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Plantas virtuales de energía para la integración de fuentes renovables de generación distribuida en sistemas de demanda de agua y energía.

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1. Introducción

Las instalaciones de bombeo de agua para riego son grandes consumidores de energía eléctrica además de un complejo sistema de gestión de agua. En general, el consumo energético representa más del 90% de los costes totales de un sistema de bombeo a lo largo del ciclo de vida de los equipos, mientras que el coste de inversión del equipo de bombeo apenas supone el 5% y el otro 5% restante corresponde al mantenimiento de los equipos [1], [2].

España es el país de la Unión Europea con mayor extensión para el regadío con casi 4 millones de hectáreas, destacando Aragón con una superficie de 415.998 hectáreas registradas en el año 2019 [3]. Las condiciones climáticas predominantes en Aragón hacen que el regadío sea un factor determinante de la diversificación productiva, así como de la dimensión económica de las explotaciones y de la productividad laboral y de la tierra; por tanto, de la renta agraria y del nivel de vida de los agricultores lo que se refleja en la distribución territorial de la ocupación agraria.

No obstante, los efectos del cambio climático están afectando seriamente a la agricultura en distintas latitudes del planeta, ya que los periodos de sequía son cada vez más frecuentes y la disponibilidad de agua para el regadío agrícola se está reduciendo. Hay que tener en cuenta que los recursos hídricos no siempre están garantizados, ya que dependen de factores climáticos cambiantes, lo que puede provocar una mala planificación de los cultivos. Las precipitaciones se distribuyen irregularmente a lo largo de los años por lo que las reservas de agua disponibles en los embalses no siempre permiten satisfacer todas las necesidades. Como consecuencia, resulta esencial la gestión eficiente de los recursos hídricos y energéticos.

En los últimos años, las instalaciones de regadío han centrado sus esfuerzos en su modernización. Para ello, se han implantado distintas soluciones para un mayor aprovechamiento de los recursos hídricos mediante sistemas de riego a presión como riego por aspersión o por goteo, según las características del terreno y los cultivos, en sustitución de los sistemas de riego tradicional por gravedad. Además, se han incrementado los elementos asociados a estos sistemas que permiten regular el agua de forma automatizada como balsas de captación, balsas de copa, variadores de velocidad y arrancadores, entre otros. Esta transformación de los sistemas de riego permite reducir las pérdidas por evaporación e infiltración y, de esta forma, conseguir una mejor gestión de los recursos hídricos, aunque la modernización lleva implícito un aumento en las necesidades de energía.

España se sitúa como uno de los países de la Unión Europea con el mayor coste de electricidad, determinado por el precio de los combustibles empleados en la generación de electricidad, la escasez de agua en algunos años, el coste de los derechos de emisión de CO_2, la insuficiente capacidad de interconexión con Francia, la falta de recursos de almacenamiento de energía, y en mayor medida los costes regulados que afectan especialmente a los consumos estacionales, como es el caso de los sistemas de bombeo de agua para riego. Como consecuencia de la eliminación de las tarifas especiales de riego agrícola en 2008 en España, que garantizaban unos precios regulados por parte del gobierno para el suministro de energía a las instalaciones de bombeo de las comunidades de regantes, ha supuesto un grave problema al incrementar considerablemente los costes energéticos en las comunidades de regantes modernizadas, poniendo en riesgo la sostenibilidad económica de las fuertes inversiones realizadas por los agricultores en la modernización de sus explotaciones agrarias y las que están pendientes de realizar, ya que la energía se ha convertido en el principal factor de coste del m^3 de agua para los agricultores en muchas regiones.

Desde 2008, las comunidades de regantes deben contratar la electricidad en el mercado liberalizado como cualquier consumidor, a precios muy superiores a los devengados con las tarifas especiales de riego. Desde esa fecha, el precio del kWh se ha duplicado, pasando de un precio medio de 7,7 céntimos de euro por kWh en 2007 a precios que alcanzaron los 15 céntimos de euro por kWh algunos años después. Cabe mencionar que el mercado eléctrico español se encuentra liberalizado desde 1998, por lo que la generación de electricidad y la compra de energía por parte de los consumidores están abiertas a la competencia. La liberalización tiene como objetivo conseguir una mayor eficiencia en las inversiones y la operación de los sistemas eléctricos, y así, reducir los costes e incrementar la calidad y fiabilidad del suministro eléctrico. En este marco legal del sector eléctrico, todos los consumidores, además del pago por la compra de energía en el mercado horario de producción, tienen la obligación de pagar unas tarifas de acceso a la red, por la utilización de las redes de transporte y distribución, más unos cargos por otros conceptos regulados por el Gobierno español. Estas tarifas de acceso son utilizadas para recaudar los ingresos que cubran los costes de las actividades reguladas de transporte y distribución de electricidad, y los cargos recuperan los ingresos para otros costes regulados del sistema eléctrico (retribución de primas a energías renovables, compensación a sistemas extra-peninsulares, y otros). Este esquema de liberalización del sector eléctrico es muy similar al empleado en todos los países desarrollados.

Los peajes de acceso no han dejado de incrementar exponencialmente en los últimos años. En el aumento del coste del suministro eléctrico ha influido fundamentalmente el incremento del término fijo anual de la potencia contratada, según la Orden ministerial IET/1491/2013, que supone más del 40% del precio final de la electricidad, siendo más elevado este porcentaje en las comunidades de regantes puesto que su consumo de electricidad es estacional, concentrándose en los meses de campaña de riego, principalmente entre los meses de mayo a septiembre, y la obligación de contratación de la potencia eléctrica para todo el año sin la posibilidad de modificarla durante el mismo perjudica seriamente a este sector. A pesar de concentrar al máximo el consumo de energía en los periodos más baratos, contribuyendo así a la mejora del factor de carga del sistema eléctrico y a la utilización más eficiente de las infraestructuras eléctricas de generación, transporte y distribución, y a pesar también del esfuerzo por gestionar las contrataciones de potencia de manera óptima cada campaña de riego en función de la planificación de cultivos y de las previsiones de reservas hídricas, la obligación de contratar la potencia eléctrica durante todos los meses del año grava injustamente la factura eléctrica de los regantes.

Respecto a la compra de energía eléctrica en el mercado horario de producción, los consumidores pueden hacerlo a través de un acuerdo con una comercializadora de energía, o bien, directamente en el mercado mayorista. Esta última opción puede suponer un ahorro en la factura eléctrica, pero a la vez implica mayor riesgo para el consumidor que debe poseer unos conocimientos avanzados sobre este sector, ya que tiene que realizar su compra diaria de energía hora a hora con una precisa previsión horaria de consumo eléctrico y estimación de pérdidas. Por estas razones, en la práctica la mayoría de los consumidores optan por la primera opción.

Además, en el último año se ha producido un fuerte incremento de los precios de los mercados mayoristas de electricidad, anticipando un futuro aún más incierto para los costes energéticos de las comunidades de regantes. En los próximos años, la penetración masiva de energías renovables permitirá una reducción del precio medio de la generación eléctrica, si bien también se espera un incremento de la volatilidad de los precios a lo largo de los días, meses y años en función de la mayor o menor disponibilidad de las fuentes intermitentes de producción eléctrica. En el futuro, la instalación de mayor capacidad de almacenamiento de energía permitirá suavizar esta volatilidad.

Para afrontar esta problemática, todos los países están promoviendo en sus planes estratégicos de energía el desarrollo de energías renovables para reducir las emisiones nocivas al medio ambiente, la dependencia de combustibles fósiles y el uso más eficiente de los recursos energéticos. La Unión Europea tiene como principales objetivos en materia de energía para 2030, la reducción de las emisiones de gases de efecto invernadero al menos un 40%, la participación de energías renovables al menos un 32% y la mejora de la eficiencia energética como mínimo un 32,5% [4]. Como resultado, se garantizará una energía asequible para todos los consumidores, la descarbonización de la economía, un aumento de la seguridad del suministro energético, la mejora de las interconexiones, así como la creación de nuevas oportunidades de crecimiento y empleo.

Para lograr estos objetivos, la actual legislación de autoconsumo en España aprobada en 2019, con la eliminación de las barreras por las tasas en la generación fotovoltaica, simplificación de los trámites administrativos y técnicos, fomento del autoconsumo colectivo, así como la eliminación del límite de potencia, [5], ha impulsado en gran medida la implantación de plantas de producción renovable. A ello han contribuido también su madurez tecnológica y la continua reducción de costes de los paneles solares experimentada a lo largo de los últimos años. Por esta razón, muchas comunidades de regantes han optado por realizar inversiones en instalaciones de energía renovable para reducir su coste energético y su dependencia de las redes eléctricas, así como para reducir la potencia contratada en los periodos tarifarios más caros. A nivel global, en términos económicos, la expansión del autoconsumo permite mayor presencia de renovables en el mercado eléctrico, con la previsible reducción de los precios de la energía al por mayor. Por otro lado, en términos técnicos, el autoconsumo permite reducir las pérdidas en las redes eléctricas al producir parte de la electricidad en el mismo lugar donde se consume.

