1.2.2.2.2. Productos de DR en mercados mayoristas de electricidad

Según la FERC se estima que la participación de la respuesta de la demanda en los mercados mayoristas de la electricidad durante 2018 fue de **29.674 MW** [18], obtenido como la suma de la participación en los productos de capacidad, energía y servicios complementarios gestionados por las RTO e ISO. Por otro lado, según la SEPA en [17], se estima que la participación de la respuesta de la demanda solo en productos de fiabilidad dentro de los mercados mayoristas de electricidad en 2018 fue de 23.430 MW.

En la Tabla 1.1 se resumen los recursos de demanda para cada uno de los operadores del sistema de las diferentes regiones, así como el porcentaje que representa este valor frente a la punta de demanda del sistema que gestionan [8]:

Tabla 1.1. Recursos de demanda de los diferentes operadores de EE. UU.

RTO/ISO	Recursos de demanda (MW)	Porcentaje de la Demanda Máxima
CAISO	2.400	5,2%
ERCOT	3.262	4,4%
ISO-NE	356	1,4%
MISO	12.931	10,6%
NYISO	1.431	4,5%
PJM	9.294	6,3%
SPP	0	0,0%
Total	**29.674**	**6,0%**

Como se ha descrito anteriormente, existen diversos mercados (energía, capacidad, servicios complementarios, etc.) en los que podrían participar los recursos de la demanda, pero en cada región existen diferentes productos para este tipo de recurso dependiendo de las necesidades de cada zona (meteorología, generación, topología de las redes, etc.) y de la evolución de dichos productos en estos mercados. En los siguientes apartados se va a describir brevemente las características más importantes de cada una de las regiones gestionadas por las RTO e ISO, así como sus productos disponibles para los recursos de demanda.

California ISO (CAISO)

Según [20], el **California ISO** (CAISO) es el operador de sistema independiente que gestiona un 80% de las redes de alta tensión (26.000 millas) del estado de California, incluida una pequeña parte de las redes del estado de Nevada, así como gestiona el mercado mayorista de electricidad de esa región. En 2019 suministró 214.955 GWh con una punta de demanda de 44.301 MW.

Según [18], la participación de los recursos de demanda ha crecido de forma constante a lo largo del tiempo pasando de 50 MW en 2014 hasta 2.400 MW en 2018, lo que representa un 5,2% de la demanda máxima registrada ese año en el sistema gestionado por el CAISO. En la Tabla 1.2 se muestran los programas disponibles para la participación de la respuesta de la demanda ofrecidos por el CAISO, indicando sus principales características:

Tabla 1.2. Programas disponibles de respuesta de la demanda ofrecidos por el CAISO en 2018. Elaborado a partir de [19].

Nombre del producto	***Proxy Demand Resource***	***Proxy Demand Resource***
Tipo de servicio	Energía	Reserva rodante/no rodante
Motivo	Económico	Económico
Potencia mínima requerida	100 kW	500 kW
Permitido agregar	Sí	Sí
Tipo de Participación	Voluntaria	Voluntaria
Tipo de respuesta	Obligatoria	Obligatoria
Lógica de activación	Precio Energía > Precio Oferta	Ofertas Capacidad y Energía por separado > Precio Oferta
Ventana de disponibilidad	Intervalo programado	Intervalo programado
Tiempo notificación	Día anterior (~1:00 pm) Tiempo real (basado en las opciones de la oferta): 2.5 min, 22.5 min, 52.5 min.	Día anterior (~1:00 pm) Tiempo real (basado en opciones de la oferta): 2.5 min, 22.5 min, 52.5 min.
Duración de la Rampa	Basado en los parámetros de los recursos	10 minutos

Nombre del producto	*Proxy Demand Resource*	*Proxy Demand Resource*
Duración de la respuesta	5 min, 15 min, 60 min (basado en las opciones de la oferta)	30 min (mínimo)
Duración de la recuperación	Basado en los parámetros de los recursos	Basado en los parámetros de los recursos
Telemetría	No disponible para menos de 10 MW	Sí

Electric Reliability Council Of Texas (ERCOT)

Según [21], ERCOT es el operador de sistema independiente que suministra electricidad al 90% de la demanda del estado de Texas, así como gestiona el mercado mayorista de electricidad de la región con más de 1.800 participantes. Dispone de 46.500 millas de redes de alta tensión y más de 680 recursos de generación. En 2019 suministró 384.058 GWh con una punta de demanda de 74.820 MW [22].

Según el informe anual sobre los recursos de demanda de ERCOT [23], la participación en 2018 se ha estimado de 3.262 MW, que representa un 4,4% de la punta de demanda para ese año, siguiendo con la tendencia creciente de los últimos años. Esto ha sido debido mayormente al aumento de la participación de la demanda en los servicios denominados “Responsive Reserve Service” (RSS), en el cual los recursos de demanda pueden proporcionar regulación de frecuencia. Pero también ha aumentado ligeramente la participación en los programas asociados a los servicios conocidos como “Emergency Response Service” (ERS), que proporcionan servicios de reducción de carga en cuatro productos diferentes de 10 a 30 minutos con recursos sensibles o no a la climatología. En la Tabla 1.3 se muestran los programas disponibles para la participación de la respuesta de la demanda ofrecidos por ERCOT, indicando sus principales características:

Tabla 1.3. Programas disponibles de respuesta de la demanda ofrecidos por ERCOT en 2018. Elaborado a partir de [19].

Nombre del producto	*Non-Weather Sensitive ERS - 10 o 30*	*Weather Sensitive ERS - 10 o 30*	*Non-Controllable Load Resources (Responsive Reserve - Frequency Relay)*	*Controllable Load Resources (Responsive Reserve)*	*Controllable Load Resources (Non-Spinning Reserve)*	*Controllable Load Resources (Regulation)*	*Controllable Load Resources (Energy via SCED Dispatch)*
Tipo de servicio	Capacidad	Capacidad	Reserva	Reserva	Reserva	Regulación	Energía
Motivo	Fiabilidad	Fiabilidad	Fiabilidad	Fiabilidad	Fiabilidad	Fiabilidad	Económico
Potencia mínima requerida	100 kW	500 kW	100 kW	100 kW	100 kW	100 kW	100 kW
Permitido agregar	Sí	Sí	No	No	Sí	No	Sí
Tipo de Participación	Voluntaria	Voluntaria	Voluntaria	Voluntaria	Voluntaria	Voluntaria	Voluntaria
Tipo de respuesta	Obligatoria	Obligatoria	Obligatoria	Obligatoria	Obligatoria	Obligatoria	Obligatoria
Lógica de activación	Procedimiento operacional	Procedimiento operacional	Procedimiento operacional o Respuesta automática	Procedimiento operacional o Respuesta automática	Procedimiento operacional	Respuesta automática	Precio Energía ≥ Precio Oferta Energía
Ventana de disponibilidad	Períodos de tiempo concedidos	Períodos de tiempo del ERS asignados	Intervalo programado (horario)	Intervalo programado (horario)	Intervalo programado (horario)	Intervalo programado (horario)	Cualquier intervalo con ofertas activas en SCED
Tiempo notificación	Ninguno	Ninguno	Ninguno	Ninguno	Ninguno	Ninguno	Ninguno
Duración de la Rampa	10 o 30 min	10 o 30 min	10 min (verbal) 30 ciclos (relé)	Respuesta de frecuencia primaria continua, y 10 minutos	30 min (20 min para liberar la capacidad al SCED)	Respuesta Instantánea	5 min
Duración de la respuesta	Según despacho/ llamada	Según despacho/ llamada	Según despacho/ llamada	Según despacho / siguiendo puntos base de SCED hasta la llamada	Según despacho / siguiendo puntos base de SCED hasta la llamada	Respuesta de frecuencia primaria continua/ AGC según despacho/ llamada	5 min
Duración de la recuperación	10 h	10 h	3 h	No disponible	No disponible	No disponible	No disponible
Telemetría	No	No	Sí	Sí	Sí	Sí	Sí

ISO-New England (ISO-NE)

Según [24], ISO-NE es una RTO creada en 1997 por la FERC para reemplazar al “New England Power Pool” (NEPOOL). En la actualidad, gestiona alrededor de 9.000 millas de redes de transporte y los recursos de generación (350 generadores y una capacidad total próxima a 31.000 MW) de los estados de Nueva Inglaterra (Connecticut, Nuevo Hampshire, Maine, Massachussets, Rhode Island y Vermont). En 2019 proporcionó 119.159 GWh de energía eléctric con una punta de demanda de 24.400 MW.

En el mercado gestionado por ISO-NE [25], la participación de los recursos de demanda fue de 356 MW durante 2018, lo que representa un 4,4% de la demanda máxima registrada en ese mismo año. En la Tabla 1.4 se muestran los programas disponibles para la participación de la respuesta de la demanda ofrecidos por ISO-NE, indicando sus principales características:

Tabla 1.4. Programas disponibles de respuesta de la demanda ofrecidos por ISO-NE. Elaborado a partir de [19].

Nombre del producto	***FCM: On-Peak Demand Resources***	***FCM: Seasonal Peak Demand Resources***	***Dispatchable Asset Related Demand***	***Demand Response Resource***
Tipo de servicio	Capacidad	Capacidad	Reserva	Energía, Reserva, Capacidad
Motivo	Fiabilidad	Fiabilidad	Económico	Económico, Fiabilidad
Potencia mínima requerida	100 kW	100 kW	1 MW	100 kW
Permitido agregar	Sí	Sí	Sí	Sí
Tipo de Participación	Voluntaria	Voluntaria	Voluntaria	Voluntaria
Tipo de respuesta	Obligatoria	Obligatoria	Obligatoria	Obligatoria
Lógica de activación	En punta (18:00-19:00 en invierno, 14:00-17:00 en verano) durante los días laborables	Carga horaria en días laborables ≥ 90% de la previsión de carga pico del sistema según temporada	Despacho económico	Acuerdo y despacho basado en la oferta al mercado de la energía
Ventana de disponibilidad	18:00-19:00 en invierno, 14:00-17:00 en verano	Horas laborables de la semana según temporada	Intervalo programado	Intervalo programado
Tiempo notificación	Conocidas con meses o años de antelación	Tiempo real	Tiempo real	Cierre mercado energía (~1:30 PM)
Duración de la Rampa	Respuesta instantánea	Respuesta instantánea	Incluido en oferta al mercado de energía	Incluido en oferta al mercado de energía
Duración de la respuesta	18:00-19:00 en invierno, 14:00-17:00 en verano	Carga horaria en días laborables ≥ 90% de la previsión de carga pico del sistema según temporada	Según programado / despacho	Según programado / despacho
Duración de la recuperación	No está monitorizada	No está monitorizada	Según programado / despacho	Según programado / despacho
Telemetría	No	No	Sí	Sí

Midwest ISO (MISO)

Según [26], "Midcontinent Independent System Operator" (MISO) es una RTO que opera las redes de alta tensión (65.800 millas) en 15 estados (Arkansas, Dakota del Norte, Dakota del Sur, Illinois, Indiana, Iowa, Kentucky, Luisiana, Michigan, Minnesota, Mississippi, Missouri, Montana, Tennessee y Wisconsin) y en la provincia canadiense de Manitoba. Asimismo, gestiona uno de los mercados más grandes del mundo con 471 participantes que suministran electricidad a aproximadamente 42 millones de personas, lo que supone cerca de 24,7 mil millones de dólares brutos al año en transacciones de energía (2019).

Según [26], la capacidad aportada por los recursos de demanda que participaron en el mercado fue de 12.931 MW, lo que representa un 10,6% de la demanda máxima registrada ese mismo año. En la Tabla 1.5 se muestran los programas disponibles para la participación de la respuesta de la demanda ofrecidos por el MISO, indicando sus principales características:

Tabla 1.5. Programas disponibles de respuesta de la demanda ofrecidos por el MISO. Elaborado a partir de [19].

Nombre del producto	***Demand Response Resource Type I***	***Demand Response Resource Type-I***	***Demand Response Resource Type II***	***Demand Response Resource Type-II***	***Demand Response Resource Type-II***	***Emergency Demand Response***	***Load Modifying Resource***
Tipo de servicio	Energía	Reserva	Energía	Reserva	Regulación	Energía	Capacidad
Motivo	Económico	Económico	Económico	Económico	Económico	Fiabilidad	Fiabilidad
Potencia mínima requerida	1 MW	1 MW	1 MW	1 MW	1 MW	100 kW	100 kW
Permitido agregar	Sí	Sí	No	No	No	Sí	Sí
Tipo de Participación	Voluntaria	Voluntaria	Voluntaria	Voluntaria	Voluntaria	Voluntaria	Voluntaria
Tipo de respuesta	Voluntaria	Obligatoria	Voluntaria	Obligatoria	Obligatoria	Voluntaria	Obligatoria
Lógica de activación	Precio Energía>Precio Oferta	Precio Energía>Precio Oferta	Precio Energía>Precio Oferta	Precio Energía>Precio Oferta	Precio Energía>Precio Oferta	Procedimiento operacional	Procedimiento operacional
Ventana de disponibilidad	Intervalo programado	Intervalo programado	Intervalo programado	Intervalo programado	Intervalo programado	oferta EDR	Verano

Nombre del producto	*Demand Response Resource Type I*	*Demand Response Resource Type-I*	*Demand Response Resource Type II*	*Demand Response Resource Type-II*	*Demand Response Resource Type-II*	*Emergency Demand Response*	*Load Modifying Resource*
Tiempo notificación	Cierre del mercado el día anterior (~4:00)	Cierre del mercado el día anterior (~4:00)	Cierre del mercado el día anterior (~4:00)	Cierre del mercado el día anterior (~4:00)	Cierre del mercado el día anterior (~4:00)	Tiempo real	Tiempo real
Duración de la Rampa	5 min	10 min	5 min	10 min	Respuesta instantánea	Incluido en la oferta	Incluido en la oferta
Duración de la respuesta	Según programado/ despacho con 1 h (mínimo)	Según programado/ despacho con 1 h (mínimo)	Según programado/ despacho con 1 h (mínimo)	Según programado/ despacho con 1 h (mínimo)	Según programado/ despacho con 1 h (mínimo)	Según programado/ despacho	Según programado/ despacho con 4 h (mínimo)
Duración de la recuperación	No está monitorizado	No está monitorizado	No está monitorizado	No está monitorizado	No disponible	No está monitorizado	No está monitorizado
Telemetría	No	No	No	No	Sí	No	No

New York ISO (NYISO)

Según [27], el “New York Independent System Operator” (NYISO) es el operador de sistema independiente que reemplazó a “New York Power Pool” (NYPP), comenzando su actividad en 1999. Opera las redes de alta tensión (11.188 millas) del estado de Nueva York, así como gestiona el mercado mayorista de electricidad de esa región (más de 400 participantes). Según [28], en 2018 suministró 158.445 GWh a más de 19 millones de personas con una punta de demanda en verano de 32.512 MW.

Según [18], la participación de la respuesta de la demanda en 2018 fue de 1.431 MW, lo que representa un 4,5% de la demanda máxima registrada ese año en el sistema gestionado por el NYISO. En la Tabla 1.6 se muestran los programas disponibles para la participación de la respuesta de la demanda ofrecidos por el NYISO, indicando sus principales características:

Tabla 1.6. Programas disponibles de respuesta de la demanda ofrecidos por el NYISO. Elaborado a partir de [19].

Nombre del producto	*Day-Ahead Demand Response Program*	*Demand Side Ancillary Services Program* (2 programs)	*Demand Side Ancillary Services Program*	*Emergency Demand Response Program*	*Installed Capacidad Special Case Resources* (Componente de capacidad)
Tipo de servicio	Energía	Reserva	Regulación	Energía	Capacidad+ Energía

Nombre del producto	***Day-Ahead Demand Response Program***	***Demand Side Ancillary Services Program* (2 programs)**	***Demand Side Ancillary Services Program***	***Emergency Demand Response Program***	***Installed Capacidad Special Case Resources* (Componente de capacidad)**
Motivo	Económico	Económico	Económico	Fiabilidad	Fiabilidad
Potencia mínima requerida	1 MW	1 MW	1 MW	100 kW (por zona)	100 kW (por zona)
Permitido agregar	Sí	Sí	Sí	Sí	Sí
Tipo de Participación	Voluntaria	Voluntaria	Voluntaria	Voluntaria	Voluntaria
Tipo de respuesta	Obligatoria	Obligatoria	Obligatoria	Voluntaria	Obligatoria
Lógica de activación	Precio Energía > Precio Oferta (Asignación de unidades con restricciones de seguridad)	Precio Energía > Precio Oferta (Despacho económico con restricciones de seguridad)	Precio Energía > Precio Oferta (Despacho económico con restricciones de seguridad)	Procedimiento operacional	Procedimiento operacional
Ventana de disponibilidad	Intervalo programado	Intervalo programado	Intervalo programado	Ventana de ejecución	Todas las horas
Tiempo notificación	Antes de las 11am del día anterior	Antes de las 11am del día anterior /Tiempo real: 75 min	Antes de las 11am del día anterior /Tiempo real: 5 min	Aviso día anterior. Durante el día 120 min	Aviso día anterior. Durante el día 120 min
Duración de la Rampa	-	10 min o 30 min	Respuesta Instantánea	2 h	2 h
Duración de la respuesta	Según programado	Según programado/ despacho	Según programado/ despacho	4 h (mínimo)	4 h (mínimo) (o 1 h para las pruebas)
Duración de la recuperación	No está monitorizado	No está monitorizado	-	No está monitorizado	No está monitorizado
Telemetría	No	Sí	Sí	No	No

PJM Interconnection (PJM)

Según el informe anual de PJM de 2019 [30], "PJM Interconnection" es una RTO que gestiona el mercado mayorista de electricidad y opera las redes de alta tensión (84.236 millas) en 13 estados (Pensilvania, Nueva Jersey, Maryland, Carolina del norte, Delaware, Illinois, Indiana, Kentucky, Michigan, Ohio, Tennessee, Virginia , Virginia Occidental) más el Distrito de Columbia, para dar suministro de forma segura a más de 65 millones de personas. En 2019 suministró 787.307 GWh con una capacidad de generación de 186.788 MW.

La participación de la respuesta de la demanda en el mercado de PJM en 2018 fue de 9.294 MW, que representa alrededor del 6,3% de la punta de demanda en ese sistema durante dicho año [31]. En la Tabla 1.7 se muestran los programas disponibles para la participación de la respuesta de la demanda ofrecidos por PJM, mostrando sus principales características:

Tabla 1.7. Programas disponibles de respuesta de la demanda ofrecidos por PJM. Elaborado a partir de [19].

Nombre del producto	***Económico Load Response* (Energía)**	***Económico Load Response* (Reserva sincronizada)**	***Económico Load Response* (Programa día anterior)**	***Económico Load Response* (Regulación)**	***Emergency Load Response* (Solo Energía)**	***Full Emergency Load Response* (Componente de capacidad)**	***Full Emergency Load Response* (Componente de Energía)**
Tipo de servicio	Energía	Reserva	Reserva	Regulación	Energía	Capacidad	Energía
Motivo	Económico	Fiabilidad	Fiabilidad	Fiabilidad	Económico	Fiabilidad	Fiabilidad
Potencia mínima requerida	100 kW	100 kW	100 kW	100 kW	100 kW	100 kW	100 kW
Permitido agregar	Sí	Sí	Sí	Sí	Sí	Sí	Sí
Tipo de Participación	Voluntaria	Voluntaria	Voluntaria	Voluntaria	Voluntaria	Voluntaria	Voluntaria
Tipo de respuesta	Voluntaria	Obligatoria	Obligatoria	Obligatoria	Voluntaria	Obligatoria	Obligatoria
Lógica de activación	Oferta casada el día anterior, o despacho en tiempo real	Procedimiento operacional	Procedimiento operacional	Procedimiento operacional	Procedimiento operacional	Procedimiento operacional	Procedimiento operacional
Ventana de disponibilidad	Intervalo programado	Intervalo programado	Intervalo programado	Intervalo programado	N / D	10am a 10 pm o 6am a 9pm (según temporada)	Basada en el tipo "Full Emergency Load Response Capacidad Component"
Tiempo notificación	Día anterior a las 1:30pm, o despacho en tiempo real (2h)	Tiempo real	hasta 2 h	Ninguno	2 h (máximo)	2 h (máximo)	2 h (máximo)
Duración de la Rampa	Recurso específico	10 min	30 min	Respuesta Instantánea	Por defecto 30 min (proceso de excepción para 1 o 2 h)	Por defecto 30 min (reducido o eliminado según necesidad)	Por defecto 30 min (proceso de excepción para 1 o 2 h)
Duración de la respuesta	Según programado / despacho	Según programado / despacho	Según programado / despacho	Según programado / despacho	Según programado / despacho	Según programado / despacho	Según programado / despacho
Duración de la recuperación	-	-	-	-	-	-	-
Telemetría	No	No	No	Sí	No	No	No

Southwest Power Pool (SPP)

Según [32], SPP es una RTO que gestiona el mercado mayorista de electricidad y opera las redes de alta tensión (68.272 millas) en 14 estados (Arizona, Arkansas, Colorado, Dakota del Norte, Dakota del Sur, Iowa, Kansas, Luisiana, Minnesota, Missouri, Montana, Nebraska, New México, Oklahoma, Texas, Utah y Wyoming), para dar suministro de forma segura a casi 19 millones de personas. Según el informe anual de SPP [33], en 2018 suministró 259.653 GWh con una capacidad de generación de 89.167 MW, y una demanda punta de 50.662 MW.

Según [18], desde que se estableció en 2014, no ha habido actividad relacionada con la respuesta de la demanda en los mercados de SPP. Independientemente, en la Tabla 1.8 se muestran los programas disponibles para la participación de la respuesta de la demanda según [19], mostrando sus principales características:

Tabla 1.8. Programas disponibles de respuesta de la demanda ofrecidos por SPP. Elaborado a partir de [19].

Nombre del producto	***Demand Resource Load***	***Controllable Load for Reserve***	***Controllable Load for Regulation***
Tipo de servicio	Energía	Reserva	Regulación
Motivo	Económico	Económico	Económico
Potencia mínima requerida	100 kW	100 kW	100 kW
Permitido agregar	Se permite dentro de un mismo punto de conexión de la red de transporte	Se permite dentro de un mismo punto de conexión de la red de transporte	Se permite dentro de un mismo punto de conexión de la red de transporte
Tipo de Participación	Voluntaria	Voluntaria	Voluntaria
Tipo de respuesta	Obligatoria	Obligatoria	Obligatoria
Lógica de activación	Precio energía > Precio oferta	Procedimiento operacional	Procedimiento operacional
Ventana de disponibilidad	Intervalo programado	Intervalo programado	Intervalo programado
Tiempo notificación	5 min (máximo)	5 min (máximo)	5 min (máximo)
Duración de la Rampa	5 min	10 min	4 s
Duración de la respuesta	5 min	60 min	10 s a 60 min
Duración de la recuperación	5 min	-	-
Telemetría	Sí	Sí	Sí

1.2.3. Situación de la respuesta de la demanda en Europa

Las políticas energéticas actuales de la Unión Europea, al igual que las de la mayoría de países a nivel mundial, están orientadas a fomentar la transición desde un modelo energético basado en los combustibles fósiles hacia un modelo descarbonizado gracias a la integración de energías limpias, principalmente de origen renovable, con objeto de reducir las emisiones de gases de efecto invernadero. Este cambio tiene como principal objetivo cumplir con el Acuerdo de Paris (COP21) de diciembre de 2015, ratificado en 2016, en cuyo artículo 2 se estableció que se debía mantener el aumento de la temperatura media global muy por debajo de +2°C con respecto a los niveles registrados en 1990, así como se deberían realizar los esfuerzos necesarios para intentar limitarla a +1,5°C, ya que se considera que esto podría reducir los riesgos asociados a los efectos del cambio climático.

Figura 1.11. Principales pilares de las políticas energéticas europeas (2019).

En esta línea, en 2019, la Unión Europea (UE) llevó a cabo la actualización de sus políticas energéticas con el llamado “Clean energy for all Europeans package” para la implementación de la “Energy union strategy” que fue publicada en febrero de 2015 (COM/2015/080). Esta estrategia tiene como objetivo principal construir una Unión Europea que proporcione a todos los consumidores una energía segura, sostenible, competitiva y con un bajo precio. Además, es importante señalar que está construida sobre cinco pilares fundamentales, tal y como se muestra en la Figura 1.11.

Dentro del citado paquete de energía limpia, en diciembre de 2018 entró en vigor la directiva 2018/2001/EU con objeto de que la UE mostrase su liderazgo global en relación con las energías renovables, así como para cumplir con el acuerdo de Paris de reducción de emisiones. Esta directiva establece como objetivo principal alcanzar el 32% de integración de energías renovables dentro de sus recursos disponibles de generación de energía en 2030.

Desde el punto de vista de las transacciones de energía, el paquete “Energía limpia para todos los europeos” incluye, a través de su directiva 2019/944 aprobada en junio de 2019, el diseño del nuevo mercado interior de la energía que pretende ser más competitivo, centrado en los consumidores, flexible y no discriminatorio.

En relación con la participación activa de los consumidores en los mercados de electricidad, esta directiva no solo intenta desbloquear las políticas de los estados miembros que pudieran frenar la explotación de dichos recursos con objeto de flexibilizar el sistema eléctrico europeo, sino que también pretende darles a estos recursos la oportunidad de demostrar el potencial beneficio asociado a su utilización, tal y como se puede apreciar a lo largo de dicha directiva.

Asimismo, se insta a los estados miembros a fomentar la participación de la respuesta de la demanda mediante su agregación junto a los productores de energía, de manera no discriminatoria, en todos los mercados de electricidad (artículo 17). En este sentido, se favorece la aparición de la figura del agregador de los recursos de demanda, como un agente clave para la correcta explotación de estos recursos.

En relación a la participación de la respuesta de la demanda en distribución, se define el marco jurídico con objeto de permitir e incentivar a los gestores de las redes de distribución la obtención de servicios de flexibilidad (generación distribuida, respuesta de la demanda, almacenamiento de energía, etc.) para la resolución de posibles problemas de congestión que pudieran existir en sus redes, la mejora de la eficiencia energética durante su explotación, así como la reducción de los costes de inversión asociados a la expansión de su redes (artículo 32). Además, el gestor de la red de distribución deberá considerar la explotación de los recursos de respuesta de demanda en el plan de desarrollo de su red.

Desde el punto de vista de la operación del sistema, con objeto de garantizar la seguridad de la red eléctrica, se establece que el operador del sistema deberá considerar todos los servicios complementarios indispensables para llevar a cabo el balance de la red con procedimientos transparentes, no discriminatorios y basados en procedimientos de mercado (artículo 40). De momento se limita a los servicios complementarios de no frecuencia los que podrán ser prestados por todos los participantes del mercado, entre los que se incluye a los participantes que presten servicios de respuesta de la demanda o los que presten servicios de agregación, y solo cuando permitan eliminar la necesidad de incrementar o sustituir la capacidad eléctrica, garantizando el funcionamiento seguro y eficiente del sistema. Además, al igual que se ha indicado en la red de distribución, el gestor de la red de transporte deberá tener en cuenta, en el plan decenal de desarrollo de la red de transporte, el potencial asociado a la respuesta de la demanda, así como de otros recursos flexibles, como alternativa a la expansión de la red (artículo 51).

Por lo tanto, esta directiva da un paso al frente para que los recursos flexibles puedan competir en igualdad de condiciones con el resto de recursos con objeto de mejorar la fiabilidad del sistema a un mínimo coste.

Además de la citada directiva, el Reglamento (UE) 2019/943 relativo al mercado interior de la electricidad establece las normas y principios que permitirán garantizar el funcionamiento y la competitividad del mercado interior de la electricidad, con objeto de ayudar a la descarbonización del sector energético y eliminar las barreras necesarias para favorecer el comercio de energía entre países europeos. Este reglamento también refuerza la necesidad de flexibilizar el sistema eléctrico, mediante la explotación del potencial existente de respuesta de la demanda y de los sistemas de almacenamiento de energía, y establece los mecanismos para llevarlo a cabo.

1.2.3.1. Estado actual de la respuesta de la demanda en Europa

Atendiendo a todas las políticas energéticas europeas descritas en el punto anterior, junto con la cantidad de proyectos de demostración desarrollados en los últimos años relacionados con la explotación de la respuesta de la demanda en toda Europa [34], se puede decir que queda demostrado el creciente interés por este tipo de recurso, aunque los avances llevados a cabo en este campo en cada estado miembro son muy diferentes [35].

En la Figura 1.12 se muestra el resultado del análisis llevado a cabo por la "Smart Energy Demand Coalition" (SEDC) en 2017 sobre las condiciones del marco regulatorio existente en los diferentes países europeos en relación con la participación de la respuesta de la demanda en los diferentes mercados de electricidad (diario, intradiario, servicios complementarios u otros).

Figura 1.12. Situación de la respuesta de la demanda en los diferentes países europeos según SEDC (2017) [35].

La evaluación llevada a cabo en dicho estudio comparativo entre los diferentes países se basó en los siguientes criterios: posibilidad de acceso de la respuesta de la demanda a los diferentes mercados de forma individual o agregada, si estaba permitida la participación del agregador independiente en dichos mercados o estaba condicionada por los contratos que tuvieran que establecer con comercializadoras o entidades responsables del balance (“Balance Responsible Parties”), si los productos existentes estaban diseñados de forma adecuada para facilitar la participación de todos los tipos de recursos, y si los estándares de verificación y medida se adaptaban a las diferentes características físicas de cada tipo de recurso (generadores y demanda), así como si el sistema de pagos era suficientemente transparente y la estructura de penalizaciones era adecuada para que no hubiera desigualdades entre los diferentes tipos de recurso. El resultado de este estudio se muestra en la Figura 1.12, en la cual se representan en color verde los países que son activos desde el punto de vista de la comercialización de este recurso, en color amarillo los países que están parcialmente abierto, en naranja los que están en una fase preliminar de desarrollo y, por último, en rojo los que están cerrados a la participación de este recurso (en gris países no estudiados).

Por tanto, mientras que hay países que ya cuentan con una considerable experiencia en el desarrollo de productos de respuesta de la demanda para la participación de estos recursos en mercados de servicios complementarios (Bélgica, Finlandia, Francia, Irlanda o Reino Unido), en otros países todavía permanecen los mercados cerrados a este recurso o tienen poco tiempo de desarrollo (España, Estonia, Italia o Portugal).

Antes de comenzar a analizar la situación en los diferentes países, no hay que pasar por alto que la nomenclatura utilizada en Europa para los servicios de balance es muy diferente de la presentada previamente para EE. UU., incluso entre países europeos se utilizan nomenclaturas diferentes. Por tanto, con objeto de facilitar la comprensión de los productos y servicios de respuesta de la demanda disponibles en Europa, se va a utilizar la nomenclatura propuesta por la “European Network Transmission System Operators for Electricity” (ENTSO-E) [36]. ENTSO-E es una asociación paneuropea de 42 operadores de sistemas de transporte de electricidad (TSO) en 25 países, que en 2009 fue registrada como parte de la legislación de la UE. Tiene como principales objetivos garantizar la seguridad de suministro en la UE y facilitar el desarrollo del mercado interno de la energía.

En la Figura 1.13 se muestran los diferentes operadores de sistema encargados de gestionar los servicios complementarios y mecanismos de balances de los diferentes países europeos, todos ellos miembros de la ENTSO-E.

Figura 1.13. Operadores del sistema en los diferentes países europeos. Elaboración propia.

Con objeto de unificar la nomenclatura entre los diferentes países para la creación del mercado interior único, La Tabla 1.9 resume los principales conceptos asociados a los mecanismos de balance según dicha nomenclatura, donde se incluyen el nombre utilizado, la definición de cada concepto y las principales características:

Tabla 1.9. Definición de los principales mecanismos de balance según la asociación europea de operadores de transporte ENTSO-E.

Nombre	Definición	Características
Frequency Containment Reserve (**FCR**)	Reservas de potencia activa disponibles para contener inicialmente la frecuencia del sistema tras un desequilibrio	-Activación automática -Duración máxima 30 s
Automatic/Manual Frequency Restoration Reserve (**aFRR/mFRR**)	Reservas de potencia activa disponible para restaurar la frecuencia del sistema a su valor de referencia y reemplazar la FCR activada previamente.	**aFRR**: -Activación automática -30 s a 15 min. **mFRR**: -Activación semiautomática o manual -Duración máxima 15 min.
Replacement Reserve (**RR**)	Reservas de potencia activa disponible para restaurar o mantener el nivel requerido de FRR con objeto de poder responder a nuevos desequilibrios en el sistema adicionales.	-Activación semiautomática o manual -Duración mínima 15 min.

En la Figura 1.14 se representa como sería el funcionamiento de los diferentes servicios de balance para devolver la frecuencia a consigna tras un desequilibrio en el sistema, donde se puede apreciar claramente como van sustituyendo unos recursos a otros, para que estos vuelvan a estar disponibles, preparando al sistema para un nuevo desequilibrio.

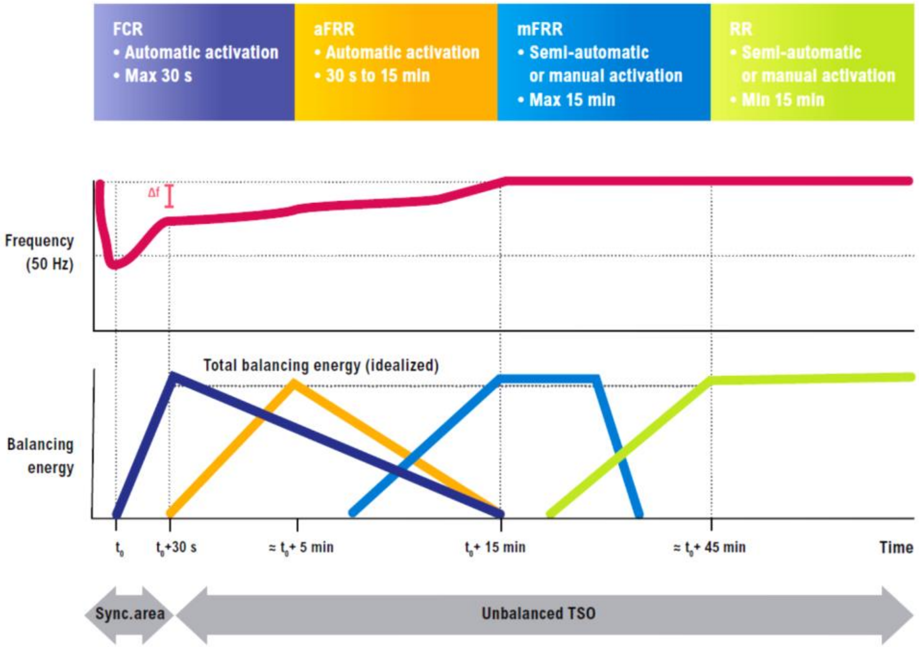

Figura 1.14. Procesos del mercado de balances para restaurar la frecuencia de la red [36].

A pesar de existir esta nomenclatura aceptada por todos los países miembros de la citada asociación de operadores europeos, en algunos países como España se siguen utilizando los conceptos de regulación primaria, secundaria y terciaria para referirse a la FCR, FRR y RR respectivamente.

En la Figura 1.15 se presentan los diferentes mercados de electricidad ("day-ahead markets") existentes en Europa, ,indicando las regiones de influencia de dichos mercados, con el objetivo de tener una visión general de estos antes de comenzar a revisar el estado actual de la respuesta de la demanda en los diferentes países.

Figura 1.15. Principales mercados de electricidad europeos según PCR Project.

En los siguientes apartados se van a revisar las características de los productos que permiten la participación de la respuesta de la demanda en los mercados de electricidad en los países que mejores resultados obtuvieron en el estudio [35] que se ha utilizado previamente para revisar la situación del marco legislativo en relación con la respuesta de la respuesta de la demanda en cada país. Por último, se presentará la situación en España, con objeto de revisar el potencial de mejora de la participación de la respuesta de la demanda existente, y con la intención de poner de relieve las importantes diferencias existentes entre países europeos comentada anteriormente.

1.2.3.1.1. Francia

En Francia, desde 2014, han existido programas para permitir a los consumidores industriales participar en la reserva primaria (FCR) y secundaria (aFRR), aunque en el caso de la secundaria no accedan directamente sino a través de un mercado secundario. En 2016, los mecanismos de balance (mFRR y RR) y los servicios complementarios ya estaban abiertos a la participación agregada de la respuesta de la demanda. Posteriormente, el operador del sistema francés fue ajustando los requerimientos de los productos a las características de los recursos de demanda con objeto de facilitar la participación de estos recursos en los citados programas.

En relación con los mercados de la energía, desde 2013 existe un mecanismo ("Notification d'Échange de Blocs d'Effacement", NEBEF) que permite ofertar al mercado diario reducciones de consumo de energía directamente, con una participación de la demanda en 2016 próxima a 10,3 GWh. Dicho mecanismo ha continuado evolucionando, y desde 2017 también permite participar a los recursos de demanda en el mercado diario e intradiario (EPEX Spot) de forma individual y/o agregada.

Por otro lado, también desde 2017, existe un mecanismo de capacidad, que obliga a las comercializadores a disponer de certificados de capacidad (subastas en EPEX) dependiendo de la demanda total de su porfolio, basado en un mercado descentralizado que está abierto a los recursos de demanda, y donde los participantes pueden realizar contratos bilaterales directamente.

Por último, un mecanismo que fue implementado inicialmente como tradicional ("DR Call for Tender"), se ha convertido en una herramienta de apoyo básica para la promoción de la respuesta de la demanda en Francia desde 2017.

Tabla 1.10. Principales características de los productos que permiten la participación de la DR en los mercados de electricidad franceses [35].

Nombre del producto	***Regulación primaria***	***Regulación secundaria***	***Reservas rápidas***	***Reservas complementarias***	***DR Call for tender***	***Mecanismo de capacidad***
Tipo de servicio (ENTSO-E)	FCR	aFRR	mFRR	RR	DSR-RR	Capacidad
Motivo	Fiabilidad	Fiabilidad	Fiabilidad	Fiabilidad	Fiabilidad	Fiabilidad
Tamaño mercado	600-700 MW	600-1.000 MW	Máx1000 MW	Máx.500 GW	750-1.400 MW	89.700 MW
Participación DR	60 MW	10 MW	480 MW		“	800 MW
Permitido agregar	A través de FCR cooperación (DE, AT, CH and NL)	A través de un mercado secundario	Sí	Sí	No	Sí
Potencia mínima requerida	1 MW	1 MW	10 MW	10 MW	1 MW	N/D
Tipo de activación	Automática	Automática	Manual	Manual	Manual	N/D
Disponibilidad	Activación continua	Sin límite de activaciones	Sin límite de activaciones	Sin límite de activaciones	Hasta 40 días/año	N/D
Tiempo notificación	< 30 s	< 400 s	13 min	30 min	2 h	N/D
Pago disponibilidad	Según oferta	Según mercado secundaria (ref. 160k€/MW año)	24 k€/MW y año	16 k€/MW y año	12-20 €/MW y año	No disponible
Pago utilización	Según precio del mercado diario	Según precio del mercado diario	Precio de oferta libre	Precio de oferta libre	N/D	Oferta libre

1.2.3.1.2. Reino Unido

En Reino Unido existen dos mercados de la energía, EPEX que se ha integrado con APX y N2EX (“Nordpool”), aunque la mayoría de la energía se negocia mediante contratos bilaterales (alrededor del 80%). Reino Unido fue uno de los primeros países europeos en permitir la participación de la respuesta de la demanda en sus mercados. En 2017, casi todos los servicios de balances estaban abiertos a la respuesta de la demanda, permitiendo también su agregación. Por el contrario, es importante señalar que, a pesar de esa disposición, los productos no estaban adaptados a los recursos de demanda, suponiendo esto una barrera importante para el desarrollo de este recurso.

Por último, hay que mencionar que los mecanismos de capacidad existentes también estaban abiertos a la respuesta de la demanda, aunque no en las mismas condiciones que los generadores. No ocurre lo mismo con los mercados diario e intradiario donde no se permite la participación de los agregadores independientes.

Tabla 1.11. Principales características de los productos que permiten la participación de la DR en los mercados de electricidad ingleses [35].

Nombre del producto	***Firm Frequency Response (FFR)***	***Fast Reserve***	***Short-Term Operating Reserve (STOR)***	***STOR Runaway***	***Demand Turn Up***	***Frequency Control by Demand Management (FCDM)***
Tipo de servicio (ENTSO-E)	FCR	FRR	RR	RR	RR	FCR
Motivo	Fiabilidad	Fiabilidad	Fiabilidad	Fiabilidad	Fiabilidad	Fiabilidad
Tamaño mercado	354,6 MW	60 MW	898 MW	78 MW	300 MW	N/D
Participación DR	N/D	N/D	N/D	78 MW	300 MW	N/D
Permitido agregar	Sí	Sí	Sí	Sí	Sí	Sí
Potencia mínima requerida	1 MW	50 MW	3 MW	1 MW	1 MW	3 MW
Tipo de activación	Automática	Manual	Manual	Manual	Manual	Automática
Disponibilidad	Continúo (previo a la falta) 11 activaciones al año (régimen normal)	10-15 activaciones por día	Varias activaciones al día	Varias activaciones al día	Varias activaciones a la semana	Aprox. 11 activaciones por año
Tiempo notificación	Primaria 10 s Secundaria 30 s	2 min	4 h	4 h	10 min (a veces el día anterior)	2 s
Pago disponibilidad	4,67 €/MW hora	6,13 €/MW hora	7,72 €/MW hora fijada 2,52 €/MW hora flexible	4,31 €/MW hora	-	Aprox. 5,51 €/MW hora
Pago utilización	2,03 €/MWh	3,21 €/MWh	218 €/MWh hora fijada 125 €/MWh hora flexible	202 €/MWh	83 €/MWh - 103 €/MWh	N/D

*se ha utiliza el valor de cambio promedio de 2016 (1 euro = £0,8195)

1.2.3.1.3. Finlandia

Una de las principales características del sistema eléctrico de Finlandia es su fuerte dependencia de la capacidad de sus países vecinos (Suecia, Noruega, Estonia y Rusia). En relación con la respuesta de la demanda, la participación de este recurso de forma individual o agregada está permitida en todos los mercados con algunas limitaciones.

En este sentido, los recursos de demanda agregados pueden participar en el mercado diario (“Nordic and Baltic day-ahead markets”) con una representación entre 200-600 MW frente a un volumen total de 374 TWh en 2015, y en el mercado intradiario (“Nordpool”) con una participación de hasta 200 MW frente a un volumen negociado del 5 TWh en el mismo año.

Tabla 1.12. Principales características de los productos que permiten la participación de la DR en los mercados de electricidad fineses [35].

Nombre del producto	***Frequency containment response for normal operation (FCR-N)***	***Frequency containment response for disturbances (FCR-D)***	***Automatic frequency restoration reserve (aFRR)***	***Balancing Market (mFRR)***	***Strategic reserves***
Tipo de servicio (ENTSO-E)	FCR	FCR	aFRR	mFRR	-
Motivo	Fiabilidad	Fiabilidad	Fiabilidad	Fiabilidad	Fiabilidad
Tamaño mercado	Aprox.140 MW	220-260 MW	70 MW	-	299 MW
Participación DR	1 MW	240 MW	0 MW	100-300 MW	10 MW
Permitido agregar	Sí	Sí	No	Sí	Sí
Potencia mínima requerida	0,1 MW	1 MW	5 MW	10 MW (5MW para activación eléctrica)	10 MW
Tipo de activación	Automática fuera de 49,90-50,10 Hz	Automática <49,9 Hz	Automática	Manual	Manual
Disponibilidad	Varias activaciones por hora	Varias activaciones al día	Varias activaciones al día	Alrededor de una activación al año	0-2 activaciones en invierno
Tiempo notificación	3 min	50% en 5 s 100% en 30 s	2 min	15 min	15 min

Nombre del producto	*Frequency containment response for normal operation (FCR-N)*	*Frequency containment response for disturbances (FCR-D)*	*Automatic frequency restoration reserve (aFRR)*	*Balancing Market (mFRR)*	*Strategic reserves*
Pago disponibilidad	13 €/MW hora	4,7 €/MW hora	-	Según oferta	Según oferta
Pago utilización	-	-	Precio marginal del mercado de balances	Marginal	-

Aunque está permitida la participación de la respuesta de la demanda en la provisión de servicios complementarios, la participación en FCR-N es muy baja (algunos pilotos) y en aFRR nula. Sin embardo la participación en FCR-D o en mFRR es bastante más significativa, como se puede observar en los números mostrados en la Tabla 1.12.

Además de los mercados comentados anteriormente, en 2013 la respuesta de la demanda fue habilitada para participar en el mecanismo de reserva estratégica ("Strategic reserves"). Posteriormente, a principios del 2017, las autoridades finesas fijaron una capacidad para el periodo 2017-2020 de 729 MW donde la respuesta de la demanda supondría 22 MW.

1.2.3.1.4. Suiza

En 2013, Suiza aplicó una serie de cambios regulatorios que abrieron considerablemente los mercados a la respuesta de la demanda agregada. En este sentido, todos los programas del mercado de balance y servicios complementarios están abiertos a este recurso: tienen acceso a la reserva primaria, donde se proporcionaron 3 MW en 2015; reserva secundaria, con 10 MW de participación en ese mismo año (principalmente calentadores eléctricos del sector residencial); y reserva terciaria (positiva y negativa), donde las cargas flexibles de los consumidores industriales proporcionaron alrededor de 49 MW.

Adicionalmente, la demanda agregada puede participar en el mercado diario (EPEX spot de Suiza), que tuvo un volumen total negociado de 24,4 TWh en 2015, y en el mercado intradiario, con un volumen total en este caso de 1,44 TWh.

Tabla 1.13. Principales características de los productos que permiten la participación de la DR en los mercados suizos [35].

Nombre del producto	*Reserva primaria*	*Reserva secundaria*	*Reserva terciaria diaria+/-*	*Reserva terciaria semanal+/-*
Tipo de servicio (ENTSO-E)	FCR	FRR	RR	RR
Motivo	Fiabilidad	Fiabilidad	Fiabilidad	Fiabilidad
Tamaño mercado	75 MW	378,23	+433,6 MW/ -258,6 MW	+232,6 MW/ -108,6 MW
Participación DR	3 MW	10 MW		49 MW
Permitido agregar	Sí	Sí	Sí	Sí
Potencia mínima requerida	1 MW	5 MW	5 MW	5 MW
Tipo de activación	Automática	Control remoto	Manual	Manual
Disponibilidad	Varias activaciones al día	Varias activaciones al día	Varias activaciones al día	Varias activaciones al día
Tiempo notificación	30 s	200 s	15 min	15 min/ 20-35 min
Pago disponibilidad	18,42 €/MW hora	24,05 €/MW hora	2,43 €/MW hora (positivo) 2,04 €/MW hora (negativo)	5,10 CHF/MW hora (positivo) 3,34 CHF/MW hora (negativo)
Pago utilización	-	Según mercado	Según mercado	Según mercado

*se ha utiliza el valor de cambio promedio de 2015 (1 euro = 1,0678 CHF)

1.2.3.1.5. Irlanda

En 2013, el operador del sistema irlandés ("Eirgrid") cambió las reglas del mercado para permitir la participación de los proveedores de respuesta de la demanda ("Demand Side Units", DSU) en el mercado "Single Electricity Market" (SEM), lo que les permitió acceder a los pagos por capacidad en dicho mercado. En este mercado la agregación de la demanda está permitida con un tamaño mínimo de oferta de reducción de 4 MW.

Posteriormente, a finales de 2016, los DSU fueron habilitados para ofrecer servicios complementarios bajo los “Interim Arrangements”, que plantean la promoción en 2018 de la respuesta de la demanda con la creación del “Integrated Single Electricity Market” (I-SEM) dentro del programa “Delivering a Secure, Sustainable Electricity System” (DS3), cuyo objetivo principal es el desarrollo de nuevos servicios y códigos de red para mejorar la integración de las energías renovables en el sistema eléctrico irlandés.

En 2017, se disponía de un servicio de interrumpibilidad “Short-Term Active Response” (STAR), que proporcionaba reservas al sistema de transporte mediante el uso de relés de subfrecuencia en consumidores industriales. Este programa no disponía de tamaño mínimo de oferta, lo que facilitaba el acceso a los diferentes recursos de demanda, aunque la participación en este podría resultar poco rentable para las unidades pequeñas, ya que debía cubrir los costes de instalación de todo el equipamiento.

Por último, durante 2016 se gestionó un programa denominado “Powersave”, que tenía como objetivo reducir el consumo de energía eléctrica y/o aumentar la generación en los momentos en los cuales la demanda total del sistema se aproximaba a la capacidad máxima del este, pudiendo ser activado por el operador de la red en cualquier momento del año.

Tabla 1.14. Principales características de los productos que permiten la participación de la DR en los mercados de electricidad irlandeses [35].

Nombre del producto	***DSU/Capacity***	***Short-Term Active Response (STAR)***	***Powersave***
Tipo de servicio (ENTSO-E)	Capacidad	Interrumpibilidad	-
Motivo	Fiabilidad	Fiabilidad	Fiabilidad
Tamaño mercado	7,046 MW	N/D	N/D

Nombre del producto	*DSU/Capacity*	*Short-Term Active Response (STAR)*	*Powersave*
Participación DR	N/D	N/D	N/D
Permitido agregar	Sí	Sí	Sí
Potencia mínima requerida	4 MW	Ninguno	100 kW
Tipo de activación	Manual	Automático	Manual
Disponibilidad	Sin límite Duración máx. 2 h	10-20 activaciones al año	Sin límite
Tiempo notificación	1 h	2 s	30 min
Pago disponibilidad	59 €/MWh	-	N/D
Pago utilización	-	8,20 €/MWh	380 €/MW (valle) 950 €/MWh(punta)

1.2.3.1.6. Bélgica

Bélgica ha implementado importantes cambios en los requerimientos de los productos para abrir los diferentes mercados a la participación de la respuesta de la demanda. En este sentido, los recursos de demanda pueden participar en reserva primaria y terciaria, así como en el servicio de interrumpibilidad. Sin embargo, no ocurre lo mismo con la secundaria que permanece cerrada a este recurso.

Aunque la figura del agregador independiente no estaba permitida en el momento del estudio, es muy probable que está situación haya cambiado en los años siguientes a esta revisión. Tampoco se permitía la participación de la respuesta de la demanda en el mercado diario de electricidad ("Belpex"), en el cual se negociaron 23,7 TWh en 2015, y donde tan solo pueden participar algunos grandes consumidores.

A continuación, en la Tabla 1.15 se muestran los productos que permiten la participación de la respuesta de la demanda: se pueden encontrar cuatro productos para la reserva primaria ("Primary frequency control", R1) gestionados por el operador del sistema belga (Elia), donde la respuesta de la demanda es más competitiva en los productos a subir; un producto de reserva terciaria ("Tertiary frequency control", R3) para los consumidores conectados a distribución DR ("R3-Dynamic Profile") que compite con un producto de reserva terciaria para generación ("R3-Prod"); el servicio de interrumpibilidad destinado a las cargas flexibles que pretende ser eliminado; y por último, la reserva estratégica (RR) en la que la respuesta de la demanda representa una décima parte de la capacidad total de este mecanismo.

Tabla 1.15. Principales características de los productos que permiten la participación de la DR en los mercados de electricidad belgas [35].

Nombre del producto	*R1-Load (Up)-4 productos:* *1) R1-symmetrical 200 mHz* *2) R1-symmetrical 100 mHz* *3) R1-upwards (Δf<-100mHz))* *4) R1-downwards (Δf >100mHZ)*	*R3-Dynamic Profile*	*R3-ICH Interruptible Service A4/A8/A12*	*Strategic Reserve (SD) SD-4/SD-12*
Tipo de servicio (ENTSO-E)	FCR	mFRR	mFRR	RR
Motivo	Fiabilidad	Fiabilidad	Fiabilidad	Fiabilidad
Tamaño mercado	27 MW	60MW	261 MW	97 MW
Permitido agregar	Sí	Sí	Sí	Sí
Potencia mínima requerida	1 MW	1 MW	1 MW	1 MW
Tipo de activación	Velocidad automática, sistema de control de frecuencia	Control remoto	Control remoto	Publicado en la Web del TSO, previsión del día siguiente, corrección en intradiario
Disponibilidad	Sin límite de activaciones, 80 minutos/ año; Duración 15 min	Max. 40 activaciones/año; Duración máx. 2 h separadas 12 h	No más de 4 veces al año, limitados a 16 h/24 h/24h al año; Duración 4 h/8 h/12 h separadas 24 h	Max. 40/20 activaciones/año con un límite de 130 h en invierno; Duración 1-4 h/1-12 h separadas 4/12 h
Tiempo notificación	15s (50%) o 30s (100%)	15 min.	3 min.	6,5h (preparación)+ 1,5h (rampa de bajada)
Pago disponibilidad	5-6 €/MW	3,07 €/MW	1,41 €/MW	No público
Pago utilización	-	-	Vinculado al precio de la oferta a subir, mínimo 75 €/MWh	68 €/MWh

1.2.3.1.7. España

Durante los últimos años, España está experimentando un crecimiento importante en la integración de la generación renovable distribuida, por lo que las necesidades de flexibilidad van a ir incrementándose en los próximos años. En la actualidad, dicha flexibilidad se obtiene mayormente de la generación hidráulica y de las centrales de gas. En este sentido, la utilización de la respuesta de la demanda en la operación del sistema ha estado limitada a la participación de grandes consumidores industriales en el denominado “Servicio de interrumpibilidad”, basado en subastas competitivas gestionadas por el operador del sistema nacional (Red Eléctrica de España, REE). En la subasta realizada por REE en 2016 para proporcionar este servicio (pasaron a ser semestrales en 2018) se asignaron 2.890 MW, repartidos en 434 bloques del producto de 5 MW y 8 bloques del producto de 90 MW (este producto pasó a ser de 40 MW en 2018), con un coste total de 503 millones de euros [37]. Según la Orden IET/2013/2013 de 31 de octubre, cada uno de estos productos puede llevar asociado tres opciones de ejecución en función del tiempo de preaviso, lo que afecta al pago percibido por el consumidor:

a) Ejecución instantánea. Sin preaviso mínimo.

b) Ejecución rápida. Preaviso mínimo de 15 minutos.

c) Ejecución horaria. Preaviso mínimo de dos horas.

La ejecución de cada una de las opciones tendrá una duración máxima de una hora, con un máximo de dos ejecuciones consecutivas. El número máximo de horas anuales de ejecución de las órdenes de reducción depende del tipo de producto, siendo 240 horas anuales para el producto de 5 MW (40 horas mensuales) y 360 horas anuales para el producto de 40 MW (60 horas mensuales). Los consumidores reciben un pago por la disponibilidad para reducir el consumo si su oferta ha sido aceptada, y otro pago asociado a la energía reducida durante un evento al precio de la reserva terciaria, pero multiplicado por un coeficiente que depende del tipo de ejecución utilizada.

Tabla 1.16. Principales características de los productos que permiten la participación de la DR en los mercados de electricidad españoles.

Nombre del producto	*Servicio de Interrumpibilidad (bloques de 5 MW)*	*Servicio de Interrumpibilidad (bloques de 40 MW)*
Tipo de servicio (ENTSO-E)	-	-
Motivo	Fiabilidad	Fiabilidad
Tamaño mercado	1.430-1.970 MW	630-1.170 MW
Participación DR	1.430-1.970 MW	630-1.170 MW
Permitido agregar	No	No
Potencia mínima requerida	5 MW	40 MW
Tipo de activación	Automática	Automática
Disponibilidad	Máx. 240 h/año y 40h/mes	Máx. 360 h/año y 60h/mes
Tiempo notificación	1. Ejecución instantánea 2. Ejecución rápida: 15 min 3. Ejecución horaria: 2 h	
Pago disponibilidad	127.563 €/MW (máx. 260.000 €/MW)	289.125 €/MW (máx. 350.000 €/MW)
Pago utilización	Precio reserva terciaria	Precio reserva terciaria

1.3. Oportunidades de la respuesta de la demanda

Como consecuencia de todo lo presentado anteriormente, se puede concluir que la respuesta de la demanda, aun siendo un recurso económicamente competitivo para facilitar la planificación y operación más eficiente y sostenible de los sistemas de energía eléctrica, no ha ocurrido “de forma natural” en el sector eléctrico.

Las razones más importantes que justifican este hecho son:

1. Se viene de una época donde la energía ha sido “tradicionalmente barata”, donde los consumidores, en general, no estaban preocupados por las consecuencias del uso de la energía eléctrica.

2. A diferencia con otros bienes de consumo, sobre todo para los pequeños consumidores, es difícil cuantificar el beneficio que obtiene un consumidor por consumir energía.

3. La evaluación de la flexibilidad técnico-económica de los consumos en procesos que demandan electricidad no es inmediata. Los consumidores necesitan asesoramiento especializado y herramientas de apoyo (empresas de servicios energéticos especializadas en estos recursos).
4. La participación individual de pequeños y medianos consumidores puede requerir la existencia de agentes intermedios (agregadores, plantas de generación virtuales, etc.) que están actualmente en evolución.
5. La tecnología (hardware y software) necesaria para que los recursos de la demanda participen de forma integrada con otros tipos de recursos para la gestión de sistemas y mercados eléctricos avanzados aún está en desarrollo, aunque ha tenido avances significativos en los últimos años.

No obstante, aunque la respuesta de la demanda ha sido utilizada desde hace muchas décadas de una forma más o menos exitosa, actualmente sigue siendo un tema en continua evolución en los países industrializados.

Hoy en día, y debido a las exigencias de prescindir de combustibles fósiles, al consecuente aumento de la necesidad de integración de generación renovable en las redes de transporte y distribución durante los últimos años, y a las expectativas para los próximos años promovidas por las políticas energéticas europeas anteriormente comentadas, ha crecido el interés por activar la flexibilidad de los consumidores conectados a dichas redes, con objeto de reducir o posponer las inversiones requeridas de expansión asociadas a los problemas de congestión que esta podría experimentar con determinados niveles de integración en ciertos momentos del día. Dentro de las redes de distribución, además de los citados consumidores residenciales, están conectados un gran número de consumidores medianos industriales y comerciales, que se ha demostrado recientemente [7] que podrían proporcionar de forma agregada, un elevado potencial de respuesta de la demanda.

Como consecuencia del análisis realizado en el apartado anterior, la respuesta de la demanda tiene que seguir evolucionando, tal y como se muestra en la Figura 1.16, donde se representa la proyección de la respuesta de la demanda a 2040 según [4].

En dicha proyección, sin considerar el impacto del vehículo eléctrico en la electrificación de la demanda (que sin duda será muy elevado), está previsto que casi se doble el potencial de la respuesta de la demanda en los sectores de la Industria (incluyendo la agricultura) y de los edificios (que se separan como una aplicación transversal a casi todos los sectores).

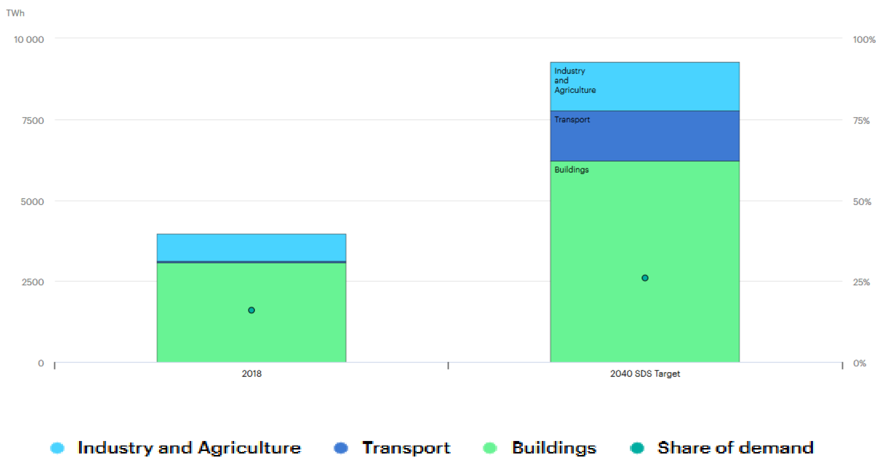

Figura 1.16. Previsión de la evolución de la respuesta de la demanda según IEA en su escenario de desarrollo sostenible [4].

Para que estas previsiones se realicen, es necesario seguir avanzando en desarrollos que permitan su implementación práctica. Concretamente, en la industria y en los edificios (normalmente vinculados a aplicaciones comerciales y de servicios) se encuentran procesos muy singulares, normalmente interrelacionados (concatenados) cuyas necesidades energéticas, flexibilidad y parámetros económicos asociados (beneficios y costos) son complicados de evaluar.

Es en este campo donde se han realizado las aportaciones contenidas en esta tesis doctoral, aportaciones que se han realizado para cubrir los objetivos que se describe en el punto siguiente.

1.4. Objetivos

El objetivo general que se plantea en esta tesis es el desarrollo de una metodología, y de las herramientas de apoyo necesarias para su implementación, que permita la determinación de la estrategia óptima de participación de grandes y medianos consumidores de energía eléctrica en productos y mercados en los que la respuesta de la demanda pueda ser económicamente competitiva y técnicamente fiable.

Puesto que los procesos de consumo en grandes y medianos consumidores (especialmente industriales) pueden ser muy diversos, se ha llevado a cabo un diseño general con el fin de poder sistematizar el análisis.

Con objeto de alcanzar este objetivo, se ha propuesto una serie de soluciones para resolver las “barreras” que se han considerado más importantes en relación con la participación de los consumidores en la operación del sistema, para lo que se han propuesto los siguientes objetivos específicos.

1.4.1. Organización del Sector Eléctrico

La estructura del sector eléctrico en los diferentes países y entornos no es muy favorable para implementar las relaciones físicas y comerciales (sobre todo minoristas) adecuadas con objeto de implantar una participación generalizada de los recursos energéticos distribuidos y de demanda.

Por tanto, se plantea como primer objetivo específico de la tesis el diseño de un marco conceptual que permita mejorar el potencial de integración de los citados recursos.

Esta propuesta debe ser realizada en el marco de las arquitecturas conceptuales que se están desarrollando para la implantación de las redes inteligentes ("Smart Grids") en el ámbito europeo, "European Smart Grid Architecture Model" (SGAM) [37] y americano, "NIST framework" [38].

1.4.2. Análisis y caracterización de los recursos de demanda

La participación de los recursos de demanda de forma integrada y fiable con el resto de los recursos necesarios para gestionar la red y el mercado eléctrico, requieren una "uniformidad" en los productos que ofrecen los consumidores y que son útiles para el resto de agentes.

Por lo tanto, se plantea como segundo objetivo específico de la tesis la creación de una metodología para la estandarización y validación de los recursos de respuesta de la demanda que pueden ofrecer los consumidores, de forma que esta metodología se pudiera transformar en un proceso de certificación.

1.4.3. Herramienta para facilitar la participación de los consumidores (I): Planificación a medio plazo

Tal como se ha mencionado anteriormente, una de las principales barreras para la implantación masiva de los recursos de demanda son las dificultades técnicas y conceptuales que se encuentran los consumidores a la hora de evaluar la conveniencia y rentabilidad de explotar este recurso.

Los dos objetivos específicos siguientes se han planteado en el desarrollo de herramientas lo más “amigables” e intuitivas de usar por los consumidores, y que les permitan planificar su participación en los mercados y productos del sector eléctrico ofreciendo sus “productos” de respuesta de la demanda. Obviamente, la capacidad de respuesta a “corto plazo” (en los próximos días) depende de la capacidad de gestión que tenga instalada el consumidor, que debe ser planificada a más largo plazo.

Por tanto, se ha planteado como tercer objetivo específico el desarrollo de una herramienta de planificación de la respuesta de la demanda a medio plazo (horizonte anual) considerando para ello todos los factores que afectan económica y técnicamente a los procesos de consumo: costes de inversión, costes de operación, beneficios esperados, etc.

1.4.4. Herramienta para facilitar la participación de los consumidores (II): Programación de la operación

Un segundo aspecto en el que los consumidores necesitan apoyo técnico y herramientas es en la programación de su participación en productos y mercados asociados a su respuesta de la demanda (y por tanto del funcionamiento de las instalaciones del consumidor) a corto plazo. Es decir, que decisiones va a tomar el consumidor en la programación de sus actividades para el día siguiente, o los próximos días. Por supuesto, en este caso se debe partir de unas instalaciones y facilidades disponibles, resultante del cumplimiento del objetivo específico anterior.

Se han planteado como requerimientos para esta herramienta el obtener una estrategia óptima de participación para consumidores con diferentes procesos flexibles de consumo y que mejore las técnicas propuestas en la literatura hasta ahora. Por tanto, se plantea como último objetivo específico el desarrollar una herramienta que aborde este problema.

1.5. Estructura

Los trabajos realizados para alcanzar los objetivos planteados han sido presentados según una estructura de tesis doctoral por compendio de artículos, donde el primer capítulo es la introducción, los capítulos del 2 al 5 se corresponden con cada una de las publicaciones en revistas científicas indexadas donde se presentan los desarrollos realizados, el capítulo 6 recoge la discusión de los resultados, y por último, el capítulo 7 integra las conclusiones generales y los posibles trabajos de investigación derivados de los resultados y contribuciones científicas de esta tesis doctoral.

A continuación, se describe con más detalle el contenido de los capítulos del 2 al 5 correspondientes con los trabajos realizados publicados en revistas científicas:

Capítulo 2: Novel conceptual architecture for the next generation electricity markets to enhance a large penetration of renewable energy (Artículo 1) [41][42].

El principal objetivo de este capítulo es presentar los desarrollos llevados a cabo para obtener la arquitectura conceptual propuesta, la cual está basada en los principales modelos existentes para redes inteligentes.

Dicha arquitectura pretende mejorar la integración masiva de fuentes de energía renovable en el sistema eléctrico garantizando la seguridad mediante la utilización del potencial de flexibilidad de los recursos energéticos distribuidos y de demanda existentes, prestando una especial atención al potencial beneficio que obtendrían los consumidores activos.

Tal y como se describe en este capítulo, para conseguir desarrollar esta arquitectura se ha realizado el análisis ontológico y orientado a servicios de los diferentes roles y actividades que deberían realizarse dentro del sector eléctrico. Partiendo de los resultados de este análisis, se han estudiado las interacciones necesarias entre estos roles desde diferentes puntos de vista: flujos de energía, servicios de operación y transacciones económicas.

Por último, se ha revisado en menor medida el impacto que tendría en la arquitectura propuesta la inclusión de los mercados locales de electricidad, con objeto de aproximarse a una solución que favorezca las negociaciones más dinámicas y la eficiencia del sistema eléctrico.

Este capítulo pretende proporcionar el marco de referencia para poder maximizar el beneficio de los consumidores activos en el seno de las redes inteligentes, suministrando los argumentos necesarios a los reguladores para eliminar algunas de las barreras existentes asociadas a la integración y explotación de los recursos energéticos distribuidos y de demanda en la red de distribución.

Capítulo 3: Design and validation of a methodology for standardizing prequalification of industrial demand response resources (Artículo 2) [43].

Una vez establecido en el capítulo anterior el marco de referencia del estudio, el capítulo 3 se centra en el desarrollo de una metodología general que permita la caracterización y validación de la flexibilidad existente en los grandes y medianos consumidores industriales (consumidores activos), basada en el análisis del uso que hacen dichos consumidores de la energía eléctrica en sus procesos productivos.

El objetivo principal que persigue la metodología propuesta es servir como base para la creación de un procedimiento de certificación de proveedores de flexibilidad que permita generar una mayor confianza a los usuarios de este tipo de recurso dentro del sector eléctrico (operadores de red, agregadores, plantas de generación virtual, comercializadoras, etc.). Adicionalmente, puede ser utilizado simplemente para determinar el potencial de flexibilidad real existente en un consumidor activo por los propios consumidores activos, empresas de servicios energéticos (ESE), agregadores de la demanda, etc.

En este capítulo se establece y se describen los parámetros asociados a la caracterización de la flexibilidad desde el punto de vista técnico existente en un determinado proceso productivo o uso final de la energía, y que formarán parte de la definición de una acción de respuesta de la demanda. La caracterización de la respuesta de la demanda propuesta es de aplicación general, es decir, independiente de la naturaleza del proceso productivo o uso final donde se aplique.

Por último, se muestran los resultados y las conclusiones obtenidas de aplicar las diferentes etapas que componen el procedimiento propuesto de validación del potencial de flexibilidad a tres instalaciones industriales diferentes (industria papelera, industria del sector cárnico, centro logístico de producto refrigerado y congelado) donde se evaluaron un total de once procesos flexibles diferentes.

<u>Capítulo 4</u>: A novel tool for the evaluation and assessment of demand response activities in the industrial sector (Artículo 3) [44].

Este capítulo pretende cumplir con el objetivo establecido en la tesis de proporcionar a los consumidores una herramienta para la evaluación del potencial beneficio asociado a la implementación de diferentes estrategias de participación de estos en un mercado de operación específico utilizando su potencial de flexibilidad, en las mismas condiciones económicas que dispondría un generador, pero teniendo en cuenta sus limitaciones desde el punto de vista técnico (disponibilidad, potencia reducible, tiempo entre eventos y duración máxima de estos, etc.), sus costes de operación y mantenimiento, así como su contrato de suministro de energía eléctrica. Por tanto, esta herramienta utiliza directamente los resultados de la caracterización de la flexibilidad por procesos o usos finales realizada mediante la metodología descrita en el capítulo 3.

En este capítulo se presenta la metodología de cálculo propuesta basada en el cálculo del margen de decisión para cada periodo de tiempo durante el proceso completo de simulación (se consideran periodos anuales), con objeto de determinar si el consumidor debería participar o no en ese instante en el mercado de operación que se esté evaluando, y con qué procesos debería llevar a cabo dicha participación. Esta metodología permite a los consumidores evaluar las diferentes estrategias de participación a largo plazo y, por tanto, mejorar la toma de decisión en relación con las inversiones asociadas.

En la parte final del capítulo, se presenta un caso de aplicación de la herramienta de simulación, donde se lleva a cabo la evaluación de la participación de uno de los consumidores activos estudiados en el capítulo 3 (industria papelera alemana) en los mercados de operación disponibles en su país, utilizando como entrada a dicha herramienta la caracterización de sus procesos flexibles presentada como resultado del capítulo anterior. Como resultado final, se obtienen los indicadores de la rentabilidad de la inversión inicial necesaria asociada a la participación de dicho consumidor en el mercado propuesto, considerando los costes de operación y mantenimiento y los beneficios económicos mensuales obtenidos con la herramienta de simulación durante el periodo simulado.

Capítulo 5: Maximizing the profit for industrial customers of providing operation services in electric power systems via a parallel particle swarm optimization algorithm (Artículo 4) [45].

La herramienta presentada en el capítulo anterior tiene como principal objetivo la evaluación de una estrategia de participación específica de un consumidor industrial o comercial en un mercado de servicios complementarios determinado, pero no pretende maximizar el beneficio que dicho consumidor podría obtener seleccionando los momentos más interesantes para realizar las ofertas a dicho mercado. El objetivo del capítulo 5 es presentar la integración realizada dentro de la citada herramienta de simulación de un proceso diario de optimización de la planificación durante el día anterior de la participación del consumidor en el mercado de servicios complementarios considerado, teniendo en cuenta no solo los precios asociados a dicho mercado sino la definición de la respuesta de la demanda de los procesos flexible y los precios de la energía asociados a su contrato de suministro de electricidad para el día siguiente (por ej. precios fijos para las diferentes franjas horarias o indexados al mercado diario).

En este capítulo se muestra el modelo matemático del problema de optimización, que ha sido planteado para respetar todas las restricciones técnicas de los procesos flexibles, incluso añadiendo otras nuevas como por ejemplo los límites de participación mensual o diaria en duración y frecuencia de activaciones. Este modelo está basado en una propuesta de codificación que pretende pasar de un problema de optimización no lineal binario a un problema no lineal entero cuyas variables de decisión son parámetros técnicos asociados a la propia implementación. Para la resolución de este problema de optimización se ha utilizado una técnica metaheurística conocida como el “enjambre de partículas” debido a su extendida utilización por otros autores en la resolución de problemas de ingeniería eléctrica similares.

Además, en este capítulo se muestran los resultados del minucioso proceso de ajuste de los parámetros de funcionamiento de dicho algoritmo, que siempre acompaña a las técnicas metaheurísticas, junto con los resultados finales de este proceso que permitieron tomar la decisión de utilizar técnicas de computación en paralelo por grupos de búsqueda independientes para asegurar el ratio de éxitos esperado en la búsqueda del máximo global, así como una reducción significativa de los tiempos de simulación.

Por último, se muestran los buenos resultados obtenidos en el caso de aplicación de la metodología de optimización propuesta para maximizar el beneficio asociado a la participación en la reserva terciaria del sistema eléctrico español de un consumidor industrial perteneciente al sector cárnico, que fue caracterizado en el capítulo 3, lo que supone la consecución del último objetivo de la tesis.

1.6. Referencias

[1] Cook, John & Oreskes, Naomi & Doran, Peter & Anderegg, William & Verheggen, Bart & Maibach, Edward & Carlton, J & Lewandowsky, Stephan & Skuce, Andy & Green, Sarah & Nuccitelli, Dana & Jacobs, Peter & Richardson, Mark & Winkler, Baerbel & Painting, Rob & Rice, Ken.. "Consensus on Consensus: A Synthesis of Consensus Estimates on Human-Caused Global Warming", Environmental Research Letters, 11, 4, April 2016, DOI: 10.1088/1748-9326/11/4/048002.

[2] IPCC, "Fifth Assessment Report: Chapter 7 Energy Systems", 2014.

[3] World Resources Institute, "Climate Analysis Indicators Tool", 2017.

[4] IEA, "World Energy Outlook 2019", November 2019.

[5] European Technology Platform Smart Grids, "Smart grids: strategic deployment document for Europe's electricity network of the future", 2degrees Community, 2degrees", 2010.

[6] "The birth of a EUropean Distributed EnErgy Partnership (EU-DEEP)", Sixth Framework Programme (FP6), retrieved on May 5, 2017. Available online at: cordis.europa.eu/project/id/503516/es.

[7] "Demand Response in Industrial Production DRIP", EU LIFE project, retrieved on May 10, 2016. Available online at: www.drip-project.eu/.

[8] FERC, "Assessment of Demand Response and Advanced Metering", Staff Report, December 2019.

[9] DOE, "Benefits of Demand Response in Electricity Markets and Recommendations for Achieving Them: A Report to the United States Congress Pursuant to Section 1252 of the Energy Policy Act of 2005", February 2006.

[10] Reglamento de Ejecución (UE) n °1348/2014 de la Comisión, de 17 de diciembre de 2014.

[11] NERC, "Potential Reliability Impacts of Emerging Flexible Resources", November 2010.

[12] DOE, "United States Electricity Industry Primer", July 2015.

[13] NERC, "Map of Four North American Power Grid interconnections", available at: www.nerc.com, retrieved on March 5, 2018.

[14] ISO/RTO Council, "ISO-RTO Map 2018", Available: isorto.org, retrieved on June 17, 2017.

[15] ARGONNE National Laboratory, "Survey of U.S. Ancillary Services Markets", January 2016.

[16] EIA, "EIA-861 Demand Response 2018 data file ", available at: www.eia.gov/electricity/data/eia861/, retrieved on June 15, 2018.

[17] SEPA, "2019 Utility Demand Response Market Snapshot", September 2019.

[18] FERC, "Demand Response and Advanced Metering", December 2019.

[19] ISO/RTO Council, "North American Wholesale Electricity Demand Response Program Comparison", November 2018.

[20] CAISO, "2019 Annual Report on Market Issues and Performance", June 2020.

[21] ERCOT, "2020 Fact Sheet", August 2020.

[22] ERCOT, "2019 State of the grid report", December 2020.

[23] ERCOT, "2018 Annual Report of Demand Response in the ERCOT Region", March 2019.

[24] ISO-NE, "Key Grid and Market Stats – Electricity Use", available at: www.iso-ne.com/about/key-stats/electricity-use, retrieved on October 13, 2019.

[25] ISO-NE, "Monthly Statistics Report, presented at Demand Resources Working Group Meeting", December 2018.

[26] MISO, "2018 State of the Market Report for the MISO Electricity Market", June 2019.

[27] NYISO, "2018 Annual Report of the New York Independent System Operator", January 2019.

[28] NYISO, "2019 Load & Capacity Data Report", April 2019.

[29] NYISO, "2018 Annual Report on Demand Response Programs of the New York Independent System Operator", January 2019.

[30] PJM, "2019 Annual report", 2020.

[31] PJM, "2018 Demand Response Operations Markets Activity Report", March 2019.

[32] SPP, "Fast Facts - An overview of the SPP System", available at: spp.org/about-us/fast-facts, retrieved on June 11, 2018.

[33] SPP, "2018 SPP Annual state of the market report", May 2019.

[34] Gangale F., Vasiljevska J., Covrig F., Mengolini A., Fulli G., "Smart grid projects outlook 2017: facts, figures and trends in Europe", EUR 28614 EN, DOI: 10.2760/701587.

[35] SEDC, "Explicit Demand Response in Europe - Mapping the Markets 2017", April 2017.

[36] ENTSO-E, "Electricity Balancing in Europe", European Electricity Balancing Guideline", November 2018.

[37] CEER (2016c): "Spanish Energy Regulator's National Report To The European Commission 2016", available at: www.ceer.eu, retrieved on March 15, 2017.

[38] Smart Grid Coordination Group, "Smart Grid Reference Architecture. CEN-CENELEC-ETSI", 2012.

[39] NIST, "Framework and Roadmap for Smart Grid Interoperability Standards, Release 3.0", 2014.

[40] FERC, "Electric Power Markets - National Overview", available at: www.ferc.gov/industries-data/market-assessments/electric-power-markets, retrieved on May 5, 2018.

[41] J. Rodríguez-García et al., "Novel Conceptual Architecture for the Next-Generation Electricity Markets to Enhance a Large Penetration of Renewable Energy," Energies, vol. 12, no. 13, p. 2605, July 2019.

[42] J. Rodríguez-García, D. Ribó-Pérez, C. Álvarez-Bel, E. Peñalvo-López. "Novel Conceptual Architecture for the Next-Generation Electricity Markets to Enhance a Large Penetration of Renewable Energy". In: Phattara Khumprom, Mladen Bošnjaković, editors. Advances in Energy Research. Hyderabad, India: Vide Leaf. 2020.

[43] J. Rodríguez-García, C. Álvarez-Bel, J.-F. Carbonell-Carretero, G. Escrivá-Escrivá, and C. Calpe-Esteve, "Design and validation of a methodology for standardizing prequalification of industrial demand response resources," Electric Power System Research, vol. 164, pp. 220–229, November 2018.

[44] J. Rodríguez-García, C. Álvarez-Bel, J.-F. Carbonell-Carretero, M. Alcázar-Ortega, and E. Peñalvo-López, “A novel tool for the evaluation and assessment of demand response activities in the industrial sector,” Energy, vol. 113, pp. 1136–1146, October 2016.

[45] J. Rodríguez-García, D. Ribó-Pérez, C. Álvarez-Bel and E. Peñalvo-López, "Maximizing the Profit for Industrial Customers of Providing Operation Services in Electric Power Systems via a Parallel Particle Swarm Optimization Algorithm," in IEEE Access, vol. 8, pp. 24721-24733, 2020, DOI: 10.1109/ACCESS.2020.2970478.

CAPÍTULO 2: **Novel conceptual architecture for the next generation electricity markets to enhance a large penetration of renewable energy**

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2.1. Abstract

A transition to a sustainable energy system is essential. In this context, Smart Grids represent the future of power systems for efficiently integrating renewable energy sources and active consumers participation. Nowadays, different studies have been performed that define the conceptual architecture of the power system and their agents. However, these conceptual architectures do not overcome all issues for the development of new electricity markets. Thus, a novel conceptual architecture is proposed. The transactions of energy, operation services and economic flows among the agents proposed are carefully analysed. In this regard, the results allow setting their activities' boundaries and state their relationships with electricity markets. The suitability to implement local electricity markets is studied to enforce competition among distributed energy resources by unlocking all the potential that active consumers have. The proposed architecture is designed

to offer flexibility and efficiency to the system thanks to a clearly defined way for the exploitation of flexible resources and distributed generation. This upgraded architecture hereby proposed establish the characteristics of each agent in the forthcoming markets and studies to overcome the barriers to the large deployment of renewable energy sources.

Keywords: Electricity markets, power system, conceptual architecture, distributed generation, flexible resources, local electricity markets

2.2. Introduction

A transition from a fossil fuel based energy system to a decarbonised one is key to perform a cost-effective strategy to mitigate climate change [1] and achieve the 2ºC threshold aim of the Paris agreement. Within this context, renewable energy sources (RES) represent the most promising technology for the transition and the future system. RES are almost free emission technologies and during the last years, RES have achieved economic competitiveness against conventional energy sources. However, their deployment in traditional power systems is not absent of challenges. The stochastic nature of renewable generation, the non-storable characteristic of electricity in a cost-effective way and the inelastic demand make their variability a major issue with a wider impact on smaller systems. Moreover, the final energy consumption will tend to become electric in order to reduce emissions. Thus, future loads will impose new demands and challenges to the power system such as the massive penetration of electric vehicles to electrify transport.

In order to overcome this problem, the Smart Grid concept has been an accepted solution for a time now. Smarts grids are electricity networks that intelligently integrate their users actions to efficiently deliver economic, secure and sustainable electricity [2]. The implementation of Smart Grids implies broad and sophisticated functionalities of electric transport and distribution systems, improving their flexibility, allowing bidirectional energy flows and facilitating RES and Demand Response (DR) integration. The demand response is based on developing active participation of customers with new requirements that consider technology and equipment for customer communications, relations and services. However, just with the participation of demand the security of supply will still be jeopardised with larger levels of stochasticity associated with renewable generation. Thus, storage systems will also be required to provide flexibility and ensure reliability to the system [3]. Moreover, the batteries' cost reductions are making them a key component in the future power systems [4].

Currently, the electricity sector finds itself making three classes of transformations. Firstly, the improvement of the current infrastructure. Secondly, the addition of the digitalisation of power systems, which is the essence of communications and data generation in Smart Grids. Thirdly, business process transformation to perform, besides the traditional activities, new ones or providing infrastructure and data to agents such as Aggregators and Virtual Power Plants (VPPs). These agents do new activities related to meet customer needs and expectations in a more efficient way than the traditional centralised system. These three transformations have been approached in several different ways, which have mainly been described on a very abstract level [5] or focused on specific aspects such as just Information and Communication Technologies (ICT) [6]. Different standardisation bodies have developed specific concepts such as the American NIST framework and roadmap for Smart Grids standards [7] and the European Smart Grid Architecture Model (SGAM) [8]. However, the necessary new activities, agents and interactions among them in the future electricity markets have not been clearly defined and authors still characterise them in different ways. Therefore, it is necessary to align specific agents to established practical conceptual architectures as it is suggested by Neuriter et al. [9].

The functionality of the future power systems and markets may look quite different according to the local social, regulatory or economic environment. Nevertheless, they have common applications and requirements for digital processing and communications to implement advanced control in all elements of the power system, allowing for bidirectional communication and energy flows [7]. Understanding as digital processing the automation of processes and systems to retrieve data and perform actions. According to this context, Smart Grids enable greater information management and efficiency compared to conventional power systems. Thus, allowing the exploitation of the benefits associated with RES, Demand Response, storage systems and real time competition and response in local markets. Local markets are arising as a new mechanism to provide an efficient allocation and pricing of the growing distributed generation and flexible demand [10], [11].

Thus, Smart Grids are emerging as a solution for the future of power systems [12]. This broad concept that comprises many different agents, actors and technology has been approached in different ways. Its future faces different problems and sub-problems, which have been widely studied. According to [13], some of these are: operation and management; energy storage; security, stability and protection; demand control or service restoration among others.

For instance, some authors propose multi-agent systems that optimise resource scheduling in Smart Grids [14], [15]. These agents enable the system to behave in a more reliable and efficient way. However, the description of these agents does not follow any standardised premise. Authors like [16], [17] propose energy management systems in Smart Grids. The agents as in [14] do not include a clear definition of the agent boundaries of action or relationships and present conflicts between them. A review of agent based models is presented in [18], where the necessity of harmonisation between studies is highlighted.

In order to tackle the previously mentioned standardisation problems, different meta-architectures have been developed. These conceptual architectures provide a family of ontologies to map Smart Grids and guidelines on how to use standards [6]. The main two developments are the previously mentioned, the NIST work and SGAM.

In the USA, the National Institute of Standards and Technology (NIST) has created relevant conceptual models for the Smart Grid. NIST considered the approach that the Smart Grid can be divided into seven domains [7]. These domains and their sub-domains enclose the conceptual roles and services, including stakeholders, interactions and types of services. On the other hand, the M/490 working group on Reference Architectures has created the SGAM which can be seen as a similar effort on European level. SGAM is based on NIST and proposes a model with 5 interoperability layers, 5 domains and 6 zones as it can be seen in Figure 2.1. Thus, every element in the model can be located in a three dimension grid according to its interoperability, domain and zone characteristics [8]. As in the case of NIST, SGAM requires stronger integration between the design and the use cases and formal semantics [19] as it lacks of precise descriptions.