La rápida penetración de estas fuentes de generación en el marco de un mercado eléctrico cada vez más competitivo requiere de nuevas tecnologías y sistemas de operación para hacer frente a los nuevos retos técnicos y económicos derivados de la integración óptima de los recursos disponibles. Las redes eléctricas inteligentes, los sistemas de almacenamiento, agregadores de gestión de la demanda, las plantas virtuales de energía y la transformación digital generalizada aparecen, así como ejes claves para hacer posible esta integración. Además, para la mejora del regadío también son fundamentales estos instrumentos para la gestión del agua y energía, contribuyendo de esta forma a mejorar la eficiencia de ambos recursos, reducir los costes de operación, y mejorar la rentabilidad económica de las explotaciones agrarias. En los últimos años, ha ido adquiriendo una creciente importancia dotar de capacidades de gestión a múltiples unidades de producción de energía integrada de manera simultánea con la demanda, de donde surge la figura de las plantas virtuales de energía. Dada la tendencia actual de generar energía de forma distribuida es primordial el control conjunto de las unidades de producción para conseguir el mayor rendimiento del sistema.

Esta tesis doctoral pretende ofrecer soluciones a los problemas planteados a lo largo de los párrafos presentados anteriormente. La tesis se ha realizado en formato de compendio de publicaciones, y las principales propuestas y resultados se han trasladado mediante cuatro publicaciones en revistas científicas de reconocido prestigio. El primer artículo clasifica y analiza en profundidad los trabajos publicados en los últimos diez años de modelos de plantas virtuales de energía con participación en diferentes tipos de mercados eléctricos en función del objetivo del problema, los métodos de resolución, los tipos de mercados eléctricos y la aplicación de los modelos a casos reales de estudio. El segundo artículo desarrolla y aplica un nuevo modelo de despacho técnico-económico óptimo de una planta virtual de energía con instalaciones de generación renovable centralizada y plantas de autoconsumo fotovoltaico *on-site* asociadas a los puntos de demanda de un gran sistema de regadío en Aragón (España) para maximizar el beneficio de operación conjunta y cubrir la demanda. Como extensión del modelo propuesto en el segundo artículo, el tercer artículo integra la gestión del agua junto con la energía, así como la optimización de la demanda contratada anual para minimizar los costes energéticos, consiguiendo un modelo de explotación más completo y realista para el sistema de estudio. Por último, el cuarto artículo presenta un modelo de despacho técnico-económico sujeto a las restricciones eléctricas e hidráulicas que permite obtener la programación óptima de los equipos de bombeo para minimizar los costes de operación de una estación real de bombeo de agua para riego con autoconsumo fotovoltaico y cumplir la demanda de agua.

1.1. Objetivos de la investigación

Objetivo general

El objetivo principal de esta investigación es el estudio, desarrollo y aplicación de nuevos modelos de operación óptima integrada de la generación y el consumo de energía eléctrica junto con las infraestructuras de agua de los sistemas generales de regadío, integrando los recursos de producción eléctrica, la demanda horaria de electricidad y la gestión del agua mediante el modelado matemático de una planta virtual de energía que participa en el mercado eléctrico mayorista para maximizar el beneficio de operación.

Objetivos específicos

Para conseguir el objetivo general de esta tesis, se definen los siguientes objetivos específicos:

1. Análisis en profundidad de los modelos de operación con integración de instalaciones de generación y demanda propuestos en los últimos años basados en modelos de planta virtual de energía con interacción en diferentes mercados eléctricos, según distintos criterios, como objetivo del problema, técnicas de modelado y métodos de resolución, tipos de mercados eléctricos y aplicación a casos reales.

2. Gestión de la energía mediante el desarrollo y evaluación de un nuevo modelo matemático de despacho técnico-económico que integra el consumo y generación de energía en estaciones de bombeo para maximizar su beneficio de operación.

3. Gestión del agua junto a la energía mediante el desarrollo y evaluación de un nuevo modelo matemático de despacho técnico-económico que integra la gestión de agua y energía en estaciones de bombeo con la optimización de los costes de energía y demanda.

4. Programación de las instalaciones de bombeo con autoconsumo fotovoltaico mediante el desarrollo y evaluación de un nuevo modelo matemático de despacho técnico-económico sujeto a las restricciones eléctricas e hidráulicas para minimizar los costes de su operación y cubrir las necesidades del sistema.

1.2. Revisión bibliográfica

El concepto de Planta Virtual de Energía o *Virtual Power Plant* (VPP por sus siglas en inglés) se define como un conjunto de unidades de generación distribuida, cargas controlables y sistemas de almacenamiento, agregados entre sí para operar como una única planta de energía en su conjunto, aunque no estén físicamente conectados mediante líneas eléctricas directas. Para su acoplamiento son necesarios sistemas de gestión de energía que coordinen los flujos de energía entre generadores, cargas y almacenamientos, con comunicaciones bidireccionales para recibir información sobre el estado actual de cada unidad y enviar señales de control a los componentes de la planta virtual de energía [6], [7], véase Figura 1. Cabe destacar que según el propósito de su agregación se pueden diferenciar dos tipos: plantas virtuales de energía comerciales (CVPP por sus siglas en inglés) y plantas virtuales de energía técnicas (TVPP por sus siglas en inglés). Primero, las CVPP centran fundamentalmente su operación en la participación en el mercado eléctrico, mediante la optimización de la producción y demanda eléctrica de sus componentes. Por otro lado, las TVPP se dedican a la oferta de servicios auxiliares al operador de la red de transporte mediante el control de los niveles de tensión y frecuencia del sistema y, así, mejorar la calidad del suministro eléctrico. A diferencia de las CVPP, en el modelado de este tipo se incluyen las restricciones de la red de distribución [7].

Las VPPs son una herramienta muy útil para la integración de energías renovables, contribuyendo al equilibrio de la red, ya que compensan mejor las posibles desviaciones respecto a las predicciones de producción. Además, al reducir los errores de predicción disminuyen las penalizaciones económicas por desvíos. Una característica importante de las VPPs es su capacidad de participar en los mercados eléctricos mayoristas de compra y venta de energía para obtener un beneficio adicional, tanto económico como técnico. Los generadores que componen la VPP tienen mejor acceso a los mercados eléctricos puesto que en ocasiones de forma individual tendrían más dificultades para alcanzar las restricciones mínimas de entrada a los mercados. También, se reducen los costes de acceso y operación, así como aumenta su visibilidad en los mercados eléctricos. Otro beneficio importante de las VPPs es la integración de vehículos eléctricos ya que actúa como una combinación de sistema de almacenamiento y carga controlable que ofrece el servicio vehículo a la red (V2G por sus siglas en inglés) [7], [8].

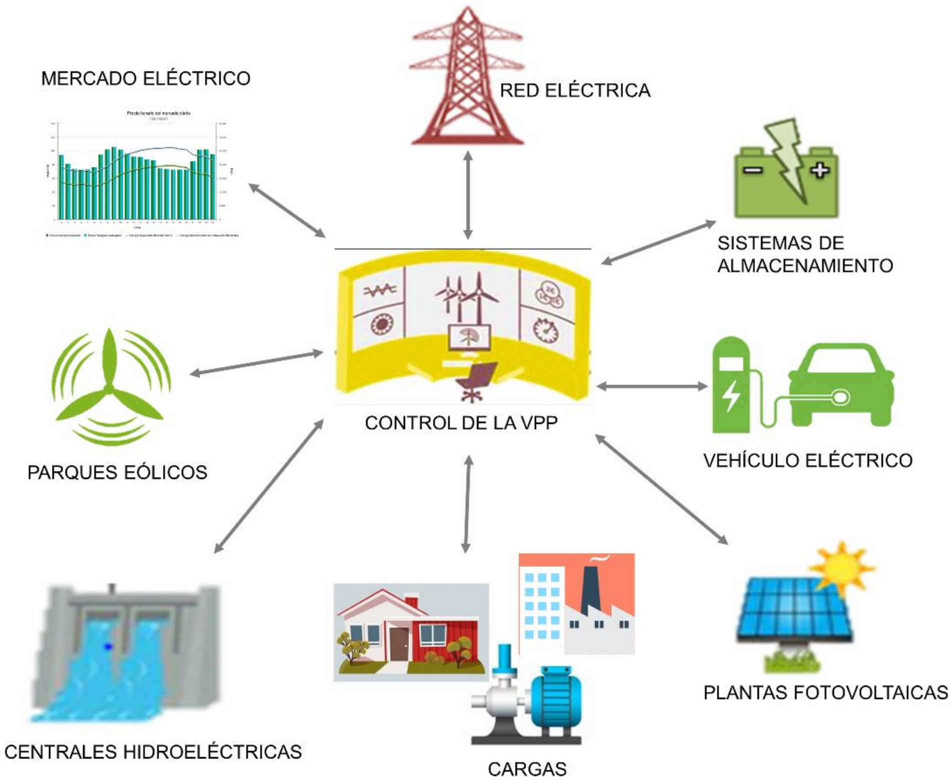

Figura 1. Concepto de planta virtual de energía

Algunos trabajos revisan los conceptos de VPPs y microrredes según distintos aspectos, como técnicas de modelado o métodos de resolución. Son descripciones generales sin entrar en demasiados detalles, centrándose en algún aspecto concreto para el modelado de una VPP. En [9], se revisa la programación de los recursos energéticos distribuidos según distintos aspectos, como técnicas de modelado, fiabilidad, impacto medioambiental o incertidumbres, basada en la comparación de los conceptos de microrredes y plantas virtuales de energía. El trabajo [10] estudia los principios de control de microrredes y analiza brevemente los diferentes tipos de plantas virtuales de energía. La referencia [11] presenta los diferentes tipos de VPP, así como sus características, tecnologías de comunicación y algoritmos de optimización y predicción. Los trabajos [12], [13], [14] dan una visión general de la operación de micorredes y VPPs. Los autores de [15] y [16] clasifican y describen las incertidumbres de los problemas de VPP y las técnicas de optimización utilizadas. El trabajo [17] describe los componentes (recursos de generación, almacenamiento y cargas flexibles) que integran la VPP. Los artículos [18], [19] dan una visión general acerca de la composición de la VPP y la optimización de sus recursos energéticos. Los autores de [20] proporcionan algunas ideas generales sobre VPP, relativas a su estructura y métodos de control. Otros trabajos analizan herramientas de simulación, en concreto, el software HOMER, para el diseño y evaluación de sistemas de energía renovables [21], [22].

La mayoría de los trabajos revisados [23]-[81] proponen el modelado y optimización de una VPP mediante técnicas de problemas típicos de despacho técnico-económico para la maximización de su beneficio de operación, dando como resultado la programación óptima de las diferentes fuentes de generación, sistemas de almacenamiento y demanda eléctrica. Estos trabajos formulan una función objetivo como la diferencia entre ingresos y costes del sistema, sujeto al cumplimiento de los balances de energía y las restricciones técnicas asociadas principalmente a la generación disponible, estado de carga de los sistemas de almacenamiento, y las operaciones de compra y venta de energía eléctrica. Otros trabajos [82]-[132] estudian estrategias óptimas de oferta de VPPs en distintas estructuras de los mercados energéticos para maximizar el beneficio de operación mientras reducen los errores de previsión de producción de energía y así, minimizar las penalizaciones económicas debido a estos desvíos.

Los trabajos revisados principalmente formulan el problema matemático como un modelo de tipo lineal mixto-entero (MILP por sus siglas en inglés) [23]-[27], [30]-[50], [52], [54]-[58], [61], [64]-[66], [71], [72], [74], [79]-[81], [84], [86]-[103], [109]-[111], [113], [122], [130], [131] con la utilización de técnicas *Branch-and-Bound* para su resolución, [23]-[28], [31], [32], [34], [37], [38], [40]-[43], [46], [48], [50], [55], [58], [71], [72], [74], [79], [84], [86]-[88], [90]-[94], [96]-[102], [122]. Este método proporciona una búsqueda inteligente de la solución óptima del problema mediante la evaluación de las distintas alternativas en función del valor de las variables enteras, la eliminación de las combinaciones que no cumplen ciertas restricciones, así como la determinación de las condiciones de óptimo según las cotas del mismo. Destaca su convergencia al óptimo global del problema ya que dispone de distintas estrategias de exploración del campo de soluciones y, puede acotar de forma significativa la búsqueda del óptimo, traduciéndose en definitiva en eficiencia. No obstante, los modelos más recientes son más realistas con la incorporación de más restricciones de la red, estudio del comportamiento estratégico de los participantes rivales en el proceso de subasta, por lo que estos son más complejos convirtiéndose en problemas de tipo no lineal (NLP por sus siglas en inglés) [69], [75], [77], [82], [104], [106]-[108], [115], [119]-[121], [132], o no lineal mixto-entero (MINLP por sus siglas en inglés) [28], [29], [51], [53], [59], [62], [67], [70], [73], [76], [78], [83], [105], [112], [114], [117], [123]-[129], requiriendo técnicas matemáticas más avanzadas o heurísticas, principalmente algoritmos genéticos u optimización por enjambre de partículas (PSO por sus siglas en inglés), [29], [59], [75], [81], [103], [120], [123], [127], [128] para obtener una solución óptima en un tiempo razonable de tiempo.

Otras investigaciones proponen problemas multi-objetivo [49], [75], [76], [77], [78] de minimización (o maximización) de diferentes criterios en la operación de la VPP de forma simultánea para lograr el equilibrio óptimo entre ellos. Los autores han propuesto diferentes objetivos como sub-funciones para analizar el problema multi-objetivo en VPPs y distintos métodos para la resolución más adecuada. El trabajo [49] busca maximizar el beneficio de operación de la VPP y minimizar el coste de autoconsumo de la VPP, otros trabajos como [75], [77], buscan maximizar el beneficio de la VPP y minimizar las emisiones de carbono, mientras que los autores de [76], [78] proponen maximizar el beneficio económico de la VPP y minimizar el riesgo económico ante las fluctuaciones del precio de mercado al participar la VPP en los mercados eléctricos. Respecto a la resolución, los autores de [76], [78] convierte el modelo multi-objetivo en un problema de único objetivo para resolverlo mediante el uso de coeficientes de ponderación. Para ello, primero definen una *payoff table* que decide los atributos para el cálculo de los coeficientes de peso de las diferentes funciones objetivo. Posteriormente, se utiliza el método *fuzzy* para analizar la distancia entre el valor de la función objetivo y el valor ideal. Por último, se determinan los coeficientes óptimos de peso para resolver el problema y, así determinar la mejor estrategia de operación de la VPP. Estos coeficientes de ponderación indican la importancia relativa de cada objetivo y se determinan utilizando los métodos de *entropy weight* [76] y *rough set* [78]. Ambos métodos se basan en datos objetivos para superar las deficiencias de los métodos subjetivos. Destaca por su simplicidad de implementación del problema y su eficiencia. El trabajo [75] utiliza el enfoque basado en el óptimo de Pareto. Se debe determinar la frontera de Pareto real, que incluye el conjunto de soluciones óptimas (soluciones no dominadas) en el espacio objetivo. Una vez generada la frontera de Pareto, la VPP selecciona la mejor solución de compromiso de acuerdo con las restricciones de las emisiones de carbono y las restricciones económicas relativas a la operación en el sistema de distribución. Por otra parte, el trabajo [77] utiliza el método de restricción épsilon que consiste básicamente en mantener un objetivo y restringir el resto de los objetivos a un valor épsilon. Este método se puede aplicar a problemas convexos y no convexos. No obstante, la dificultad de este enfoque es conocer el rango apropiado de valores a seleccionar al vector épsilon para las funciones objetivo y su alto tiempo de cálculo debido al nivel de variabilidad que se requiere para los valores épsilon.

Como se ha mencionado anteriormente, la integración de los recursos de energía distribuida en una VPP ayuda a una participación más activa en los mercados eléctricos, ya que de forma individual tendrían más dificultades de acceso a los mercados debido a su pequeña capacidad. Todos los modelos propuestos participan en el mercado diario para la compra y venta de energía para maximizar su beneficio operativo. No obstante, el crecimiento de las energías renovables en los últimos años ha impulsado los contratos bilaterales [23], [25], [36], [43], [45], [46], [65], [72]-[74], [97], [129], basados en un acuerdo directo de venta de electricidad entre un generador de energía y un comprador de dicha energía. Ambas partes acuerdan una serie de características tales como el precio, volumen de entrega de energía, el tiempo de vigencia del contrato además de la potencia mínima a suministrar/consumir. Hay que resaltar que es una buena oportunidad para un gran consumidor de gestionar y minimizar los riesgos de precios altos en un futuro, y asegura la rentabilidad de los nuevos proyectos renovables. Además, reduce el impacto medioambiental al optar por una fuente renovable estable a largo plazo. Otros trabajos incorporan la participación de la VPP en los mercados de futuros [44], [45], [46], [50], [103], basados en contratos de compra-venta de energía firme durante un periodo de tiempo especificado y a un precio fijo, por lo que evita los riesgos derivados de la alta incertidumbre de los precios del mercado eléctrico diario. Los modelos [45], [46] y [103] aprovechan las oportunidades de arbitraje entre el mercado eléctrico diario y el mercado de futuros para incrementar el beneficio de operación.