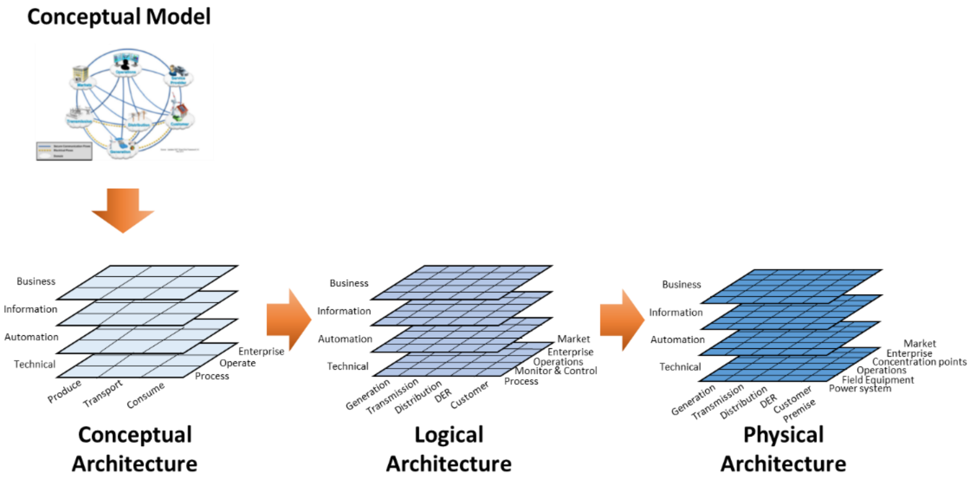

Figure 2.1. SGAM iterations, layers, and planes. Own elaboration based on Reference [8].

Highly correlated with Smart Grids development, the three novel agents of Aggregator, Storage and Virtual Power Plant (VPP) are being developed. In all these cases, several authors have been publishing on the topic. However, if the case of Smart Grid is still not clear and no standard definitions are used yet, VPP, Storage and Aggregators offer an even wider range of variation and disagreement. The importance of these three agents is relevant for the conception of Smart Grids since these agents are going to be crucial for the security and reliability of power systems with increasing levels of renewable penetration [20]. For instance, some authors have optimised VPP bidding strategies [21]–[23], renewable energy integration [24], [25] or the use of demand response in smart grids [26]. However, it exists a lack of a standardised definition, interactions and roles performed by a VPP in them.

Demand Response is also stated to have an increasing role in power systems due to its potential capacity to help to manage renewable variability [27]. Work has been done in analysing cost of automated DR systems [28];

the suitability of different customers [29]; the evaluation of the actions performance [30] or its optimisation in smart grid programs [31]. Storage is seen as the key technology to enable RES integration in the future power systems [32], [33]. Under this paradigm, storage systems have already became a key agent in the power system as in the case of the Tesla Battery of South Australia [34]. However, the particularities and services that they provide are far from being homogenous or clear among scholars and systems. Finally, in a similar line, aggregators have been approached in different ways by authors and regulators but also lack of a clear common definition [35]. In sum, agents are not clearly defined and the interactions between them vary among authors.

The conceptual architecture here developed is based on the NIST framework [7] and builds on to provide the relationships and interactions design between the different agents. These agents can be performed by different entities or one entity, company or organisation that could hold more than one of the agents' responsibilities. Reference levels of power, voltage and minimum bidding levels have been parametrised to be chosen depending on the system. Thus, providing an easy way to implement the conceptual architecture to any power system. Thus, the proposed conceptual architecture can be applied to any type of power sector, independently of the level of decentralisation and its size.

The main contributions of this paper are the following:

- A novel conceptual architecture for the development of the next generation electricity markets to unlock all the hidden potential of flexible and distributed energy resources, taken into special consideration the potential benefits for active consumers, is proposed based on the analysis of the shortcomings of the current standardised models that can be found in the literature. This model provides a path that policy makers can follow to eliminate barriers to integrate DER in a competitive way at distribution level.

- A complete description of the main roles/activities that should be assumed by the different agents in the proposed architecture based on an ontological and a service-oriented analysis.
- A detailed proposal of the interactions that would occur among agents of the developed architecture is presented. These interactions have been carefully analysed from all the points of view: energy flows, operation services and economic transactions.
- The impacts on the performance of the conceptual model associated with the inclusion of Local Energy Markets are analysed and presented in this paper. This could help to overcome the current flaws in real time trading.

The rest of the paper is structured as follows. Section 2 outlines the NIST methodology used for building up the proposed design to upgrade the current one. Then, the specific agents proposed for a standardise architecture are developed in Section 3. Finally, in Section 4 some conclusions are drawn.

2.3. Materials and methods

The power system and markets conceptual design methodology will be described in this section. This method is framed under the framework of the NIST roadmap for Smart Grids [7]. The methodology proposed by the NIST has been considered as a base to develop Smart Grid conceptual architectures by several authors and other standards [8], [36]. In this regard, this methodology has been selected as a meta architecture to develop the proposed upgrade of the existing architecture.

According to [7], the first action is the specification of the roles/services that should be expected from the general implementation of Smart Grids. Besides the traditional roles/services that are inherent in an electricity distribution system (i.e., generators and retailers), some additional agents should be expected from the combination of the new environmental requirements and advanced technology.

In this regard, the smart grid agents need to be designed to enable the system to successfully response to the following needs:

- Provide a full technical and economic integration of distributed generation. This generation is generally difficult to integrate because of their low size, intermittent production, quality problems and inability to provide operation services.
- Provide enhanced services and opportunities to the customers allowing more tailored trading of their demand/generation resources, including interaction with retail energy and services markets/products.
- Provide an enhanced operation of the distribution system, both in normal conditions (such as reconfiguration for more efficient operation or for more secure supply) and in faulty conditions in order to allow a faster and more effective reaction to faults (fault location, reconfiguration, self-healing, etc.).
- Provide information services, based on measurements, to actors in the field of the energy supply such as Aggregators, ESCOs, VPPs, etc.
- Provide the ability to accommodate and manage the presence of new loads at the customer level, such as the massive connection of Electric Vehicles.

It is important to highlight that the implementation of these agents can require the participation of new entities or the redesign of functions that will have to be performed by existing organisations.

A conceptual architecture is necessary to design a system capable to carry out the roles/services that Smart Grids must perform according to the abovementioned needs. At this point, it is necessary to define a set of concepts that will be widely used along the description of the architecture:

- **Agent**: is a specific function, capability or sum of services played by an entity that cannot be split. In some systems, one entity can have in its business portfolio duties of several agents of this conceptual architecture.
- **Activities**: things that an agent does or has the capability to do.
- **Component**: a basic part from which something is made. The physical assets that are intrinsic to each agent.
- **Transaction**: agreement between two agents (one buys and the other one sells) to exchange goods, services or financial instrument.

In order to align the architecture with the required services of the system, an ontological definition is required according to [7]. For doing so, the methodology proposed in NIST and showed in Figure 2.2 has been used.

According to this procedure, four architectural levels must be considered to design the agents: business; information; automation and technology. All these levels must be described to answer the four required layers: conceptual, logical, physical and its implementation.

After this first context analysis, the interactions among the different agents have been carefully studied to satisfy the required relationship needs among them. The entities required to implement a Smart Grid are, in general, quite standard but some agents' activities assigned to these entities may not be so established and, in some cases, can be a bit confusing in the literature, where different approaches to the same

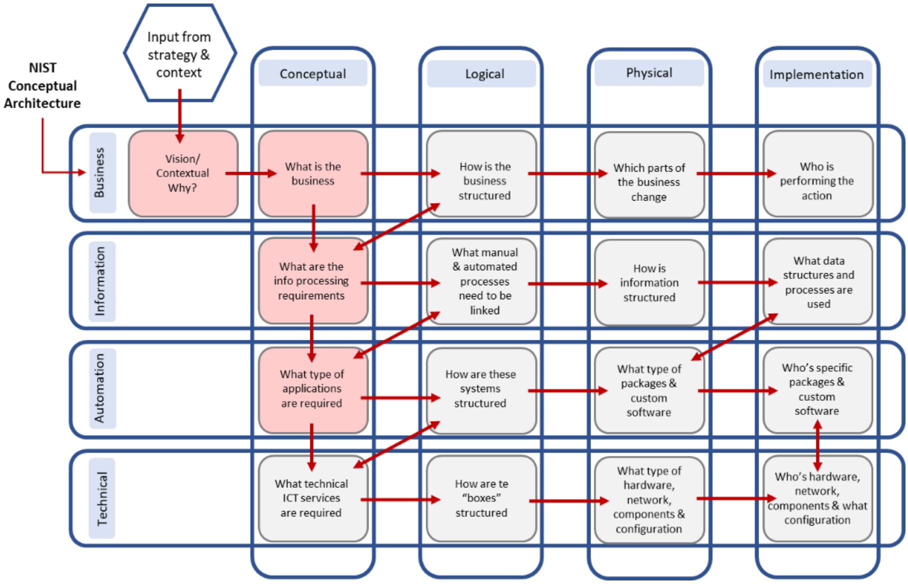

Figure 2.2. NIST Conceptual Architecture Mapped onto the Architecture Matrix Service Orientation and Ontology. Own elaboration based on [7].

The next section is devoted to present the novel conceptual architecture. First, each agent is defined based on the existing knowledge and literature and the activities expected for the agent are identified. According to these activities, the necessary physical components that each agent owns are described. Thus, includes assets like physical generators, transmission lines, etc. Finally, the power flows, operating service or economic transactions of each agent with the rest of them are described to fulfil the expected new requirements and functionalities of Smart Grids.

2.4. Discussion of agent conceptual architecture for markets implementation

The agents and nomenclature required for the upgraded conceptual architecture proposed in this paper are depicted in Table 2.1. The integration of different types of distributed generation, storage and demand response resources to provide firm power production and the active participation of the customers have been considered in detail.

Table 2.1. Summary of agents and elements considered in the future electricity markets framework

Agents	**Characteristics**
Active consumers	Self-generation, flexible demand, buying/selling electricity and operation services
Generators	Electricity generation and procurement of operation services
Virtual Power Plants (VPP)	Buying/selling electricity and operation services to different agents in a coordinated way
Aggregators	Buying and selling of small and medium demand resources in a coordinated way
Storage	Highly flexible elements that can consume, generate and provide operation services
Transmission System Operator (TSO)	Ensures power quality and security at a transmission level
Transmitter	Owns transmission grid and it is in charge of its maintenance
Distribution System Operator (DSO)	Ensures power quality and security at a distribution level
Distributer	Owns distribution grid and it is in charge of its maintenance
Wholesale Market Operator (WMO)	Ensures independency and the good functioning of the wholesale market
Local Market Operator (LMO)	Ensures independency and correct functioning of the local market
Retailers	Provides electricity supply to consumers, buys excess of self-generated electricity

Key Concepts	Definition
Smart grids	A group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid [37]
Demand Response	Changes in electric usage by end-use customers from their normal consumption patterns [38]
Smart metering	All agents in the system have Smart Meters that provide data acquisition, transmission, processing, and interpretation [39].
Self-generation	Share of the total energy production directly consumed by the energy production system owner (based on [40])
Distributed generation	Power generation within distribution networks [41]
Parameters	**Definitions**
V_{HV}	Minimum voltage defined as High Voltage in the systems parameters
$E_{W\text{-}S}$	Minimum energy required to sell electricity in the electricity market during a Period of Time Unit (PTU)
$E_{W\text{-}B}$	Minimum energy required to buy electricity in the electricity market during a PTU
$E_{L\text{-}S}$	Minimum energy required to sell electricity in the local electricity market during a PTU
$E_{L\text{-}B}$	Minimum energy required to buy electricity in the local electricity market during a PTU
$P_{OS\text{-}T}$	Minimum power required to participate in operation services at transmission level
$P_{OS\text{-}D}$	Minimum power required to participate in operation services at distribution level

The conceptual architecture is completed with the transactions allowed between agents as summarized in Table 2.2, where economic, energy and operation services transactions between the different agents are proposed. A matrix representation of the allowed transactions among agents are shown in different colours in this table. The possible transactions from the agent in a row to the agent in the column are represented by triangles. For instance, position T_{12} shows the transactions from consumers to generators, which are only economic as consumers just pay to generators for consuming electricity. On the other hand, T_{21} shows how generators provide energy to consumers. Another example could be position T_{43}, aggregators provide power flows and operating services to VPPs. In exchange to this, T_{34}, VPPs make economic payments to aggregators.

Table 2.2. Summary of the transactions among agents on the proposed Smart Grid framework

(▲ (red): Economic transaction; ▲ (blue): Energy transaction; ▲ (green): Operation services transaction).

	Consumers	Generators	VPP	Aggregators	Storage	TSO	Transmitter	DSO	Distribution	MO	LMO	Retailers
Consumers		▲ (red)	▲ (red) ▲ (blue) ▲ (green)	▲ (green)	▲ (red)	▲ (red) ▲ (green)	▲ (red)	▲ (red) ▲ (green)	▲ (red)	▲ (red)	▲ (red)	▲ (red) ▲ (blue)
Generators	▲ (blue)		▲ (red) ▲ (blue) ▲ (green)		▲ (blue)	▲ (green)	▲ (red)	▲ (green)	▲ (red)	▲ (red)		
VPP	▲ (red) ▲ (blue)	▲ (red) ▲ (green)		▲ (red)	▲ (red) ▲ (blue)	▲ (green)		▲ (green)			▲ (red)	
Aggregators	▲ (red)		▲ (green)			▲ (green)		▲ (green)				
Storage	▲ (blue)	▲ (green)	▲ (red) ▲ (blue) ▲ (green)			▲ (green)	▲ (red)	▲ (green)	▲ (red)	▲ (red)	▲ (red)	
TSO	▲ (red)	▲ (red)	▲ (red)	▲ (red)	▲ (red)							
Transmitter												
DSO	▲ (red)		▲ (red)	▲ (red)	▲ (red)							
Distribution												
MO		▲ (red)	▲ (red)		▲ (red)							
LMO	▲ (red)	▲ (red)	▲ (red)		▲ (red)							
Retailers	▲ (red)	▲ (red)	▲ (red)							▲ (red)		

The different agents must accomplish these transactions (economic, energy or services) in a coordinated way and what requires interchanging (receive and send information to) the rest of the participants in the power system. Traditional and new entities coexist in the proposed model. Agents whose activities change from traditional models are described in more detail in this chapter, while traditional will be described when some of their original characteristics change.

2.4.1. Active consumers

Consumers are the end users of electricity and they use it to perform its specific activities (industrial, commercial or residential). Three different types of consumers are considered depending on their connection point to the grid:

i. **Low Voltage (LV):** Consumers. The voltage supply is lower than $\boldsymbol{V_{HV}}$ kV, and they are connected to the LV distribution network. They are usually residential or small commercial customers.

ii. **High Voltage (HV):** Consumers to distribution. Connected to the distribution power system with a voltage larger than $\boldsymbol{V_{HV}}$ kV. They are typically medium industrial and commercial consumers.

iii. **High Voltage (HV):** Consumers to transmission. Connected to the transmission or subtransmission power system level with a voltage larger than $\boldsymbol{V_{HV}}$ kV. They are typically large industrial and commercial consumers.

Consumers used to be a static agent that only consumed energy. Nowadays, this activity can be complemented with the production of electricity with self-generation, providing demand response resources and being an active participant in electricity markets.

Consumers can be understood as a sum of loads that can own the metering equipment. Nowadays, it is becoming more and more common that customers may build their own generation resources, especially by using renewable resources. These generation facilities may range from a few kW to several MW. When generated electricity excesses the demand, it can be sold to the main grid through retail companies that will be responsible to ensure the economic compensation to small consumers by providing an electricity net balance with the system specified prices.

Regarding Demand Response Resources (DRR), they may exist in the customer facilities as a part of the demand that can be reduced/incremented according to the prices in the operation markets. Currently, it is becoming common that consumers own Electric Vehicles and small storage systems that can be operated by aggregators or themselves to offer operation services. Consumers should have the required communication systems to provide DRR in this case. Consequently, and depending on their size, consumers may require communication systems with other agents. For example, large flexible consumers will require direct communication with the TSO if they are connected to the transmission grid or direct communication with the DSO if they are connected to the distribution system. On the other hand, small and medium consumers will just interact with aggregators.

Consumer's main traditional transaction is to buy electricity from the grid and pay for it. Consumers can also now sell electricity to the grid and, eventually, may offer DRR directly to the Distribution System Operator (DSO) in case the size of the operable load is higher than the required $\boldsymbol{P_{OS\text{-}D}}$. Additionally, these DRR could also be offered directly to the Transmission System Operator (TSO) if they are larger than $\boldsymbol{P_{OS\text{-}T}}$ or through the aggregator. Regarding the economic transactions, consumers pay for the electricity consumed to retailers if they do no access directly to the markets. If they do, they pay for energy to the wholesale market operator or the local market operator, to whom they can also sell electricity for dynamic balancing. Additionally, they can also establish bilateral contracts with generators or VPPs. Regarding the operation services, consumers receive payments for the use of their flexible resources from the TSO, DSO, aggregators, VPPs and generators, depending on who uses their flexibility. Finally, since consumers are the end users of the system, they defray most of the incurred costs, such as transmission and distribution systems usage, market and system operators, etc. They may pay them directly to the involved agents or, more commonly, they make a single payment to the retailer who divides up with the rest of agents that receive payments from the consumer.

2.4.2. Generators

An electricity generator is an agent that owns the facilities to convert any type of primary energy into electricity.

The main activity of generators is to produce the electricity that is used by consumers. Moreover, generators have the capability to provide operation services (OS), that are mandatory in some cases and optional in the rest. Optional OS may be traded in markets or through contracts. Both energy and operation services can be provided to other agents via markets or bilateral contracts. Moreover, regulation in most countries enforce the obligation to provide some type of primary (spinning) reserve to the TSO from any committed generator [20].

In addition to the generators and turbines, the generation plants have the control and communication systems to ensure the correct operation to supply in a reliable and secure way the electricity to the grid. New generation capacity can also own the new assets regarding substations and transmission lines. Traditional generators were large centralised power plants, normally far away from the consumers. Now electricity generation occurs also at the distribution level and lower, scales, which is known as DER [7]. Thus, electricity generators can be differentiated regarding their connection point with the grid (transmission or distribution), size and dispatchability. Thus, generators can be bulk generators if they have large sizes and are connected to the transmission network or can be connected to the distributed network as DER. Moreover, a key characteristic of generating technologies is if they have the capability of varying their power output at will. Therefore, generating technologies can be differentiated in dispatchable and non-dispatchable technologies. It is common today for renewable generators to include batteries in their facilities to operate as conventional generators and provide operation services. Among all technologies, they can also be categorised between renewable (green), non-renewable (orange), nuclear (yellow) and renewable with storage (blue). The most common ones are the following: gas, coal, fuel, CHP, nuclear, hydroelectric, wind, solar PV, solar thermal and biomass. These classifications of technologies based on their connection point, dispatchability and availability can be seen in Figure 2.3.

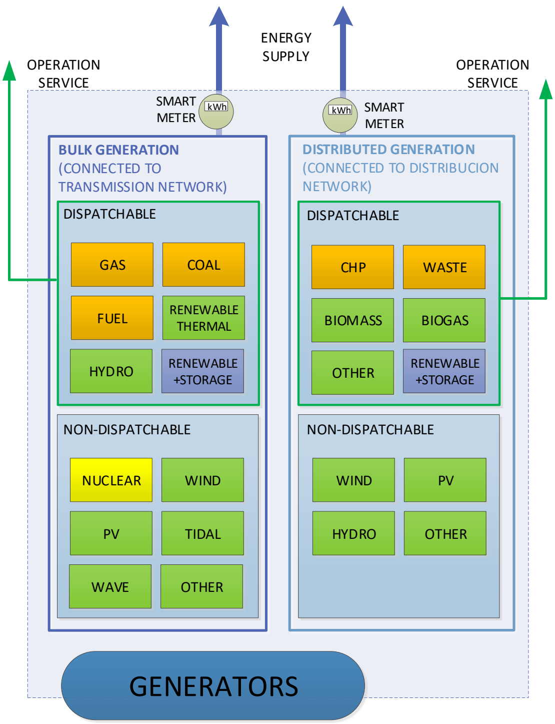

Figure 2.3. Generator technology types.

Generators mainly receive payments for the energy they produce and the operation services they offer. Generators provide electricity to the grid they are connected at (transmission or distribution) and this electricity can be managed by themselves or via a VPP that operates its assets. Regarding the operation services, they also provide them at the network level they are connected to. These services can be provided to the transmission and distribution operators if they meet the system operation services requirements ($\boldsymbol{P_{OS\text{-}T}}$, $\boldsymbol{P_{OS\text{-}D}}$). Thus, generators produce electricity that they sell in the wholesale market, local market (if connected to distribution) or *via* bilateral contracts to consumers, VPPs and storage agents in exchange of economic transactions. Moreover, generators can also provide operation services *via* markets or contracts with the TSO, DSO, VPPs and Storage. Receiving in exchange for them economic transactions. On the other hand, they can also purchase operation services from VPPs and storage agents. Finally, generators may pay fees for participating and using WEM, LMO and the transmission and distribution grids (if connected to them).

2.4.3. Virtual Power Plants (VPPs)

VPPs are defined as an entity that integrates small and geographically distributed generators connected to the distribution system with the objective to provide firm and tradable generation.

VPPs integrate small and disperse generation to perform as a single entity in the wholesale market and power system [24]. Therefore, VPPs behaves as a traditional generator in the system, providing energy but also operation services. VPPs help small generators, usually with no control capability, to become a viable and fully qualified generator in the market. The VPP provides this control capacity for them (primary and secondary reserve and voltage regulation) so that they can compete in energy and operation services and markets. The generation resources included in one VPP can easily be modified or switched on or off providing the required flexibility for operation purposes. This flexibility can also be obtained from DRR by interacting directly with large consumers or through demand Aggregators for small and medium size demand resources. Energy storage may be also a key asset to provide the VPP services.

The generators belonging to a VPP usually are spread out over a limited geographical area. The basic activities, relations and minimum conditions in the framework of the proposed model are shown in Figure 2.4.

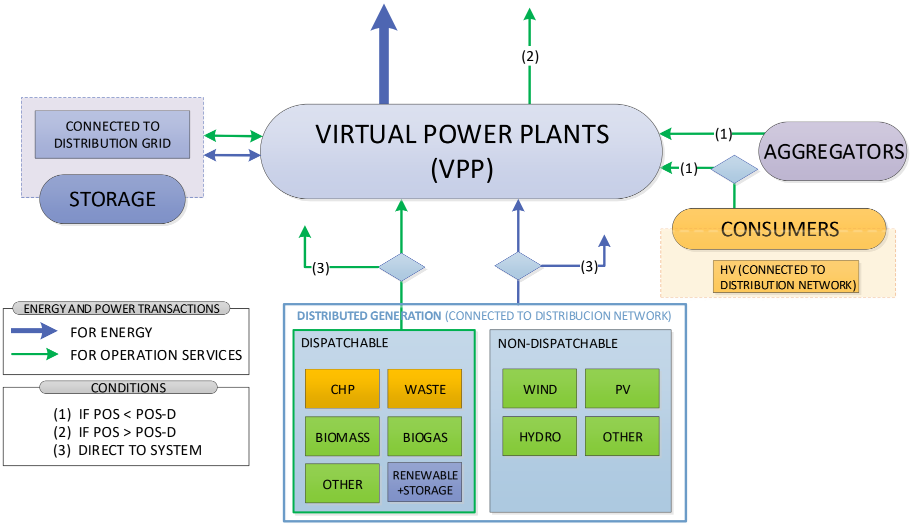

Figure 2.4. VPP activities and relations.

VPPs agents may own or control generators such as renewables, cogeneration plants, traditional thermal generators or storage systems. Moreover, VPPs need to have available the same communication and control needs than the traditional generators. These requirements should be more complex by the fact that the VPP has to control downstream are large amounts of very distributed resources and, in some cases, very small according to their rated power. Therefore, their communication and computing systems have to be more complex to participate in energy markets.

Regarding its transactions, VPPs interact with many agents. VPPs buy electricity from DG generators connected to the distribution grid and storage agents or from the Local Energy Market. VPPs sell the electricity to the different markets (wholesale or local). Regarding operation services, VPPs purchase them from medium consumers connected to distribution, aggregators and storage facilities. These are offered to DSO (if they are larger than $\boldsymbol{P_{OS\text{-}D}}$), TSO (if they are larger than $\boldsymbol{P_{OS\text{-}T}}$) or to other generators via bilateral contracts. Regarding their economic transactions, VPPs purchase electricity from generators and storage to sell them. Bilateral contracts can also be established between VPPs and consumers, retailers or storage. Between storage and VPPs bidirectional energy flows may exist. Finally, VPPs agents receive payments from the TSO, DSO and generators after proving the above-mentioned services. In order to obtain these services, VPPs have to purchase them from consumers, aggregators and storage systems. The VPP is not supposed to pay any fee for participating in the market or using the transmission or distribution grids as these costs will be translated to the generators that they operate or the consumers that buy electricity from them.

2.4.4. Aggregators

An aggregator is and entity that groups different consumer agents of a power system to represent and operate them as a single agent that participates in the operation services markets [35], [42].

Its main activity is to put into value for the system the small customer Demand Response Resources that independently considered are not valuable by themselves for other network operators. Thus, they unlock potential resources based on economies of scale [35]. The aggregator manages the customer demand by clustering small (a few kW) demand resources with similar characteristics, or combining them to provide valuable resources to the operator, in terms of size, duration, advance notification time, etc.

These products are able to compete in quality and price to those offered by other actors like generators. One special type of Aggregator activity will be the Electric Vehicle Charging Manager, that will manage the EV load charging process (and discharging) in a specific EV concentration point or area, with the objective to manage this special and flexible load and provide additional storage to the system. Aggregators will be also responsible of managing the small generation so that they could offer DRR products combining load and generation.

The aggregator requires tools to evaluate the individual consumer response (or in low aggregation levels as in the case of residential customers) so that it may evaluate and foresee the main parameters of the customer response such as reduced power, duration, up and down ramps, etc. Then, it may proceed to the associated settlement when the transaction is completed. In addition, aggregators may also implement on/off control for small generators.

The basic activities, relations and minimum conditions for the Aggregator in the proposed model are shown in the Figure 2.5.

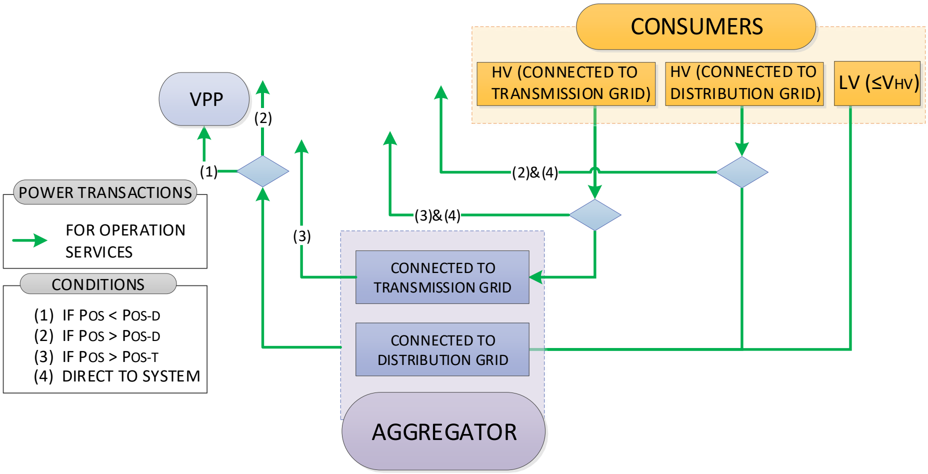

Figure 2.5. Aggregators activities and relations.

The aggregators' main components are an extensive communication facilities system and computational capability. The first has to provide a fast and reliable performance and the second to properly receive the requests from the network operators and respond to it using for that the suitable resources without compromising the customer requirements and expectations.

Aggregators' main clients are VPPs, DSO and TSO, to whom they provide operation services and power in exchange of economic payments. These operation services are provided according to the minimum required levels at distribution ($\boldsymbol{P_{OS\text{-}D}}$) and transmission ($\boldsymbol{P_{OS\text{-}T}}$). Moreover, they may also offer their services to other actors such as energy suppliers (retailers) and generators so that they may balance their buy/sell portfolio if necessary. Since all their resources come from consumers, aggregators will have to pay to consumers for their resources. These economic incentives that they have to provide to them are crucial for the seamless operation of this agent and to unlock the disaggregated opportunities.

2.4.5. Storage

This agent consumes and generates electricity and has the ability to store it for using it afterwards.

Storage is rapidly becoming a key technology in energy systems. Storage systems can help to balance and flatten the electricity load profile. They are characterised by very fast responses, which provides storage with the capability to efficiently deliver operation services such as frequency response, black-start capability, load following or capacity mechanisms [43]. Additionally, storage can participate in the wholesale market levelling the load, competing with other peak power plants [44] and balancing short term deviations. Storage has been pointed out as one of the key factors to ensure reliable large renewable penetration in power systems [3], mainly because its ability for balancing the excess and deficit of renewable production, so avoiding curtailment and also helping the system operator.

This agent has the capability to store energy in other forms such as thermal, potential, mechanical or chemical. This includes technologies such as pumped hydro, flywheels, molten salts, hydrogen, electrochemical batteries [45]. The storage agent also has to have available information and controls systems to be allowed to participate in the electricity market.

The storage agent will implement power and energy transactions with the grid it is connected to either distribution or transmission. If connected to the transmission grid, storage will inject and absorb electricity from the grid to perform its activity and provide operation services with a minimum power ($\boldsymbol{P_{OS\text{-}T}}$) to the TSO that manages the transmission grid. If connected to the distribution grid, the Storage may exchange power and operation services with a minimum size ($\boldsymbol{P_{OS\text{-}D}}$) not only in the distribution grid and the DSO but also through VPP. These could be implemented through bilateral contracts, which can occur for aggregating capacities to better participate in the markets. With respect to economic transactions, Storage can receive payments from the Wholesale Market, Local Market and VPPs for the energy sold. It can also receive payments from the TSO, DSO, VPP and generators for operation services. Storage can also buy electricity from the Wholesale market, Local Markets and VPPs and it may have to pay for the associated fees of markets and grid assets.

2.4.6. Transmission system operator

This agent ensures the correct operation of the transmission system. Its main activities are to guarantee secure operation of the power system. This agent has to obtain the resources to operate the network not only from traditional generators and, eventually, from VPPs, large customers and storage as it is proposed in the architecture. To do so, the TSO needs information that is provided by the WMO, transmitter and other agents connected to the transmission grid. The TSO is committed to balance the system and identify network restrictions, which requires a reliable monitoring and control capability either for committed generators or VPPs and, eventually, demand response resources, directly managed or through aggregators. These control signals require fast and reliable communication.

For doing so, the TSO needs to have assets to ensure the information and measurements flows available regarding the operation of the transmission network through a control centre. The communication and cooperation between DSO and TSO will be essential in this new conceptual architecture. Furthermore, the TSO will also have to manage exchanges with other power systems considering the capacity of the interconnections.

In the proposed model the TSO has to also consider the use of resources to operate the transmission network not only from traditional generators but, eventually, from VPPs, large customers connected to transmission and storage. All these operation services will require a minimum but homogeneous power ($\boldsymbol{P_{OS\text{-}T}}$) for all participants that will be determined according to the size of the system. Agents will need to fulfil these requirements to compete in equal conditions. The TSO will reward with economic payments in exchange of operation services to generators, VPPs, aggregators, storage systems and consumers connected to the transmission network. As the main beneficiaries of the reliable and secure operation of the transmission grid are consumers, they will pay the maintenance of the TSO via fees.

2.4.7. Transmitter

This agent is in charge of carrying the electricity from the bulk generation to the distribution system. The activity that performs is to transport the electricity throughout the assets that it owns. Moreover, the transmitter has to plan and build (usually in a regulated framework) new lines and reinforce the ones to account on future demand perspectives. It also verifies the connection procedure of new generation capacity.

This agent has the physical infrastructure between the large generators and the distribution grid or large consumers. This includes high voltage transformers and mainly transmission lines.

This agent is highly regulated since it is a natural monopoly [46]. Therefore, the only transactions of this agent are the received fees from generators, storage and consumers. The users of the transmission system bear the costs of its maintenance and modernisation via taxes.

2.4.8. Distribution system operators

This agent refers to the entity in charge of ensuring the operation of the distribution system. The DSO plays the important role of managing the distribution system. Moreover, since Distributed Generation is usually embedded in the distribution system the system behaviour is increasing in complexity (direction of energy flows, distribution operation constraints, etc.). To account for this situation, the DSO needs to have the necessary resources, which come from the customer resources directly operated or, desirable, through Aggregators. Among the new roles that DSOs will realise are to extreme importance:

- Enhancement of the competition and usage of different local resources to manage technical constraints at a distribution level. Allowing for optimising network planning and solving congestions at the distribution level [47]
- Provision of the forecast and availability of flexible resource to both TSO and Local Market Operators. Helping both to accurately predict and contrast the reliability of the resources [48].
- Improvement of power quality monitoring and control strategies associated with the inclusion of Distributed Energy Generation at the distribution level [49].

Therefore, this agent needs to have assets to ensure the information and measurements flows available regarding the operation of the distribution network so that he may detect or predict undesirable conditions (current flows or voltages) and find the resources to cope with the situation. According to this fact, fast and reliable communication channels with the TSO, aggregators, VPP and generators connected to the distribution system are crucial. Moreover, they also own control centres to safeguard the operation of the system.

In the proposed model the DSO has to also consider the use of resources to operate the network not only from traditional generators but, eventually, from VPPs, large customers, aggregators and storage. All these operation services will require a minimum but homogeneous power ($\boldsymbol{P_{OS\text{-}D}}$) for all participants that will be dictated by the size of the system. Agents will need to fulfil these requirements to compete in equal conditions. Thus, the DSO will be able to provide economic payments in exchange of operation services to generators, VPPs, aggregators, storage systems and consumers connected to the distribution network. On the other hand, since the beneficiaries of the safe and secure operation of the distribution grid are consumers connected to distribution, they will pay the maintenance of the DSO via fees.

2.4.9. Distributors

This agent is in charge of carrying the electricity at the final stage of the delivery, between the transmission grid and the final consumers connected to distribution.

Traditionally, the only objective of this agent was to provide the physical infrastructure between the transport grid and the final consumers. However, its activities are now larger due to the amount of information that they manage generated by smart meters. Therefore, they have become an information provider too, since it manages all the telemetry and metering infrastructure. This agent has traditionally been highly regulated since it has been considered a natural monopoly [46]. Nevertheless, efforts to make the sector more competitive are arising [50].

A new critical activity for the distributor is the “Information Provider”. They have to be responsible for gathering measurements and other information of the rest of the agents so that they may evaluate the response. For doing so, the distribution agent owns a large number of physical assets. Among them are medium and low voltage grids, transformers and consumer’s telemetry equipment, the distributor owns a large Advanced Metering Infrastructure (AMI) that collects large quantities of information. After this, thanks to a Measured Data Management (MDM) System all this information is filtered, processed and organised in order to obtain valuable information for the correct functioning of the system.

The entities in charge of this agent have to maintain, monitor and improve the physical assets and provide the collected information. Therefore, the only transactions of this agent are received fees from generators, storage and consumers. The users of the distribution system bear the costs of its maintenance and modernisation via taxes.

2.4.10. Wholesale market operator

This agent is an entity that provides a service whereby the offers to sell electricity are matched with bids to buy electricity, ensuring the balance between them [51], [52].

The main objective to ensure the correct and transparent functioning of the economics transactions associated with the power sector. Organising the different electricity markets, including wholesale, future markets and the collection of all the bilateral contracts over the counter (OTC) that will have an impact on the system. This information has to be provided to the TSO to ensure the correct functioning of the system.

The WMO is an independent actor in liberalized frameworks, strictly regulated. The WMO is characterised by a trading platform that it controls in order to manage all the bids to buy and sell products. One of its main tasks is the couple the market by matching the sell and buy offers.

Regarding transactions among agents, the generators, Storage and the consumers bear the costs associated with the MO, paying the fees directly or via a third party. Regarding energy transactions, a minimum level for buying ($\boldsymbol{E_{W\text{-}B}}$) and selling ($\boldsymbol{E_{W\text{-}S}}$) electricity in this market will be established depending on its size. Generators and VPPs offer electricity in the market and are compensated with cash flows. These come from the retailers and consumers that participate in the market. Storage has the capacity to buy and sell electricity to obtain benefits. Thus, cash flows between storage and the WMO are bidirectional.

2.4.11. Local Market Operators

Currently, Local Electricity Markets (LEMs) are probably the least developed component of Smart Grids. The implementation of electricity markets in the last 20 years has not resulted in significant reduction in the price ties of the energy or the increment of opportunities for most of the final consumers. Local markets are being designed to bring competitive advantages to these consumers, by implementing local trading (peer-to-peer) either directly or through aggregators and VPPs [53].

LEM need to be reliably established to enhance the fair-trading for customer owned renewable generation and flexible resources.

This will require the development and implementation of dynamic and automatic trading platforms, for the negotiation of energy for short periods of time (shorter than the ones applied to wholesale markets) and probably closing a minute before delivery. LME platforms have to offer consumers, aggregators and VPPs the chance to virtually trade energy services in a geographically constrained area [54]. These markets complement wholesale markets and bilateral contracts that do not have the capability to react in real-time to the myriad of small demand resources and distributed generation [55]. The LMO manages and operates the LEM from an independent perspective enabling a more dynamic trading of electricity.

Its main activity is to promote the diversity and competitiveness of the market, while ensuring the correct functioning of it by matching buying and selling bids. Furthermore, they have to monitor all the energy transactions to communicate it to the DSO to ensure a reliable operation under the technical limits. This information is provided according to the geographic control area of the DSO associated with the LEM.

The main components that characterise the LMO are the trading platform that it controls to manage all the bids to buy and sell products. All these agents have to be in a local area and interconnected in a distribution grid. This allows a fast negotiation process and the dynamic response to prices.

Due to its role of market operator, the LMO receives payments from all the agents participating in this market. The Local Market manages payments among the participating agents, to do so a minimum level for buying ($\boldsymbol{E_{L\text{-}B}}$) and selling ($\boldsymbol{E_{L\text{-}S}}$) electricity in these markets will be established depending on its size. While generators and VPPs agents receive payments for the energy traded, consumers and retailers pay for it. As well as in other markets, the storage has bidirectional energy flows, having the capacity to buy and sell electricity in it. Finally, consumers, storage and generators pay an established fee for participating in the market directly or throughout a third party.

2.4.12. Retailers

Electricity retailers are entities that bridge the gap between consumers and the wholesale markets [52]. The activities of this agent do not change significantly from the traditional one. They buy the electricity in the market and sell it to their customers. Nevertheless, in the proposed model, the self-generation becomes a common possibility for small customers, being the interaction for these customers directly handled by retailers. These interactions translate in contracts with consumers to absorb the self-generation excess and economically compensate them afterwards

The retailers do not have specific components on their assets. They play a role of intermediary, thus owing a strong communication and prediction systems for optimising their performance.

This agent needs to interact for energy trading with wholesale and local markets. They can also sign these transactions through bilateral contracts with generators and VPPs. For these reasons they need reliable and secure communication and information channels. Moreover, according to the proposed architecture, retailers are also allowed to interact with customers and aggregators for portfolio balancing purposes, needing for that the capability to interact through dynamic pricing (not control capabilities) with the customers. They are also responsible for implementing the self-consumption or net balance contracting, needing for that information about the customer buys and sells of electricity. Retailers are also responsible to pay the fees in representation of consumers to the different market operators.

In sum, interactions between retailers are with customers, aggregators, VPPs, generators and market operators.

2.4.13. Conceptual architecture and interactions among agents

The above-described agents will establish a series of relationships among them as summarized in Table 2. More specifically, the following figures map the different interactions that will take place in the newly proposed conceptual architecture. Thus, these figures explicit each of the transactions above explained.

Figure 2.6 shows the transactions among agents associated with the physical commodity (electricity), which can be due to power, operation services or balancing requirements. The blue arrows show transactions among agents related to energy, for instance generators can supply power to the grid if they are connected to generation. In contrast, if they are connected to the distribution grid, they can supply its energy to the grid or through a VPP if their capacity is small. Another example can be storage, which have the capability to provide or purchase electricity from the grid. Depending to which grid, transmission or distribution, are connected the energy fluxes will vary. The green arrows represent the operation services transactions. These ones are related to frequency and voltage control, energy imbalance or system protection [20]. It can be seen that these transactions are applied to the transmission or distribution grid, depending to which grid the resources are connected. Afterwards, these operation resources at distribution level can be managed at higher levels by the TSO thanks to the communication among DSO and TSO.

Figure 2.7 shows the economic transactions among agents, these ones differentiated depending if they are associated with an energy supply, bilateral contracts, operation services, balancing of own assets, fees and grid usage transactions. Thus, blue arrows refer to an economic payment associated with a power exchange; dashed blue arrows show energy bilateral contracts, green arrows represent payments associated with operation services, green dashed arrows represent payments for balancing portfolios or demands, orange arrows represent fees and grey arrows taxes for the usage of the grid. For instance, Aggregators receive payments for operation services from the DSO, TSO and VPP but they pay these operation services to consumers. Retailers buy energy from wholesale and local markets and bilateral contracts with VPPs and generators. Afterwards, this energy is sold to consumers that pay for it. On the other hand, the transmitter agent and the distributor agent only receive payments associated with taxes, which are only paid by consumers, storage and generators, the agents that are considered the final users of the infrastructure. Particularly, only agents connected to the distribution grid pay to the distributor.

Finally, some agents associated with energy services providing can also balance their own portfolio to optimise their performance in the market. These last arrows can be appreciated in green dash lines.

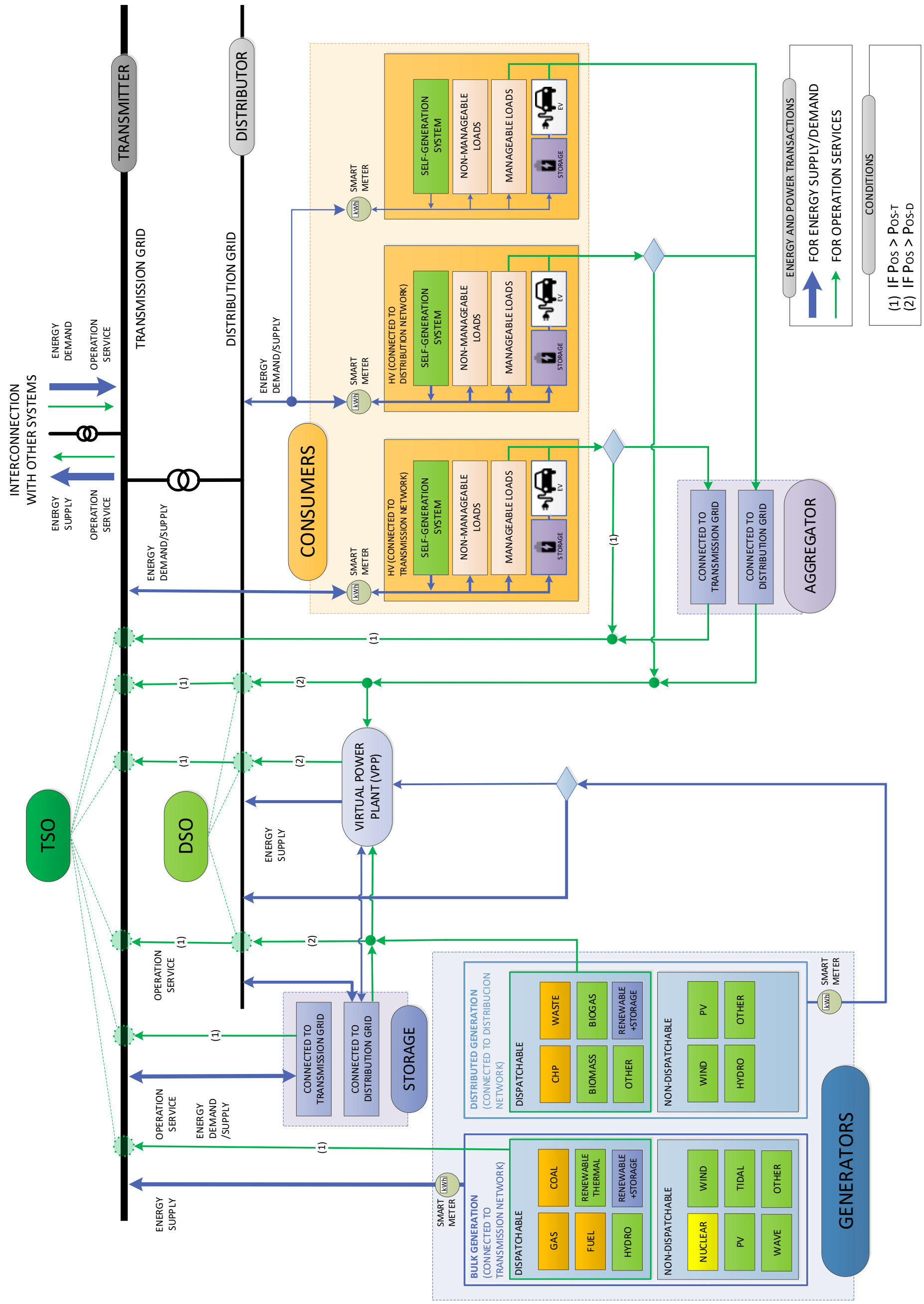

Figure 2.6. Conceptual architecture. Physical transactions.

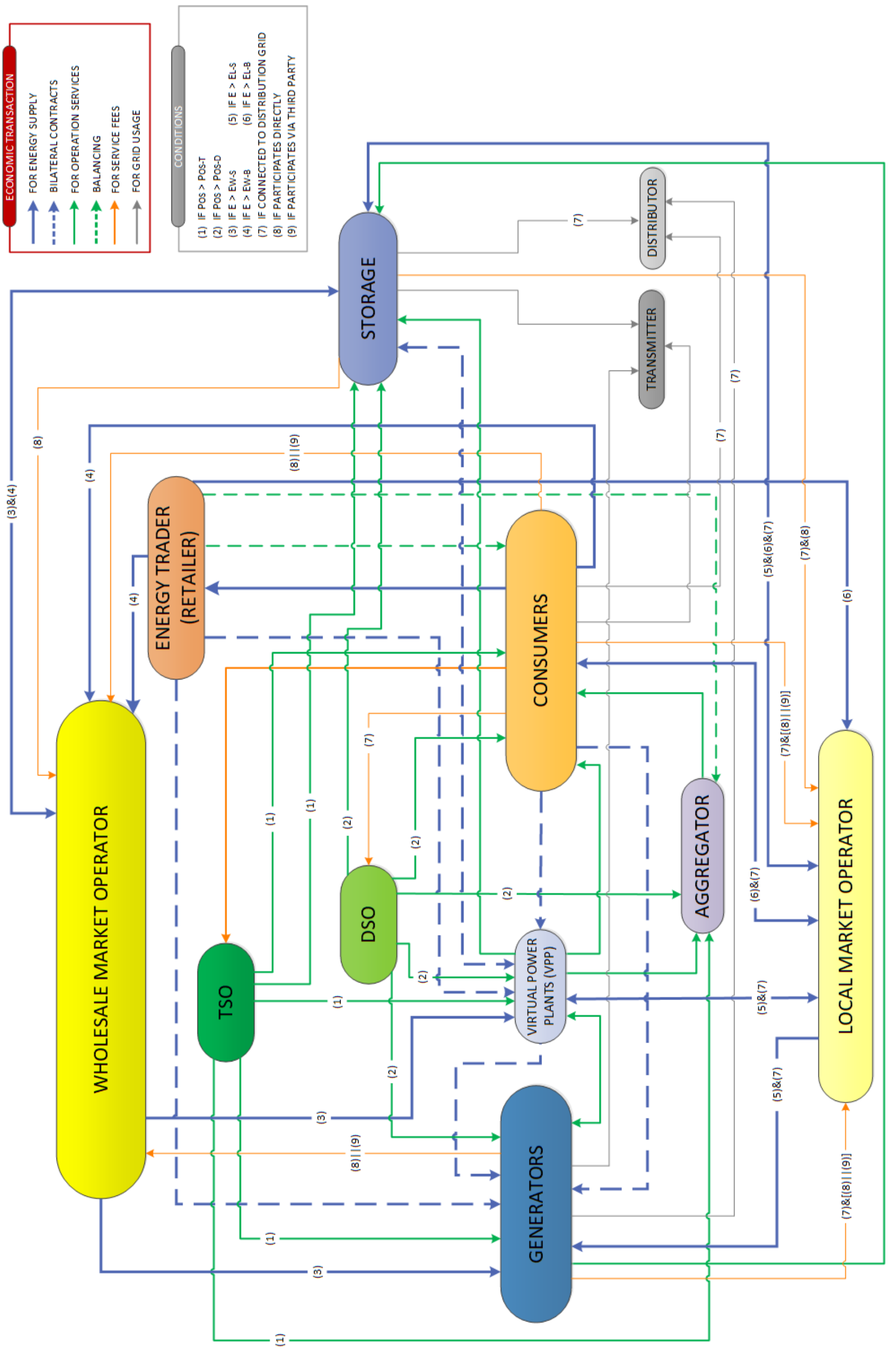

Figure 2.7. Conceptual architecture. Economic transactions.

2.5. Conclusions

This paper presents a novel conceptual architecture for the development of the next generation electricity markets. The architecture helps to unlock all the hidden potential of flexible and distributed energy resources, taken into special consideration the potential benefits for active consumers. The novel architecture is proposed based on the analysis of the shortcomings of the existing models that can be found in the literature. This model provides a path that policy makers can follow to eliminate barriers to integrate DER in a competitive way at distribution level.

In this new paradigm with a massive integration of renewables, the need for electricity storage and for enhancing the value of demand response resources force agents' services and transactions to appear. The proposed new architecture focuses on agents who enable flexible resources to be exploited such as Storage, Virtual Power Plants and Aggregators. These agents are already operating in some systems and emerging in others. However, the model includes the transactions among them based on an ontological analysis. Furthermore, the transactions among the presented agents are separated in energy, operating services and economic transactions, which have been clearly analysed and described regarding the offered services considered the technical restrictions. This results in a clear proposal of how the future electricity markets could be implemented.

This architecture also presents and characterises the flexible resources available in the next generation electricity markets paving the way for its transactions. This flexibility can be available for two functions: provide operation services and fast and dynamic balancing of electricity consumption and generation at different network levels. Three types of flexibility have been shown in the proposed conceptual architecture. Similar to traditional generators, intermittent renewables with batteries are also able to provide flexibility. Consumers with self-generation and batteries can also become a flexible resource for the systems. This also helps them to optimise their electricity cost by unlocking resources and allowing them to use their flexibility with an economic purpose. Finally, electric vehicles will also become a major source of flexibility on the system. Even though being a concrete application, the massive electrification of transport gives as an opportunity to provide flexibility to the system. EV can be described as consumers with self-generation and batteries if vehicle to grid chargers are implemented or just as flexible consumers if only grid to vehicle chargers are installed.

Another novel element is the inclusion of Local Electricity Markets in the conceptual architecture. Currently, these markets are gaining importance and interest due to their capability to react to the novel scenario of larger intermittency and decentralised generation at distribution level. However, their relationships with other agents of the system have not been studied so far from an ontological perspective. These relationships have been carefully studied and stated. LEMs represent a valuable tool to exchange energy locally in a more dynamic and cost-efficient way for the power system (grid loss reduction). Furthermore, they also present an opportunity for decentralisation and enhancement of competition in real time. It is important to highlight the need to have a fast and reliable communication channel between the Local Market Operator and the DSO. The last one provides the technical restrictions that determines under what limits energy can be traded in these LEMs.

Finally, future work should assess the implementation of a case study with the proposed architecture to assess how the model enhances a more competitive electricity markets and how agents are integrated in existing systems. It is also necessary to develop a clear cost-benefit analysis of the implemented model to gain knowledge of it. Moreover, simulations of the market behaviour under different time domains remains also as a future objective.

2.6. References

[1] IPCC, "Fifth Assessment Report: Chapter 7 Energy Systems," 2014.

[2] European Technology Platform Smart Grids, "Smart grids: strategic deployment document for Europe's electricity network of the future | 2degrees Community | 2degrees," 2010.

[3] S. Weitemeyer, D. Kleinhans, T. Vogt, and C. Agert, "Integration of Renewable Energy Sources in future power systems: The role of storage," Renew. Energy, vol. 75, pp. 14–20, Mar. 2015.

[4] N. Lebedeva, D. Tarvydas, and I. Tsiropoulos, "Li-ion batteries for mobility and stationary storage applications - Scenarios for costs and market growth," 2018.

[5] I. Kaitovic and S. Lukovic, "Adoption of model-driven methodology to aggregations design in Smart Grid," in 2011 9th IEEE International Conference on Industrial Informatics, 2011, pp. 533–538.

[6] M. Albano, L. L. Ferreira, and L. M. Pinho, "Convergence of Smart Grid ICT Architectures for the Last Mile," IEEE Trans. Ind. Informatics, vol. 11, no. 1, pp. 187–197, Feb. 2015.

[7] NIST, "Framework and Roadmap for Smart Grid Interoperability Standards, Release 3.0," 2014.

[8] Smart Grid Coordination Group, "Smart Grid Reference Architecture. CEN-CENELEC-ETSI," 2012.

[9] C. Neureiter, M. Uslar, D. Engel, and G. Lastro, "A standards-based approach for domain specific modelling of smart grid system architectures," in 2016 11th System of Systems Engineering Conference (SoSE), 2016, pp. 1–6.

[10] P. Goncalves Da Silva, D. Ilic, and S. Karnouskos, "The Impact of Smart Grid Prosumer Grouping on Forecasting Accuracy and Its Benefits for Local Electricity Market Trading," IEEE Trans. Smart Grid, vol. 5, no. 1, pp. 402–410, Jan. 2014.

[11] M. Ampatzis, P. H. Nguyen, and W. Kling, "Local electricity market design for the coordination of distributed energy resources at district level," in IEEE PES Innovative Smart Grid Technologies, Europe, 2014, pp. 1–6.

[12] A. Ipakchi and F. Albuyeh, "Grid of the future," IEEE Power Energy Mag., vol. 7, no. 2, pp. 52–62, Mar. 2009.

[13] V. N. Coelho, M. Weiss Cohen, I. M. Coelho, N. Liu, and F. G. Guimarães, "Multi-agent systems applied for energy systems integration: State-of-the-art applications and trends in microgrids," Appl. Energy, vol. 187, pp. 820–832, Feb. 2017.

[14] T. Logenthiran, D. Srinivasan, and A. M. Khambadkone, "Multi-agent system for energy resource scheduling of integrated microgrids in a distributed system," Electric Power System Research, vol. 81, no. 1, pp. 138–148, Jan. 2011.

[15] B. M. Radhakrishnan and D. Srinivasan, "A multi-agent based distributed energy management scheme for smart grid applications," Energy, vol. 103, pp. 192–204, May 2016.

[16] C.-H. Yoo, I.-Y. Chung, H.-J. Lee, and S.-S. Hong, "Intelligent Control of Battery Energy Storage for Multi-Agent Based Microgrid Energy Management," Energies, vol. 6, no. 10, pp. 4956–4979, Sep. 2013.

[17] B. Zhao, M. Xue, X. Zhang, C. Wang, and J. Zhao, "An MAS based energy management system for a stand-alone microgrid at high altitude," Appl. Energy, vol. 143, pp. 251–261, Apr. 2015.

[18] P. Ringler, D. Keles, and W. Fichtner, "Agent-based modelling and simulation of smart electricity grids and markets – A literature review," Renew. Sustain. Energy Rev., vol. 57, pp. 205–215, May 2016.

[19] C. Dänekas, C. Neureiter, S. Rohjans, M. Uslar, and D. Engel, "Towards a Model-Driven-Architecture Process for Smart Grid Projects," Springer, Cham, 2014, pp. 47–58.

[20] Q. Wang, C. Zhang, Y. Ding, G. Xydis, J. Wang, and J. Østergaard, "Review of real-time electricity markets for integrating Distributed Energy Resources and Demand Response," Appl. Energy, vol. 138, pp. 695–706, Jan. 2015.

[21] H. Pandžić, I. Kuzle, and T. Capuder, "Virtual power plant mid-term dispatch optimization," Appl. Energy, vol. 101, pp. 134–141, Jan. 2013.

[22] H. Pandzic, J. M. Morales, A. J. Conejo, and I. Kuzle, "Offering model for a virtual power plant based on stochastic programming," Appl. Energy, vol. 105, pp. 282–292, 2013.

[23] M. Rahimiyan and L. Baringo, "Strategic Bidding for a Virtual Power Plant in the Day-Ahead and Real-Time Markets: A Price-Taker Robust Optimization Approach," IEEE Trans. Power Syst., vol. 31, no. 4, pp. 2676–2687, Jul. 2016.

[24] D. Pudjianto, C. Ramsay, and G. Strbac, "Virtual power plant and system integration of distributed energy resources," IET Renew. Power Gener., vol. 1, no. 1, p. 10, 2007.

[25] D. Pudjianto, C. Ramsay, and G. Strbac, "Microgrids and virtual power plants: Concepts to support the integration of distributed energy resources," Proc. Inst. Mech. Eng. Part A J. Power Energy, vol. 222, no. 7, pp. 731–741, Nov. 2008.

[26] A. Mnatsakanyan and S. W. Kennedy, "A Novel Demand Response Model with an Application for a Virtual Power Plant," IEEE Trans. Smart Grid, vol. 6, no. 1, pp. 230–237, Jan. 2015.

[27] B. Dupont, C. De Jonghe, L. Olmos, and R. Belmans, "Demand response with locational dynamic pricing to support the integration of renewables," Energy Policy, vol. 67, pp. 344–354, Apr. 2014.

[28] M. A. Piette, D. Black, and R. Yin, "Comparison of Actual Costs to Integrate Commercial Buildings with the Grid," Proc. 2016 ACEEE Summer Study Energy Effic. Build. LBNL, Jun. 2016.

[29] D. Alfonso, A. Pérez-Navarro, N. Encinas, C. Álvarez, J. Rodríguez, and M. Alcázar, "Methodology for ranking customer segments by their suitability for distributed energy resources applications," Energy Convers. Manag., vol. 48, no. 5, pp. 1615–1623, May 2007.

[30] J. Rodríguez-García, C. Álvarez-Bel, J.-F. Carbonell-Carretero, M. Alcázar-Ortega, and E. Peñalvo-López, "A novel tool for the evaluation and assessment of demand response activities in the industrial sector," Energy, vol. 113, pp. 1136–1146, Oct. 2016.

[31] G. Derakhshan, H. A. Shayanfar, and A. Kazemi, "The optimization of demand response programs in smart grids," Energy Policy, vol. 94, pp. 295–306, Jul. 2016.

[32] S. Weitemeyer, D. Kleinhans, T. Vogt, and C. Agert, "Integration of Renewable Energy Sources in future power systems: The role of storage," Renew. Energy, vol. 75, pp. 14–20, Mar. 2015.

[33] M. McPherson and S. Tahseen, "Deploying storage assets to facilitate variable renewable energy integration: The impacts of grid flexibility,

renewable penetration, and market structure," Energy, vol. 145, pp. 856–870, Feb. 2018.

[34] Electrek, "Hornsdale Power Reserve, Year 1 Technical and Market Impact case study," 2019.

[35] S. Burger, J. P. Chaves-Ávila, C. Batlle, and I. J. Pérez-Arriaga, "A review of the value of aggregators in electricity systems," Renew. Sustain. Energy Rev., vol. 77, pp. 395–405, Sep. 2017.

[36] A. J. Lopes, R. Lezama, and R. Pineda, "Model Based Systems Engineering for Smart Grids as Systems of Systems," Procedia Comput. Sci., vol. 6, pp. 441–450, Jan. 2011.

[37] Y. Kabalci, "A survey on smart metering and smart grid communication," Renew. Sustain. Energy Rev., vol. 57, pp. 302–318, May 2016.

[38] U.S. Department of Energy, "Benefits of demand response in electricity markets and recommendations for achieving them a report to the United States congress pursuant to section 1252 of the energy policy act of 2005," 2006.

[39] D. Alahakoon and X. Yu, "Smart Electricity Meter Data Intelligence for Future Energy Systems: A Survey," IEEE Trans. Ind. INFORMATICS, vol. 12, no. 1, p. 425, 2016.

[40] R. Luthander, J. Widén, D. Nilsson, and J. Palm, "Photovoltaic self-consumption in buildings: A review," Appl. Energy, vol. 142, pp. 80–94, Mar. 2015.

[41] T. Ackermann, G. Andersson, and L. Söder, "Distributed generation: a definition," Electr. Power Syst. Res., vol. 57, no. 3, pp. 195–204, Apr. 2001.

[42] J. Ikäheimo, C. Evens, and S. Kärkkäinen, "DER Aggregator Business: the Finnish Case," 2010.

[43] N. Günter and A. Marinopoulos, "Energy storage for grid services and applications: Classification, market review, metrics, and methodology for evaluation of deployment cases," J. Energy Storage, vol. 8, pp. 226–234, Nov. 2016.

[44] A. A. Akhil et al., "Sandia Report DOE/EPRI Electricity Storage Handbook in Collaboration with NRECA," 2015.

[45] M. Analysis, "Full report Australian energy storage," 2018.

[46] R. W. Künneke, "Electricity networks: how 'natural' is the monopoly?," Util. Policy, vol. 8, no. 2, pp. 99–108, Jun. 1999.

[47] E. I. Rivero Puente, H. Gerard, and D. Six, "A set of roles for the evolving business of electricity distribution," Util. Policy, vol. 55, pp. 178–188, Dec. 2018.

[48] J. Silva et al., "Estimating the Active and Reactive Power Flexibility Area at the TSO-DSO Interface," IEEE Trans. Power Syst., vol. 33, no. 5, pp. 4741–4750, Sep. 2018.

[49] M. Armendariz., D. Babazadeh, D. Brodén, and L. Nordström, "Strategies to Improve the Voltage Quality in Active Low-Voltage Distribution Networks Using DSO's Assets," IET Gener. Transm. Distrib., vol. 11, no. 1, pp. 73–81, Jan. 2017.

[50] D. Helm, Burn Out, The endgame for fossil fuels. 2017.

[51] EC, "Proposal for a Directive of the European parliament and of the council on common rules for the internal market in electricity," 2016.

[52] D. Kirschen and G. Strbac, Fundamentals of Power System Economics. Chichester, UK: John Wiley & Sons, Ltd, 2004.

[53] A. Lüth, J. M. Zepter, P. Crespo del Granado, and R. Egging, "Local electricity market designs for peer-to-peer trading: The role of battery flexibility," Appl. Energy, vol. 229, pp. 1233–1243, Nov. 2018.

[54] E. Mengelkamp, B. Notheisen, C. Beer, D. Dauer, and C. Weinhardt, "A blockchain-based smart grid: towards sustainable local energy markets," Comput. Sci. - Res. Dev., vol. 33, no. 1–2, pp. 207–214, Feb. 2018.

[55] A. Monacchi and W. Elmenreich, "Assisted Energy Management in Smart Microgrids," Jun. 2016.

CAPÍTULO 3: **Design and validation of a methodology for standardizing prequalification of industrial demand response resources**

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3.1. Abstract

Current energy policies around the world are encouraging integration of renewable electricity generation into the power system. However, these resources are so unpredictable and variable that the need of more flexible resources increases. Demand Response (DR) resources may be a realistic solution but increasing the credibility among agents by means of the standardization of DR procedures is necessary.

This paper proposes a methodology based on an energy analysis of industrial processes to quantify and validate the flexibility potential of industrial customers in order to contribute to create a certification procedure. This methodology can be helpful for industrial customers themselves, energy service companies (ESCO) and DR aggregators, among others.

The methodology was validated in three different factories whose industrial segments have a high-energy intensity in Europe: a paper factory (Klingele, Germany), a meat factory and a refrigerated logistics centre (Campofrio, Spain).

Keywords: Industrial production, Renewable integration, Demand response, Practical demonstration, Load management.

3.2. Introduction

The progressive integration of Renewable Energy Sources (RES) in the mix of electricity generation brings unquestionable environmental benefits. However, it requires wider variety of solutions to guarantee the electricity supply due to the variability of RES. In this context, Demand Response (DR) could be an important resource to integrate RES [1-3], considering demand-side resources in electric usage, shaping their normal consumption patterns in response to the variations in the electricity price over time or to incentive revenues designed to induce lower electricity usage at times when system reliability is jeopardized [4].

According to this, DR policies and directives have already been established to address the demand side participation in electricity markets in many countries, such as EU member countries [5], United States of America (National action plan-FERC) [6], China [7], etc. There are several examples in Europe, and especially in the United States, of DR programs that have already been offered by system operators or utilities [8]. For instance, large industries such as metal industry, cement, chemistry, iron and steel and vehicle manufacturing have traditionally been willing to reduce part of their energy consumption in exchange for some economic benefits [9-12]

There are different prequalification procedures to validate balancing resources in which the conventional generators must be qualified according to some technical specifications that are tested before taking part into balancing markets [13, 14]. However, there is not a common standardized procedure to guarantee the reliability of DR resources.

In this vein, the only DR standards that currently exit around the globe are related to communication protocols for control systems in commercial and residential sectors [15]. Some examples are "ISI/IEC 15067-3:2012" that is an international smart appliance standard [16], "Open Automated Demand Response (OpenADR)" developed in the United States [17], "AS/NZN 4755" that is from Australia [18] and "Echonet Life" from Japan" [19].

Due to a lack of specific standards for the certification of DR resources, most system operators have developed their own procedures to guarantee the reliability of customers' DR bids prior to take part into their energy markets [20, 21].

In fact, there are some studies with special focus on the technical aspects of the procedure for the validation of DR resources [22], but they focus on the specific problems that aggregators could have using this kind of resources instead of on the flexible demand of customers.

In this context, , a standardized procedure for the certification of DR resources was proposed in the "Demand Response in Industrial Production (DRIP)" project [23] attending to three different points of view: Certification of DR Providers, Certification of DR Products and Certification of Energy Service Traders [24]. Regarding the certification of DR Providers, it could be used to prove if an industrial customer is able to reliably implement their DR actions, which are defined as the technical specifications associated with a change in the electricity usage of a particular industrial process in response to specific request from a system operator on a type of day.

Industrial customers can hide a high DR potential in their production processes [25-27], but it is necessary to carry out sophisticated analyses to take into account all the constraints linked to critical parameters of production processes such as temperature, humidity and pressure, among others. In other words, the inadequate implementation of DR actions could affect to the final quality of products, which could be a relevant barrier for the participation of industrial customers in any DR option [28].

As a whole, this paper presents a novel methodology whose main objective is to determine and demonstrate the flexibility potential that exists in industrial customers (DR Provider). This methodology could be used as a basis for the development of a certification procedure of reliable industrial DR resources. In order to address the abovementioned objective, the following issues were performed:

- The actual minimum reducible or interruptible power for each identified DR actions was demonstrated in a set of field tests whose results were compared with the theoretical values identified on the flexibility audits previously performed.
- The evolution of the critical parameters of the industrial processes was analysed to determine the potential impact on the final products during the field tests.
- The potential participation of industrial customers in reserve electricity markets was validated by means of the implementation of a set of DR events in order to simulate a real situation.

The methodology was applied to three different customers with sensitive production processes: a paper factory (Klingele, Germany), a meat factory and a logistics centre of the same segment (Campofrio, Spain).

These customers were selected because both the paper and the food industries represent a high percentage, 11.7% (10,071 ktoe) and 11.65% (9,981 ktoe) respectively, of the total electrical consumption in the industrial sector (235,665 ktoe) [29].

Additionally, the aforementioned segments have a high degree of replicability in Europe, as it can be observed in the following figures that present the number of European factories [30]:

- Around 2,300 paper factories manufacture pulp, paper and paperboard.
- Around 28,000 meat factories manufacture pork products.
- Around 2,400 refrigerated logistics centres belong to the meat segment.

This work was carried out in the framework of the aforementioned DRIP project that was co-funded by the Environment LIFE programme of the European Commission and developed by six partners with different roles: a grid operator, two industrial customers, a certifier, a retailer and a research centre.

The paper is structured as follows: Section 2 describes the proposed methodology that includes two relevant points such as the description of the verification process for the assessment of a DR event and the technical parameters of DR actions according to the presented methodology. In Section 3, the DR actions implemented in the industrial processes involved in this study and the results obtained are described in detail. The final conclusions are drawn in Section 4.

3.3. Proposed methodology

The methodology was developed to demonstrate the actual potential flexibility of industrial customers that will enable their involvement in a reserve electricity market to provide ancillary services in a profitable way for both the customers themselves and the power system. Figure 3.1 presents an overview of the proposed methodology:

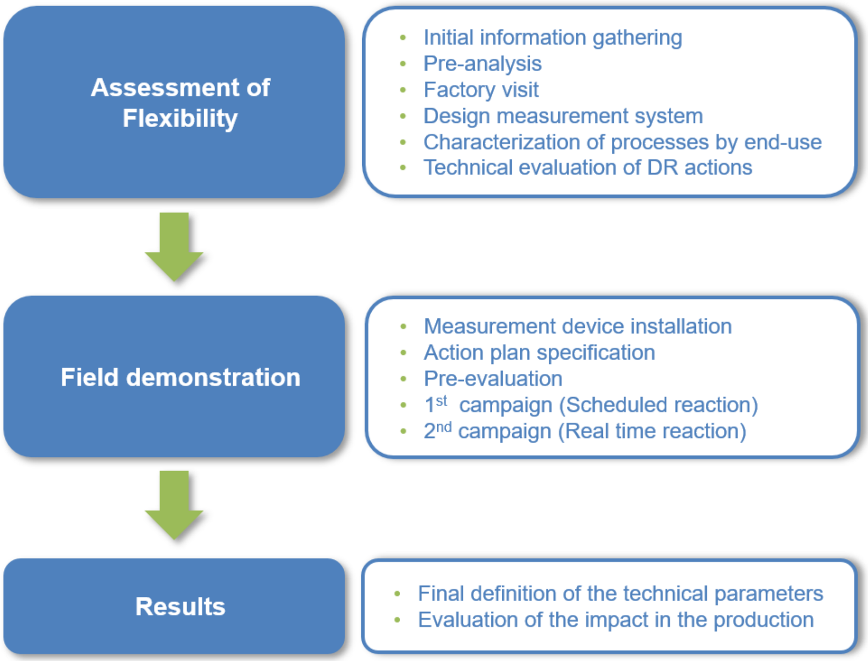

Figure 3.1. Proposed methodology.

According to the Figure 3.1, three main stages are proposed. The first stage focuses on the theoretical assessment of the flexible industrial processes. Firstly, the most relevant information related to the industrial facilities and their production processes are requested to the industrial customer. Secondly, this general information is analysed to prepare the visit to the plant. At this point, some potential flexible processes or DR actions should be identified. Then, the potential impacts on the production process and the internal interdependencies among them are analysed in collaboration with the engineers and technical staff of the plant. The aim of this analysis is to guarantee that the identified DR actions can be carried out and quantify the potential cost associated with the implementation like the extra labour cost due to implementation of the flexible actions. Apart from the technical evaluation, an economic assessment, which is completely described in [31], is also performed at the same time.

In addition, the **measurement system** has to be designed taking into account the further tasks of flexibility validation in the field demonstration. Moreover, the total electricity consumption of the factory is disaggregated by flexible processes in which some DR actions can be implemented. According to this, a total number of 31 power meters was installed in the three factories and they were integrated into the control and monitoring system provided by the "**Polytechnic University of Valencia"** (UPV) [32]. Apart from this, one of the most relevant tasks at this stage is the technical evaluation of the DR actions in which all the technical parameters described in Section 2 are properly assessed. The second stage is the field demonstration where the DR actions in each industrial customer are tested empirically. A detailed **action plan** has to be designed for the implementation of the field tests, and customers have to receive it and accept it before starting the pre-evaluation. The field demonstration was divided into three parts: pre-evaluation, first and second campaign.

In the **pre-evaluation,** customers have to carry out the first reduction in their production processes in a controlled way. The main objective is to demonstrate their ability for reducing demand power without considering the duration time of the implementation. Once the pre-evaluation is finished, a more intensive campaign of implementation of scheduled DR actions started in the three factories (**first campaign**) and it lasted around three months. In this period, each customer had to perform at least four valid implementations for each DR action. In the first campaign, the customers were not allowed to change any scheduled event without a notification prior to the event day. They received some feedback after each implementation with the technical results and some recommendations to improve the performance.

As mentioned above, the last part of the field demonstration was the **second campaign** that is defined as a set of unscheduled implementations of the involved DR actions. The main goal of the second campaign is to check the ability of customers to react to prices or any signal sent by a DR requester (TSO/DSO/DR aggregator) in real time taking into account the different notification time in advance defined for each flexible process. Therefore, each involved customer received a notification in advance (telephone call or email) for each DR event and they had to react according to the technical parameters included in the notification. In this stage, the date and time of each DR event was unknown for the customers until they received the notification.

Finally, the **evaluation and assessment** of the implementations of each DR action is performed taking into account the results of the field demonstration. Then, it is obtained the final definition of the technical parameters of each DR action. The different parts of a DR event are shown in Figure 3.2:

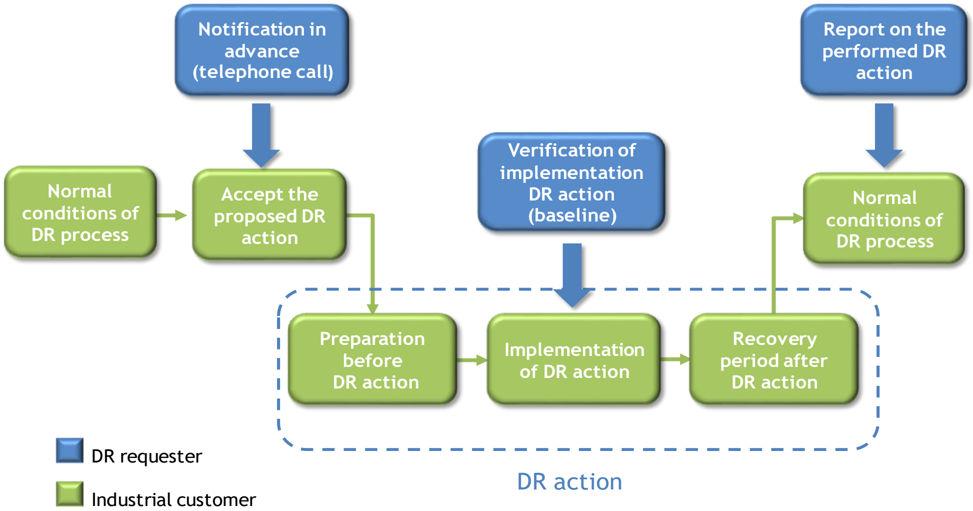

Figure 3.2. Process of DR events implemented during the second campaign.

3.3.1. Baseline calculation for the verification process

When a DR event is carried out, the load curve of the involved process changes and it is not possible to know what would happen in the absence of the DR event. Therefore, the only way to assess the reduced power is to compare the actual load curve with a baseline for that period. There are several methodologies to calculate a baseline for demand response purposes [33-36]. Considering the type of electric load linked to the flexible process, it was chosen a baseline calculation with a multiplicative adjustment, as it is recommended in [35], with a 10-in-10 non-event day selection and other additional exclusion rules, which are explained below.

The values of the selected baseline for the evaluation of a DR event are calculated as follows:

$$\boldsymbol{B_i = IB_i \times SA_i} \qquad (1)$$

Where:

$\boldsymbol{B_i}$ is the value of power related to the baseline at the time $\boldsymbol{i}$, in kW.

$\boldsymbol{IB_i}$ is the value of the initial baseline at the time $\boldsymbol{i}$, in kW.

$\boldsymbol{SA_i}$ is the adjustment factor at the time $\boldsymbol{i}$.

On the one hand, a period prior to the event day (***D***) has to be defined depending on the variability of the daily load profiles of each flexible process because of the selection of a set of days with similar electrical consumption. The most common value among the studied DR processes was 30 days, but it was necessary to increase this value up to 90 days for some of them. In this vein, a set of tests were carried out to adjust it for each DR process in order to minimize the difference between the calculated baseline and the load curve using non-event days.

On the other hand, some of the selected days were excluded to calculate $\boldsymbol{IB_i}$ according to the following **exclusion rules**:

- **Event days**. An event day is any day on which a DR action has been implemented, and therefore, they cannot be considered as a normal day to estimate the initial baseline.

- **Holidays/weekends**. Electric energy consumption on holidays (or weekends) is usually different to electric energy consumption on working days. For example, if a DR event is performed on a working day, the holidays and weekends included in the selected period have to be excluded.

- **Type of day**. The days that have a different electrical consumption pattern comparing with the event day cannot be considered in the calculation of the initial baseline.

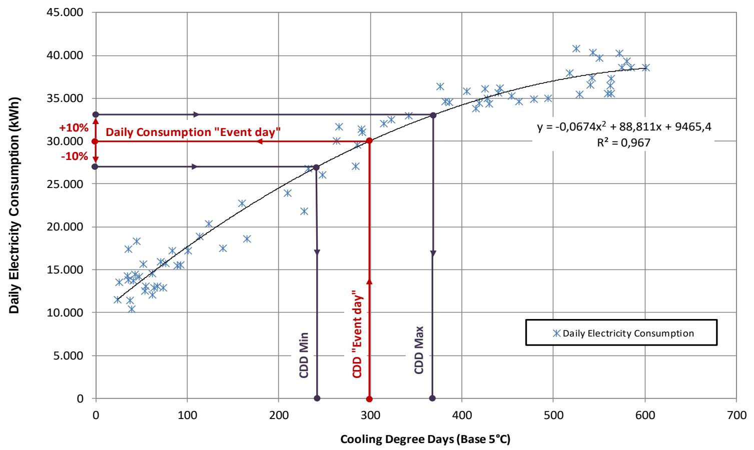

Figure 3.3. Regression analysis between CDD and daily electricity consumption on weekdays.

- **External temperature**. In some cases, the external temperature can directly affect the electrical consumption of an industrial process (i.e. cooling production and ventilation). The relation between the two parameters is considered using the regression function of the cooling or heating degree days (CDD or HDD) and the daily energy consumption. The minimum and maximum values of CDD or HDD are established depending on the daily energy consumption of a DR event day. Figure 3.3 shows an example of the "Cooling production and ventilation process" in the logistics centre of Campofrio (Spain), where a range of +/-10% of the daily energy consumption of the event day is defined to determine the upper and lower CDD limits that are used to exclude some days from the selection.

- **Lower RMSPE** (Root Mean Square Percentage Error) of the previous hours of the DR event. This condition, which has never been used as an exclusion rule before according to [35], is only used with DR processes that do not present a clear electricity consumption pattern. RMSPE (Expression

2) represents how much the baseline deviates from the reference load curve and it is calculated as follows:

$$\boldsymbol{RMSPE} = \sqrt{\frac{\sum_{i=1}^{n} \frac{(y_i - x_i)^2}{x_i^2}}{n}} \qquad (2)$$

Where:

i: time interval counter ***i = 1, …, n***.

n: number of time intervals (of 15 minutes) during which the baseline was calculated

n = 1, …, 96.

$\boldsymbol{x_i}$: value of the reference load curve.

$\boldsymbol{y_i}$: value of the evaluated load curve

According to this criterion, the days with RMSPE value higher than a fixed limit have to be excluded. After the selection process, $\boldsymbol{IB_i}$ is calculated as an average of the ten closest selected days prior to the event day (***D***). It is important to highlight that the baseline is calculated in the period between the beginning of the preparation and the end of the recovery period because this is the period when the load curve changes due to the implementation of a DR event.

According to [21, 35], $\boldsymbol{IB_i}$ is proposed to be adjusted with an adjustment factor ($\boldsymbol{SA_i}$) that is limited to a typical value of DR programs +/- 20%. The aim of this adjustment factor is to adapt the calculated baseline to the specific conditions on the event day. This kind of adjustment is known as "symmetric multiplicative adjustment" and it can be calculated using Expression 3:

$$\boldsymbol{SA_i} = \frac{\boldsymbol{CH_A}}{\boldsymbol{CH_B}} \qquad (3)$$

where CH_A is the energy consumption (kWh) in the three hours prior to the event and CH_B is the total energy (kWh) in these three hours of the initial baseline that is calculated as the average of the non-event days. Finally, the final baseline is obtained using Expression 1, and the DR event is evaluated comparing the load curve on the event day with the calculated baseline.

3.3.2. Definition of technical parameters of DR actions

According to the presented methodology, all the DR actions have to be defined using the same parameters [31] that are represented in Figure 3.4:

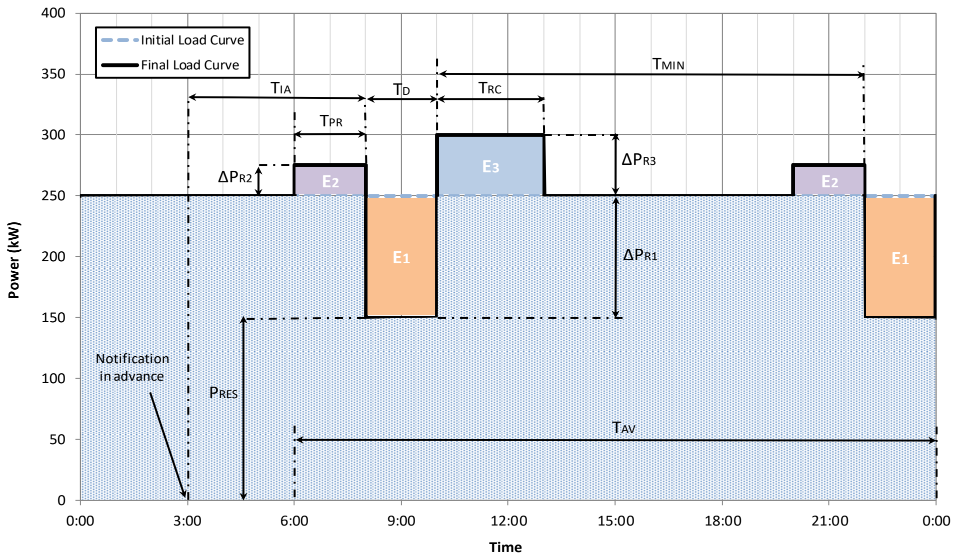

Figure 3.4. Technical parameters of DR actions.

A brief definition of these technical parameters is included below:

- ***ΔP$_{R1}$***: Maximum reduced power over the expected value that a flexible process is able to certainly decrease during the implementation of a DR action. This value is calculated as the minimum reduced power that is obtained during the field demonstration (kW).

- $\boldsymbol{P_{RES}}$: The residual power is the amount of demanded power that can be measured during the reduction. This parameter is relevant because some DR options compare this value with a specific limit as a verification method that is known as “firm power level” (kW).
- $\boldsymbol{\Delta P_{R2}}$: Increased power over the expected value required to accumulate additional energy (thermal, potential, kinetic, etc.), prior to the load shedding, in order to guarantee the proper implementation without any impact on the production process (kW).
- $\boldsymbol{\Delta P_{R3}}$: Increased power over the expected value required to recover the normal working conditions of the manufacture process in which the reduction was implemented in order to avoid any impact on the final product (kW).
- $\boldsymbol{T_{av}}$: Operation time. It is defined as the time windows in which a DR action is available to be implemented.
- $\boldsymbol{T_{D}}$: Duration of the action. This is the maximum time in which a load shedding in an industrial process can be maintained in order to guarantee that there is not any impact on the final products (Hours).
- $\boldsymbol{T_{PR}}$: Duration of the preparation period. If it is necessary, this is the time before a load shedding in which the flexible process is prepared to the reduction or interruption (Hours).
- $\boldsymbol{T_{RC}}$: Duration of the recovery period. If it is necessary, this is the time after a load shedding in which the flexible process recovers the normal working conditions (Hours).

- ***T_{IA}***: Notification time in advance. This is the minimum time in which a DR action can be implemented to guarantee that the reduced power is delivered to the power system on a specific time. This period starts with the receipt of the system operator's notification (Hours).
- ***T_{MIN}***: Minimum time between DR events. This parameter is defined as the time between the end of a load shedding and the beginning of the next one; Therefore, ***T_{MIN}*** must be equal or higher than ***$T_{PR} + T_{RC}$***. ***T_{MIN}*** represents the minimum time needed to guarantee that there will not be any impact on the final product if two DR actions are implemented consecutively (Hours).

Regarding the energy balance of a DR event, it is calculated as the difference between the reduced energy (***E_1***) during the load shedding and the additional energy consumption before (***E_2***) and after (***E_3***) the power reduction, in the preparation and the recovery periods respectively.

3.4. Field demonstration and results

As mentioned in Section 2, after the pre-evaluation, a more intensive campaign for the implementation of DR actions started in the three factories. The first campaign lasted three months for each factory and several DR events were scheduled to be implemented in the flexible processes studied in the project.