Por otra parte, algunos trabajos analizan la participación de la VPP en el mercado de servicios auxiliares [24], [36], [40], [41], [47], [64], [77], [91], [93], [98], [113], [125] para garantizar la seguridad y fiabilidad de la generación de electricidad y el sistema de transmisión (principalmente control de tensión y frecuencia y gestión de congestiones), por lo que la VPP puede obtener un ingreso adicional al participar en este mercado. Otros autores optan por la participación de la VPP en el mercado eléctrico a tiempo real [29], [48], [61], [62], [63], [70], [85], [86] [87], [89], [94], [95], [96], [102], [105], [106], [110], [111], [112], [114], [130], [131], [132], basado en la última oportunidad de mercado para que la VPP actualice la programación de los recursos en función de la información en tiempo real y evitar penalizaciones por desviaciones entre la producción prevista y la real. El objetivo de este mercado es programar el intercambio de energía lo más cerca posible de la producción real más que obtener un beneficio adicional.

Para validar la eficiencia del modelo matemático de optimización de VPP, algunos trabajos aplican el modelo a un caso real de estudio y estudiar el alcance real de la implantación de las VPPs mediante la coordinación óptima de las fuentes de generación y almacenamiento de energía disponibles para cubrir una determinada carga en cualquier momento del periodo de estudio establecido. Los modelos más antiguos son simples e incluyen pocos componentes sin estudiar el impacto de la integración de almacenamiento en el problema [43], [48]. No obstante, otros artículos incluyen sistemas de almacenamiento, principalmente bombeo hidroeléctrico [23], [28], [91], o baterías [24], [36], [55], [63], [85], [86], [110], permitiendo una gestión óptima de los recursos renovables y la demanda, con una mayor autonomía energética y una mejor correlación entre las curvas de producción y demanda de electricidad, asegurando la estabilidad de la red. En estos trabajos, la VPP reduce los riesgos por la volatilidad de los precios de mercado eléctrico y los riesgos de operación debido a la naturaleza estocástica de los recursos eólico y fotovoltaico. Además, distintos mercados eléctricos se analizan para determinar su interacción con el modelo propuesto en los trabajos revisados y maximizar su beneficio de operación mediante la compra de energía cuando los precios de mercado son bajos y venderla a precios más elevados. La VPP toma las mejores decisiones, por ejemplo, comprar/vender energía adicional en el mercado a tiempo real, y/o utilizar el sistema de almacenamiento para compensar los errores de predicción y garantizar el cumplimiento de las operaciones del mercado.

Por otra parte, merece la pena destacar que los problemas de disponibilidad de agua no paran de crecer en todo el mundo y puede suponer un riesgo para la viabilidad económica de las instalaciones de impulsión y distribución del agua para riego, por lo que es esencial proponer estrategias para conseguir una gestión óptima de este recurso. Con motivo del incremento y volatilidad del precio de energía, investigaciones revisadas se centran en optimizar al máximo el aprovechamiento del agua disponible para riego y mejorar la eficiencia energética para minimizar los costes de operación de las estaciones de bombeo.

Dadas las recientes inversiones en instalaciones de generación fotovoltaica en sistemas de regadío para ayudar a mantener la sostenibilidad económica de las fuertes inversiones realizadas por los agricultores en la modernización de sus explotaciones y permitir finalizar los proyectos que están todavía pendientes de realizar, varios trabajos se centran en el estudio de la incorporación de estas instalaciones de producción en las estaciones de bombeo. Hay que tener en cuenta que para que esta integración sea eficiente y sostenible económicamente se debe considerar el acoplamiento de la producción de electricidad con la demanda de energía eléctrica de las estaciones de bombeo, además de cumplir las limitaciones técnicas de las instalaciones hidráulicas de bombeo, almacenamiento y distribución del agua. El trabajo [133] presenta una revisión completa sobre los sistemas de bombeo de agua con generación fotovoltaica, centrándose en los componentes, parámetros que afectan al rendimiento, métodos de optimización, así como aplicaciones. Los autores de [134] establecen un método para la selección de bombas asociadas al bombeo solar que funcionan a una frecuencia variable. El trabajo [135] presenta una metodología que permite definir el número de paneles solares requerido para grandes sistemas de regadío con el objetivo de evitar pérdidas de producción de la energía fotovoltaica, incluyendo en estas pérdidas, la influencia de ciertos factores, como la tensión del motor, la tensión de red o temperatura, entre otros. La investigación [136] incluye el coste de inversión de la instalación fotovoltaica en el modelo de optimización.

Por otra parte, otros trabajos analizan la gestión eficaz del agua desde los puntos de vista económico y ambiental mediante el estudio de la sectorización en el diseño de redes de regadío y la incorporación de bombas con variadores de velocidad [137]. Los resultados muestran un gran ahorro energético a la vez que se garantiza la presión de servicio en los hidrantes. Los autores de [138] estudian la programación óptima de varias bombas de velocidad variable en un sistema de distribución de agua localizado en Tailandia. Los autores de [139] proponen una metodología para calcular la presión óptima y minimizar así la energía consumida por la estación de bombeo. Los resultados demuestran que la instalación de elementos de regulación de presión variable del sistema de bombeo permite una mayor eficiencia energética del sistema. Recientemente, el trabajo [140] analiza, desde el punto de vista técnico y económico, el uso de dos estrategias de programación de las bombas en sistemas de distribución de agua basadas en bombas de velocidad constante y con variador de velocidad. En ocasiones, los ahorros económicos debido al uso de variadores de velocidad no compensan los costes iniciales de los drives, sobre todo, en estaciones de bombeo de baja potencia. No obstante, merece la pena resaltar que, desde el punto de vista ambiental, se consigue aumentar significativamente los ahorros energéticos y reducir las emisiones de dióxido de carbono.

Esta es un área novedosa de investigación, que está adquiriendo creciente importancia con la integración de la generación distribuida en los sistemas eléctricos, la introducción masiva de tecnologías TIC con instalación de contadores inteligentes, el desarrollo de los mercados eléctricos competitivos, además de la necesidad de gestionar conjuntamente los recursos de agua y energía, pero que todavía se encuentra en una etapa incipiente a nivel internacional.

A partir de la literatura revisada, se han identificado algunos temas de investigación aún no cubiertos. En primer lugar, no se han encontrado estudios que realicen una clasificación precisa de los trabajos publicados centrándose en el impacto de los modelos de VPP en los distintos mercados eléctricos a lo largo de los últimos años, lo que resulta esencial analizar debido a la actual evolución de los mercados eléctricos para adaptarse a la alta participación de energías renovables en el sistema eléctrico. Respecto al modelado de VPP, los trabajos previos no incluyen la gestión conjunta de plantas de generación de energía a gran escala que evacuan toda la energía eléctrica producida a la red con instalaciones de autoconsumo fotovoltaico de pequeña escala ni la optimización de los costes de demanda junto con los de producción de energía. Además, apenas se aplican los modelos propuestos a casos reales para analizar la gestión de agua y energía de forma conjunta. Por último, en cuanto a la programación de las estaciones de bombeo, los modelos propuestos en la literatura son bastante simples y no incorporan instalaciones de autoconsumo con energías renovables, ni balsas de regulación interna y almacenamiento para una gestión eficaz del agua, ni bombas de varios tipos (velocidad fija y variables), ni aplicaciones de los modelos a sistemas reales de bombeo de agua para riego.

Por tanto, se espera que esta tesis doctoral contribuya al progreso del conocimiento en esta área de investigación.

1.3. Presentación de los trabajos publicados

Los artículos que componen esta tesis por compendio de publicaciones son los siguientes:

1. Natalia Naval, Jose M. Yusta. **Virtual power plant models and electricity markets – A review.** *Renewable and Sustainable Energy Reviews*, vol. 149, 111393, 2021.

2. Natalia Naval, Raul Sanchez, Jose M. Yusta. **A virtual power plant optimal dispatch model with large and small-scale distributed renewable generation**. *Renewable Energy*, vol. 151, pp. 57-69, May 2020.

3. Natalia Naval, Jose M. Yusta. **Water-Energy Management for Demand Charges and Energy Cost Optimization of a Pumping Stations System under a Renewable Virtual Power Plant Model**. *Energies*, vol. 13, no. 11, p. 2900, 2020.

4. Natalia Naval, Jose M. Yusta. **Optimal short-term water-energy dispatch for pumping stations with grid-connected photovoltaic self-generation.** *Journal of Cleaner Production*, vol. 316, p.128386, 2021.

1.3.1. *Virtual power plant models and electricity markets – A review*

La regulación del sector eléctrico permite una participación más activa de la generación distribuida y la demanda en los mercados eléctricos. Como resultado, nuevas estrategias son desarrolladas para afrontar los desafíos técnicos y económicos consecuencia de la integración óptima de los recursos disponibles. En los últimos años, ha ido creciendo la importancia de dotar de capacidades de gestión a la producción de energía agregada simultáneamente con la demanda, mediante distintas tipologías de plantas virtuales de energía y aprovechar su capacidad de participación en los mercados eléctricos para maximizar el beneficio de operación.