During the first campaign, it was defined that the customers had to carry out at least four valid reductions for each DR action. In order to avoid a high impact on the production schedule of the factories, each industrial customer who took part in this study proposed before starting the first campaign a set of suitable days on which the DR actions associated with their different flexible processes could be tested. Although they were allowed to plan the dates and times for the implementation of the DR actions, they were banned to change anything related to this once the first campaign started, at least without sending a formal notification in advance. Therefore, any load shedding or shifting performed out of the initial plan was considered invalid and it had to be repeated.

After the first campaign, the initial definition of each DR action was updated according to the results obtained and taking into account customers' experiences during the first campaign. An example of the technical parameters of the four valid reductions performed in the "Stock Preparation" process in the paper factory during the first campaign is detailed in Table 3.1.

Table 3.1. Technical parameters of the process "Stock Preparation" during the first campaign.

Technical Parameter	***28/04/14***	***08/05/14***	***15/05/14***	***22/05/14***	***Final***
Start time of the reduction	*10:00*	*10:00*	*10:00*	*10:00*	*-*
Duration of the reduction (min)	*30*	*30*	*30*	*30*	*30*
Maximum reduced power (kW)	*1,059*	*992*	*1,116*	*1,198*	*1,198*
Minimum reduced power (kW)	*776*	*775*	*710*	*1,189*	*710*
Average reduced power (kW)	*917*	*883*	*913*	*1,193*	*977*
Total reduced energy (kWh)	*459*	*442*	*456*	*597*	*488*
Maximum residual power (kW)	*1,093*	*1,089*	*1,381*	*914*	*-*
Minimum residual power (kW)	*882*	*884*	*974*	*900*	*-*
Average residual power (kW)	*988*	*986*	*872*	*907*	*1,015*

The technical parameters in the process "Stock Preparation" were calculated using the four reductions that were carried out in the first campaign. Consequently, the average of the interruptible power in "Stock

Preparation" was 977 kW and the average of the reduced energy was 488 kWh. The average residual power of all the reductions was around 1,015 kW.

As an actual example, Figure 3.5 compares the daily load curve and the baseline implemented in "Stock Preparation" process on an event day. Moreover, this figure presents the most relevant technical parameters related to this DR event such as the reduced energy (***E_1***), the energy required associated with the preparation (***E_2***) and the energy related to the recovery period (***E_3***), among others.

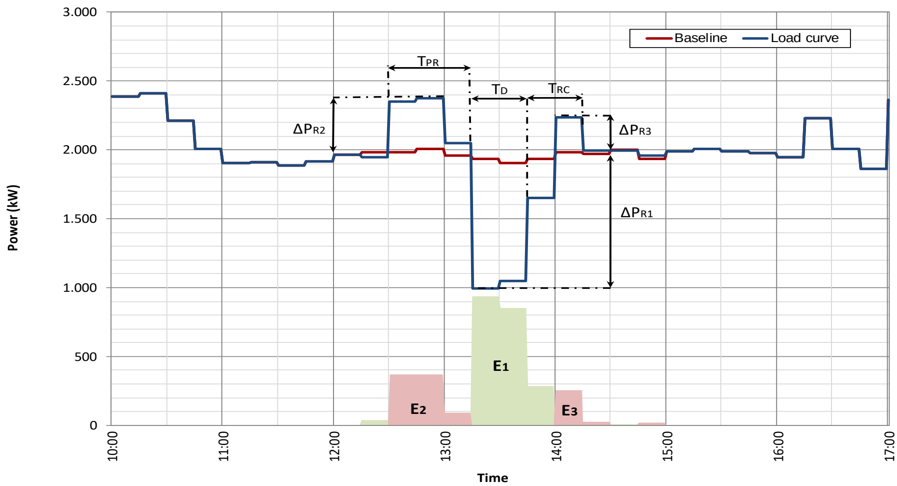

Figure 3.5. Load curve and baseline of "Stock Preparation" process on a DR event day.

Figure 3.6 shows the details of the load curve and the evolution of the tank level during an event day implemented in "Stock Preparation" process. As it can be observed, the critical parameter of this process (tank level) was within the valid range (30-90%) during the DR event, but the high rates of emptying presented after the disconnection of the pulpers highlights the relevance of monitoring critical parameters in order to avoid any problems during the implementation of DR actions in industrial process.

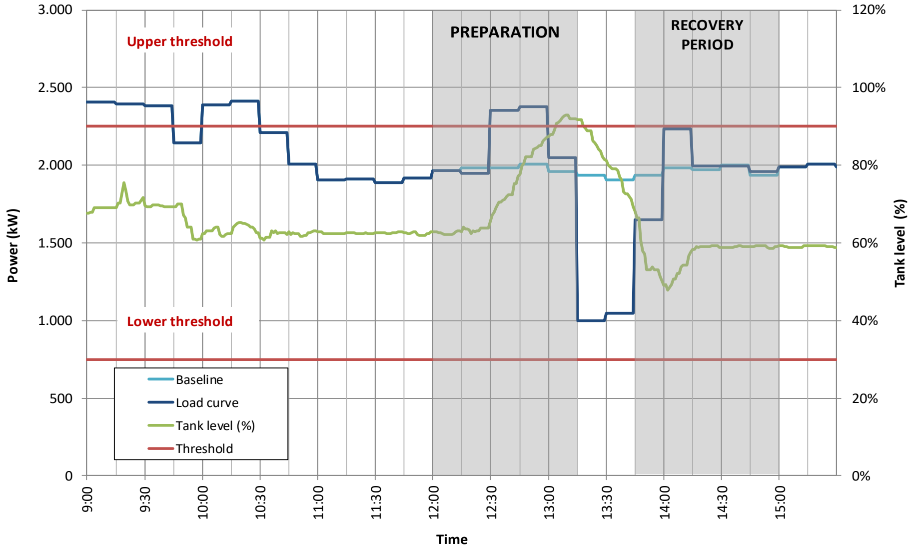

Figure 3.6. Load curve and tank level of "Stock Preparation" process on a DR event day.

According to the described methodology, the second campaign consists of a set of DR events designed to verify the ability of customers to react to prices or any signal sent by a DR requester in order to change their load. In this part, some real situations were simulated in which a DR requester called a DR event to reduce their electricity consumption. The involved customers received a notification in advance (telephone call or email) for each DR event according to the technical definition that was specified in the assessment of flexibility (Table 3.6), and then they had to implement the load shedding or load shifting according to the technical parameters defined in the notification. As mentioned above, the date and time of each DR event was unknown to the customers before getting the associated notification, but they were notified following the technical parameters of the different DR actions. This stage lasted two months, and the three customers had to carry out at least two valid reactions for each DR action during this period.

The results of the DR events performed in the "Stock Preparation" process during the second campaign are presented in Table 3.2. Additionally, the first column named "Expected" includes the initial theoretical values that were updated taking into account the results of the first campaign.

Table 3.2. Technical parameters of the process "Stock Preparation" during the second campaign.

Technical Parameters	***Expected***	***26/06/2014***	***18/07/2014***
Notification time in advance (h)	*1*	*1*	*1*
Duration of the reduction (min)	*30*	*30*	*30*
Maximum reduced power (kW)	*1,198*	*835*	*1,206*
Minimum reduced power (kW)	*710*	*762*	*268*
Average reduced power (kW)	*977*	*798*	*737*
Reduced energy (kWh)	*488.5*	*399*	*368*
Average residual power (kW)	*1,015*	*986*	*1,584*

As it can be observed in Table 3.2, despite the average reduced power was similar in both DR events, the minimum reduced power on 18th July 2014 (268 kW) was a great deal lower than the expected value due to an incorrect execution in which the loads were switched on before the expected ending time of the reduction. As a result, this DR event was not considered in the final evaluation of the second campaign. Furthermore, it can be claimed that it is highly recommended the full automation to implement DR actions in order to obtain the expected reduced power along the whole DR event.

In this regard, it can be concluded that the final average reduced power in the second campaign was 798 kW, which is the result of the only DR event implemented during the second campaign. Due to the fact that this value is lower than the value obtained during the first campaign (977 kW), the results of the second campaign were considered more reliable to describe the final definition of the technical parameters, as it can be observed in Table 3.3.

Table 3.3. Final definition of the technical parameters of the process "Stock Preparation".

Technical Parameter	***First campaign***	***Second campaign***	***Final definition***
Duration of the reduction (h)	*30*	*30*	*30*
Maximum reduced power (kW)	*1,198*	*835*	*835*
Minimum reduced power (kW)	*710*	*762*	*762*
Average reduced power (kW)	*977*	*798*	*798*
Reduced energy (kWh)	*488*	*399*	*399*
Average residual power (kW)	*1,015*	*986*	*986*

In order to evaluate the accuracy of the implementation of the DR actions performed in the second campaign, the real-time data of the electricity consumption of each flexible process just before and after the reduction was analysed. A detailed analysis of the disconnection and reconnection process (ramp down and ramp up respectively) of the involved electric loads was performed to characterize the execution of the presented DR actions. For example, the DR event carried out between 9:00 and 11:00 on 23rd July

2014 in “Cooling production and ventilation” process of the logistics centre (second campaign) is represented in Figure 3.7 with a sample rate of 5 seconds. As can be observed, all the involved electrical loads were completely turned off in less than three minutes.

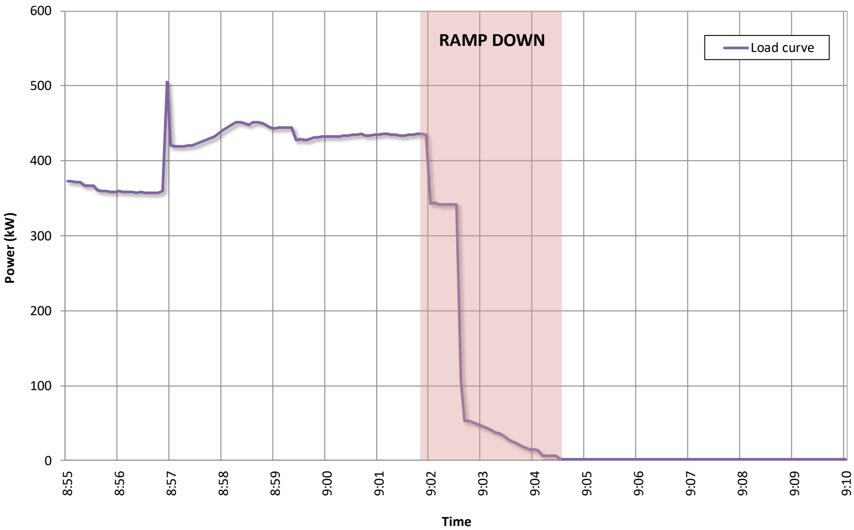

Figure 3.7. Ramp down of “Cooling Production and Ventilation” process in a DR event.

The implementation of the DR action was semi-automatic, and the reduction started around 2 minutes later comparing with the proposed start time. In order to improve the local control system to implement a full-automatic response, it is necessary, not only the automation of the implementation of the DR actions in the facilities, but also the automation of the communication between the DR requester and the DR provider using specific communication protocols like OpenADR. Around 90% of the expected total reducible power was reached in around 1 minute (Table 3.4):

Table 3.4. Analysis of the ramp down of the process “Cooling Production & Ventilation” in a DR event.

Time stamp	Ramp time	Ramp time (%)	Reducible power (%)	Residual power (kW)
9:01:55	0:00:00	0%	0%	435
9:03:12	0:01:17	50%	91%	40
9:04:30	0:02:35	100%	100%	2

Regarding the advance notification time, it is divided into five stages as explained below (Figure 3.8):

- **Customer feedback**: it is the period between the receipt of a notification and the response to the DR requester, and it includes the customer decision-making.
- **Implementation of preparation**: it is the period required to carry out the preparation process for the implementation of a DR event manually or automatically.
- **Preparation period**: it is the necessary period to prepare the process for the reduction, and it is generally related to an increment of the demanded power before the load shedding.
- **Implementation of the disconnection or reduction**: it is the time required to carry out the complete disconnection or power reduction of the electric loads associated with a flexible process manually or automatically and this time generally depends on the type of load.
- **Ramp down**: it is defined as the period between the disconnection of the electrical loads and the time at which the demanded power reaches the expected interruptible or reducible power.

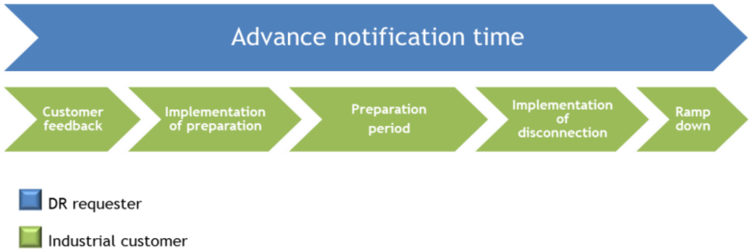

Figure 3.8. Structure of the advance notification time.

Table 3.5 summarizes the defined notification time in advance and the calculated ramp down for each DR action during the second campaign:

Table 3.5. The results of the analysis of the advance notification time for each DR action.

Factory	***DR Action***	***Advance notification time***	***Ramp down duration***
Paper factory (Germany)	*Stock preparation*	*1 h (1)*	*2 min*
	Short maintenance	*24 h*	*13 min*
	Winder	*15 min*	*0 sec*
	Storage	*10 min*	*0 sec*
Meat factory (Spain)	*Drying*	*15 min*	*1 min*
	Maturing	*15 min*	*2.5 min*
	Freezing store 81	*15 min*	*3 min*
	Slicing	*15 min*	*30 sec*
Logistics centre (Spain)	*Cooling production and ventilation*	*30 min*	*2.5 min*
	Freezing tunnel	*30 min*	*30 sec*
	Recharge of batteries	*30 min*	*5 sec*

(1) The preparation period lasted around 1 hour

In Table 3.5, the values of the column named “Advance notification time” were estimated by the industrial customer at the beginning of the project and the values of the ramp down duration were obtained by observing the load curve registered every second during each DR event, as it was presented in Figure 3.7. In this vein, it was found out that the ramp down duration was not properly considered by the industrial customers in the implementation of the DR events that took place in the second campaign, as it was seen in the mentioned load curves. On the other hand, if the implementation process of these DR actions, apart from the “Stock preparation” process that needs a preparation period, were adequately performed by an automatic control system, the advance notification time would be lower than one minute because the customer feedback would not be removed and the time required to the disconnection would be considerably reduced. After the field demonstration, the expected parameters (Table 3.6) were updated with the results of the field tests as shown in Table 3.7.

Table 3.6. Theoretical parameters of the studied DR actions.

DR action	**ΔPR_1**	**ΔPR_2**	**ΔPR_3**	**T_D**	**T_{AV}**	**T_{PR}**	**T_{RC}**
Unit	kW	kW	kW	hour	hour	hour	hour
Paper factory							
1-Stock preparation	665	665	0	0.5	24	0.5	0
2-Short maintenance	7,800	0	7,800	1	7-13 Tu	0	1
3-Winder	30	0	30	0.5	24	0	0.5
4-Storage	12	0	12	0.5	22-6 Sa-Su	0	0.5
Meat factory							
1-Drying	261/234	0	55/49	2/2	24	0	1/0.75
2-Maturing	93/89	0	93/89	2/3	24	0	2/3
3-Freezing Store 81	44/26(1)	0	44/26(1)	2/3	24	0	2/3(1)
4-Slicing	65/35(1)	0	65/35(1)	1/2(1)	Mo6-Sa6	0	1/2

DR action	ΔPR1	ΔPR2	ΔPR3	TD	TAV	TPR	TRC
Logistic centre							
1-Cooling/ventilation	337/183(1)	0	337/183(1)	2	24	0	2
2-Freezing tunnel	89	0	89	2	-	0	2
3-Recharge batteries	23	0	23	2	Mo0-Sa0	0	2

(1) Summer / Winter

(2) If it is possible to postpone the recovery period. Y (yes) and N (no)

(3) Number of the DR actions that cannot be implemented at the same time.

Table 3.7. Final definition of technical parameters of the studied DR actions.

DR action	ΔPR1	ΔPR2	ΔPR3	TD	TAV	TPR	TRC	TIA	TMIN	P	L
Unit	kW	kW	kW	hour	hour	hour	hour	hour	hour	(2)	(3)
Paper factory											
1-Stock preparation	798	200	200	0.5	24	1	1	1	2	N	2
2-Short maintenance	6,659	0	6,659	1	7-13 Tu	0	1	24	164	N	1-3
3-Winder	36	0	4	0.5	24	0	4.5	0.25	4.5	Y	2
4-Storage	5	0	2,5	0.5	22-6 Sa-Su	0	1	0.2	1	Y	-
Meat factory											
1-Drying	283	0	0	2	24	0	0	0.25	22	N	-
2-Maturing	102	0	15	3	24	0	21	0.25	21	N	-
3-Freezing Store 81	70/45(1)	0	30/27(1)	3	24	0	7/5(1)	0.25	21	N	-
4-Slicing	82/36(1)	0	82/72(1)	1/2(1)	Mo6-Sa6	0	1	0.25	22	N	-
Logistic centre											
1-Cooling/ventilation	230/95(1)	0	368/380(1)	2	24	0	1.25/0.5(1)	0.5	22	N	-
2-Freezing tunnel	67	0	67	2	-	0	2	0.5	22	Y	-
3-Recharge of batteries	22	0	22	2	Mo0-Sa0	0	2	0.5	22	Y	-

(1) Summer / Winter

(2) If it is possible to postpone the recovery period. Y (yes) and N (no)

(3) Number of the DR actions that cannot be implemented at the same time.

After comparing Table 3.6 and Table 3.7, it can be observed that there are relevant differences between the theoretical values and the results in the field demonstration, especially the minimum amount of electric power reduced, as well as the parameters associated with the preparation and recovery periods. In most cases, the average power during the recovery period was lower than the theoretical value since the recovery period was longer than the expected value. The duration of the action or the operation time were equal to the theoretical values that were proposed by the facilities manager during the visit to the plant.

According to the customers' feedback, most of the DR actions performed during the field demonstration did not produce any impact on the production, so that it can be assumed that the DR events carried out during the field demonstration do not affect either the quality of the final product or the productivity of the plant. However, it was found out some restrictions in some of these industrial processes:

- **Refrigerated working rooms** (i.e. "Slicing" process in the meat factory): the temperature in the working rooms on the days with extreme weather conditions increases quickly until the safety limit during the implementation of a DR action, consequently, on these days the duration of DR actions have to be shorter than in normal conditions.
- **"Sewage treatment" processes** (paper factory): the critical parameters of this process have to be monitored in real-time in order to be able to perform a secure and accurate DR action without any impact on the production process according to the customer experience.

- **"Drying" processes** (meat factory): the relative humidity inside the drying rooms reached the upper limit during the implementation of some DR events. If some DR events are implemented successively, it could cause a negative effect in the final product according to the customer's quality department. For this reason, the minimum time between two DR events of this industrial process was increased during the second part of the field demonstration.

On the other hand, most of the analysed DR actions need some additional energy after their implementation in order to restore the normal working conditions in the process. In most cases, industrial processes, which did not retrieve the reduced energy after the implementation of a DR action (for example, "the speed reduction in the paper machine drives" or "Drying" process), often produce an impact on the production. This impact should be quantified as an additional cost of using this flexibility. In conclusion, the total reducible power validated in the field demonstration for each factory is presented below:

- In the paper factory, the total reducible power on working days was 839 kW.
- In the meat factory, the total reducible power on working days was 537 kW and 466 kW in summer and winter respectively.
- In the logistics centre, the total reducible power on working days was 319 kW and 184 kW in summer and winter respectively.

Lastly, according to these figures and the mentioned high replicability in Europe, it can be claimed that the segments associated with the three factories present a high DR potential, which should be considered to increase the integration of renewable energy in future scenarios.

3.5. Conclusions

According to the presented results, it can be concluded that the implementation of DR actions has to be completely automated (communication, monitoring and control) in order to avoid human errors, as well as to reduce the required advance notification time. The automation of the implementation of DR actions is essential to comply with the time restrictions associated with the reserve electricity markets (secondary reserve, tertiary reserve or balancing services). However, if the disconnection and reconnection processes of the electric loads associated with a DR action are not properly studied and included in the required advance notification time, especially the ramps up and down, the automatic response does not guarantee that either the power reductions or reconnections will take place on the precise time according to the system operator's requirement. To this end, the methodology includes the study in detail of the ramps up and down of each test performed in the field demonstration.

On the other hand, due to the nature of industrial customers, it is important to highlight that there are always inevitable and unpredictable situations that will produce invalid reactions such as unplanned changes in the production schedule and maintenance tasks (none of them related to the implementation of DR actions).

One of the most relevant aspects of the proposed methodology is the way of controlling the risk of the potential impact on the production processes or final products. To this end, the methodology considers three key points: the monitoring of critical parameters to find the main restrictions (e.g. temperature of refrigerated working rooms), the progressive increment of the duration of tests (e.g. sewage treatment plant) and the involvement of technical staff during the whole evaluation process.

Another good point of the proposed prequalification process is the replicable assessment and characterization of the technical parameters, especially the preparation and the recovery periods. These aspects are not generally considered in this kind of evaluations, but they could be as relevant as the reduced power for the system operator in a scenario with a high share of DR resources. If the aggregation of DR resources of several customers can help the system operator balance out the generation and demand, the aggregation of unexpected increase of electricity demand due to the simultaneity of preparation and recovery periods of several processes could cause the opposite effect jeopardising the balance of the power system.

In conclusion, this paper provides a novel methodology to test and validate the flexibility potential of industrial customers prior to provide ancillary services. The proposed methodology includes a specific procedure that can be applied to any type of industrial customer as it is based on an analysis performed by processes and considers the main characteristics to be analysed in this kind of facilities. Finally, it can be concluded that this methodology could serve as a basis for the development of a new prequalification procedure for industrial DR resources, although it will be probably necessary additional efforts in this line to definitively standardise it due to the huge diversity of different types of processes that are present in the industrial segment.

3.6. Acknowledgements

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3.7. References

[1] Karl Critz D., Busche S., Connors S., "Power systems balancing with high penetration renewables: The potential of demand response in Hawaii", Energy Conversion and Management 2013, 76, pp. 609–619.

[2] Aghajani G.R., Shayanfar H.A., Shayeghi H., "Presenting a multi-objective generation scheduling model for pricing demand response rate in micro-grid energy management", Energy Conversion and Management 2015, 106, pp. 308–321.

[3] Behboodi S, Chassin D.P., Crawford C., Djilali N., "Renewable resources portfolio optimization in the presence of demand response", Applied Energy 2016, 162, pp. 139–148.

[4] Murthy Balijepalli V.S.K., Pradhan V., Khaparde S.A., "Review of Demand Response under Smart Grid Paradigm", IEEE PES International Conference on Innovative Smart Grid Technologies-India 2011, ISGT India 6145388, pp. 236-243.

[5] Torriti J., Hassan M.G., Leach M., "Demand response experience in Europe: Policies, programmes and implementation", Energy 2010, 35, pp.1575–1583.

[6] The Federal Energy Regulatory Commission Staff. "National Action Plan on Demand Response, 2010". Retrieved on November 15, 2017. Available online at: https://www.energy.gov/sites/prod/files/oeprod/DocumentsandMedia/FERC_NAPDR_-_final.pdf.

[7] Dong J., Xue G., Li R., "Demand response in China: Regulations, pilot projects and recommendations – A review", Renewable and Sustainable Energy 2016, Reviews 59, pp. 13–27.

[8] Alcázar-Ortega M., "Evaluation and Assessment of New Demand Response Products Based on the Use of Flexibility in Industrial Processes: Application to the Food Industry". Polytechnic University of Valencia and the University of South Florida, Tampa, Florida, 2011, Ph.D. dissertation. Retrieved on November 14, 2017. Available online at: https://riunet.upv.es/handle/10251/10078.

[9] Mingtao YAO (&), Zhaoguang HU, Ning ZHANG, Wei DUAN, Jian ZHANG, "Low-carbon benefits analysis of energy-intensive industrial demand response resources for ancillary services", J. Mod. Power Syst. Clean Energy 2015, 3(1), pp.131–138.

[10] D. Olsen, "Opportunities for Energy Efficiency and Demand Response in the California Cement Industry", Lawrence Berkeley National Laboratory Report 2012, pp.1–25.

[11] Dionysios P. Xenos, Izzati Mohd Noor, Mitra Matloubi, Matteo Cicciotti, Trond Hauge, Nina F. Thornhill, "Demand-side management and optimal operation of industrial electricity consumers: An example of an energy-intensive chemical plant", Applied Energy 2016, 182, pp. 418–433.

[12] Moritz Paulus, Frieder Borggrefe, "The potential of demand-side management in energy-intensive industries for electricity markets in Germany", Applied Energy 2011, 88, pp. 432–441.

[13] European Commission. "Commission Regulation (EU) 2016/631 establishing a network code on requirements for grid connection of generators, 2016". Retrieved on December 12, 2017. Available online at: http://eur-lex.europa.eu/legalcontent/EN/TXT/PDF/?uri=CELEX:32016R0631&from=EN.

[14] North American Electric Reliability Corporation. "Standard PRC-024-2-Generator Frequency and Voltage Protective Relay Settings", 2015. Retrieved on December 5, 2017. Available online at: http://www.nerc.com/pa/Stand/Reliability%20Standards/PRC-024-2.pdf.

[15] Zhang J., Wang T., Li B., "Research on Technical Standardization for Electric Demand Response", Proceedings of the Chinese Society of Electrical Engineering 2014, 34 (22), pp. 3623-3629.

[16] International Organization for Standardization. "ISO/IEC 15067-3:2012, Information Technology-Home Electronic System (HES) application model-Part 3: Model of a demand-response energy management system for HES", 2012. Retrieved on December 1, 2017. Available online at: https://www.iso.org/standard/55596.html.

[17] Piette M.A., Ghatikar G., Kliccote S., Koch E., Hennage E., Palensky P., et al. "Open automated demand response communications specification (Version 1.0)". Berkeley, California: Public Interest Energy Research (PIER), California Energy Commission; 2009.

[18] Australian/New Zealand Standard. "SAS/NZS 4755.3.1: 2014, Demand response capabilities and supporting technologies for electrical products-Interaction of demand response enabling devices and electrical products-Operational instructions and connections for air conditioners", 2014. Retrieved on November 30, 2017. Available online at: https://shop.standards.govt.nz/catalog/4755.3.1:2014(AS%7CNZS)/scope?.

[19] Matsumoto S., "Echonet: A home network standard", IEEE Pervasive Computing 2010, 9 (3), 5510899, pp. 88-92.

[20] California ISO, "Demand Response User Guide v4.3", May 2017. Retrieved on December 20, 2017. Available online at: http://www.caiso.com/Documents/DemandResponseUserGuide.pdf.

[21] NYISO, "Manual 7: Emergency Demand Response Program Manual", June 2016. Retrieved on November 15, 2017. Available online at: http://www.nyiso.com/public/webdocs/documents/manuals/operations/edrp_mnl.pdf.

[22] Bondy D. E. M., Gehrke O., Thavlov A., Heussen K., Kosek A. M. and Bindner H. W., "Procedure for validation of aggregators providing demand response", Power Systems Computation Conference (PSCC) 2016, Genoa, 7540997, pp. 1-7.

[23] "Demand Response in Industrial Production (DRIP)". Research Project supported by Environment LIFE+ Programme of European Commission. Retrieved on October 15, 2017. Available online at: http://www.drip-project.eu/.

[24] Alcázar-Ortega M., Calpe C., Theisen T., Rodríguez-García J., "Certification prerequisites for activities related to the trading of demand response resources", Energy 2015, 93, pp. 705–715.

[25] Paulus M., Borggrefe F., "The potential of demand-side management in energy-intensive industries for electricity markets in Germany", Applied Energy 2011, 88, pp. 432–441.

[26] Maryam H. Shoreh, Pierluigi Siano, Miadreza Shafie-khah, Vincenzo Loia, João P.S. Catalão, "A survey of industrial applications of Demand Response", Electric Power Systems Research 2016, 141, pp. 31–49.

[27] A.T. Mckane, M.A. Piette, D. Faulkner, G. Ghatikar, A. Radspieler, B. Adesola, S. Murtishaw, S. Kiliccote, "Opportunities, barriers and actions for

industrial demand response in California", Lawrence Berkeley Natl. Lab. R 2009, pp. 1–48.

[28] Alcázar-Ortega M., Calpe C., Theisen T., Carbonell-Carretero J.F., "Methodology for the identification, evaluation and prioritization of Market handicaps which prevent the implementation of Demand Response: Application to European electricity markets", Energy Policy 2015, 86, pp. 529–543.

[29] European Commission. Energy balance sheets 2015 data – Eurostat, 2017. Retrieved on December 7, 2017. Available online at: http://ec.europa.eu/eurostat/documents/3217494/8113778/KS-EN-17-001-EN-N.pdf/99cc20f1-cb11-4886-80f9-43ce0ab7823c.

[30] European Commission. "Manufacturing statistics - NACE Rev. 2 – Eurostat, 2013". Retrieved on November 29, 2017. Available online at: http://ec.europa.eu/eurostat/statistics-explained/index.php/Manufacturing_statistics_-_NACE_Rev._2.

[31] Rodríguez-García J., Álvarez-Bel C., Carbonell-Carretero J.F., Alcázar-Ortega M., Peñalvo-López E., "A novel tool for the evaluation and assessment of demand response activities in the industrial sector", Energy 2016, 113, pp. 1136-1146.

[32] Escrivá G., Alcázar M., Álvarez C., "Integral management system for the energy efficiency improvement in commercial facilities: application to the polytechnic university of Valencia", International Conference on Renewable Energies and Power Quality (ICREPQ'09), Valencia, Spain.

[33] Goldberg M.L., Kennedy-Agnew G. DNV KEMA. "Energy and Sustainability - Measurement and Verification for Demand Response - National Forum of the National Action Plan on Demand Response, 2013".

Retrieved on November 28, 2017. Available online at: https://eetd.lbl.gov/sites/all/files/publications/napdr-measurement-and-verification.pdf.

[34] DNV KEMA. "Development of Demand Response Mechanism - Baseline Consumption Methodology - Phase 1 Results". Australian Energy Market Operator - Project No. 20320008, 2013. Retrieved on November 28, 2017. Available online at: https://www.aemo.com.au/-/media/Files/PDF/Baseline-consumption-methodology---Phase-I-Reportpdf.pdf.

[35] Lake C. KEMA. "Empirical Analysis of Demand Response Baseline Methods", Prepared for the PJM Markets Implementation Committee, 2011. Retrieved on December 7, 2017. Available online at: https://www.pjm.com/-/media/markets-ops/dsr/pjm-analysis-of-dr-baseline-methods-full-report.ashx?la=en.

[36] Cappers P., Goldman C., Kathan D., "Demand response in U.S. electricity markets: Empirical evidence", Energy 2010, 35, pp. 1526-1535.

CAPÍTULO 4: **A novel tool for the evaluation and assessment of demand response activities in the industrial sector**

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4.1. Abstract

This paper introduces a novel tool for industrial customers to perform a cost-benefit analysis regarding the implementation of Demand Response (DR) strategies in their facilities with the final goal of softening the impact of RES intermittency in the grid. The dynamic simulation tool focuses on assessing the participation of industries in reserve energy markets in the same conditions as generators offering capacity reserve, energy reserve or both of them and taking into account all the technical restrictions of production processes as well as possible extra costs due to the implementation of DR (additional labour cost, productivity losses, etc.) Main innovations of the methodology are the DR assessment carried out per process and the introduction of the “margin of decision” as a decision-making strategy for the energy consumer.

Along the paper, the methodology behind this tool is introduced step by step in order to show how the technical, economic and environmental analyses are performed. At the end, it is included the application of the methodology to a real paper factory in Germany. Results of the dynamic simulation tool are provided and discussed, showing the potential of the paper manufacturing in DR programmes as well as the benefits associated with it.

Keywords: Demand response, Renewable integration, Industrial production, End-user tool, Load management, Economic evaluation.

4.2. Nomenclature

B_{NE}, expected benefit for the customer (€)

B_R, real benefit (€)

C_0, initial investment (€)

CE_k, CO_2 emission balance in the period k ($tonCO_2/kWh$)

CF, annual cash flow (€)

C_{VAR}, variable cost (€)

E_1, energy reduced during a DR event (kWh)

E_2, additional energy consumed before a DR event (kWh)

E_3: additional energy consumed after a DR event (kWh)

EB_{Total}, *total* energy balance involved in a DR process and month (kWh)

f_k, CO_2 emission factor in the period k ($tonCO_2/MWh$)

M_D, margin of decision (€)

p_k, price of the electricity in the time period k (€/kWh)

P_M, revenues from the DR program operator (€)

ΔP_{R1}, average power reduced or interrupted during a DR event (kW)

ΔP_{R2}, average power increased before a DR event (kW)

ΔP_{R3}, average power increased after a DR event (kW)

P_{RES}, residual power during a DR event (kW)

S_{ij}, availability of the process *i* in the quarter-hour *j*

S_{MA}, economic savings in a DR action due to extending the useful lifetime of machines (€)

S_S, economic balance in the implementation of a DR action (€)

r, discount rate (%)

T_{av}, availability time (h)

T_D, duration of a DR event (h)

T_{IA}, notification time in advance (h)

T_{MIN}, minimum time between two DR events (h)

T_{PR}, duration of the preparation period (h)

T_{RC}, recovery period (h)

4.3. Introduction

Horizon 2020 context is promoting the reduction of CO_2 emissions, which is related to the increasing integration of Renewable Energy Sources (RES) in the electricity generation mix as it appears in the European Directive (2009/28/EC). However, higher penetration of fluctuating energy sources, such as solar and wind, makes difficult the task of maintaining a predictable and reliable system operation at all voltage levels [1]. Therefore, the implementation of mechanism allowing a specific regional transmission system operator (TSO) to interact directly with demand response resources could be beneficial from different points of view: a) environmental, reducing the required capacity reserve of thermal power generation and avoiding curtailments of RES in periods of excess generation; b) for customers, enhancing their opportunities by means of providing ancillary services to the grid; and c) for TSOs, increasing the number and quality of fast resources for balancing the grid which allows cheaper and more reliable operation [2].

According to this, demand response (DR) can be a significant resource to integrate RES where customers will shape their normal consumption patterns in response to the variations in the electricity price over time or to incentive revenues designed to induce lower electricity usage at times with high wholesale market prices or when system reliability is jeopardized [3]. Traditionally, industrial customers have had a passive role in European power systems, where only large consumers (i.e. melting furnaces or electrolytic cells) have provided (if any) some kind of interruptibility services to the grid. However, it is a fact demonstrated in different research and applications [4-6] that many medium industrial customers may be also able to offer DR services to the TSO if they were allowed, directly or through an aggregator. For this reason, it is important to provide them with new tools and mechanisms so as to enable them for estimating the DR potential that could remain hidden in their production processes [7, 8].

Currently, some tools for the estimation of the DR potential of customers in the primary and tertiary sectors (agricultural sector and commercial buildings) are available in different sources [9-12]. However, such tools are just focused on buildings [13] (like the Demand Response Quick Assessment Tool –DRQAT- described in [14]), existing a significant gap regarding industrial applications. Existing models are focused on very specific processes (for example, air conditioning or lighting), which have been traditionally used for DR applications. However, more specific processes of industrial consumers have not traditionally been involved in DR issues due to misgivings about potential risks in the degradation of the production processes. This is especially true when DR actions are applied to sensitive processes directly related to the quality of the final product, which tend to make customers wary of changing any element or parameter of those processes. The tool here presented permits the modelling of industrial and non-industrial processes so as to evaluate the impact of specific DR actions and providing a detailed economic, technical and environmental evaluation every 15 minutes. In addition, the tool provides a holistic approach, linking the impact of DR actions on a process with each other, so that the application of any specific action is constrained to what happened with the rest of processes. Moreover, the tool provides a detailed analysis about when and how the different types of DR actions may be implemented in order to maximize the economic benefit for both the consumer and the power system.

On the other hand, existing tools deal with economic models using Time-of-use or similar fix price schemas [15] but neither research studies nor tools have been found so as to evaluate the economic benefit of the participation of industrial customers in reserve energy markets (offering capacity reserve, energy reserve or both of them). Conversely, this tool provides the simulation of customers participation in ancillary services based on a dynamic prices scheme with the possibility to consider a set of different prices for different services (capacity reserves, balancing services, interruptibility, etc.) every 15 minutes.

In this paper, a dynamic simulation tool based on previous works of the authors (described in [16]) is presented so as to fill this gap. This tool does not consider industrial customers as a black box, but they are evaluated as a sum of parts (manufacturing processes) which can be modified individually while the effect in the total electricity pattern of consumption for the whole facility is analysed. In this regard, the results of the economic evaluation are obtained for each DR process enabling customers to select the most cost-effective options. Moreover, the simulation tool includes an environmental evaluation that calculates the reduction of CO_2 emitted by the replaced thermal power generators to the atmosphere.

The tool was developed in the framework of the project “Demand Response in Industrial Production (DRIP)” [17], co-funded by the Environment LIFE Program of the European Commission, and it was empirically validated in the four factories involved in that project, which belong to some of the most suitable segments for DR implementation [18]: a paper factory in Germany, two meat factories in the Netherlands and Spain (respectively) and a logistics warehouse for food products in Spain.

The paper is organized as follows: Section 2 describes the calculation methodology of the new simulation tool. In Section 3 the methodology is applied to a paper factory. Finally, some conclusions are drawn in Section 4.

4.4. Calculation methodology

4.4.1. General description

In order to assess the potential benefit of the participation of an industrial customer in a particular reserve energy market, a set of information is required:

- On one hand, information related to the customer, such as the load curves of the processes, the definition of DR actions of the processes according to standardized parameters (see section 2.2) and electricity contract.
- On the other hand, the reserve energy market prices where the participation of the consumer would be simulated and CO_2 emission factors, which depend on the country where the consumer is located.

Based on this information, the simulation tool performs the technical, economic and environmental evaluation of the DR potential in the customer facility considering all the complex relationships among all the variables in a mathematical model that takes into account the chronological order of events. Figure 4.1 shows an overview of the required information (inputs) and the main results of the simulation tool (outputs).

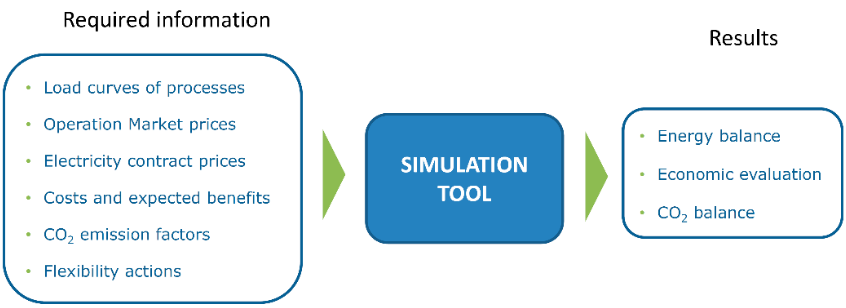


Figure 4.1. The required information (inputs) and the results of the simulation tool (outputs).

4.4.2. Required information (Inputs)

Most of the medium industrial customers are not aware of their energy consumption profile and the possible flexibilities in their production processes due to the fact that they usually do not have experts specialized in energy and flexibility trading [19]. In order to address that, a flexibility audit has to be performed to characterize the electrical consumption of the different processes and to identify the DR actions that could be implemented in the industrial customer facilities.

4.4.2.1. Identification of typical days and building of typical day profiles

Typical days represent repeatable daily patterns of consumption for the customer during the year. Using the quarter-hourly load curves collected during the flexibility audit, the typical daily consumption profiles are calculated with the help of the simulation tool. Figure 4.2 presents an example of the average daily load curve on working days in the Spanish meat factory involved in the abovementioned DRIP project.

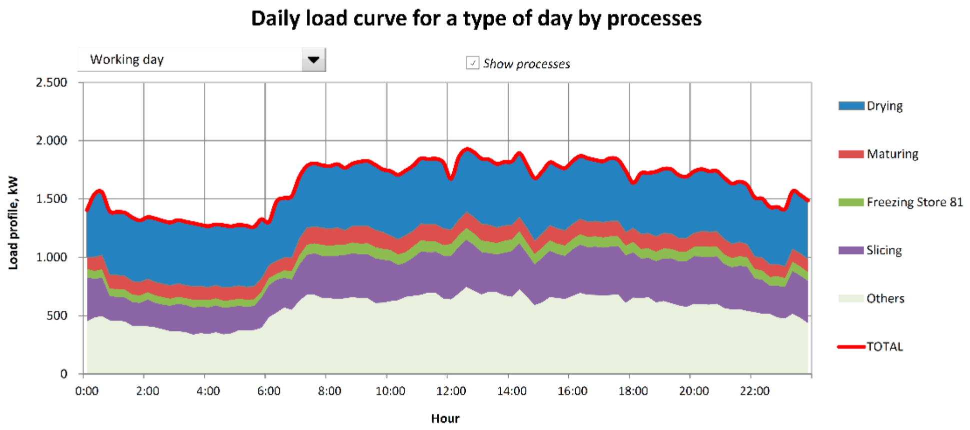


Figure 4.2. Example of the average daily load curve disaggregated by DR processes on working day in a Spanish meat industry.

In order to obtain the cited daily load curves, it is necessary to carry out the process described below.

- The first step is to identify and remove the days that enclose anomalous data (lack of data, blackouts, maintenance periods, etc.).
- Then, the daily profiles are compared and clustered by groups (type of day) according to similar energy consumption patterns trying to reduce the standard deviation of each group as much as possible. When the standard deviation value of all the groups becomes acceptable, the average electrical load curve of all the selected days is considered representative of each group (typical day).

As aforementioned, the simulation tool allows customers an easy performance of the previous analysis and building of the typical load curves by means of a friendly user interface. Figure 4.3 shows an example of the typical profile of a working day in July (peak season) in the same Spanish meat factory. When seasonality (or other factors) affects the shape of the load curve of any process, it results on a new typical day.