Este primer artículo tiene como objetivo la clasificación de los trabajos publicados en los últimos diez años sobre modelos de planta virtual de energía con interacción con los diferentes mercados eléctricos además de analizar en profundidad los aspectos más relevantes en este campo de estudio, destacando el objetivo del problema, el tipo de formulación matemática, métodos de resolución, tipos de mercados eléctricos y la aplicación de los modelos propuestos a casos reales de estudio. Otros criterios como la composición de la VPP [9], [17], [18] y la gestión de incertidumbres [9], [15], [16] no se han incluido en este artículo debido a que estos ya han sido estudiados en detalle en otros trabajos previos. La Figura 2 muestra de forma esquemática los criterios seguidos para la clasificación de los trabajos revisados e incluidos en este artículo de revisión.

Para realizar esta revisión se ha seguido el siguiente proceso de selección de artículos:

1. Búsqueda exhaustiva de artículos en diferentes revistas y bases de datos con el objetivo propuesto.
2. Prioritariamente, selección de artículos de revistas indexadas por la mayor fiabilidad y calidad.
3. Adicionalmente, incorporación de artículos presentados en congresos internacionales debido al interés de su contenido.
4. Selección de artículos en función del objetivo propuesto, novedad y año de publicación.

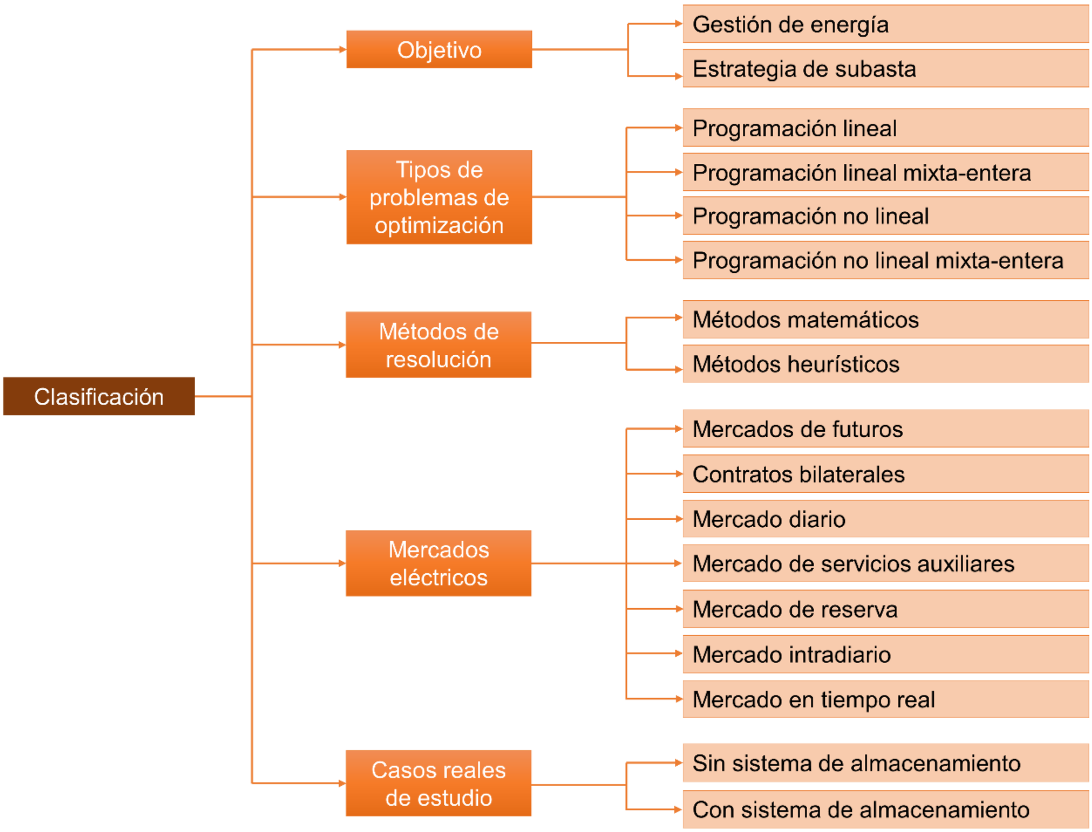

Figura 2. Categorías de clasificación de los trabajos de VPP con interacción de los mercados eléctricos

Los artículos tienden hacia modelos de VPP más completos y realistas, con la participación más activa en diferentes mercados eléctricos debido a la integración distribuida en la VPP. Como se ha comentado en los apartados anteriores, una ventaja importante de las VPPs es favorecer la entrada de los generadores que la componen a los mercados, ya que individualmente tendrían más dificultades para cumplir las restricciones mínimas de entrada a los diferentes mercados. Las investigaciones recientes incluyen contratos bilaterales, mercados de futuro y de balance para maximizar el beneficio y asegurar el equilibrio entre generación y demanda en todo momento.

Los modelos recientes también incluyen más restricciones de operación y red de distribución convirtiéndose en problemas más complejos de resolver, por lo que se requiere técnicas de optimización más avanzadas para conseguir una solución óptima eficiente.

Este artículo de revisión ayuda a los investigadores a identificar el esquema más rentable de planta virtual de energía a aplicar en cada marco regulatorio. Además, indica los desafíos todavía pendientes en este campo de estudio, resaltando los siguientes:

- Modelado de CVPPs que consideren simultáneamente varias estrategias de compra-venta de energía eléctrica en los mercados mayoristas.
- Análisis de la interacción entre CVPP y TVPP en el modelo.
- Incorporación de técnicas de inteligencia artificial.

- Aplicación de los modelos de VPP a casos reales de estudio.

1.3.2. *A virtual power plant optimal dispatch model with large and small-scale distributed renewable generation*

La factura de energía es una de las partidas de mayor gasto económico en las estaciones de bombeo de agua para riego agrícola. Como consecuencia, las comunidades de regantes están realizando importantes inversiones en instalaciones propias de generación de energía de origen renovable para reducir los costes energéticos. Esto es posible debido a que todos los países están apostando en sus estrategias de política energética por el desarrollo de energías renovables para hacer frente al calentamiento global, así como para reducir la alta dependencia de los combustibles fósiles para la producción de energía eléctrica, mejorar la seguridad de suministro energético y fomentar el desarrollo de la industria y la economía de la región donde se instalan.

Además, las comunidades de regantes son grandes consumidores de energía por lo que resulta esencial proponer nuevos modelos de operación para gestionar de manera conjunta óptima el consumo y generación de energía y reducir los costes de energía a la vez que las emisiones de dióxido de carbono. Aquí, se utiliza el concepto de planta virtual ya que permite el control y coordinación de diferentes fuentes de energía distribuida y la demanda de electricidad para maximizar el beneficio económico de operación.

Por todo lo anterior, este segundo artículo tiene como objetivo la formulación y aplicación de un nuevo modelo matemático de despacho horario óptimo con la integración de la gestión técnica y económica de todas las instalaciones de demanda y producción de energía de los sistemas generales de regadío, bajo el enfoque de modelado de una VPP. El modelo propuesto es de tipo lineal mixto-entero que busca maximizar el beneficio de la operación conjunta de la VPP para cada periodo horario durante un año de estudio. En caso de defecto de energía para cubrir la demanda de las estaciones de bombeo, el sistema puede comprar energía en el mercado eléctrico mediante un contrato tipo *pass-through* indexado al precio del mercado mayorista español OMIE. Por el contrario, si existe exceso de energía producida se venderá a la red recibiendo en cada hora el precio establecido en el mercado diario OMIE. La Figura 3 muestra los agentes que componen la VPP propuesta en este artículo.

Adicionalmente, se analiza la sensibilidad del modelo de despacho óptimo respecto a distintos precios del mercado eléctrico y producción eólica, ya que son los parámetros con mayor influencia en los resultados económicos obtenidos en la VPP.

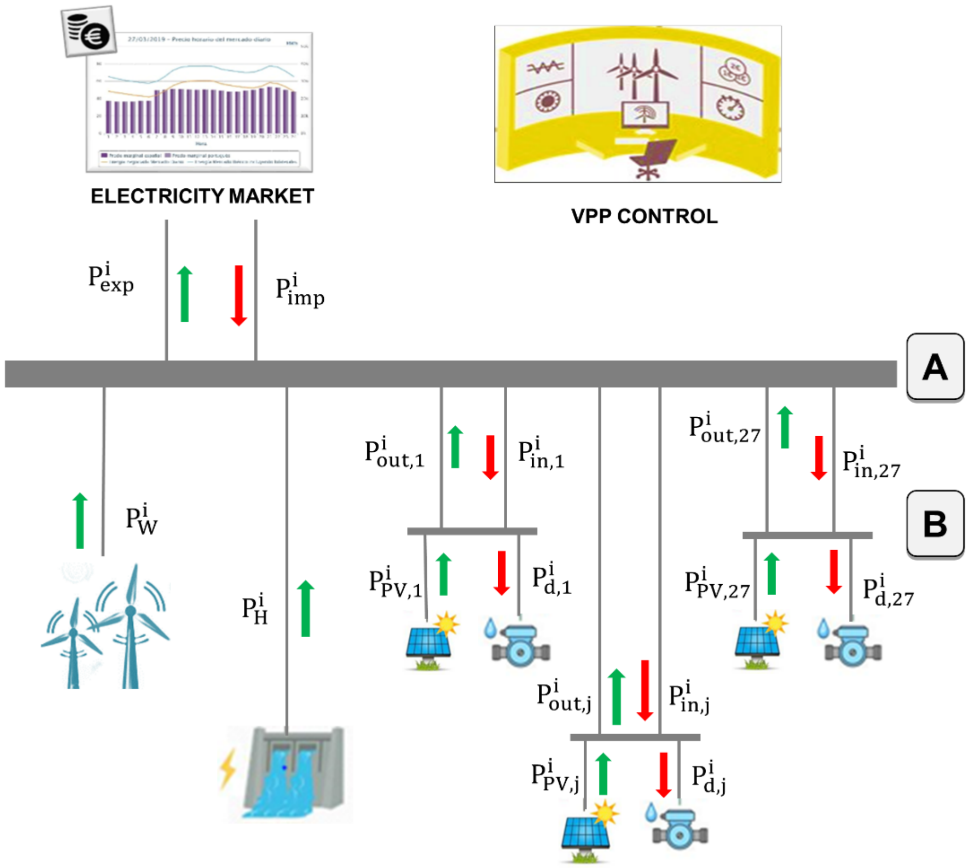

Figura 3. Componentes de la VPP propuesta en el segundo artículo

En resumen, las novedades más importantes a destacar de esta investigación son las siguientes:

- El diseño de un modelo de gestión horaria óptima de una planta virtual de energía para un año entero con dos niveles de integración de energías renovables:

    1. Generación eólica e hidroeléctrica con evacuación de energía directamente a la red eléctrica.
    2. Instalaciones de autoconsumo fotovoltaico *on-site* asociadas a cada estación de bombeo.

- La aplicación del modelo propuesto a la operación real de un centro de control de energía en un gran sistema de bombeo de agua para riego de 135.000 ha con 39 GWh anuales de consumo y 180 GWh de producción de electricidad en Aragón (España).

1.3.3. *Water-Energy Management for Demand Charges and Energy Cost Optimization of a Pumping Stations System under a Renewable Virtual Power Plant Model*

El coste energético asociado al bombeo del agua ha sufrido un notable incremento en los últimos años, entre otras razones por los cargos de demanda máxima que se aplican anualmente según la potencia contratada en cada instalación, lo que puede poner en peligro la sostenibilidad de las explotaciones que precisan de energía eléctrica para impulsar el agua a los campos. Frente a esta situación, muchas comunidades de regantes han empezado a realizar importantes inversiones en instalaciones de producción de energía eléctrica con fuentes renovables para minimizar estos costes.

Adicionalmente, otro problema al que tienen que hacer frente las comunidades de regantes es la incertidumbre acerca de la disponibilidad de los recursos hídricos para satisfacer la demanda, poniendo en peligro la viabilidad económica de las estaciones de bombeo. Algunas comunidades de regantes para gestionar de forma eficiente el agua disponen de una balsa de copa que permite almacenar temporalmente una cantidad de agua que satisfaga el riego en los días siguientes. Desde esta balsa, se distribuye el agua por gravedad a los diferentes terrenos de regadío. Otras estaciones de bombeo, sin embargo, captan el agua de canales de transporte en uno o varios puntos, almacenándola temporalmente en balsas de captación para el bombeo directo a la red de distribución de riego.

Como consecuencia de la necesidad de conseguir una gestión eficiente conjunta del agua y energía y reducir los costes energéticos en el sector de regadío, este tercer artículo tiene como objetivo el desarrollo de un nuevo modelo matemático de despacho técnico-económico horario que busca maximizar el beneficio de operación de una VPP para un año entero mediante la optimización de la demanda contratada anual, de la gestión horaria del consumo de agua y energía eléctrica de las estaciones de bombeo, y de los recursos propios de producción de electricidad (hidroeléctrica, eólica y fotovoltaica de autoconsumo). La VPP incluye 27 estaciones de bombeo que participan en el mercado eléctrico mayorista OMIE como una sola entidad permitiendo la contratación de una única potencia máxima en cada periodo tarifario. La Figura 4 muestra el esquema de flujo de energía del modelo propuesto en este artículo.

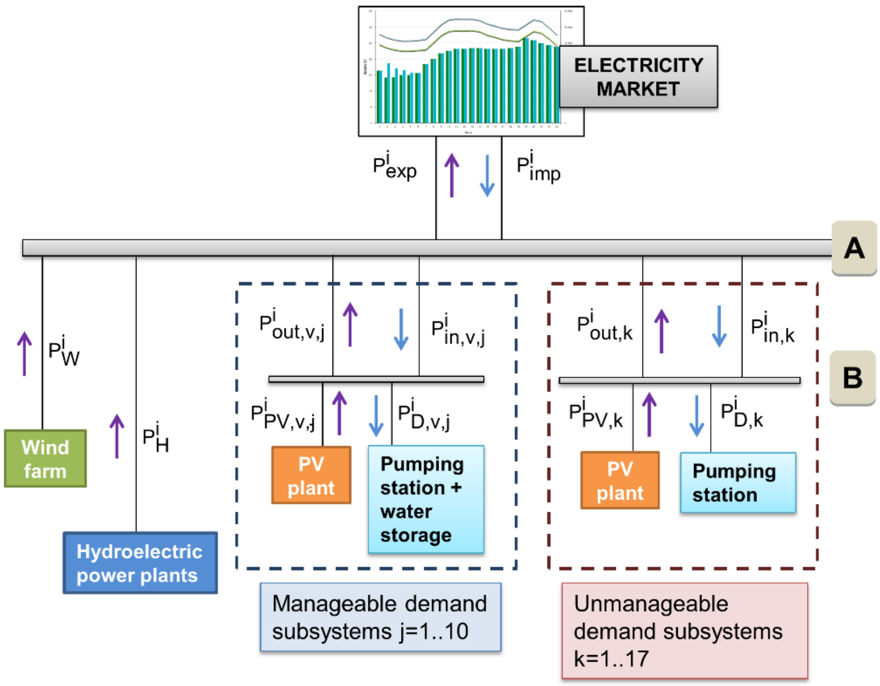

Figura 4. Esquema de la VPP propuesta en el tercer artículo

El modelo propuesto es un problema de programación no lineal mixto-entero con un gran número de variables continuas y enteras lo que requiere un elevado tiempo de cálculo para obtener una solución óptima. Las técnicas avanzadas *Branch-and-Bound* favorecen la obtención de una solución óptima global y evitar los óptimos locales. De esta forma, se ofrece un modelo de explotación más completo y realista.

Además, se proponen distintos escenarios para analizar la variabilidad del beneficio de operación de la VPP con y sin gestión intradiaria de la demanda (bombeo a balsa de copa y bombeo directo) además de la influencia del precio del mercado eléctrico en el modelo.

En resumen, las principales novedades introducidas en esta investigación son las siguientes:

- La integración de la gestión horaria del binomio agua-energía bajo el enfoque de un modelo de planta virtual de energía.
- La optimización de la demanda contratada anual junto con los recursos de generación de energía.
- La aplicación a un gran sistema de bombeo de agua para riego en Aragón (España) y analizar el alcance real de gestión de la VPP.

Cabe resaltar que este enfoque resulta útil no solo para el caso de sistemas de bombeo de agua, sino también puede aplicarse a un grupo de empresas industriales donde la electricidad y otros suministros (agua, calor) deben gestionarse junto con sus propios recursos de generación de energía, incluso si esas instalaciones de producción de electricidad están repartidas en una gran área geográfica.

1.3.4. *Optimal short-term water-energy dispatch for pumping stations with grid-connected photovoltaic self-generation*

Durante los últimos años, todos los países están incentivando la implantación de instalaciones de generación renovable para hacer frente a los efectos del cambio climático y el aumento del precio de energía. Las estaciones de bombeo no solamente buscan optimizar al máximo el aprovechamiento del agua disponible para el riego sino también mejorar su eficiencia energética, por lo que, aprovechando los incentivos de las normativas en materia energética, muchas comunidades de regantes están invirtiendo en instalaciones de autoconsumo fotovoltaico para el bombeo de agua para riego y así reducir los costes energéticos y mejorar la viabilidad económica de las explotaciones. Hay que destacar la buena correlación existente entre las necesidades de agua y la producción de agua con los paneles solares. En general, en caso de no poder satisfacer la demanda con la instalación propia de producción fotovoltaica, la energía puede ser adquirida de la red eléctrica normalmente con un precio fijo según los periodos tarifarios, mientras que cuando se produzcan excesos de generación fotovoltaica, estos pueden exportarse a la red para obtener unos ingresos adicionales.