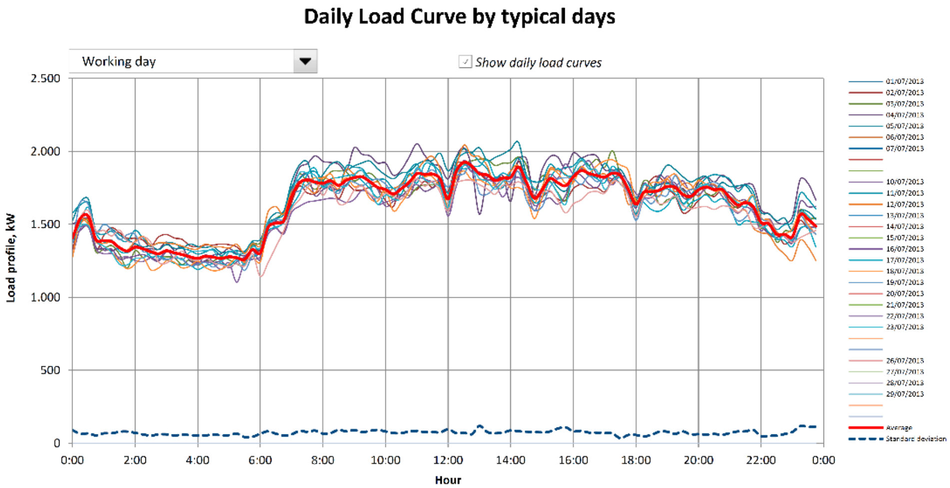


Figure 4.3. Example of a typical profile on working day in the Spanish meat industry including the resulting standard deviation.

4.4.2.2. Definition and standardization of DR actions

Once all the typical days are defined, the DR actions are specified for each process. Each DR action is characterized according to the technical parameters proposed in [20]. In this regard, the relevant technical parameters considered in this analysis are represented in Figure 4.4. The figure illustrates a theoretical flat load curve for a process when a flexibility action involving the reduction of an amount of energy ***E1*** during the time T_D is applied. For a period of time T_{PR}, an amount of energy ***E2*** is consumed in order to make adaptations to prepare for an interruption. Similarly, at the end of the interruption, the reduced supply is switched back on, and an extra consumption ***E3*** is produced to re-establish the original settings. Once the period T_{RC} has happened, the load curve returns to the initial level of demand. The time T_{IA} represents the notification in advance that is necessary for the customer before the implementation of the action.

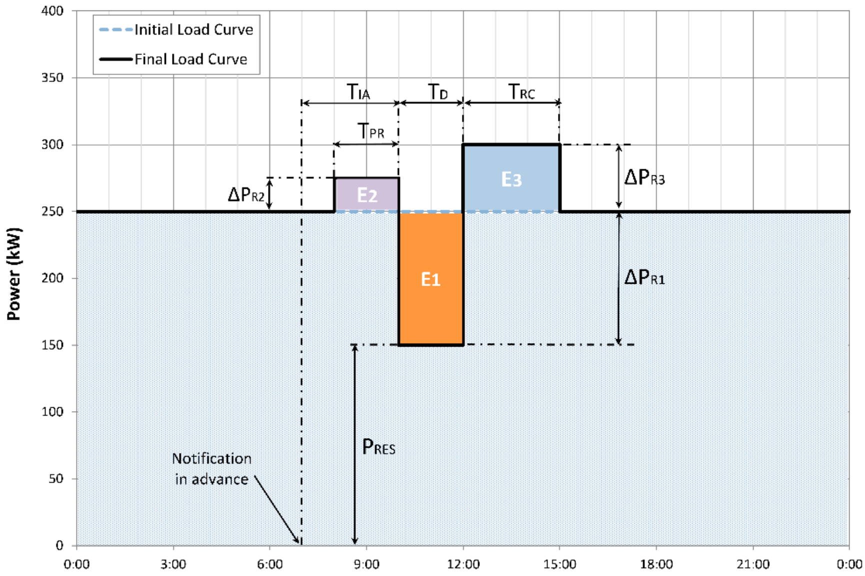


Figure 4.4. Technical parameters proposed to define DR actions (source: project DRIP).

The technical parameters involved in each DR action need to be specified for each type of day and month in order to consider the possible variations due to changes in the boundary conditions (external temperature, scheme of productions, etc.)

4.4.2.3. Economic and environmental inputs

Regarding the information needed to the economical evaluation, the characteristics of the electricity supply contract of the studied industrial customer (electricity prices) are required, as well as the historical prices of the reserve energy market in which the industrial customer could participate and their future trends for a more sophisticated estimation.

Lastly, regarding the environmental evaluation, the hourly CO_2 factors associated with the electricity generation mix are necessary, as explained below.

4.4.3. Calculation process

4.4.3.1. Identification of availability: when flexibility is activated or not

Firstly, the availability of the interruptible power for each DR process is evaluated at each quarter-hour (***j***), which is the time step (so-called "Programme Time Unit") in most of the European reserve energy markets [21], considering its technical parameters. The state of the analysed DR process ***i*** at the quarter-hour ***j*** (S_{ij}) is calculated based on the state of the previous quarter-hour (***j-1***) in order to determine if the DR process ***i*** is available to be interrupted during the quarter-hour ***j*** or not. In this regard, the reasons why a DR process ***i*** at the quarter-hour ***j*** (PR_{ij}) could not be available to be interrupted (S_{ij} = 1) are described below:

- The DR process ***i*** is in the middle of a DR event, and therefore it is already interrupted.
- It is in the preparation period or recovery period of another DR event.
- It is between two DR events, and although the first DR event is finished, the DR process needs an additional time (minimum time between interruptions) in order to implement the second one without causing any impact in the production process.

If the DR process ***i*** is available to be interrupted for example at the quarter-hour ***j*** (S_{ij} = 0), an economical evaluation will be performed to determine the margin of decision (M_D) that is the difference between the real benefit (B_R), which is the net amount of money that receives the industrial customer due to the participation in the reserve energy market, and the expected benefit for the customer (B_{NE}):

$$M_D = B_R - B_{NE} \tag{1}$$

This parameter, proposed in [16], is used to verify the potential participation of a customer in a DR program at a specific time:

- If $M_D \leq 0$, the customer will not participate in the DR program because economic benefits are not obtained.
- If $M_D > 0$, the customer will provide the DR Service, modifying the power load according to the DR event requirements and obtaining economic benefits.

In order to calculate the real benefit (B_R) at the quarter-hour j, it is necessary to assess a set of parameters in advance such as the economic balance (S_s), the benefit of the extension of machinery useful life (S_{MA}), the variable costs (C_{VAR}) and also considering the payment offered by the TSO in the reserve energy market:

$$B_R = S_S + S_{MA} + P_M - C_{VAR} \tag{2}$$

4.4.3.2. Technical evaluation

The energy balance (EB_{Total}) involved in the DR process *i* in the month *l* is calculated as the difference between the energy reduces during the DR events (E_1) and the additional energy consumed before and after these DR events (E_2 and E_3 respectively):

$$EB_{Total} = E_1 - (E_2 + E_3) = \sum_{h=1}^{p} E_1^h - \left[\sum_{h=1}^{p} E_2^h + \sum_{h=1}^{h} E_3^k\right] \quad (3)$$

where ***h*** is the number of the DR event and ***p*** is the total number of DR events in the month ***i****.*

4.4.3.3. Economic evaluation

The economic balance (S_s) during a DR event is the difference between the economic savings due to the energy not consumed and the extra costs generated by the additional energy consumed before and after the interruption (preparation and recovery periods):

$$S_S = \sum_{k=1}^{n} E_1^k \cdot p_k - \left[\sum_{k=1}^{n} E_2^k \cdot p_k + \sum_{k=1}^{n} E_3^k \cdot p_k\right] \quad (4)$$

where p_k is the electricity price in the time period **k** (i.e. prices of electricity for on-peak, shoulder and valley periods.)

The tool calculates S_s during the whole month ***I*** for each DR process as the difference between the economic savings due to the energy not consumed and the extra costs generated by the additional energy consumed before and after the implemented interruptions (preparation and recovery periods), and it is assessed using (2) as explained above.

When the production machinery stops during the implementation of a DR event, its useful lifetime will be generally increased, which is considered as an economic saving. Occasionally, the benefit of the extension of machinery useful life (S_{MA}) may also have an opposite effect. In this regard, if the start/stop cycles of the production machinery due to the interruptions have a high frequency, their lifetime could be lessened. In this case, S_{MA} will be zero and the possible extra cost will be included as a variable cost in the simulation tool.

As stated above, B_R also includes the variable costs (C_{VAR}) associated with the implementation of DR actions such as the labour cost that is the extra cost paid to the employees for overtime work and the possible cost due to the loss of productivity (if it exists).

Considering the previous considerations, it can be concluded that the revenue offered by the TSO (marginal price) has to be higher than the minimum price required by the customer. In this case, the matching will be achieved and the DR process ***i*** will be interrupted during the quarter-hour *j* (S_{ij} = 2), reducing the available interruptible power (P_{ij}). Otherwise, the customer will not tender the flexible power. The following equation summarizes the above statements:

$$P_M \geq C_{VAR} + B_{NE} - S_S - S_{MA} \quad (5)$$

This equation is represented in Figure 4.5.

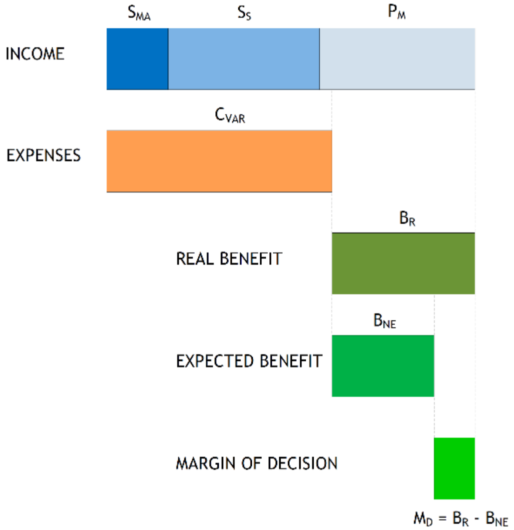
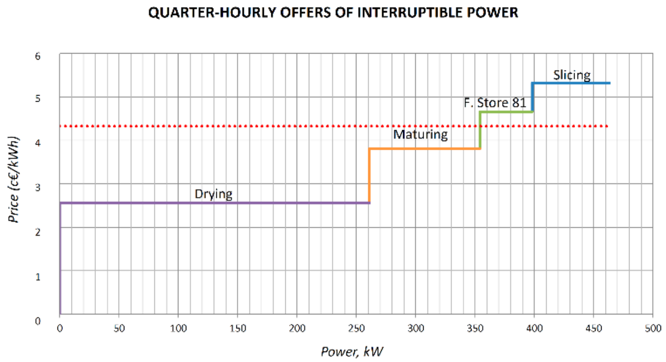


Figure 4.5. Economical evaluation associated with the margin of decision.

Using (4), the simulation tool calculates the quarter-hourly offers of all the DR processes during the simulated month ***m***. Figure 4.6 represents an example of a quarter-hourly offer on a working day in the cited Spanish meat factory, which includes four different processes sorted by price. In this example, if the TSO offers 43 €/MWh at the quarter-hour ***j*** and all the DR processes are available to be interrupted, the customer could interrupt the maturing and drying processes in a cost-effective way resulting in a total interrupted power of 354 kW.



	Power (kW)	Price (c€/kWh)
Slicing	65	5,32
Freezing Store 81	44	4,66
Maturing	93	3,81
Drying	261	2,56
PM offered by the TSO		4,33

Figure 4.6. Example of a quarter-hourly offer of interruptible power of an industrial customer.

Following with the description of the calculation process, the simulation tool saves the information related to the state and interrupted power for each DR process ***i*** at the quarter-hour ***j***. Then, the described part of the algorithm is repeated from the next quarter-hour (***j+1***) to the last one (***m***) in the month ***l***. After that, the simulation tool applies this procedure to the rest of DR processes from ***i+1*** to ***n***, that is the total number of DR processes identified in the industrial customer facilities.

Figure 4.7 shows an example of the results of the calculation procedure applied to the "Winder" process in the paper factory on a working day (5th of

December 2013). The upper graph shows the final load curve and the margin of decision comparing the minimum payment required by the customer with the payment offered by the TSO while the lower graph provides the associated economic evaluation in detail.

Figure 4.7. Example of the results of the calculation procedure applied to the "Winder" process in the paper industry on a working day (05/12/2013).

Using the saved results of the simulations of all the DR processes in the month ***l***, a monthly technical, economic and environmental evaluation is performed for each DR process.

4.4.3.4. Environmental evaluation

The environmental impact of all the DR events associated with all the DR processes in the month *l* is calculated as the CO_2 emission balance (***CE_{Total}***) between the avoided CO_2 (***CE_1***) and the extra CO_2 emitted to the atmosphere due to the extra electrical consumption before and after all the DR events (***CE_2*** and ***CE_3***):

$$\boldsymbol{CE_{Total}} = \boldsymbol{CE_1} - (\boldsymbol{CE_2} + \boldsymbol{CE_3}) = \sum_{k=1}^{n} \boldsymbol{E_1^k} \cdot \boldsymbol{f_k} - \left[\sum_{k=1}^{n} \boldsymbol{E_2^k} \cdot \boldsymbol{f_k} + \sum_{k=1}^{n} \boldsymbol{E_3^k} \cdot \boldsymbol{f_k}\right] \quad (6)$$

where *k* is associated with the time period of each different CO_2 emission factor (i.e. CO_2 emission factor of on-peak, shoulder and valley periods.)

As explained above, the aforementioned CO_2 emission factors should be calculated considering the CO_2 emission factors of the replaced technologies used in the reserve energy market in each quarter-hour. It is important to point out that the emissions impact here calculated is only related to the use of electricity. It means that the amount of CO_2 emitted or avoided into the atmosphere evaluated by the tool is just related to the carbon footprint linked to the technology producing the electricity used by the consumer. It means that the evaluation of the CO_2 impact related to the use of fuel for other purposes (thermal energy, transport, etc.) is out of the scope of this research.

After that, the described calculation process is carried out for each month of the selected year from January to December in order to obtain the annual results for each DR process. Based on these results, the final economic profitability of each DR process is evaluated using the Net Present Value (NPV), the Internal Return Rate (IRR) and the Discounted Payback Period (DPP). To that end, the involved fixed costs (initial investment) are calculated as all the expenses incurred by the customer and needed before providing DR services such as the initial flexibility audit, the acquisition and installation of all the required equipment (monitoring and control systems and metering devices), etc. The expressions that are used to evaluate the economic profitability of each DR process (NPV, IRR and DPP) are presented below:

$$\boldsymbol{NPV} = \sum_{t=0}^{n} \frac{\boldsymbol{CF}}{(1+\boldsymbol{r})^{t}} - \boldsymbol{C_0} \quad (7)$$

$$\boldsymbol{NPV} = \sum_{t=0}^{n} \frac{\boldsymbol{CF}}{(1+\boldsymbol{IRR})^{t}} - \boldsymbol{C_0} = \boldsymbol{0} \quad (8)$$

$$\boldsymbol{DPP} = \frac{-\boldsymbol{ln}\left(1-\frac{\boldsymbol{C_0}\times \boldsymbol{r}}{\boldsymbol{CF}}\right)}{\boldsymbol{ln}(1+\boldsymbol{r})} \quad (9)$$

where ***t*** is the number of the year and ***n*** is the total number of years associated with the investment.

After selecting the cost-effective DR processes and discarding the rest, the total annual results of the technical, economic and environmental evaluations are obtained as the sum of the particular results of all the selected DR processes during the whole year.

Figure 4.8 schematizes the presented calculation process in a flowchart:

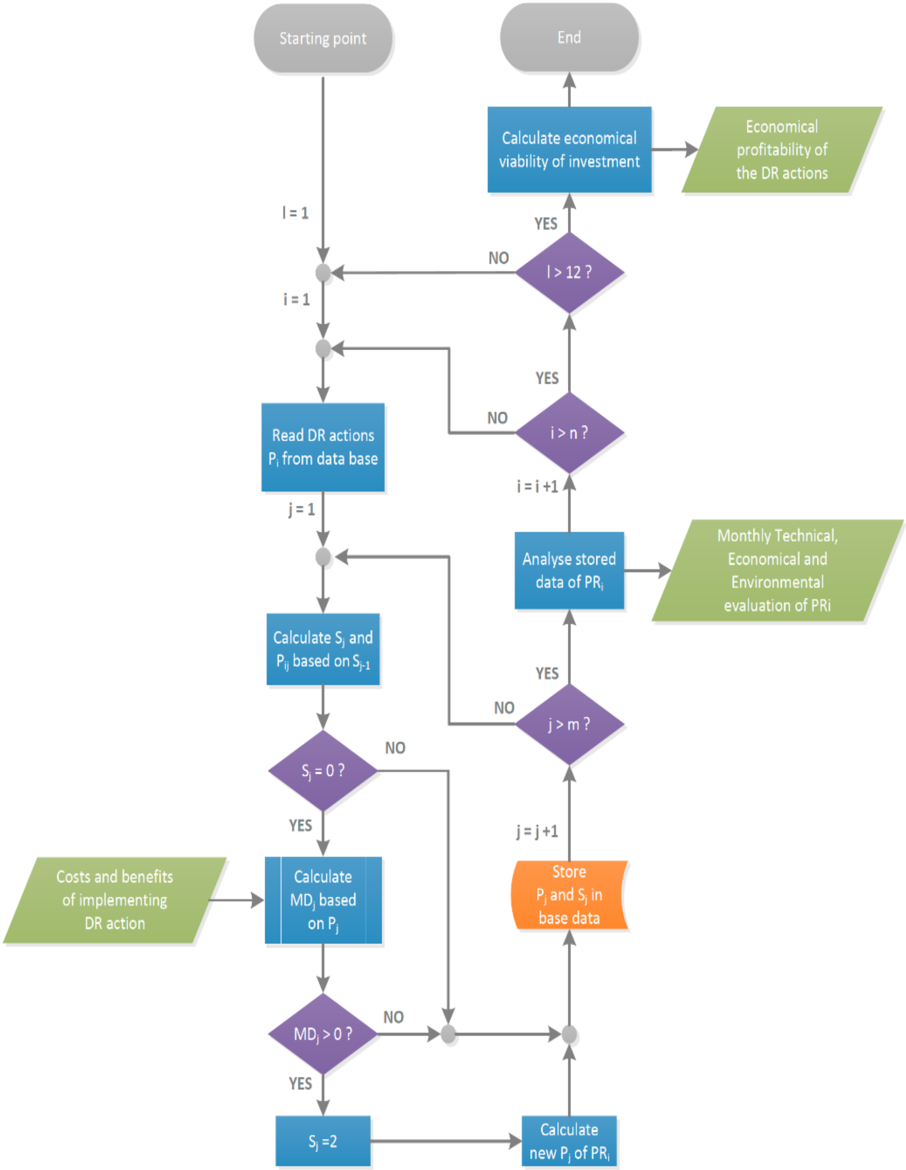


Figure 4.8. Flow chart of the calculation process.

Lastly, the final economic profitability of providing DR services for an industrial customer is calculated with the expressions (7), (8) y (9) using the aforementioned total annual results of the economical evaluation.

4.5. Application of the simulation tool in a paper factory

In this section, the results of the participation of the paper factory in the German reserve energy market using the simulation tool are presented. Currently, the tender block size required by TSOs [22] is too high for medium industrial customers in most cases, so an aggregator is required to use the DR services offered by them. Generally, the aggregator is a legal organisation that consolidates or aggregates a number of individual customers and/or small generators into a coherent group of business players [23]. This implies that changes in the regulation of some countries around the world could be necessary to encourage medium industrial customers to contribute to the improvement of grid management.

Assuming the above-mentioned requirements, the participation of industrial customers in the reserve energy markets was simulated considering possible restrictions due to the reaction time of the analysed DR actions. Moreover, it was considered that all the DR actions are implemented automatically or semi-automatically depending on the required reaction time. Consequently, the associated costs of control were included in the total flexibility expenses for all DR actions.

The description of the results of the application of the simulation tool in a paper factory is structured as follows: Subsection 3.1 describes of the relevant production process in the studied paper factory and the final technical evaluation. In Subsection 3.2 the results of the economic evaluation of each DR process and as a whole are presented. Finally, the environmental effects of providing DR services are presented in Subsection 3.3.

4.5.1. Description of the paper factory and technical evaluation

The analysed manufacturing plant is devoted to the production of test liner paper with different grammages, winding the paper throughout reels. The production is continuous and stable at all times except during maintenance periods. It exists long and short maintenance stops, the first one occurs every 6 weeks while the other one happens every week for a 3 to 4 hours period.

The manufacturing process of the paper factory begins on the reception of raw materials classified and directly supplied from the **stock preparation**. In this section the pulp is prepared to supply the paper machine and depending on the state of the tanks, the pulpers and the turbo-separators used to prepare the pulp could be switch off. This is the first DR action identified in the industrial process.

Next, the pulp feeds the paper machine distributing the pulp and producing the layers which compose the paper sheet. Following, the vacuum pumps drains the water and the paper sheets go through different pressing rolls. Subsequently, in the dryer section, a high percentage of dry content is achieved by means of steam heated drying cylinders.

Afterwards, the paper is treated with starch, colour and/or synthetic glues and it is wound in reel drums throughout the winding section. Once the drum leaves the paper machine, the paper is re-winded according to the characteristics required by the final customers. At this stage, the **winder** can be interrupted so that several drums can be stored at the end of the winding section to be re-winded and cut later (second DR action).

The final product is driven to the **storage** for its shipment. At this point, there are two suction lifts to move the reels in the warehouse which work using vacuum. The use of these machines could be managed in order to avoid their use when a reduction is required (third DR action).

Table 4.1 shows the main parameters of the three DR actions found in the performed flexibility audit.

Table 4.1. The results of the technical evaluation of the paper industry.

DR Process	Maximum Interruptible power	Maximum Duration	Minimum notification in advance	Recovery period	
				Maximum Increased Power	Maximum Duration
Stock preparation	980 kW	30 min	1 hour	245 kW	2 hours
Winder	36 kW	30 min	15 min	4 kW	4.5 hours
Storage	5 kW	30 min	10 min	2.5 kW	1 hour

4.5.2. Economic evaluation

In order to calculate the economic evaluation, it was assumed that the customer will receive the same payment (PM) as a generator that is participating in the German reserve energy market when a DR event is implemented.

According to this, it was used the average imbalance pricing system (reBAP) that is based on TSO's payments or proceeds for the activated control energy (secondary and minute reserve) in the whole Germany. On the basis of these prices, it was simulated a whole year using the tool.

As explained in section 5.4.3, the involved fixed costs (initial investment) were calculated as the sum of expenses incurred by the customer that are needed before providing DR services, such as the initial flexibility audit, the acquisition and installation of all the required equipment (monitoring and control systems and metering devices), etc. In this regard, the total initial investment for providing DR services was estimated around 130 k€, considering the mentioned fixed costs and the installation of an additional pulp storage tank for ensuring the duration of interruptions.

After that, the economic profitability of each DR process was evaluated in order to exclude from the final results the DR processes that are not cost-effective according to the proposed scenario. As discussed before, the economic profitability of each DR process is evaluated using the Net Present Value (NPV), the Internal Return Rate (IRR) and the Discounted Payback Period (DPP).

Table 4.2 shows the NPV for the different DR processes and different discount rates considering a total of 3 years to recover the investment. Additionally, it is summarized the IRR and the DPP for each DR process.

Table 4.2. Economic profitability analysis of the implementation of the involved DR actions.

DR process	NPV (euros)				IRR (%)	DPP (years)
	Discount rate (5%)	Discount rate (10%)	Discount rate (15%)	Discount rate (20%)		
Stock preparation	64,307	47,822	33,622	21,296	30.6%	2.2
Winder	272	75	-95	-242	12.1%	3
Storage	-1,978	-1,980	-1,982	-1,983	-83.2%	>5

According to Table 4.2. Economic profitability analysis of the implementation of the involved DR actions., the “Stock preparation” process is the most profitable one with a DPP of around two years and two months, the highest values of IRR and NPV in this group of three DR processes. “Winder” process has a DPP of three years and the IRR is 12.1%, consequently it was also considered as a cost-effective process in the final economic evaluation of the factory. On the other hand, the “storage” process can be considered as a non-profitable (DPP>5 years).

After discarding the non-profitable DR processes, the final economic evaluation was carried out where the annual net benefit (€/year) that was calculated as the sum of the difference between the monthly incomes and variable costs of the considered DR processes throughout a year was around 70 k€ per year. In this regard, Figure 4.9 shows that the maximum unitary benefit for the customer was in December (68 €/MWh).

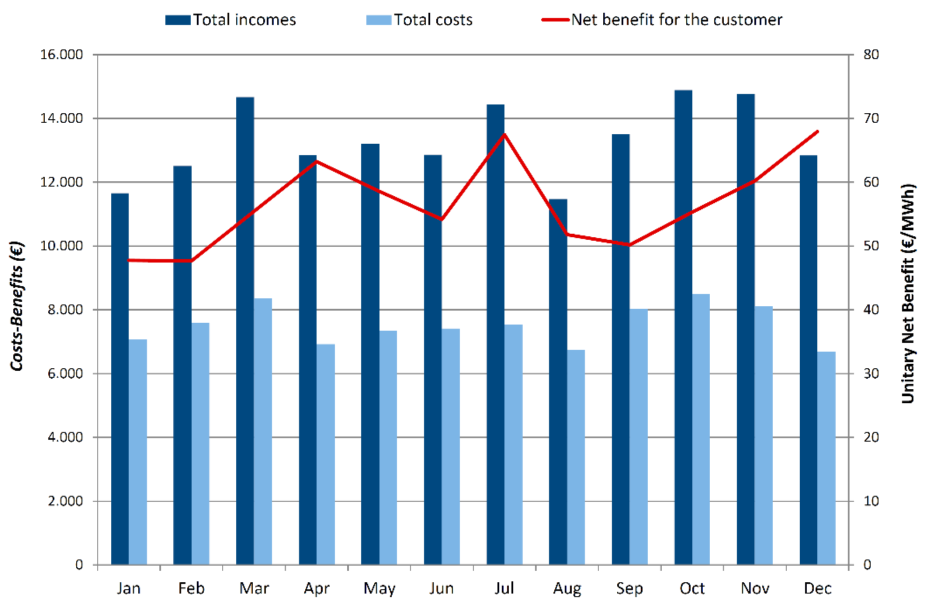


Figure 4.9. The monthly unitary net benefit of the cost-effective DR processes in the final economic evaluation.

Using the annual net benefit and the initial investment, the final economical evaluation of the participation of the studied paper factory in the German reserve energy market is presented in Figure 4.10 where the NPV that was calculated using different discount rates. The intersection between the NPV curve and the abscissa axis is the discount rate value of the IRR, equals to 30.3% as shown in Figure 4.10.

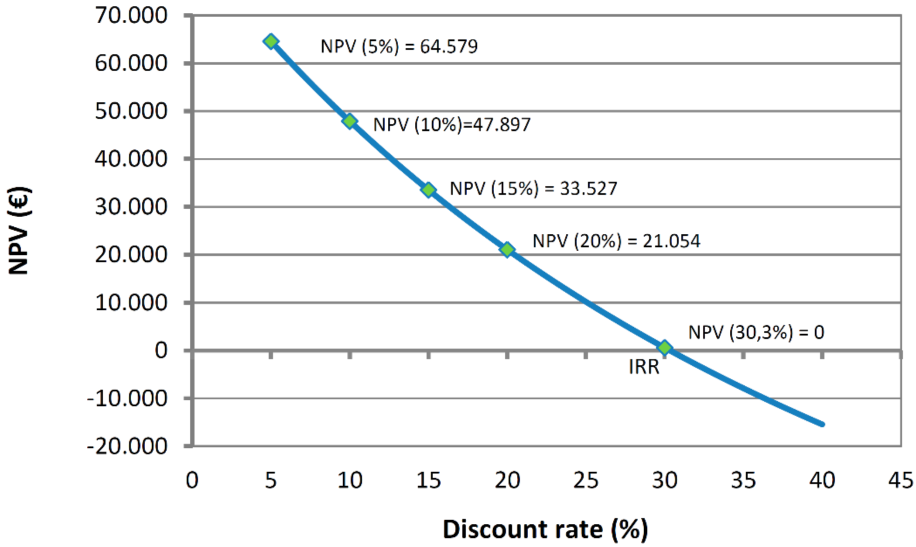


Figure 4.10. NPV and IRR of the final economic evaluation.

In this regard, the DPP of the considered investment was around two years and two months.

According to the results of the previous economic evaluation, the participation of the studied paper factory in the German reserve energy market was considered as a cost-effective measure to be implemented in the customer facilities.

4.5.3. Environmental evaluation

In order to assess the amount of CO_2 emitted into the atmosphere when a DR action is performed, the hourly CO_2 emission factor curve (tonCO_2/MWh) was calculated using PLEXOS® [24] in the studied year and considering the conventional generation used in the German reserve energy markets. After analysing this information, it was observed that there is not a direct relationship between CO_2 emissions and market prices since it strongly depends on the constitution of the generation mix for each particular country. Consequently, the possible environmental effects of the implementation of DR actions could be even negative. During the simulation, the result of the DR events triggered by the market price had a tiny positive environmental effect avoiding 397 tonne CO_2 emissions per year.

The European emission market, regulated under the Directive 2003/87/CE, is related at present to the CO_2 emitted when consumers use fuels for their main activity. Therefore, a paper factory can trade emission rights related to the emissions linked, for example, to the combustion of a fuel to produce steam. On the contrary, the CO_2 related to the use of electricity in different periods of time is not considered in the current emission market rules. Therefore, there are not incentives for consumers so as to use of electricity in periods when the technologies producing power are less contaminant (e.g. when the share of renewables is higher) and vice versa. Although currently there is not an economic incentive scheme for the reduction of the CO_2 emissions using DR resources in Europe, it is presumable that this fact will change in the coming years. Then such time comes, this simulation tool will allow industrial customers to estimate the environmental benefits of providing DR services, based on the aforementioned results.

4.6. Conclusions

Considering the increment in electricity cost as well as RES integration in the grid, the need for simulation tools capable to provide a "decision-support" approach for quick decision making is valuable not just for customers but also for the agents who must guarantee the optimal power system management.

As highlighted above, there are different tools for assessing DR potential; however, none of them provides the economic profitability for industrial customers participating in a specific operation market, where consumers may provide different services such as capacity or energy reserve. The novel simulation tool that is here presented performs this kind of evaluation, as well as the evaluation of the potential impact based on processes that DR actions may have in the usual pattern of consumption of industrial customers. In addition, the potential environmental impact related to the use of DR is also quantified considering the carbon footprint of the replaced generators.

The tool provides an innovative approach to the customer flexibility evaluation throughout a detailed analysis of customers' DR potential. This "processes approach" analyses the impact of the proposed DR actions at each individual energy consuming process in the manufacturing course. Instead of simply assessing the impact of a given DR action in the total energy demand of the customer, the effect of different DR actions is studied in every superposed process, thus contributing to fill the gap in consumer knowledge on load management.

Finally, the tool has been empirically validated in four real industrial sites from different parts of Europe (Germany, The Netherlands and Spain). As an example of the validation process, it was presented the simulation of the participation of a paper factory in the German reserve energy market. According to the results, it was demonstrated that industrial customers can provide DR services to the power system in a cost-effective way, with significant benefits not just for the customer but for the whole power system.

4.7. Acknowledgments

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4.8. References

[1] Bañosa R., Manzano-Agugliaro F., Montoya F.G., Gila C., Alcayde A., Gómez J., "Optimization methods applied to renewable and sustainable energy: A review". Renewable and Sustainable Energy Reviews 2011; 15, pp. 1753–1766.

[2] Cecati C., Citro C., Siano P., "Combined Operations of Renewable Energy Systems and Responsive Demand in a Smart Grid". IEEE Transactions on Sustainable Energy 2011; 2, pp. 468-476.

[3] FERC, "Reports on Demand Response & Advanced Metering", Federal Energy Regulatory Commission 2014. Retrieved on April 10, 2015. Available online at: www.ferc.gov/industries/electric/indus-act/demand-response/dem-res-adv-metering.asp

[4] Valencia-Salazar I., Álvarez-Bel C., Escrivá-Escrivá G., Alcázar-Ortega M., "Simulation of demand side participation in Spanish short-term electricity markets". Energy conversion and management 2011, 52, pp. 2705-2711

[5] Greening LA, "Demand response resources: Who is responsible for implementation in a deregulated market?". Energy 2010; 35: 1518-1525.

[6] Shen B., Ghatikar G., Lei Z., Li J., Wikler G., Martin P., "The role of regulatory reforms, market changes, and technology development to make demand response a viable resource in meeting energy challenges". Applied Energy 2014; 130, pp. 814-823.

[7] Álvarez-Bel C., Alcázar-Ortega M., Escrivá-Escrivá G., Gabaldón-Marín A., "Technical and economic tools to assess customer demand response in commercial sector". Energy conversion and management 2009; 50, pp. 2605-2612.

[8] Dashti R., Afsharnia S., "Demand response regulation modeling based on distribution system asset efficiency". Electric Power Systems Research 2011; 81, pp. 667-676

[9] "Demand Limiting Assessment Tool (DLAT)" Version 1.07, 8/2010. Ray W. Herrick Laboratories, Purdue University. Retrieved on April 23, 2015. Available online at: https://engineering.purdue.edu/DLAT/

[10] "Demand response assessment tool", UT Power Engineering Laboratory, University of Tennessee. Retrieved on April 23, 2015. Available online at: power.eecs.utk.edu/research_demandresponsepotential.html

[11] "The Agricultural Irrigation Demand Response Estimation Tool", Demand Response Research Center, Laurence Berkeley National Laboratory. Retrieved on April 24, 2015. Available online at: drrc.lbl.gov/tools/agricultural-irrigation-dr-estimation-tool

[12] Goy S., Finn D., "Estimating demand response potential in building clusters". Building and Environment 2016; 96, pp. 270-282

[13] Neves D., Pina A., Silva C.A., "Demand response modeling: A comparison between tools". Applied Energy 2015; 146, pp. 288-297

[14] "Demand Response Quick Assessment Tool (DRQAT) for buildings". Demand Response Research Center, Laurence Berkeley National Laboratory. Retrieved on April 24, 2015. Available online at:

drrc.lbl.gov/tools/demand-response-quick-assessment-tool-drqat

[15] Mohajeryami S., Moghaddam I.N., Doostan M., Vatani B., Schwarz P., "A novel economic model for price-based demand response". Electric Power Systems Research 2016; 135, pp. 1-9

[16] Alcázar-Ortega M., Álvarez-Bel C., Escrivá-Escrivá G., Domijan A., "Evaluation and assessment of demand response potential applied to the meat industry". Applied Energy 2012; 92, pp. 84-91.

[17] "Demand Response in Industrial Production DRIP", EU LIFE project. Retrieved on May 10, 2015. Available online at: www.drip-project.eu/

[18] Alfonso D., Pérez-Navarro A., Encinas N., Álvarez-Bel C., Rodríguez-García J., Alcázar-Ortega M., "Methodology for ranking of customer segments by their suitability for distributed energy resources applications". Energy Conversion and Management 2007; 48, pp. 1615-1623.

[19] Alcázar-Ortega M., "Evaluation and assessment of new demand response products based on the use of flexibility in industrial processes": application to the food industry [Ph.D. Dissertation]. Tampa, Florida: Dual Programme between the Polytechnic University of Valencia and the University of South Florida; 2011.

[20] Alcázar-Ortega M., Calpe C., Theisen T., Rodríguez-García J., "Certification prerequisites for activities related to the trading of demand response resources". Energy 2015; 93, pp. 705-715.

[21] "Imbalance management Tennet analysis report". Tennet. April 2011. Retrieved on December 2, 2014. Available online at: http://www.tennet.eu/nl/nl/over-tennet/nieuws-pers-publicaties/publicaties/technische-publicaties/imbalance-management-analysis-tennet.html

[22] "Description of load-frequency control concept and market for control reserves". Consentec GmbH. February 2014. Retrieved on December 16, 2014. Available online at https://www.regelleistung.net/ip/action/static/marketdesc

[23] Smart Inverter Working Group. "Recommendations for Utility Communications with Distributed Energy Resources (DER) Systems with Smart Inverters". California Energy Commission, California Public Utilities Commission. October 2014. Retrieved on April 17, 2015. Available online at: http://www.cpuc.ca.gov/NR/rdonlyres/899E4077-36AE-4946-8515E68 EA95C0B32/0/SIWGPhase2CommunicationsRecommendationsv2_Updated10222014.pdf

[24] "PLEXOS". Products and Services. Energy exemplar. Retrieved on December 4, 2014. Available online at: http://energyexemplar.com/our-company/brochures-and-flyers/

CAPÍTULO 5: **Maximizing the profit for industrial customers of providing operation services in electric power systems via a parallel particle swarm optimization algorithm**

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5.1. Abstract

Integration of renewable energy sources require an increase in the flexibility of power systems. Demand response is a valuable flexible resource that is not currently being fully exploited. Small and medium industrial consumers can deliver a wide range of underused flexibility resources associated with the electricity consumption in their production processes. Flexible resources should compete in liberalized operation markets to ensure the reliability of the system at a minimum cost. This paper presents a new tool to assist industrial demand response to participate in operation markets and optimize its value. The tool uses a combined physical-mathematical modelling of the industrial demand response and a Parallel Particle Swarm

Optimization algorithm specifically tuned for the proposed problem to maximize the profit. The main advantages of the proposed tool are demonstrated in the paper through its application to the participation of a meat factory in the Spanish tertiary reserve market during a whole year using a quarter-hourly time resolution. The enhanced performance of the proposed tool with respect to previous methodologies is shown with these four flexible processes examples, where the maximum available profit obtained in the simultaneous consideration of all different flexible processes is computed. The flexible processes are technical and economically characterized in a way that makes the tool valid for most of the processes in the industry.

Keywords: Demand Response; Energy Resource Management; Industrial production; End-user tool; Parallel Particle Swarm Optimization;

5.2. Nomenclature

Indices:

t	Time period
g	Flexible process
d	Day of the month
m	Month
r	DR event

Sets:

T	Set of time periods on a day in a month
G	Set of flexible processes

D_m	Set of days in a month *m*
M	Set of months in a year
R_{dm}	Set of DR events on a day *d* in a month *m*

Parameters:

t_{PTU}	Program Time Unit (h)
ΔP^1_{gdm}	Power reduced during any DR event (kW)
ΔP^2_{rgdm}	Power increased before DR event (kW)
ΔP^3_{rgdm}	Power increased after DR event (kW)
T^{Max}_{gdm}	Maximum time duration of a DR event (h)
T^2_{rgdm}	Preparation time of a DR event (h)
T^3_{rgdm}	Recovery time of a DR event (h)
T^{Min}_{gdm}	Minimum time between DR events (h)
T^E_{gdm}	Recovery time from previous day event (h)
T^{ava}_{tgdm}	Availability of a DR event
T^{IA}	Notification time in advance (h)
π^{CB}_{tdm}	Price of the capacity band (€/kW)
π^{ED}_{tdm}	Price of the energy delivery (€/kWh)
π^{e}_{tdm}	Price of the consumed electricity (€/kWh)
CF_g	Investment cost of a DR process (€)
CV_{gdm}	Variable cost of a DR process (€/h)
E^{Max}_{gdm}	Maximum number of DR events
D^{Max}_{gdm}	Maximum duration of all DR events (h)

Auxiliary Variables:

S_{tgdm}	Binary to express the start of a DR event

Decision variables:

A_{rgdm}	Starting time of a DR event
D_{rgdm}	Duration of a DR event

5.3. Introduction

Integration of Renewable Energy Sources (RES) to generate electricity has become a global priority. Renewable Energy Sources (RES) represent a key measure to reduce CO_2 emissions by replacing fossil fuel combustion with renewable electricity production. Nevertheless, RES are unpredictable, not dispatchable and present large variabilities in their generation profile due to their reliance on natural resources. This variability creates a major issue for traditional power systems and the security of supply. To overcome generation and consumption mismatches with massive integrations of RES, power systems will require three major changes: network reinforcement, deployment of storage and untapping demand response resources [1]. These actions will allow power systems to increase their flexibility and integrate a larger share of RES without jeopardizing their security [2].

Demand Response (DR) can be defined as changes in the use of electricity of end consumers from normal patterns to respond with economic incentives or price changes [3]. The scientific literature agrees that unlocking DR benefits both consumers and the power system due to its faster and more reliable response [4]–[7]. DR can also provide ancillary services in a fast and reliable way in comparison with conventional generation. In this sense, the European Clean Energy Package launched in 2016 established the foundations to unlock the potential of DR in Europe. The European Commission (EC) estimates a demand flexibility potential of 100 GW increasing up to 160 GW in 2030.

The industrial sector represents around of a third of the World's electricity consumption and it is the fastest growing energy demanding sector [8]. However, most of industrial consumers do not use their flexibility to obtain an additional income in order to reduce their energy cost, especially in the case of Small and Medium-sized Enterprises (SMEs). Despite the existence of some DR programs in several countries, this resource is currently used below its potential [5]. This is related to the complexity and uniqueness of the underlying specific production processes of industry [6], [9]. Nevertheless, previous studies keep stating how industrial DR can provide significant benefits not only to the power system as a whole, but also to DR providers [10]. Moreover, different studies show how SMEs can deliver a large variety of flexible resources to the power system [11], especially through aggregators [2]. However, to facilitate the participation of SMEs, it remains essential to develop and make available analysis tools to industrial consumers and other agents such as aggregators or Virtual Power Plants (VPP). Clear analysis and data can optimize the potential profit associated with the use of their flexible resources and can help the industrial sector to participate in DR programs.

In [12], the authors present a tool for simulating the participation of industrial consumers in operation markets. This tool presents an adequate flexibility characterization of industrial processes. It considers all the technical and economic parameters associated with flexible processes, including their impact on the electricity supply cost [13]. The tool deals with flexible processes that must return to their normal conditions just after a DR event occurs to avoid any problem in the production process. The characterization considers the production experts' recommendations to avoid any impact on the final product or on the production performance. Other methods and tools coordinate both production schedule and DR actions in the daily energy planning of specific types of factories [14], [15]. However, these methods need essential data for companies associated with their productive know-how. This knowledge sharing makes companies extremely reluctant to cooperate and hence blocks the use of their flexibility.

In contrast, the inputs of the abovementioned tool were defined to avoid the provision of critical information of companies, trying to ease companies' collaboration. The weak point of the presented tool is the incapability to guarantee the maximum possible profit of using flexible processes [12]. The absence of any optimization algorithm does not allow the tool to capture all the benefits associated with load shifting and market participation. Therefore, it is necessary to choose on a daily basis, for each flexible process, the most profitable time periods to offer flexibility in reserve markets.

As presented in [12], [13], the flexibility of industrial processes has a complex response with several links between decision variables and intermediate dynamic information. This condition makes it difficult to achieve the formulation of the required optimization algorithm as a linear problem without altering its original features. To overcome this issue, we have selected a metaheuristic approach to maintain all the characteristics of a parametrized industrial process. Metaheuristic approaches are a valid alternative and a promising method to solve this type of optimization problem [16], [17], since they allow us to include all the links between variables without compromising computability.

Among the different metaheuristic methods, we selected the Particle Swarm Optimization (PSO) algorithm due to several positive features. Authors use it to solve electrical engineering problems, it can solve nonlinear problems, it has a high computation efficiency, it is robust and it can be easily adapted to solve any optimization problem [18].

Particle Swarm Optimization (PSO) is a nature-inspired technique developed by Eberhart and Kennedy [19]. In contrast with other genetic algorithms, each particle establishes its new position based on its own previous experience and those of its neighbours. The particle $\boldsymbol{i}$ at iteration $\boldsymbol{d}$ has a position defined by an n-dimension vector $\boldsymbol{x_{id} = (x_{id1}, x_{id2}, \ldots, x_{idn})^T}$ and particles' velocity is another n-dimension vector $\boldsymbol{v_{id} = (v_{id1}, v_{id2}, \ldots, v_{idn})^T}$. The parameter $\boldsymbol{p_{id}}$ shows the best visited position $\boldsymbol{(p_{id1}, p_{id2}, \ldots, p_{idn})^T}$ and $\boldsymbol{p_{gd}}$ represents the particle that had the best result of the swarm at iteration d. After a proposal to improve exploitation made by Shi and Eberhart [20], the velocity and position of the resulting particles commonly applied is:

$$\boldsymbol{v_{i(d+1)} = w * v_{id} + c_1 r_1 (p_{id} - x_{id}) + c_2 r_2 (p_{gd} - x_{id})} \qquad (1)$$

$$\boldsymbol{x_{i(d+1)} = x_{id} + v_{i(d+1)}} \qquad (2)$$

Where the characteristic parameters are inertia weight ($\boldsymbol{w}$), the cognitive and social scaling parameters ($\boldsymbol{c_1}$ and $\boldsymbol{c_2}$) and random numbers from a normal distribution ($\boldsymbol{r_1}$ and $\boldsymbol{r_2}$), these parameters must be specifically tuned for solving the targeted optimization problem.

Based on a real meat processing factory, the tool optimizes and evaluates the participation of four flexible processes (drying, maturing, freeze storing and slicing) in the Spanish tertiary reserve market. The operation results and the cost-benefit analysis involved largely improve the solution obtained with the previous tool [13], which used a margin of profit to decide whether or not to perform a DR event.

The optimization method included in the tool for the participation of industrial consumers in operation markets presented in this paper provides two main contributions to the existing literature:

- A new tool for evaluating the participation of flexible consumers in operation markets. The proposed solution respects the mathematical complexity of the original problem and optimizes the consumer profit through a tailored Parallel Particle Swarm Optimization (PPSO) algorithm. Furthermore, we applied it to a real case, and the results obtained validate the profitable participation of flexible processes of SMEs in reserve markets and the efficiency of a PPSO algorithm to model electrical engineering problems.

- A new mathematical codification of decision variables related to physical parameters of DR events in matrix format. This codification replaces the classical binary representation. The selected parameters are the starting time and the duration of each DR event, which allow movement from a non-linear binary problem to a non-linear integer problem.

The rest of the paper presents the following organization: Section 2 describes the problem description and mathematical approach of the problem. Section 3 describes the PSO algorithm and presents how it is tuned for this problem. Section 4 shows a real case application. Finally, Section 5 summarizes the main conclusions.

5.4. Problem description and mathematical approach

This section presents the problem and mathematical descriptions. Subsection A briefly describes the discussed problem. Subsection B deals with the decision variables and other parameters involved in the proposed optimization problem. Subsection C presents the objective function to be maximized and subsection D enumerates the constraints that apply in the calculation process.

5.4.1. Problem description

Flexibility is going to be essential in future power systems and demand side management will be a key part of it. These resources will participate under competition in operation markets. SMEs can offer their demand flexibility to the system in a cost-effective way, but they tend to lack the technical and human resources to effectively offer it. There is a need to assess how consumers could maximize the benefits associated with the participation of this flexibility based on technical and economic parameters. These parameters include power demand profiles, technical restrictions of flexible processes (maximum duration of reduction and minimum time between them), power available for flexibility (capacity band), reserve market price and electricity supply price. It is also important to prepare these analyses for future changes such as future quarter-hourly markets and contractual restrictions. In this sense, the tool aims to solve this problem and optimize the potential profits of providing the flexibility of SME’s processes in reserve markets and at the same time shifting electricity usage to periods when electricity is cheaper

5.4.2. Description of the variables

To optimize the participation of DR processes in reserve markets the decision makers need different parameters. First, the energy delivery ($\boldsymbol{\pi}_{tdm}^{ED}$) and capacity ($\boldsymbol{\pi}_{tdm}^{CB}$) prices of the involved reserve market for the evaluation period. Second, the power reduction that a DR event may imply during, before and after the events. Third, the electricity prices ($\boldsymbol{\pi}_{tdm}^{e}$) associated with the flexible consumer's electricity supply contract. Fourth, the initial investment ($\boldsymbol{CF}_{g}$) to adapt an industrial flexible process to participate actively in reserve markets. Fifth, the variable cost ($\boldsymbol{CV}_{gdm}$) associated with the implementation of flexibility.

The main features to characterize a flexible process are illustrated in Figure 5.1. Based on the tool and technical requirements previously developed by authors in [12], the figure shows the power variations during, before and after a DR event, as well as their timings. Following the methodology illustrated in [14], the parameters of each process are characteristic for each month of a year considering the particularities of each process, the type of day and the potential seasonality linked to the effect of external weather conditions or the variations in production. This allows us to obtain the maximum power capacity to offer ($\Delta\boldsymbol{P}_{gdm}^{1}$), the maximum duration of a DR event ($\boldsymbol{T}_{gdm}^{Max}$) and the minimum time between two consecutive DR events ($\boldsymbol{T}_{gdm}^{Min}$).

The power required during the preparation ($\Delta\boldsymbol{P}_{rgdm}^{2}$) and recovery ($\Delta\boldsymbol{P}_{rgdm}^{3}$) periods of a DR event depends on the duration of the event, type of day and flexible process, as well as the month. Consequently, a set of formulas describe how these parameters vary according to the mentioned variables, but all of them depend on the duration of each specific DR event.

This feature provides the mathematical formulation enough flexibility to optimize different types of nonlinear responses. In the same way, similar restrictions apply to the duration of the preparation (T^2_{rgdm}) and recovery (T^3_{rgdm}) periods, as shown below:

$$\Delta P^2_{rgdm} = f(D_{rgdm}) \quad (3)$$

$$T^2_{rgdm} = f(D_{rgdm}) \quad (4)$$

$$\Delta P^3_{rgdm} = f(D_{rgdm}) \quad (5)$$

$$T^3_{rgdm} = f(D_{rgdm}) \quad (6)$$

Therefore, the dependency among all these variables causes a nonlinearity in the optimization process which makes it impossible to use linear programming algorithms without modifying the proposed formulation.

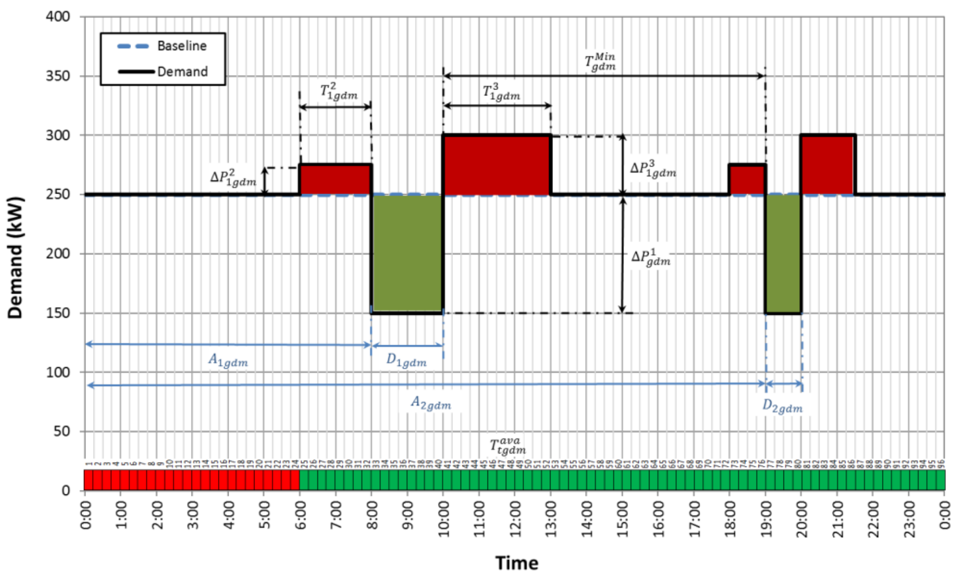

Figure 5.1. Parameters' description of a DR event.

The optimization of a flexible process occurs daily considering the results from the previous day. Regarding decision variables represented in Figure 5.1, two types of variables define a DR event, $\boldsymbol{A_{rgdm}}$ and $\boldsymbol{D_{rgdm}}$. $\boldsymbol{A_{rgdm}}$ holds the number of the period when the event starts, while $\boldsymbol{D_{rgdm}}$ represents the duration of the event expressed as the number of time intervals. Moreover, $\boldsymbol{S_{tgdm}}$ is an auxiliary binary variable that indicates the start of a DR process.

5.4.3. Objective function

The objective function considers the consequences of the participation in the reserve markets to maximize the industrial consumer's performance. The first term of the objective function relates to all income obtained for the participation in the market. This participation can provide revenues associated with both capacity and energy delivery. The second term represents the variable costs which the customer incurs for participating in the market. The final three elements characterize the shifts in electricity consumption. While the reduction during the event generates a net profit, the increase of electricity consumed for preparing and recovering of the event has a net cost.

$$\boldsymbol{Max}\left[\sum_{r}^{R_{dm}}\left(\sum_{t=A_{rgdm}}^{t=A_{rgdm}+D_{rgdm}-1}\left(\left(\pi_{tdm}^{CB}+\pi_{tdm}^{ED}*t_{PTU}\right)*\Delta P_{gdm}^{1}-CV_{gdm}*t_{PTU}+\pi_{tdm}^{e}*\Delta P_{gdm}^{1}*t_{PTU}\right)-\sum_{t=A_{rgdm}-T_{rgdm}^{2}-1}^{t=A_{rgdm}-1}\pi_{tdm}^{e}*\Delta P_{rgdm}^{2}*t_{PTU}-\sum_{t=A_{rgdm}+D_{rgdm}}^{t=A_{rgdm}+D_{rgdm}+T_{rgdm}^{3}}\pi_{tdm}^{e}*\Delta P_{rgdm}^{3}*t_{PTU}\right)\right] \quad (7)$$

The objective function applies to each flexible process ($\forall \boldsymbol{g \epsilon G}$) every day during a whole year ($\forall \boldsymbol{d \epsilon D_m}, \forall \boldsymbol{m \epsilon M}$) in chronological order, considering the result of the previous day, the availability of the reducible power and the market prices one day ahead.

5.4.4. Constraints

The participation of the industrial consumer in the reserve market needs to fulfil the physical constraints of the processes, expert's recommendations and some economic constraints decided by the consumer. First, the duration of any event must be shorter than its technical time restriction.

$$\boldsymbol{D_{rgdm} \leq T_{gdm}^{Max}}, \forall \boldsymbol{r} \in \boldsymbol{R_{dm}}, \boldsymbol{g} \in \boldsymbol{G}, \boldsymbol{d} \in \boldsymbol{D_m}, \boldsymbol{m} \in \boldsymbol{M} \qquad (8)$$

Consecutive events must occur respecting the minimum time between events. Therefore, the first event of the day will have to consider the last event of the previous day, the rest of them will consider the minimum duration between events, while the last one will have to occur inside the day ***d***.

$$\boldsymbol{A_{1gdm} - T_{1gdm}^{2} \geq T_{gdm}^{E}}, \quad \forall \boldsymbol{g} \in \boldsymbol{G}, \boldsymbol{d} \in \boldsymbol{D_m}, \boldsymbol{m} \in \boldsymbol{M} \qquad (9)$$

$$\boldsymbol{A_{(r+1)gdm} \geq A_{rgdm} + D_{rgdm} + T_{gdm}^{Min}}, \quad \forall \boldsymbol{r} \in \boldsymbol{R_{dm}}, \boldsymbol{g} \in \boldsymbol{G}, \boldsymbol{d} \in \boldsymbol{D_m}, \boldsymbol{m} \in \boldsymbol{M} \qquad (10)$$

$$\boldsymbol{A_{(r+1)gdm} \geq A_{rgdm} + D_{rgdm} + T_{(r+1)gdm}^{2} + T_{rgdm}^{3}}, \quad \forall \boldsymbol{r} \in \boldsymbol{R_{dm}}, \boldsymbol{g} \in \boldsymbol{G}, \boldsymbol{d} \in \boldsymbol{D_m}, \boldsymbol{m} \in \boldsymbol{M} \qquad (11)$$

$$\boldsymbol{1 \leq A_{rgdm} \leq T_d - D_{rgdm}}, \quad \forall \boldsymbol{r} \in \boldsymbol{R_{dm}}, \boldsymbol{g} \in \boldsymbol{G}, \boldsymbol{d} \in \boldsymbol{D_m}, \boldsymbol{m} \in \boldsymbol{M} \qquad (12)$$

On each day, a maximum number of DR events per process ($\boldsymbol{E^{Max}_{gdm}}$) and their total duration $\boldsymbol{D^{Max}_{gdm}}$ is set before starting the calculation process, considering consumers' preferences and market rules.

$$\sum_{t}^{T} \boldsymbol{S_{tgdm}} \leq \boldsymbol{E^{Max}_{gdm}}, \forall \boldsymbol{g} \in \boldsymbol{G}, \boldsymbol{d} \in \boldsymbol{D_m}, \boldsymbol{m} \in \boldsymbol{M} \tag{13}$$

$$\sum_{r}^{R_{dm}} \boldsymbol{D_{rgdm}} \leq \boldsymbol{D^{Max}_{gdm}}, \forall \boldsymbol{g} \in \boldsymbol{G}, \boldsymbol{d} \in \boldsymbol{D_m}, \boldsymbol{m} \in \boldsymbol{M} \tag{14}$$

The reducible power of each flexible process is available during a specific period on a day $\boldsymbol{d}$ in a month $\boldsymbol{m}$, and hence the process is not able to deliver the reducible power outside of this period.

$$\begin{gathered} \boldsymbol{1} \leq \boldsymbol{T^{ava}_{tgdm}}, \forall \boldsymbol{t} \in \{\boldsymbol{A_{rgdm}}, \boldsymbol{A_{rgdm}} + \boldsymbol{D_{rgdm}} - \boldsymbol{1}\}, \\ \forall \boldsymbol{r} \in \boldsymbol{R_{dm}}, \boldsymbol{g} \in \boldsymbol{G}, \boldsymbol{d} \in \boldsymbol{D_m}, \boldsymbol{m} \in \boldsymbol{M} \end{gathered} \tag{15}$$

It is important to highlight that metaheuristic algorithms do not work directly with constraints, and hence it is necessary to include a penalty in the objective function if the solution is not a feasible solution of the problem.

5.5. PSO's parameter adjustments

Metaheuristic algorithms greatly depend on the adjustment of certain parameters to ensure efficient optimizations. It is necessary to carry some tests to tune the algorithm. Damping factor, inertia coefficient, cognitive and social scaling parameters ($\boldsymbol{c_1}$ and $\boldsymbol{c_2}$ respectively) are the main adjustment parameters in the PSO algorithm. Additionally, two other parameters have been studied to solve the problem described above:

- Percentage of particles without movement (stop criterion). This parameter expresses the number of particles with a zero-velocity vector in an iteration. Meaning that this swarm has reached the maximum in the iteration and allowing us to avoid unnecessary iterations. Tuning this parameter aims to reduce calculation time.

- Percentage of initialized particles inside the feasible solution space. Due to the nature of the presented problem, particle initialization highly correlates with the probability of finding a global maximum as a problem solution. To improve it, a loop ensures a certain number of initialized particles inside the feasible solution space.

Different tests with real data of energy and market prices have determined the adjustment of these parameters in four flexible adjustment processes. Each process has a different correlation between event duration and duration of recovery period. In this sense, process 1 has no recovery period, but it has a cost of impact on the productivity of the process. Processes 2, 3 and 4 have respectively a recovery period of three, two and one times the duration of the event.

The next subsections present and discuss the obtained results for each different test. At each comparable configuration, 100 tests determined the optimal value depending on its success rate, defined as the finding of a global maximum of each process and the total (previously calculated using deterministic methods). This analysis also considers other parameters such as the total daily profit, the successful first iteration and calculation time.

All the tests performed in this section considered the following default values: each swarm has 100 particles, the cognitive and social scaling parameters are equal to 2, social inertia coefficient value is 1 with a damping factor of 0.99, the number of initialized particles in the feasible region and the percentage to stop the algorithm are both 100% and the maximum iterations are 500.

5.5.1. Cognitive and social scaling parameters

Kennedy et al., state that the sum of both cognitive and social scaling parameters should be a value close to four [21]. Nevertheless, in a previous work [19], the same author did some testing and concluded that the social scaling parameter tends to increase the probability to get caught in a local maximum. Therefore, he proposed a solution based on the asymmetry of the components, giving more weight to the cognitive component.

Regarding these premises, it is necessary to adjust both parameters considering that the feasibility space of the solutions is unknown. A sensitivity analysis varying these coefficients from 0.5 to 2 showed the success rate and the dispersion of the total net profit. The results presented in Table 5.1 validate how better results arise from setting the cognitive scaling parameter to 2 and 1.75, obtaining for both a total success rate of 11%.

Table 5.1. Cognitive scaling parameter sensitivity analysis

C_1	2	1,75	1,5	1	0,5
Process 1	55%	51%	39%	39%	37%
Process 2	69%	64%	50%	40%	25%
Process 3	54%	59%	41%	25%	11%
Process 4	53%	63%	59%	35%	22%
Total	**11.0%**	**11.0%**	**8.0%**	**2.0%**	**0.0%**

In Figure 5.2, a box and whisker plot represents the daily net profit for each calculation. This representation shows how with larger values of the cognitive scale parameter (2 and 1.75), the simulations present higher medians and smaller dispersion. In conclusion, these values provide better simulating results. The maximum daily net profit is 195.96 €/day. For the case of c_1 equal to 2, the median value is 191.7 €/day with a standard deviation of 3.27 €/day, while the median value for c_1 equal to 1.75 is 191.2 €/day with a standard deviation of 3.42 €/day.

Table 5.2 shows how the social scaling parameter (c_2) is more influential

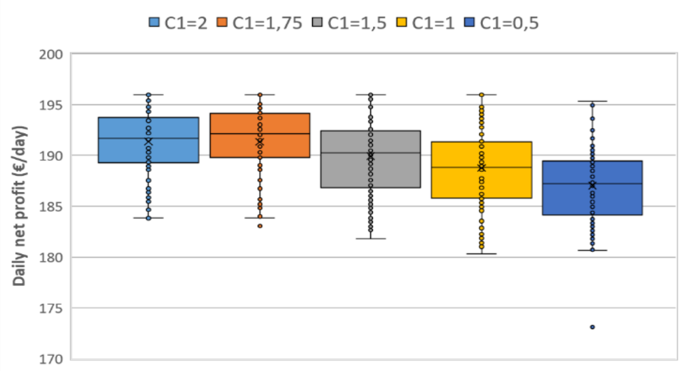

Figure 5.2. Daily net profit with respect to C_1.

in the success rate than c_1. Smaller values of c_2 considerably reduce this rate. Therefore, the best value for c_2 will be 2, which provides an average success rate of 11%.

Table 5.2. Social scaling parameter sensitivity analysis

C_2	2	1,75	1,5	1	0,5
Process 1	55%	50%	47%	17%	2%
Process 2	65%	54%	31%	27%	1%
Process 3	55%	40%	22%	18%	1%
Process 4	66%	59%	33%	19%	1%
Total	**11.0%**	**6.0%**	**1.0%**	**1.0%**	**0.0%**

Figure 5.3 represents the same box and whisker plot for c_2. As well as for c_1, higher values (2 and 1.75) present higher medians and smaller dispersion. These values provide better simulating results. For the case of c_2 equal to 2, the median value is 191.9 €/day with a standard deviation of

3.42 €/day, while the median value for c_2 equal to 1.75 is 191 €/day with a standard deviation of 3.32 €/day.

The last analysis of this subsection considers a matched variation of

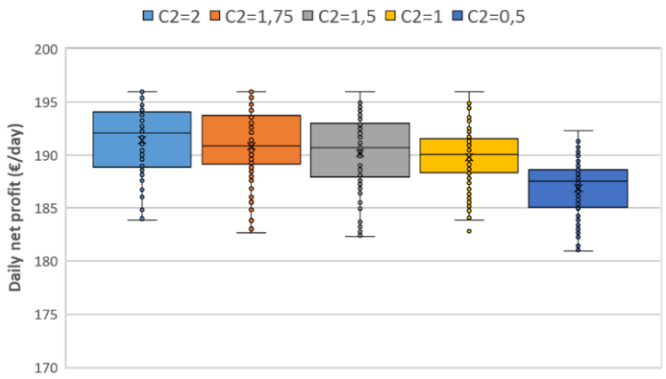

Figure 5.3. Daily net profit with respect to C_2.

both c_1 and c_2 parameters to see the effect of their reduction. The obtained results are clearer, and the algorithm obtains the best adjustment if both scaling parameters are set in 2. Table 5.3 shows an average success rate of 9%, while setting both at 1.75 will diminish it to 3%.

Table 5.3. Cognitive & social scaling parameter sensitivity analysis

C_1 & C_2	2	1,75	1,5	1	0,5
Process 1	50%	50%	28%	3%	1%
Process 2	57%	58%	17%	8%	1%
Process 3	61%	37%	20%	5%	1%
Process 4	70%	46%	21%	4%	1%
Total	**9.0%**	**3.0%**	**1.0%**	**0.0%**	**0.0%**

However, the variation between 2 and 1.75 does not affect the total profits. As can be seen in Figure 5.4 for the case of c_2 equal to 2, the median value is 191.3 €/day with a standard deviation of 3.41 €/day, while the median value for c_2 equal to 1.75 is 191 €/day with a standard deviation of 3.41 €/day. Showing that not much difference in the result is observed for this problem.

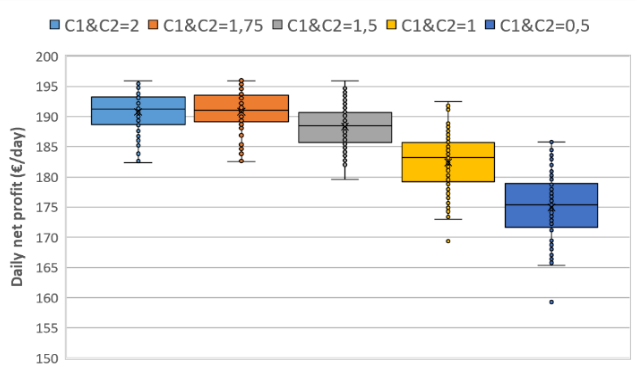

Figure 5.4. Daily net profit with respect to C_1&C_2.

Finally, Table 5.4 shows the different time values for each simulation. It can be concluded that varying these paraments does not affect the computational time.

Table 5.4. Computational time sensitivity analysis.

Time	2	1,75	1,5	1	0,5
C_1	2.23s	2.24s	2.25s	2.26s	2.33s
C_2	2.23s	2.24s	2.25s	2.25s	2.14s
C_1&C_2	2.22s	2.25s	2.24s	2.26s	2.07s

Regarding the different values obtained and following the recommendations of Kennedy et al. [21], both cognitive and social scaling parameters were set at 2 for the simulations in the case study.

5.5.2. Damping factor

The first version of the PSO algorithm did not include this coefficient [19], which was included afterwards by its authors [20]. The damping factor tries to balance the exploration of possible optimums and the capacity of the particles to converge into a solution. Shi and Eberhart [22] stated that large inertia coefficients enhance the global search of solutions, while a smaller ones improves local search. Many authors have tried to find the best dynamic adjustment of this coefficient.

A comparison of different strategies to dynamically obtain this coefficient occurs in [18]. The results of this study show that the better strategies to obtain the minimum error are "Constant Inertia Weight" and "Linear decreasing Inertia Weight", while the least average error can be obtained with "Chaotic Inertia Weight". Nevertheless, the presented algorithm uses a different controlled inertia weight. In this case, a constant damping factor multiplies the inertia coefficient in each iteration as shown in Eq. (14).

$$\boldsymbol{\omega_{i+1} = \lambda_{\omega}\omega_i} \qquad (16)$$

This method provides different ways to dynamically modify the inertia coefficient depending on the selected damping factor. Some authors propose a damping factor of $\boldsymbol{\lambda_{\omega}}$ equal to 1, but Kalivaraput et al. [23] propose a damping of 0.95 as the optimal. The use of different damping factors explores the best strategies to obtain the inertia coefficient in the presented problem. Figure 5.5 shows the evolution of the inertia coefficient at each iteration applying different damping factors.

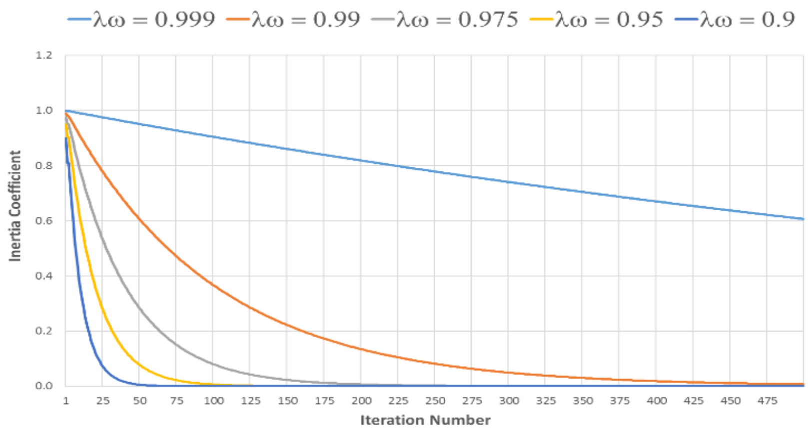

Figure 5.5. Inertia coefficient evolution.

Table 5.5 shows the best damping factor with a value of 0.99, which provides a success rate of 19%. However, process 2 has long recovery periods and the best damping factor for it resulted in 0.999. This shows an interesting research point to determine why some processes are better suited for different damping factors.

Table 5.5. Dumping factor parameter sensitivity analysis.

λ_ω	0,999	0,99	0,975	0,95	0,9
Process 1	55%	65%	50%	58%	51%
Process 2	72%	59%	64%	69%	61%
Process 3	58%	65%	55%	56%	49%
Process 4	61%	66%	50%	59%	60%
Total	**14.0%**	**19.0%**	**4.0%**	**14.0%**	**6.0%**

In Figure 5.6 a box and whisker plot represent the daily net profit for each damping factor. For all cases the median and the standard deviation values are very similar. Therefore, we select a value of λ_ω equal to 0.99 with a median value of 192 €/day and a standard deviation of 3.58 €/day. As in the

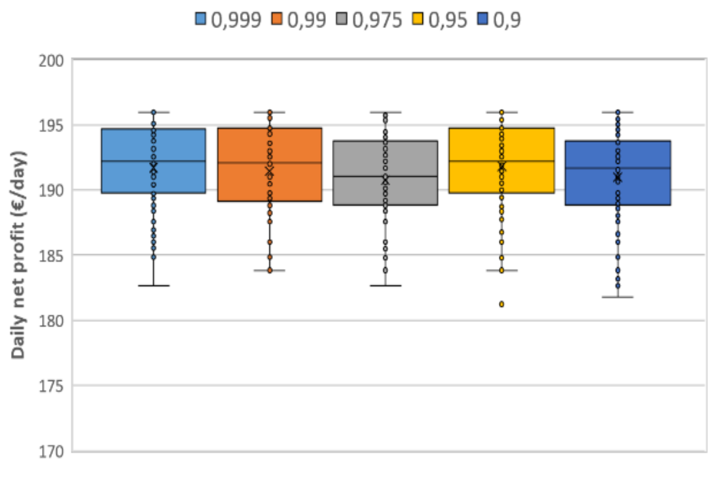

Figure 5.6. Daily net profit by damping factors.

case of cognitive and social scaling factors, no meaningful computational time differences exist between damping factors.

5.5.3. Initialized particles within the feasible zone

Aiming to reduce the computational time of each simulation, we performed an analysis of each of the described tests dividing the algorithm in two parts. First, the algorithm initializes the particles. Then, the algorithm performs an iterative process to find a global maximum that ends after reaching the maximum number of iterations or other stop criteria.

This process of analysis showed that simulation consumed 60% of the time in the loop for initializing the particles in the feasible zone. Table 5.6 shows how less initialized particles reduce successful cases. This might seem obvious. However, a closer analysis shows how passing from larger rates of initialized particles to lower rates does not always imply a reduction in the total number of successful cases. This might occur because the proposed value of the initialized particles fixes the lower limit but more particles than the proposed number can be inside the feasible solution space.

Table 5.6. Particle initialization sensitivity analysis.

Initialization	100%	75%	50%	25%	10%
Process 1	51%	62%	54%	49%	55%
Process 2	68%	68%	59%	53%	58%
Process 3	55%	60%	49%	45%	47%
Process 4	68%	58%	60%	54%	58%
Total	**14.0%**	**14.0%**	**4.0%**	**5.0%**	**7.0%**

Figure 5.7 shows the different studied parameters. Initializing 100% or 75% of the particles in the feasible solution space achieves a median daily profit of 192.2 €/day and standard deviation of 3.41 €/day and 3.21 €/day respectively. The rest of the options had values below these numbers. Therefore, the rest of the options are only recommended to be used when computational cost is a priority.

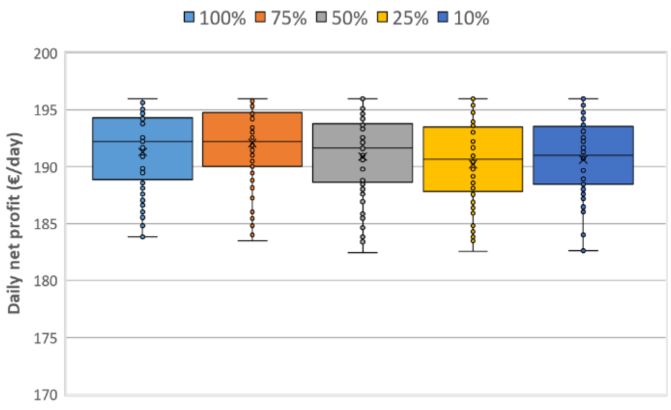

Figure 5.7. Daily net profit respect initializations.

Table 5.7 shows the different computing average times for the different processes, as well as the sum of all of them. In this respect, minor reductions in accuracy reduce the computational time. This can help and speed up complex models. In this case, 100% of initialized particles ensure the reliability of the results.

Table 5.7. Average particle initialization calculation time.

Initialization	100%	75%	50%	25%	10%
Process 1	4.01s	3.55s	3.18s	2.73s	2.45s
Process 2	9.15s	7.37s	5.56s	3.92s	3.00s
Process 3	8.72s	6.99s	5.36s	3.90s	2.94s
Process 4	4.05s	3.61s	3.20s	2.77s	2.51s
Total	**25.92s**	**21.53s**	**17.31s**	**13.32s**	**10.90s**

5.5.4. Inactive particles

As previously discussed, we included an additional criterion that revises the particle velocity in each iteration. If the percentage of particles without movement is higher than a set number, the algorithm considers that the search for a global maximum has already finished. Table 5.8 represents the success rate regarding the number of particles that must stop in order to finish the algorithm. If fewer particles need to have a zero velocity to stop it, success rate tends to diminish. However, this does not seem to occur with the percentage of 90%, which has a higher success rate than considering 100% of inactive particles.

Table 5.8. Inactive particles sensitivity analysis.

Inactive P.	25%	50%	75%	90%	100%
Process 1	49%	55%	52%	60%	48%
Process 2	46%	68%	72%	67%	68%
Process 3	38%	54%	51%	52%	55%
Process 4	60%	53%	54%	64%	65%
Total	**6.0%**	**8.0%**	**3.0%**	**13.0%**	**9.0%**

The results are completely different when the analysis considers the daily net profit. Figure 5.8 shows how in this case, 75% and 90% of inactive particles present the same median, higher than the rest of the percentages chosen. Therefore, both values are valid according to these results.

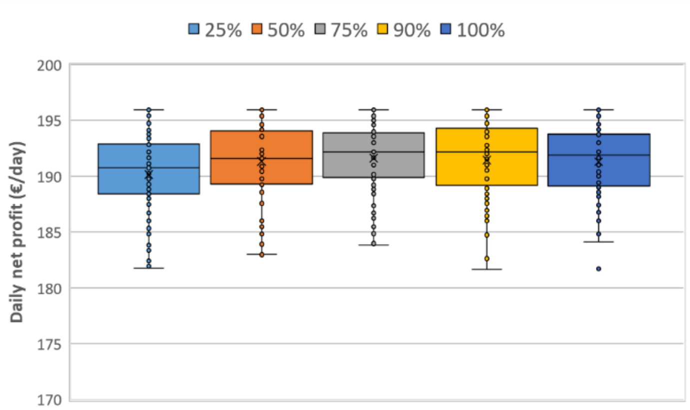

Figure 5.8. Daily net profit with respect to Inactive particles.

Finally, the analysis of the calculation time for each percentage of inactive particles in Table 5.9 shows that only a significant reduction occurs if the rate is set to 25%. Nevertheless, this value considerably reduces the success rate. After this analysis, it can be determined that a value between 75% and 90% could be selected. Therefore, a value of 90% was chosen according to the presented results.

Table 5.9. Inactive particles calculation time.

Inactive P.	**25%**	**50%**	**100%**	**75%**	**90%**
Process 1	1.87s	3.52s	4.30s	4.25s	4.28s
Process 2	6.85s	8.56s	8.78s	8.67s	8.80s
Process 3	6.90s	8.19s	8.88s	8.15s	8.72s
Process 4	1.94s	4.08s	4.25s	4.22s	4.21s
Total	**17.57s**	**24.35s**	**26.20s**	**25.29s**	**26.01s**

5.5.5. Number of particles

The size of the swarm depends on the specific problem solved [9]. Large numbers of particles are not necessary to obtain good quality results. The same study states that 10 particles could be enough to solve almost any problem. However, more complex problems need between 100 and 200 particles to obtain reliable results. Following these considerations, we tested swarms between 5 and 500 particles to show that swarms with more than 200 particles do not improve the results. However, less than 10 particles do not provide optimal results.

Table 5.10. Number of particles sensitivity analysis

n Particles	5	50	100	200	500
Process 1	2%	49%	50%	66%	79%
Process 2	1%	37%	69%	83%	95%
Process 3	1%	40%	55%	70%	92%
Process 4	4%	51%	69%	77%	90%
Total	**0.0%**	**2.0%**	**14.0%**	**27.0%**	**64.0%**

Table 5.10 shows success rates regarding the number of particles. In this case, there is a positive correlation between number of particles and success rates. In process 1 not even 500 particles are enough to provide reliable results. Moreover, 500 particles do not guarantee a total success rate but only 64%.

Figure 5.9 shows a similar pattern, the dispersion for larger number of particles does not vary in excess. This data reinforces the idea that populations of 100, 200 and 500 provide similar results. The three samples have the same median 192.2 €/day, and the standard deviation ranges from 3.44 €/day for 100 particles to 2.40 €/day for 500 particles.

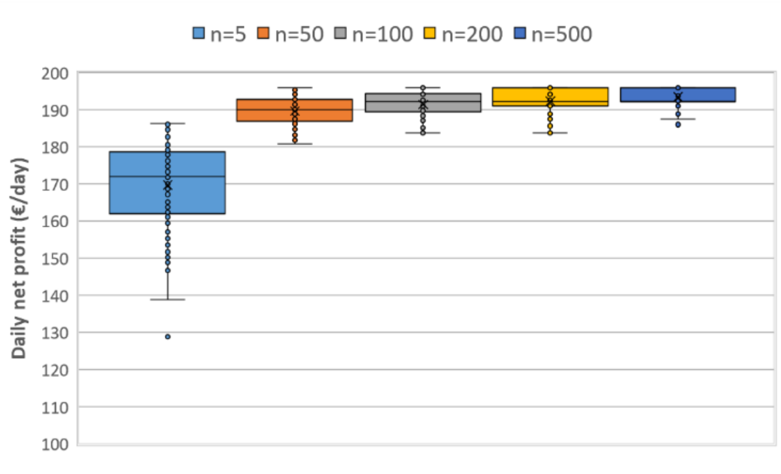

Figure 5.9. Daily net profit with respect to number of particles.

These results show how the probability of obtaining the global maximum of four processes only reached 65% with 500 particles. Moreover, the computational times invested in each simulation showed that this time was proportional to the swarm population in an average (0.25 s/particle) as Table 5.11 presents.

Table 5.11. Number of particles calculation time.

n Particles	**5**	**50**	**100**	**200**	**500**
Process 1	0.18s	2.06s	4.26s	8.48s	21.00s
Process 2	0.39s	4.24s	8.44s	16.89s	41.58s
Process 3	0.37s	4.08s	8.18s	17.05s	41.87s
Process 4	0.19s	2.11s	4.26s	8.61s	21.21s
Total	**1.12s**	**12.49s**	**25.14s**	**51.02s**	**125.65s**

To overcome the computational burden, parallel computing is used by sending an individual problem to each core. Therefore, the premature convergence problem is solved by distributing local maximums in the solution space with different initial positions using Parallel Particle Swarm

Optimization [24]. Table 5.12 presents the results obtained with the application of parallel computing with four independent cores. Four independent swarms of 200 particles present much better results than one swarm of 500 particles in half of the total computational time.

Table 5.12. Parallel computing calculation time.

PC	200	500	4x200	200	500	4x200
Process 1	66%	79%	99%	8.5s	21.0s	10.4s
Process 2	83%	95%	100%	16.9s	41.6s	21.5s
Process 3	70%	92%	99%	17.0s	41.9s	20.8s
Process 4	77%	90%	100%	8.6s	21.2s	10.0s
Total	**27.0%**	**64.0%**	**98.0%**	**51.0s**	**125.7s**	**62.7s**

To sum up, Table 5.13 shows the final values for the PSO parameters, which will be used in the simulation of the case study.

Table 5.13. PSO optimization values.

Coefficient	Value
C_1	2
C_2	2
λ_ω	0.99
Initialized P.	100%
Inactive P.	90%
n Particles	200x4

5.6. Application and case study

We apply the PPSO optimization to the participation of a meat factory in the Spanish tertiary reserve market during a whole year. Selecting this period and factory allows us to compare the novel solution with a profit margin decision making methodology presented in [12].

Currently, no market participation is allowed to DR resources in the Spanish operation market apart from the interruptible service for electro intensive consumers, which have to provide at least 5 MW. However, with the European integration directive [25], the Spanish regulator will have to allow demand resources to participate in operation markets in the same conditions as generators. In this regard, most small and medium consumers will rely on the figure of aggregators to participate in these markets [2].

Therefore, simulating a typical DR contract with an aggregator was established with limits for the number of events and total hours per day. In this case study, the total hours per day for which the consumer can be asked to provide flexibility was set at three hours, while the total number of events per day was four. These numbers are only the upper limits for the optimization algorithm, which will calculate the optimal values depending on the profits obtained in each case. On the one hand, four events per day determined an upper limit that the optimized solution never reached for any process in the completely modelled year. In case this appeared as a limiting factor, the tool accepts an increase in the number of events. On the other hand, a maximum value of three hours per day intends not to affect industrial production too much and to be similar to other demand response contracts available in several markets, as stated above.

The different flexible processes of the meat factory were presented in [12] and its main characteristics are summarized in Table 5.14 This factory focuses on the drying of ham and slicing different products. The two other flexible processes correspond to maturing and a controllable freezing store. Each of them provided flexibility based on its characteristics:

-**Drying**: disconnection of the end units in charge of controlling the drying process, while maintaining the temperature and relative humidity between preestablished levels. This process entails a production cost due to possible delays in the industrial process even though no delay could be observed during the different tests performed.

-**Maturing**: disconnection of the end units in charge of maturing the ham. This stage is characterized by larger drying periods.

-**Freezing store**: thermally controllable loads inside the freezing store, which has thousands of tons of frozen product inside it, providing a vast thermal inertia.

-**Slicing**: disconnection of the air handling units in the slicing area allowed by the thermal inertia of the installations.

Table 5.14. DR processes characteristics.

Parameters	ΔP^{1}_{gdm}	ΔP^{2}_{rgdm}	ΔP^{3}_{rgdm}	T^{Max}_{gdm}	T^{2}_{rgdm}
Units	kW	kW	kW	hour	hour
Drying	283	0	0	2	0
Maturing	102	0	34	3	0
Freezing	70/45(1)	0	35/22.5(1)	3	0
Slicing	82/36(1)	0	82/36(1)	1/2(1)	0

Parameters	T^{3}_{rgdm}	T^{ava}_{tgdm}	T^{IA}	T^{Min}_{gdm}	**Rec**
Units	hour	hour	hour	hour	(2)
Drying	0	24	0.25	4	N
Maturing	9	24	0.25	4	N
Freezing	6	24	0.25	4	N
Slicing	1/2(1)	Mo6-Sa6	0.25	4	N

(1) Summer / Winter

(2) If it is possible to postpone the recovery period. Yes and No

To make the different simulations and compare, we use data from 2013. A flexibility study in the factory provided all the data. The electricity tariff contracted by the factory has 6 different periods with fixed prices, corresponding to a 6.1 contract under Spanish legislation [26]. Table 5.15 shows the prices used in the simulation.

Table 5.15. Electricity tariff prices (€/kWh).

Tariff period	P1	P2	P3	P4	P5	P6
Electricity price	0.12	0.10	0.09	0.08	0.07	0.06

Although the studied company had an electricity supply contract based on fixed prices, the simulation tool internally works as if they were quarter-hourly prices, so there is no difference in the search for the maximum daily profit when it works with daily wholesale market prices.

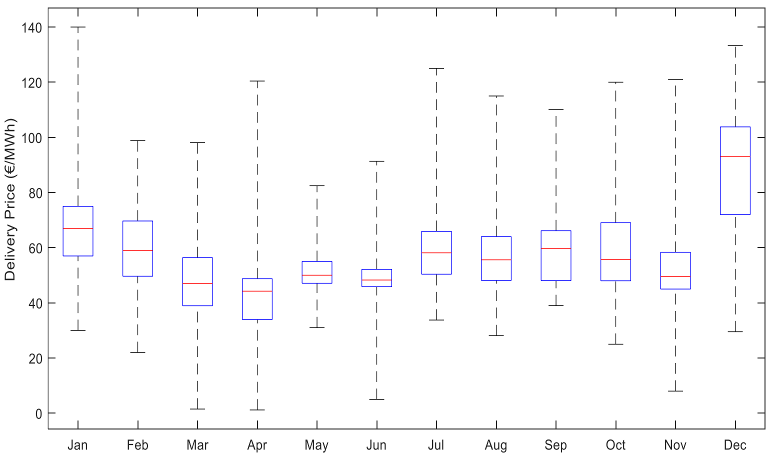

Figure 5.10. Monthly tertiary reserve prices.