Este trabajo se centra en dar respuesta al gran reto de gestión conjunta de consumo de agua y energía en las instalaciones de bombeo de agua. Para ello, se propone el desarrollo de un modelo matemático de despacho técnico-económico a corto plazo que minimice los costes de operación de una estación de bombeo con autoconsumo fotovoltaico mediante la gestión óptima de agua y energía para satisfacer la demanda de agua requerida. Como resultado, se obtiene el número de bombas óptimo en funcionamiento de cada tipo (velocidad constante y variable) con sus respectivos valores de potencia y caudal, los niveles de agua de las balsas de captación y almacenamiento, así como la cantidad de electricidad importada y exportada a la red para cada hora durante las 168 horas de una semana (véase Figura 5).

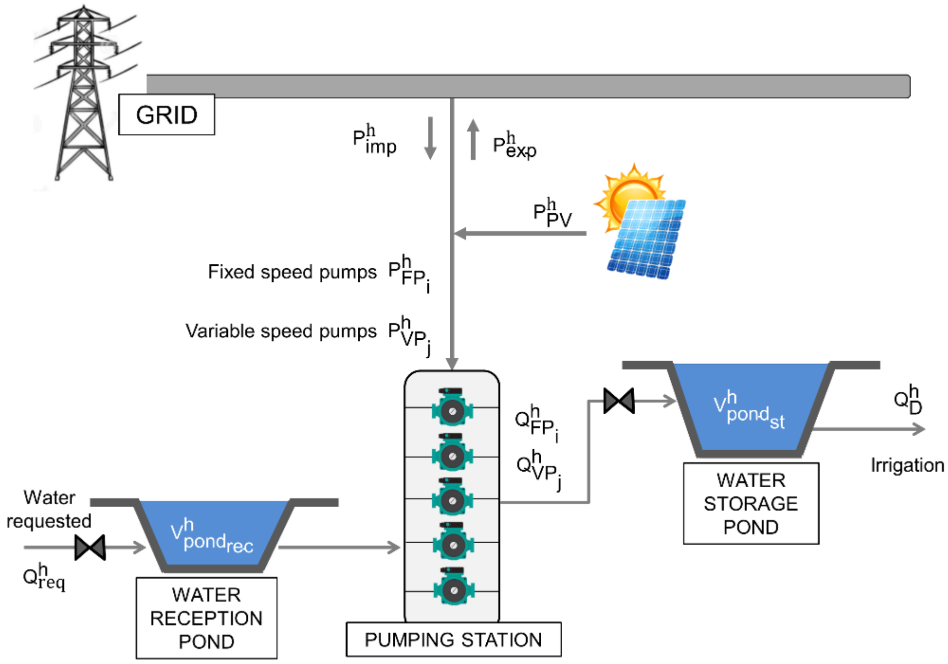

Figura 5. Esquema del modelo propuesto en el cuarto artículo

El modelo propuesto es un problema de programación no lineal mixto-entero con 14 variables continuas, 8 variables de tipo entero y 11 de tipo binario para cada hora durante una semana, por lo que, debido a los diferentes tipos de variables y la incorporación de restricciones no lineales, se requiere un elevado tiempo de cálculo para obtener una solución óptima.

Para la resolución de este problema se utilizó el *solver* de optimización BONMIN-HYB disponible en GAMS® por su robustez y la gran eficiencia para obtener una solución válida. Este método utiliza una aproximación externa híbrida fundamentada en las técnicas de ramificación y corte para la obtención de una solución óptima de problemas complejos de tipo no lineales mixto-entero.

Además, para ilustrar el comportamiento del modelo, se estudian tres semanas típicas a lo largo de la campaña de riego con diferentes datos de demanda de agua y producción solar.

En resumen, las principales contribuciones de este trabajo de investigación son las siguientes:

- El desarrollo de nuevo modelo óptimo de despacho técnico-económico que obtiene la programación de bombeo óptima para satisfacer la demanda de riego al mínimo coste.
- La integración de diferentes tipos de bombas centrífugas (velocidad fija y variable), una planta fotovoltaica de autoconsumo y dos balsas de agua para la captación y almacenamiento de agua en el modelo propuesto.
- La aplicación del modelo a la operación de una estación real de bombeo de agua.

En definitiva, el modelo propuesto en este trabajo resulta una buena estrategia de gestión eficiente del consumo de agua y energía con la utilización de energías renovables para satisfacer total o parcialmente la demanda en instalaciones de bombeo, por lo que su aplicación puede suponer una buena oportunidad para contribuir a la mejora de la competitividad y viabilidad de las explotaciones agrarias.

1.4. Justificación de la unidad temática

Los cuatro trabajos presentados en el apartado anterior proponen y aplican modelos matemáticos de despacho técnico-económico para optimizar la operación de las instalaciones de bombeo de agua para riego. Todos ellos incluyen instalaciones de generación renovable y demanda eléctrica además de la participación en los mercados eléctricos con la compra y venta de energía.

En primer lugar, el primer artículo consiste en una completa revisión bibliográfica que clasifica los trabajos publicados y analiza los aspectos más relevantes para el modelado matemático de la operación conjunta de grupos de producción y consumo de energía no interconectados físicamente, bajo el enfoque de plantas virtuales de energía con interacción con diferentes mercados eléctricos para la compra y venta de energía.

El segundo y tercer artículo proponen un modelo matemático de despacho técnico-económico con integración de las instalaciones de demanda y producción de electricidad para maximizar el beneficio de operación bajo el enfoque de planta virtual de energía aplicado a un gran sistema de regadío en Aragón. Además, el tercer trabajo incluye la gestión de agua como restricción del problema matemático y la optimización de los costes de demanda.

Por último, el cuarto artículo se centra en la propuesta y aplicación de un modelo matemático de despacho técnico-económico sujeto a restricciones eléctricas e hidráulicas para cubrir las necesidades de energía y agua de una estación de bombeo con autoconsumo fotovoltaico y minimizar los costes de operación.

En conclusión, a lo largo de estos trabajos de investigación se han estudiado y evaluado en profundidad los modelos de operación conjunta de grupos de producción y consumo de energía además de la propuesta de nuevos modelos de despacho con la incorporación de nuevas variables que no habían sido optimizadas en los trabajos previos publicados, dando lugar a modelos más completos y realistas para los sistemas de bombeo de agua. Por consiguiente, la unidad temática está completamente justificada, lo cual es un requisito a cumplir para la presentación de una tesis como compendio de artículos.

2. Trabajos publicados

Los trabajos publicados que conforman esta tesis son:

1. Natalia Naval, Jose M. Yusta. **Virtual power plant models and electricity markets – A review.** *Renewable and Sustainable Energy Reviews*, vol. 149, 111393, 2021.

2. Natalia Naval, Raul Sanchez, Jose M. Yusta. **A virtual power plant optimal dispatch model with large and small-scale distributed renewable generation**. *Renewable Energy*, vol. 151, pp. 57-69, May 2020.

3. Natalia Naval, Jose M. Yusta. **Water-Energy Management for Demand Charges and Energy Cost Optimization of a Pumping Stations System under a Renewable Virtual Power Plant Model**. *Energies*, vol. 13, no. 11, p. 2900, 2020.

4. Natalia Naval, Jose M. Yusta. **Optimal short-term water-energy dispatch for pumping stations with grid-connected photovoltaic self-generation.** *Journal of Cleaner Production*, vol. 316, p.128386, 2021.

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Virtual power plant models and electricity markets - A review

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ABSTRACT

In recent years, the integration of distributed generation in power systems has been accompanied by new facility operations strategies. Thus, it has become increasingly important to enhance management capabilities regarding the aggregation of distributed electricity production and demand through different types of virtual power plants (VPPs). It is also important to exploit their ability to participate in electricity markets to maximize operating profits.

This review article focuses on the classification and in-depth analysis of recent studies that propose VPP models including interactions with different types of energy markets. This classification is formulated according to the most important aspects to be considered for these VPPs. These include the formulation of the model, techniques for solving mathematical problems, participation in different types of markets, and the applicability of the proposed models to real case studies. From the analysis of the studies, it is concluded that the most recent models tend to be more complete and realistic in addition to featuring greater diversity in the types of electricity markets in which VPPs participate. The aim of this review is to identify the most profitable VPP scheme to be applied in each regulatory environment. It also highlights the challenges remaining in this field of study.

1. Introduction

Most countries are currently promoting renewable growth policies to achieve a stable, sustainable, and affordable energy system and mitigate the effects of climate change. Hydroelectricity is the most important renewable energy source on the planet, supplying approximately 17% of global electricity demand. However, hydroelectric projects must be properly planned and studied to avoid negative impacts on ecosystems [1,2]. In addition, the global growth of solar and wind energy is accelerating due to cost reductions and technological advancements.

The transformation of the electricity sector is mainly based on the digitalization of the power system, such as the installation of smart meters that establish bidirectional communications between consumers and the system operator. This transformation also results from the emergence of new agents, such as demand aggregators, storage systems, and virtual power plants (VPPs), which ensure the security and quality of the electricity supply given the growing introduction of renewable energy [3].