Regarding the different prices in the operation, Figure 5.10 shows the monthly distribution of hourly prices of upwards tertiary energy reserve in

2013 [27], although the tool also works as if they were quarter-hourly prices. This resource was active between 33% and 59% hours during different months. The maximum price reached was 140 €/MWh in January, while the maximum median price was reached in December with 93 €/MWh.

With these parameters, the different PPSO evaluated the results arising from optimizing the daily participation of each one of the four processes throughout the 365 days of a year in the market. Figure 5.11 shows the results obtained with the methodology related to the margin of decision considering 20% profit over the flexibility implementation. This percentage allows us to adjust the minimum offer price for which each flexible process triggers its participation in the market. This rate obtained the best result in the profit margin tool. The larger net profit by energy reduced in a month ascended to 102.3 €/MWh in December, while the annual average is 76.2 €/MWh. This ratio is the difference between incomes and variable costs. In this case, the annual reduced energy is 513.4 MWh, which produces a total profit of 39,123 € after earning 73,525 € and has a total variable cost of 34,402 €.

Figure 5.12 presents the results obtained with the PPSO simulation tool. This figure also shows December as the most profitable month. The net profit per energy reduced rises to 151.4 €/MWh instead of the previous 102.3 €/MWh, while the annual average increases from 76.2 €/MWh to 106 €/MWh. These results present an increase of approximately 40% of the unitary profit compared with the profit of the previous tool. With the PPSO simulation tool, the annual reduced energy is 513.4 MWh, which produces a total profit of 53,905 € after earning 87,452 € and having a total variable cost of 33,547 €.

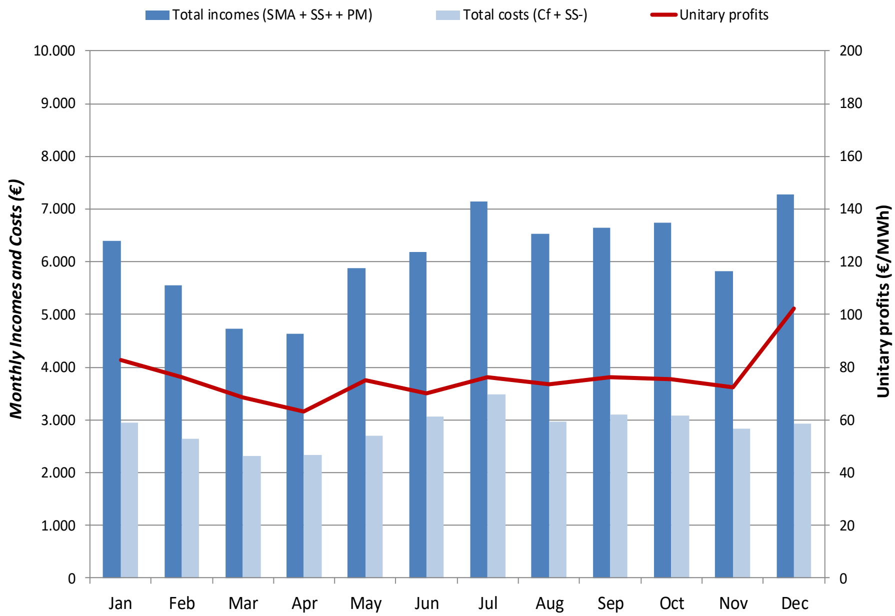

Figure 5.11. Monthly profits without PSO optimization.

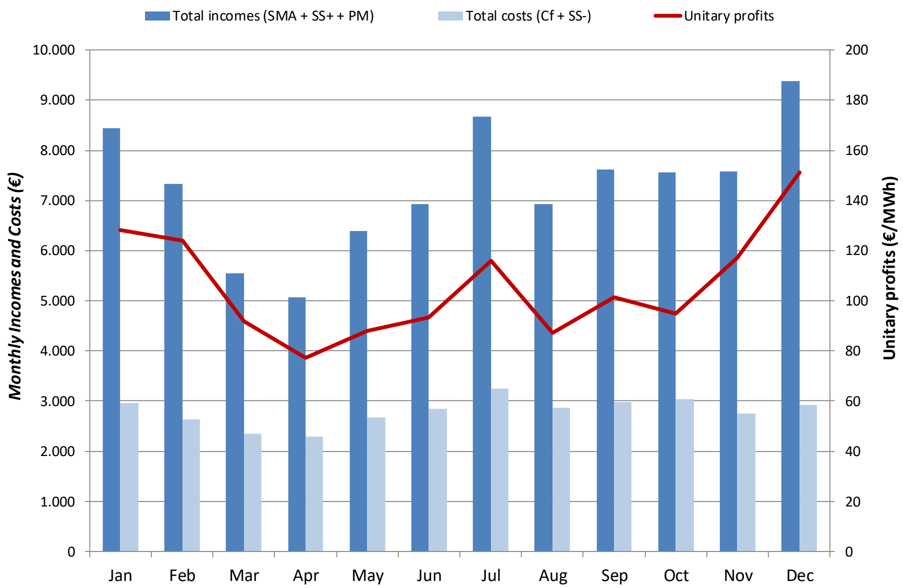

Figure 5.12. Monthly profits with PSO optimization.

The initial investment costs ($\sum_{g}^{G} \boldsymbol{CF_g}$) necessary to prepare the identified processes are approximately 44,500 €. These costs include the study and the flexibility validation, the required monitoring and control equipment, including the modification of existing control systems and other costs on certification processes and documentation.

To show the profitability of industrial consumers participating in tertiary reserve markets, different economic indicators analyzed the participation. The Net Present Value (NPV), Internal Rate of Return (IRR) and the Discounted Payback Period (DPP) are analyzed for a 3-year period. Table 5.16 shows the different values obtained for each process of these indicators. For a typical 10% investment rate (r), the NPV has risen from 52,793 € to 89,553 €, meaning a 70% increase on capital profitability. The values obtained for the IRR show an improvement in all the processes. In total, the IRR has grown from 70% to above one hundred per cent (108%).

Table 5.16. Main economic indicators summary.

Method of decision making	**Flexible process**	**NPV (€)**				**IRR (%)**	**DPP (years)**
		r = 5%	**r = 10%**	**r = 15%**	**r = 20%**		
Simulation tool based on margin of decision	Drying	49,707	43,960	39,009	34,712	136%	0.7
	Maturing	3,822	2,362	1,104	12	20%	2.5
	Freezing	6,250	5,056	4,028	3,136	45%	1.7
	Slicing	2,263	1,416	686	52	20%	2.5
	Total	62,042	52,793	44,827	37,912	70%	1.3
Simulation tool based on PPSO	Drying	72,142	64,447	57,819	52,066	189%	0.5
	Maturing	14,837	12,420	10,339	8,532	59%	1.4
	Freezing	11,615	9,956	8,526	7,286	77%	1.2
	Slicing	3,701	2,729	1,891	1,164	30%	2.1
	Total	102,295	89,553	78,576	69,049	108%	0.9

With the same discount rate, the DPP of all the processes decreases, reaching in total an improvement from 1.3 years to just 0.9 years. These results exhibit an easy commercial exploitation of these flexible resources by third agents such as Virtual Power Plants or aggregators due to the large profit margins observed.

Paying attention to each individual process, it is important to note that the process with the largest improvement is the one with the largest recovery period, maturing. For a typical 10% investment rate (r), the NPV of this process has risen from 2,362 € to 12,420 € and the DPP has reduced from 2.5 years to 1.4 years, as well as the IRR having grown from 20% to around 60%. This is one of the stronger points of the PPSO simulation tool compared with its predecessor.

The PSO algorithm was implemented in MATLAB from scratch and solved with a machine with 8 GB RAM and Intel(R) Core (TM) i7-7700 CPU clocked at 3.6 GHz with 4 main cores.

5.7. Conclusions

The massive integration of renewable energy sources in power systems requires an increase in the use of flexible resources from both the generation and demand side. These resources will participate, in a competitive context, in operation markets to guarantee the security of supply of the system. Small and medium industrial consumers can offer their demand flexibility to the system in a cost-effective way. However, it is still necessary to develop tools to evaluate and exploit the potential profit associated with the participation of industrial consumers in these markets.

This paper proposes a new simulation tool that maximizes, for a very wide range of multi process flexible industries, the profit obtained throughout the use of flexible demand of industrial processes in operation markets. This tool selects the best daily participation strategy using a metaheuristic algorithm based on PPSO, which allows us to maintain the technical and economic complexity associated with the characterization of demand response of industrial processes. Moreover, the use of a metaheuristic technique also facilitates the inclusion in the optimization algorithm of any complex function linked to flexible process behavior such as the ones related to the preparation and the recovery periods of a DR event shown in the section 2 mathematical approach.

The formulation of the proposed optimization algorithm considers a new codification of the decision variables to move from a non-linear binary problem to a non-linear integer problem, in which the decision variables are the starting time and the duration of each DR event. This codification allows the use of a PSO algorithm that would otherwise be extremely difficult to make use of and facilitates the consideration of the technical constraints in the optimization algorithm associated with flexible resources and restrictions of participating in operation markets.

The article also presents a comparison with a previous advanced tool used to solve the proposed problem in order to validate the solution, by using a multi-process application case in the industry. In this case study, both tools analyzed the participation of a meat factory in the Spanish tertiary reserve market during a whole year using a quarter-hourly time resolution. According to the results of the case study, the new tool can enhance the maximum profit per unit of reduced energy up to 40%, which considerably improves the economic results.

Regarding the results of each individual process, the simulation tool based on PPSO significantly improved the economic indicators associated with longer recovery periods. This is because the previous tool only considered the possibility to reduce the demand at time periods when additional specific payment for reserve services was offered by the system operator. In contrast, the new tool analyzes if it is profitable to reduce the power also depending on the energy prices, even if there is no payment for ancillary services.

The inclusion of the daily optimization algorithm logically results in an increment in the overall simulation time in comparison with the previous tool. Nevertheless, this increment does not represent any restrictive burden to the use of the tool according to its main goal. Moreover, the parallel computing was only applied to the optimization algorithm, and hence the parallelization of other calculation processes of the simulation tool will considerably improve this aspect.

5.8. Acknowledgements

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5.9. References

[1] D. Helm, Burn Out, The endgame for fossil fuels. Yale University Press, 2017.

[2] J. Rodríguez-García et al., "Novel Conceptual Architecture for the Next-Generation Electricity Markets to Enhance a Large Penetration of Renewable Energy," Energies, vol. 12, no. 13, p. 2605, Jul. 2019.

[3] U.S. Department of Energy, "Benefits of demand response in electricity markets and recommendations for achieving them a report to the United States congress pursuant to section 1252 of the energy policy act of 2005," 2006.

[4] S. Nolan and M. O'Malley, "Challenges and barriers to demand response deployment and evaluation," Appl. Energy, vol. 152, pp. 1–10, Aug. 2015.

[5] M. H. Shoreh, P. Siano, M. Shafie-khah, V. Loia, and J. P. S. Catalão, "A survey of industrial applications of Demand Response," Electr. Power Syst. Res., vol. 141, pp. 31–49, Dec. 2016.

[6] M. Alcázar-Ortega, C. Álvarez-Bel, G. Escrivá-Escrivá, and A. Domijan, "Evaluation and assessment of demand response potential applied to the meat industry," Appl. Energy, vol. 92, pp. 84–91, Apr. 2012.

[7] P. Siano and D. Sarno, "Assessing the benefits of residential demand response in a real time distribution energy market," Appl. Energy, vol. 161, pp. 533–551, Jan. 2016.

[8] U. Energy Information Administration, "International Energy Outlook 2016," 2040.

[9] D. Ramin, S. Spinelli, and A. Brusaferri, "Demand-side management via optimal production scheduling in power-intensive industries: The case of metal casting process," Appl. Energy, vol. 225, pp. 622–636, Sep. 2018.

[10] S. Feuerriegel, P. Bodenbenner, and D. Neumann, "Value and granularity of ICT and smart meter data in demand response systems," Energy Econ., vol. 54, pp. 1–10, Feb. 2016.

[11] A. Pechmann, F. Shrouf, M. Chonin, and N. Steenhusen, "Load-shifting potential at SMEs manufacturing sites: A methodology and case study," Renew. Sustain. Energy Rev., vol. 78, pp. 431–438, Oct. 2017.

[12] J. Rodríguez-García, C. Álvarez-Bel, J.-F. Carbonell-Carretero, M. Alcázar-Ortega, and E. Peñalvo-López, "A novel tool for the evaluation and assessment of demand response activities in the industrial sector," Energy, vol. 113, pp. 1136–1146, Oct. 2016.

[13] J. Rodríguez-García, C. Álvarez-Bel, J.-F. Carbonell-Carretero, G. Escrivá-Escrivá, and C. Calpe-Esteve, "Design and validation of a methodology for standardizing prequalification of industrial demand response resources," Electr. Power Syst. Res., vol. 164, pp. 220–229, Nov. 2018.

[14] X. Zhang, G. Hug, Z. Kolter, and I. Harjunkoski, "Industrial demand response by steel plants with spinning reserve provision," in 2015 North American Power Symposium, NAPS 2015, 2015.

[15] G. Dalle Ave, J. Hernandez, I. Harjunkoski, L. Onofri, and S. Engell, "Demand side management scheduling formulation for a steel plant considering electrode degradation," in IFAC-PapersOnLine, 2019, vol. 52, no. 1, pp. 691–696.

[16] L. Bianchi, M. Dorigo, L. M. Gambardella, and W. J. Gutjahr, "A survey on metaheuristics for stochastic combinatorial optimization," 2008.

[17] H. Cui and K. Zhou, "Industrial power load scheduling considering demand response," J. Clean. Prod., vol. 204, pp. 447–460, Dec. 2018.

[18] J. C. Bansal, P. K. Singh, M. Saraswat, A. Verma, S. S. Jadon, and A. Abraham, "Inertia Weight strategies in Particle Swarm Optimization," in 2011 Third World Congress on Nature and Biologically Inspired Computing, 2011, pp. 633–640.

[19] J. Kennedy and R. Eberhart, "Particle swarm optimization," in Proceedings of ICNN'95 - International Conference on Neural Networks, vol. 4, pp. 1942–1948.

[20] Y. Shi and R. Eberhart, "A modified particle swarm optimizer," in 1998 IEEE International Conference on Evolutionary Computation Proceedings. IEEE World Congress on Computational Intelligence (Cat. No.98TH8360), pp. 69–73.

[21] J. F. Kennedy, R. C. Eberhart, and Y. Shi, Swarm intelligence. Morgan Kaufmann Publishers, 2001.

[22] Y. Shi and R. C. Eberhart, "Parameter selection in particle swarm optimization," Springer, Berlin, Heidelberg, 1998, pp. 591–600.

[23] V. Kalivarapu, J.-L. Foo, and E. Winer, "Improving solution characteristics of particle swarm optimization using digital pheromones," Struct. Multidiscip. Optim., vol. 37, no. 4, pp. 415–427, Jan. 2009.

[24] H. L. Chen et al., "Towards an optimal support vector machine classifier using a parallel particle swarm optimization strategy," Applied Mathematics and Computation, vol. 239. Elsevier Inc., pp. 180–197, 15-Jul-2014.

[25] European Comission, "DIRECTIVE (EU) 2019/944 on common rules for the internal market for electricity," 2019.

[26] T. official G. BOE, "Real Decreto 1164/2001, de 26 de octubre, por el que se establecen tarifas de acceso a las redes de transporte y distribución de energía eléctrica.," 2001.

[27] REE, "Generación y consumo | ESIOS electricidad · datos · transparencia," 2019. [Online]. Available: https://www.esios.ree.es/es/generacion-y-consumo.

CAPÍTULO 6: **Discusión general de los resultados**

6.1. Introducción

En el siguiente capítulo se recapitulan los principales resultados que se han obtenido durante el desarrollo de la tesis doctoral, los cuales han sido organizados en tres apartados diferentes según su ámbito de aplicación a la hora de conseguir los objetivos específicos planteados.

El apartado **“6.2 Resultados en el marco regulatorio”** se centra en la descripción de los resultados que pueden ayudar a eliminar las principales barreras regulatorias identificadas para poder explotar los recursos energéticos distribuidos y de demanda, prestando un especial interés a estos últimos por ser el objetivo principal de los trabajos desarrollados.

En el apartado “**6.3 Resultados en el marco de aplicación”** se han recogido los puntos de la discusión más cercanos al consumidor industrial, tanto las barreras psicológicas encontradas en los propios consumidores frente a la implementación de acciones de respuesta de la demanda en sus procesos de consumo, como las barreras técnicas inherentes a los propios procesos flexibles o a la falta de herramientas y conocimiento para gestionarlas adecuadamente.

Por último, en el apartado **“6.4 Resultados en el marco teórico”** se recopilan los avances teóricos realizados durante el proceso de búsqueda de las soluciones a los problemas que se han planteado en la consecución de los objetivos específicos de la tesis.

6.2. Resultados en el marco regulatorio

Dentro de los resultados relacionados con el primer objetivo específico de la organización del sector eléctrico, con el fin de eliminar las barreras para la explotación de los recursos energéticos distribuidos y de demanda, se ha obtenido mediante una revisión de la literatura y un análisis ontológico, un listado con la descripción completa de los principales roles/actividades que deberían asumir los diferentes agentes en la arquitectura propuesta, definiendo claramente las funciones de cada uno. En este análisis se ha intentado separar aquellos roles que se comportan de forma natural como un monopolio, de los que teóricamente funcionan mejor en competencia. También se ha tenido en cuenta si los roles forman parte activa de las transacciones físicas de energía y servicios de operación de alguna forma, o son roles puramente económicos.

Otro resultado asociado a este análisis es la propuesta detallada de las interacciones que son necesarias entre los diferentes roles de la arquitectura desarrollada. Este resultado se ha materializado en dos diagramas diferentes:

- **Diagrama de transacciones físicas**: donde vienen recogidos los flujos de energía y de provisión de servicios de operación entre los diferentes roles. Estos flujos han sido condicionados por la ubicación dentro de la red desde donde son proporcionados y por su tamaño.

- **Diagrama de transacciones económicas**: donde se han considerado los pagos por el suministro de energía, por la provisión de servicios de operación, por el uso de la red, por la participación en los mercados, entre otros. Al igual que ocurría a nivel físico, estas interacciones están condicionadas por su ubicación relativa dentro de la red, por los límites de tamaño del recurso establecidos para ofertar en los diferentes mercados de operación o de energía, etc.

Como parte de este resultado, destaca la inclusión en el modelo planteado de los Mercados Locales de Electricidad, que podría ayudar a superar los actuales defectos del comercio en tiempo real. Estos mercados supondrán una herramienta muy interesante para intercambiar energía poco antes de ser consumida, proporcionando una solución local a las restricciones impuestas en distribución a la generación renovable debido a los problemas causados por las congestiones puntuales en la red, lo que permitirá maximizar la utilización de este recurso en el sistema eléctrico, mejorando su rentabilidad, así como ayudando a reducir el coste energético de los prosumidores.

Para la implementación exitosa de la arquitectura propuesta es necesario, además de la activación del consumidor, el desarrollo y promoción de tres roles nuevos que, aunque ya existen en algunos países no están suficientemente extendidos. Por un lado, es necesario que se reconozca como agente independiente el almacenamiento de energía eléctrica conectado a red. Por otro lado, también se debería permitir la agregación de los recursos energéticos distribuidos y de demanda para ser gestionados de forma conjunta, a través de las figuras de la planta de generación virtual o del agregador.

En este sentido, el modelo no puede funcionar de forma eficiente sin considerar en la solución la integración de nuevas alternativas (poco extendidas) con objeto de incrementar la flexibilidad del sistema, como los parques de generación renovables con almacenamiento de energía eléctrica, los consumidores en régimen de autoconsumo con almacenamiento y, por último, la gestión centralizada de la recarga del vehículo eléctrico.

También dentro del marco regulatorio, aunque más relacionado con los trabajos asociados a la consecución del segundo objetivo específico de la tesis “Análisis y caracterización de los recursos de demanda”, se ha obtenido un resultado fundamental para mejorar la explotación de la flexibilidad en el sector industrial, un procedimiento general de evaluación y validación de los recursos de demanda aplicable a cualquier consumidor en dicho sector. Este resultado puede servir como base para el futuro desarrollo de un proceso de certificación de recursos de demanda que permita la estandarización de los distintos productos de respuesta de la demanda que se desarrollen en los diferentes mercados.

6.3. Resultados en el marco de aplicación

Como se ha comentado anteriormente, este apartado recopila los resultados más próximos al consumidor industrial, la mayoría de los cuales proceden de aplicar la metodología propuesta a tres consumidores industriales diferentes que presentan de una alta replicabilidad en Europa: una industria papelera, una industria cárnica y un centro logístico de producto refrigerado y congelado. En dichos resultados se ha mostrado una parte importante de la complejidad asociada a la evaluación del potencial real de flexibilidad en los consumidores industriales, lo que pone en valor el uso del procedimiento propuesto u otro similar para garantizar la fiabilidad de la respuesta de los recursos de demanda en el sector industrial.

Uno de los puntos más interesantes dentro de este apartado, es la metodología desarrollada para la caracterización de los procesos flexibles desde el punto de vista técnico y económico, totalmente vinculada al segundo objetivo específico de la tesis “Análisis y caracterización de los recursos de demanda”.

Dentro de esta caracterización, se han identificado claramente las diferentes etapas que componen un evento de respuesta de la demanda, entre las cuales se ha prestado un especial interés a la inclusión de los periodos necesarios por los procesos flexibles tanto para prepararse como para recuperar las condiciones normales de trabajo de estos. En este sentido, se ha observado la importancia de caracterizar de forma precisa la evolución de la potencia demanda por el proceso durante la preparación y recuperación en un proceso industrial, ya que, si no se tienen en cuenta estas, de forma agregada podrían causar un nuevo desvío en el sistema, resultando en un incremento de los recursos necesarios para gestionarlo y, por tanto, del coste. Además, se ha comprobado que llevar a cabo un adecuado control de dichas etapas durante un evento puede evitar penalizaciones por el incremento de la potencia total máxima demandada por la planta.

Por otro lado, con objeto de eliminar la barrera psicológica en el consumidor relacionada con el posible impacto en la calidad de sus productos y servicios asociado a la implementación de acciones de respuesta de la demanda, se ha identificado la necesidad de monitorizar la evolución de los parámetros críticos de los procesos flexibles que se vayan a explotar, con una triple intención: en primer lugar, asegurar que en ningún caso durante un evento se sobrepasan los límites de seguridad preestablecidos por el consumidor como críticos, lo que permite incrementar la confianza del consumidor frente a la implementación de estos (tal y como se ha observado durante las pruebas de campo); en segundo lugar, conocer el potencial real existente en dicho proceso en tiempo real; y por último, determinar en función de la evolución de estos parámetros durante las diferentes pruebas realizadas el potencial real de flexibilidad existente (observando la situación de este parámetro frente a los límites críticos), incluso en algunos casos puede permite evaluar la posibilidad de incrementar el potencial de flexibilidad de dicho proceso realizando alguna modificación en las instalaciones con una inversión reducida.

En relación con la eliminación de la citada barrera psicológica del consumidor frente a la implementación de acciones de respuesta de la demanda, además de monitorizar los parámetros críticos del proceso, se ha observado (están incluidos en el diseño de la metodología de evaluación) que hay otros factores que pueden ayudar a superarla: por un lado, es importante que durante la etapa de realización de las pruebas de evaluación se incremente la duración y nivel de automatización de los eventos gradualmente, partiendo de eventos de corta duración totalmente controlados a eventos más largos y más automatizados; por otro lado, es fundamental involucrar de forma activa en la implementación de las pruebas que se realicen a los técnicos responsables del mantenimiento y operación de las instalaciones, de forma que al final estos sean capaces de llevar a cabo todo el proceso por sí mismos.

Respecto al nivel de automatización de la implementación de los eventos, estos se han clasificado en tres tipos: automatizado de extremo a extremo, parcialmente automatizado o sin automatizar. Se ha demostrado experimentalmente que para garantizar un cierto nivel de fiabilidad en la provisión de servicios de operación es necesario no solo disponer de al menos un nivel de automatización parcial en la ejecución de los eventos, sino que además se debe llevar a cabo un estudio previo particularizado por procesos (incluido en la metodología propuesta) para tener en cuenta en la configuración del sistema de control los tiempos de reacción de los diferentes equipos (temporizaciones a la desconexión y conexión), tanto en la rampa de inicio como de fin del evento.

En ciertos procesos flexibles, especialmente en aquellos que no recuperaban la energía reducida, se observó y cuantificó que la implementación de un evento se puede traducir en un impacto en el proceso productivo. En este caso, es importante que los pagos recibidos del operador soporten dicho coste, para lo cual se debe considerar este coste junto con el resto de costes en el cálculo del precio de la oferta de ese recurso.

Adicionalmente, hay que comentar que se ha propuesto y validado dentro de esta metodología, como punto clave debido al elevado nivel de incertidumbre que presentan en el sector industrial, una forma de cuantificar la capacidad real de los recursos flexibles a lo largo del año (estacionalidad), que en la mayoría de procesos industriales está asociada a parámetros como el nivel de producción, el tipo de producto fabricado, la temperatura y humedad del aire en el exterior, etc.

Los resultados de la caracterización de los recursos de demanda han servido como base para el desarrollo de las dos herramientas de planificación a medio plazo y de operación que tienen por objeto facilitar la participación de los consumidores industriales en los mercados de operación, relacionadas con los objetivos específicos tercero y cuarto de la tesis respectivamente.

Respecto a la herramienta de planificación a corto plazo, se ha desarrollado una metodología para la evaluación del potencial beneficio de un consumidor industrial participando en un mercado de operación específico durante un año completo, considerando todos los aspectos técnicos (caracterización de los diferentes procesos flexibles, restricciones de implementación asociadas a estos procesos, etc.) y económicos (los diferentes costes directos e indirectos asociados a la implementación de la flexibilidad asociada a cada proceso, el coste de la energía eléctrica del suministro para cada periodo, etc.) resultantes del proceso de caracterización de los recursos de demanda, además de una serie de parámetros que definen la estrategia de participación del consumidor (margen de beneficio por proceso, mercado de operación seleccionado, limitación de la banda de capacidad, etc.). Esta herramienta de simulación está basada en el cálculo del margen de decisión como el resultado del balance entre los pagos ofrecidos por el operador y los costes de la implementación de la flexibilidad para cada proceso flexible en cada intervalo de cálculo (cuarto de hora).

Tras la validación del funcionamiento de la citada herramienta mediante la simulación de las tres instalaciones comentadas anteriormente y considerando unos costes de flexibilidad similares para los diferentes procesos, los resultados obtenidos mostraron que existe una fuerte vinculación entre la rentabilidad de explotar un cierto proceso flexible y la potencia reducible asociada a dicho proceso. Tanto es así que en ciertos casos se ha llegado a la conclusión de que no era rentable la explotación de un cierto recurso flexible, al menos en la situación existente en el momento del estudio (nivel de automatización del proceso, pagos del operador en el mercado seleccionado, etc.).

Por el contrario, algunos procesos que en principio estaban asociados a consumidores industriales poco flexibles (por ejemplo, la industria papelera que producía papel con diferentes gramajes en función de la velocidad avance de la máquina), tras la evaluación realizada resultaron ser muy rentables (retorno de la inversión inferior a un año), lo que despertó el interés del propio consumidor por profundizar en el conocimiento de este potencial beneficio sin explotar.

En relación con la herramienta de operación desarrollada en la tesis, el principal resultado es la aplicación de un algoritmo de optimización metaheurístico (“Parallel Particle Swarm Optimization”, PPSO) al proceso de planificar la operación diaria de un consumidor industrial con objeto de maximizar el beneficio que este puede obtener mediante la explotación de sus procesos flexibles en un determinado mercado de operación. Este proceso de optimización se integró en la herramienta de simulación a medio plazo para comparar las diferencias en el beneficio económico resultante del proceso de simulación de una de las citadas instalaciones industriales (industria del sector cárnico).

De la realización del ejercicio anterior, se observó que la herramienta era capaz de maximizar el beneficio por unidad de energía reducida hasta un 40%, lo que mejoraba considerablemente los resultados económicos frente a la versión anterior. Asimismo, se pudo comprobar que la nueva versión de la herramienta de simulación basada en el PPSO consiguió mejores indicadores económicos en los recursos flexibles que presentaban un proceso de recuperación más largo. En general, el algoritmo no solo era capaz de encontrar la mejor estrategia de participación en el mercado de operación seleccionado, sino que adicionalmente mostró ser capaz de aprovechar mejor las diferencias en los precios asociados al contrato de suministro de electricidad.

6.4. Resultados en el marco teórico

Como ya se comentó en la introducción de este capítulo, en este apartado se van a describir los resultados de la tesis que han supuesto un avance desde el punto de vista teórico dentro del campo de estudio.

Dentro del segundo objetivo específico de la tesis durante el desarrollo de la metodología de análisis y caracterización de los procesos flexibles, aunque en el capítulo correspondiente no se hace mucho hincapié puesto que no es su objetivo principal, fue necesario profundizar en el estudio de las metodologías de medida y verificación existentes para cuantificar cada uno de los eventos implementados. En primer lugar, se observó que cada proceso dependiendo de su naturaleza requería del uso de unos parámetros diferentes en la selección de días. Por otro lado, en los procesos de consumo que presentaban un comportamiento más impredecible, en los cuales no funcionaban las técnicas de cálculo de las líneas de referencia más utilizadas, fue necesario establecer un criterio adicional a los que normalmente se incorporan en este tipo de procedimiento para la exclusión de días en el proceso de selección de perfiles diarios. El criterio de exclusión adicional estaba asociado a la selección de los perfiles de consumo de dichos procesos que presentaban un valor más bajo de RMSPE ("Root Mean Square Percentage Error") durante las horas previas a un evento. Con este criterio se logró, utilizando los datos históricos disponibles, una mejora sustancial en el ajuste de las líneas de referencia obtenidas para este tipo de proceso.

Durante el desarrollo del tercer objetivo específico de la tesis relacionado con la herramienta de planificación a medio plazo para el consumidor industrial, se ha obtenido como un avance, desde el punto de vista teórico, la formulación vectorial completa del algoritmo de cálculo asociado al funcionamiento de dicha herramienta. Esta vectorización del problema resultó en una reducción significativa de los tiempos de simulación, gracias a la reducción de bucles en el programa. Es necesario realizar una aclaración en este punto, puesto que el presente documento no muestra los detalles de dicha formulación en el capítulo correspondiente

(Capítulo 4. "A novel tool for the evaluation and assessment of demand response activities in the industrial sector"), ya que se ha querido proteger dicho detalle, incluyendo tan solo los fundamentos de dicho algoritmo, con la idea de desarrollar una aplicación de software que integré estos resultados, y otros derivados que se pueden llevar a cabo en futuros desarrollos.

Con relación al cuarto objetivo específico de la tesis relacionado con la herramienta de operación de los recursos flexibles, uno de los avances más interesantes es que se ha logrado utilizar con éxito una técnica de optimización metaheurística en la resolución de problemas no lineales con restricciones, cuando en la literatura técnica son varios los autores que no recomiendan este uso. En este sentido, habría que mencionar que esto ha sido posible mediante dos procesos, por un lado, la transformación de las restricciones en penalizaciones y, por otro lado, la paralelización del proceso de búsqueda.

El citado proceso de paralelización tiene la particularidad de haberse programado de una forma muy peculiar, ya que se han creado diferentes grupos de búsqueda independientes en el mismo espacio de búsqueda asociando a cada uno de estos un núcleo del procesador. De esta forma, se ha reducido considerablemente el problema de la convergencia prematura, que como se ha demostrado en las pruebas realizadas tiene difícil solución tan solo configurando los parámetros de funcionamiento del algoritmo "Particle Swarm Optimization". Esta paralelización ha permitido mejorar la tasa de éxito a la hora de encontrar el máximo global en todos los casos analizados (diferentes procesos flexibles), pasando de valores próximos al 60% a otros del 99-100%, y tan solo con un incremento del tiempo de cálculo inferior al 25% en el peor de los casos.

Con objeto de simplificar la interpretación de los resultados, se ha propuesto como variables de decisión del problema de optimización los instantes de inicio de los eventos y la duración de cada uno de estos (en formato matricial), lo que ha resultado en una nueva forma de codificación matemática de este tipo de problemas que ha permitido transformar un problema de optimización binario no lineal a un problema entero no lineal.

CAPÍTULO 7: **Conclusiones**

En el primer apartado de este último capítulo se recogen las principales conclusiones del trabajo realizado. En el segundo apartado, se destacan las aportaciones realizadas en la presente tesis y, en el último apartado, se proponen futuras investigaciones complementarias al trabajo realizado.

7.1. Conclusiones

Atendiendo a los desarrollos presentados, se puede concluir que se han cumplido completa y justificadamente los objetivos que se plantearon al inicio de la tesis aplicando de forma organizada el método científico a la resolución de cada uno de los problemas planteados asociados a los diferentes objetivos específicos.

En **primer lugar**, se ha diseñado una arquitectura conceptual que establece un marco de referencia adecuado para la explotación de los recursos energéticos distribuidos y de demanda, considerando las arquitecturas existentes actualmente para el desarrollo de las redes inteligentes. Con esta arquitectura conceptual y los resultados asociados expuestos, se resuelve la falta de un marco de referencia para la integración de los citados recursos, cumpliendo de esta forma con el primer objetivo específico de la tesis.

En **segundo lugar**, se ha elaborado y validado una metodología para la estandarización y validación de los recursos de demanda, y que puede servir como base para la creación de un proceso de certificación que permita a los recursos de demanda ser considerados como productos "uniformes" de cara al resto de agentes que puedan estar interesados en su explotación. Por tanto, esta metodología y los resultados derivados de su aplicación, ayudan a la eliminación de barreras muy importantes, como la falta de estandarización de los productos que pueden ofrecer los diferentes consumidores industriales debido a la gran diversidad de procesos productivos asociados a cada uno de estos, o la falta de confianza de los consumidores industriales de cara a proporcionar servicios al sistema utilizando sus recursos flexibles por miedo a afectar a sus procesos productivos o la calidad final de sus productos, alcanzando de esta forma el cumplimiento del segundo objetivo específico.

En **tercer lugar**, se ha desarrollado y validado una metodología que, a partir de la caracterización y evaluación de los procesos flexibles realizada, permite a los consumidores activos de energía en el sector industrial y comercial evaluar cuantitativamente la rentabilidad asociada a las diferentes estrategias que este puede adoptar a la hora de utilizar estos procesos flexibles para participar en un determinado mercado de operación. Esta herramienta cubre una barrera importante que tienen estos consumidores a la hora de tomar decisiones respecto a la planificación a medio plazo de la explotación de sus recursos de demanda respecto a aumentar su capacidad de reacción a precios. Por tanto, se puede concluir que con estos desarrollos se ha cumplido el tercer objetivo específico, ayudando a eliminar cualquier barrera relacionada con las dificultades técnicas o conceptuales para determinar la conveniencia y rentabilidad de explotar este recurso.

Por último, en **cuarto lugar**, se ha desarrollado una nueva herramienta para que el consumidor industrial que ha decidido participar en un cierto mercado de operación con uno o varios de sus procesos flexibles, pueda optimizar la misma a corto plazo, teniendo en cuenta los parámetros más dinámicos (temperaturas, precios de los mercados a corto plazo, etc.) y complementando los resultados de la aplicación de la metodología anterior. Esta nueva herramienta se considera fundamental para programar la operación de sus recursos flexibles. En este sentido, se ha presentado una metodología que le permite optimizar la programación de la operación de sus recursos de demanda para el día siguiente, ofreciéndole el apoyo técnico y las herramientas necesarias para maximizar el beneficio asociado a dicha participación. Además, se ha utilizado un método de optimización que respetase el problema original sin aproximaciones, garantizando el éxito en la búsqueda del máximo global, mejorando o igualando en eficacia a la mayoría de metodologías existentes en la literatura. Por tanto, también se puede concluir que se ha cumplido con el cuarto y último objetivo específico de la tesis.

7.2. Aportaciones de la tesis

A continuación, se describen las principales aportaciones realizadas en la presente tesis doctoral:

- Se ha diseñado y documentado una **arquitectura conceptual novedosa** para el desarrollo de la próxima generación de los mercados de electricidad con objeto de liberar el potencial asociado a los recursos energéticos flexibles y distribuidos, teniendo especialmente en cuenta los posibles beneficios para los prosumidores, basado en los modelos conceptuales que pueden encontrarse en la literatura (“NIST framework and roadmap for Smart Grids standards”, “the European Smart Grid Architecture Model”, etc.). Este modelo proporciona una alternativa a los reguladores para eliminar las barreras asociadas a la integración de los recursos energéticos distribuidos de forma competitiva en las redes eléctricas de distribución.

- Se ha elaborado una **metodología que permite determinar y validar el potencial de flexibilidad existente en cualquier consumidor industrial**, que se ha propuesto utilizar como parte de un proceso de certificación de productos de respuesta de la demanda en el sector industrial.

- Se ha desarrollado una novedosa **herramienta que permite simular las diferentes estrategias de participación en los mercados de operación de un consumidor industrial utilizando sus recursos flexibles, proporcionando como resultado la rentabilidad económica de dicha participación.** Esta herramienta no considera a los clientes industriales como una caja negra, sino que se evalúan como una suma de partes (procesos de producción) que pueden modificarse individualmente mientras se analiza el efecto en la pauta total de consumo de electricidad para toda la instalación.

- Se ha llevado a cabo, en base a las metodologías desarrolladas, una segunda **herramienta que permite optimizar la programación de la operación de los recursos flexibles de un consumidor industrial** para el día siguiente. La solución propuesta respeta la complejidad matemática del problema original teniendo en cuenta los resultados de la caracterización de los recursos flexibles, además de maximizar el beneficio para el consumidor mediante un algoritmo de optimización basado en un método heurístico denominado “Parallel Particle Swarm Optimization” (PPSO), cuyos parámetros de funcionamiento han sido cuidadosamente evaluados y ajustados para mejorar su eficacia y eficiencia en la resolución del problema planteado.

7.3. Investigación futura

Esta disertación abre la puerta a una perspectiva innovadora sobre:

- Desarrollo de nuevos modelos y productos de respuesta de la demanda a precios, que aumenten las opciones de los agentes de un mercado eléctrico de transar local y directamente energía y otros servicios de forma que se minimice la necesidad de intermediarios ("Automatic Local Energy Markets", ALEM) y se reduzca consecuentemente el coste de la energía final.
- Investigación en modelos de negocio para la implantación de los resultados de la tesis en empresas de apoyo a los consumidores (Empresas de Servicios Energéticos).
- Desarrollo de herramientas de apoyo al agregador, añadiendo la componente estocástica asociada a los procesos de consumo, estadísticamente modelables, de forma que permita acotar riesgos y maximizar beneficios a nivel local y global.
- Continuar el estudio de las nuevas potencialidades de aplicación que se han descubierto en el PPSO para gestionar recursos energéticos locales de forma integral, como por ejemplo la gestión a corto plazo para maximizar el beneficio individual y de conjunto de la generación renovable, el almacenamiento eléctrico y los recursos de demanda conectados a un alimentador de una subestación, teniendo en cuenta todas las restricciones asociadas a la topología de la red.

ACRÓNIMOS

aFRR	Automatic Frequency Restoration Reserve
ALEM	Automatic Local Energy Markets
CAISO	California ISO
CHP	Combined Heat and Power
CPP	Critical Peak Pricing
CT	Communications Technology
DA	Distribution Automation
DAS	Distribution Automation System
DCU	Data Concentrator Unit
DER	Distributed Energy Resources
DG	Distributed Generation
DLC	Direct Load Control
DMS	Distribution Management System
DOE	Department of Energy
DPP	Discount Payback Period
DR	Demand Response
DRAS	Demand Response Automation Server
DRIP	Demand Response in Industrial Production
DRMS	Demand Response Management System
DRQAT	Demand Response Quick Assessment Tool
DRR	Demand Response Resources
DS3	Delivering a Secure, Sustainable Electricity System
DSM	Demand Side Management
DSO	Distribution System Operator
DSU	Demand Side Units
EMS	Energy Management System
ENTSO-E	European Network Transmission System Operators for Electricity
EPRI	Electric Power Research Institute

ERCOT	Electric Reliability Council Of Texas
ESCO	Energy Service Company
ESE	Empresa de Servicios Energéticos
EU	European Union
EV	Electric Vehicle
FCR	Frequency Containment Reserve
FERC	Federal Energy Regulatory Commission
HV	High Voltage
IEA	International Energy Agency
IEEE	Institute of Electrical and Electronics Engineers
IRC	ISO/RTO Council
IRR	Internal Return Rate
I-SEM	Integrated Single Electricity Market
ISO	Independent System Operator
ITC	Information and Communication Technologies
LME	Local Energy Market
LMO	Local Market Operator
LV	Low Voltage
MAPE	Mean Absolute Percentage Error
MDM	Measured Data Management
mFRR	Manual Frequency Restoration Reserve
NAESB	North American Energy Standards Board
NEBEF	Notification d’Échange de Blocs d’Effacement
NERC	North American Electric Reliability Corporation
NIST	National Institute of Standards and Technology
NPV	Net Present Value
OCPP	Open Charge Point Protocol
OpenADR	Open Automated Demand Response
OS	Operation Services
OTC	Over The Counter
PPSO	Parallel Particle Swarm Optimization
PS	Power System
PSO	Particle Swarm Optimization
PV	Photovoltaic
REE	Red Eléctrica de España

RES	Renewable Energy Resources
RR	Replacement Reserve
RTO	Transmission System Operator
RTP	Real Time Pricing
SAO	Service Oriented Architecture
SCADA	Supervisory Control And Data Acquisition
SEDC	Smart Energy Demand Coalition
SEPA	Smart Electric Power Alliance
SGAM	Smart Grid Architecture Model
SME	Small and Medium-sized Enterprises
SPP	Southwest Power Pool
STAR	Short-Term Active Response
TIC	Tecnologías de la Información y la Comunicación
TOU	Time of Use
TSO	Transmission System Operator
UE	Unión Europea
UPV	Universitat Politècnica de València
V2G	Vehicle to grid
VE	Vehículo Eléctrico
VPP	Virtual Power Plant
WEM	Wholesale Energy Market
WMO	Wholesale Market Operator