Virtual power plants represent the most immediate future of electricity generation, as they allow for intelligent consumption of energy in a distributed environment through the optimal management of demand and power generation. This means that users produce and consume their own energy, which leads to more active consumer participation in decision-making. Moreover, VPPs are useful tools for the integration of renewable energy in contributing to the balance of the grid. They better compensate for possible deviations from predicted production and demand. In addition, reducing prediction errors decreases economic penalties for deviations. The generators that compose VPPs have better access to electricity markets as a collective than they do individually, in which case it would be more difficult to reach the minimum market entry constraints. In addition, their access and operation costs are reduced, while their visibility in electricity markets is greater. Another important advantage of VPPs is the integration of electric vehicle load management, as this combines the storage systems and controllable loads offered by the vehicle-to-grid (V2G) service [4,5].

Study [6] reviews the scheduling of distributed energy resources according to different aspects, such as modeling techniques, reliability, environmental impact, and uncertainties. This review is based on the comparison of microgrids and VPPs. Paper [7] focuses on the principles of microgrid control and briefly analyzes the different types of VPPs. Reference [8] presents the different types of VPPs and their characteristics, communication technologies, and optimization and prediction algorithms. References [9,10] provide an overview of microgrid and VPP operations. Similarly, study [11] analyzes the differences between these two concepts. The authors of [12,13] classify and describe

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Abbreviations

ADMM	Alternating direction method of multipliers
CHP	Combined heat and power plant
CVPP	Commercial virtual power plant
EV	Electric vehicle
FCAS	Frequency control ancillary services
GA	Genetic algorithm
LP	Linear programming
MILP	Mixed-integer linear programming
MINLP	Mixed-integer nonlinear programming
NLP	Nonlinear programming
PBUC	Price-based unit commitment
PPA	Power purchase agreement
PSO	Particle swarm optimization
PV	Photovoltaic energy
TVPP	Technical virtual power plant
VPP	Virtual power plant
V2G	Vehicle-to-grid
WPP	Wind power plant

uncertainties regarding VPP problems and the optimization techniques used. Study [14] describes the components (generation resources, storage, and flexible loads) that compose a VPP. Articles [15,16] provide an overview of VPP composition and the optimization of its energy resources. The authors of [17] present arguments regarding the structure and control methods of VPPs. Other papers focus on the analysis of tools for the design and assessment of renewable energy systems. References [18,19] propose the modeling and technical-economic optimization of hybrid renewable energy systems by using HOMER software, a powerful tool for the design of renewable energy sites.

In conclusion, most review articles focus on comparing VPPs and microgrids according to various aspects, such as modeling techniques and problem solving methods, to determine their differences. These works tend to provide general descriptions without delving into further details, focusing on a specific aspect of VPP modeling.

Given the current evolution in electricity markets regarding renewable energy, it is essential to study the contributions of VPP models in maximizing operating profits and guaranteeing the security of the electricity supply in relation to different types of electricity markets, such as the day-ahead market, balancing services, and power purchase agreements (PPAs). The main objectives of this review article are to consider VPP models that include interactions with electricity markets and to identify and analyze in depth the relevant aspects in this field of study, such as the type of mathematical formulation and solving methods, the types of electricity markets, and the application of the proposed models to real case studies.

The regulation of the power sector allows for more active participation of distributed generation and demand in electricity markets. As a result, new tools are being developed to address unique technical and economic challenges derived from the optimal integration of available resources. This review contributes to the field by classifying and providing a detailed analysis of recent papers that model VPPs and their interactions with energy markets.

Identifying relevant articles to include in a review is a substantial challenge, as it involves an exhaustive search of a large number of articles in different journals and databases that focus on the chosen topic. In this case, the selection was based mainly on articles published in indexed journals. These articles are generally more reliable and of higher quality because they completed a peer review process. However, this study also includes articles presented at conferences due to the relevance of their content. In addition, the selection criteria account for the topic and novelty of papers, focusing on articles related to the objective of this review: the proposal of VPP models that include interactions with different types of electricity markets.

Nevertheless, there are certain limitations regarding the selection criteria of this study. This review considers aspects that have not been deeply evaluated before regarding the modeling and calculation of VPPs for participation in energy markets. These aspects include the type of problem, problem solving methods, energy markets, and real case studies. However, this article does not consider other aspects, such as VPP composition [6,14,15] and the management of uncertainties [6,12,13], due to their analysis in previous papers. Finally, this review also considers the year of publication when selecting studies, as it only includes articles published in the last ten years.

2. Objective of the problem

The development of VPPs is accelerating worldwide through the penetration of distributed generation in electricity systems, the massive introduction of ICT technologies, and the advancement of competitive electricity markets. This all offers new tools for the integrated management of energy resources.

By definition, a VPP consists of the integration of a group of distributed generation facilities managed by a single control system with bidirectional communications between its components to achieve more efficient operation. An important characteristic of VPPs is their ability to participate directly in electricity markets to obtain greater economic and technical profits. There are two types of VPPs that are distinguished by the objective of their aggregation: commercial virtual power plants (CVPPs) and technical virtual power plants (TVPPs). First, CVPPs fundamentally focus their operation on participation in the electricity market by optimizing the production and electrical demand of their components. Second, TVPPs offer ancillary services to the operator of the transmission grid by controlling the voltage and frequency levels of the system and thus improving the quality of the electricity supply. Unlike for CVPPs, TVPP modeling includes the constraints of the distribution network.

Next, the works in this review are classified according to the main objective of VPP modeling in relation to its interaction with wholesale electricity markets.

2.1. Energy management

The main aim of reviewed studies [20–50, 51-78] is to optimize the management and scheduling of different generation facilities, storage systems, and electricity demand to maximize the final VPP profit. The development of these models is primarily based on typical problems of technical-economic dispatch. To maximize economic profit, these models create an objective function formulated as the difference between system income and costs. In addition, each model is subject to compliance with the energy balances and technical constraints associated with different factors. These mainly include the available generation, state of charge of the storage systems, and electricity purchase and sale transactions. Within this type of problem, the authors of [68–70] propose the modeling of a cooperation system among neighboring CVPPs to maximize opportunities for the commercialization of electricity. Other articles, such as [72–75], include other aspects in the formulation of the VPP optimization model in addition to the economic profit, such as the environmental impact and the risk management of the variability of the VPP profit while participating in competitive markets. These studies propose a multiobjective problem for the management of VPP energy resources that seeks to maximize profits and minimize both carbon emissions and operational risk. In other words, the aim of these papers is to achieve an optimal balance among the economy, reliability, and environment. It should be noted that problems in the real world generally involve more than one objective at a time. Given the growing development of more efficient techniques for solving these problems, multiobjective optimization problems have been proposed for the realistic management of VPPs in recent years.

Fig. 1 presents a typical diagram of a VPP and its interaction with electricity markets and networks.

2.2. Bidding strategy

All the articles reviewed are listed in Table 1. Almost half of these studies examine optimal VPP bidding in different energy market structures [79–129]. The aim is to maximize the operating profit while reducing energy production forecast errors and economic penalties due to these deviations. In these problems, the objective function is subject to a series of technical and temporal constraints for the generators, such as reserve regulation requirements, state of the generator groups (connection-disconnection), ramp limits of the units, and compliance of energy balances. For this type of problem, some studies propose a price-based unit commitment (PBUC) model [120–126]. Other studies, such as [127,128], include the allocation of the VPP profit among the distributed energy sources of which it is composed. In addition, some of these works, such as [79,81,82,85,88,94–96,122], and [126–128], exploit the arbitrage opportunities among the different electricity markets to maximize VPP profit.

Fig. 2 presents the methodology used to obtain the optimal bidding strategy in a VPP. It is based on the articles classified in this section, such as [88,121].

As the figure shows, most of the studies reviewed focus on highlighting the management power of different models of VPPs. Given the importance of transforming the current energy model towards a distributed system, it is essential to optimize the control and coordination between the power generation sources and storage systems of the VPP. This should satisfy the electricity demand at any time and obtain greater profits by providing access to the same electricity markets as traditional power plants. For this reason, VPPs eliminate an important barrier to maximizing the integration of renewable energy into the grid and achieving sustainable development.

3. Methods of problem solving

As the previous section shows, most of the studies reviewed formulate a mathematical problem for maximizing the profit of a VPP, including all the characteristics of the hourly energy balance of the production and consumption of electricity, along with the costs of the supply and sale of electricity. The objective function is defined as the difference between income and costs, and technical constraints for the variables are imposed. Once the mathematical model is developed, the appropriate selection of the problem solving method becomes essential. The studies use different optimization techniques to obtain both an optimal solution to the VPP management problem and optimal selection of the bidding strategy in different electricity markets. In addition, due to the growing importance of multiobjective optimization problems, this section also addresses the most important characteristics of the approaches used for their resolution.

3.1. Types of optimization problems

The optimization problems are divided into the following categories according to the type of variable (continuous, integer) and the linear or nonlinear nature of the constraints:

- Linear programming (LP) [57,60,65,82,113,115],
- Mixed-integer linear programming (MILP) [20–24,27–47,49,51–55,58,61–63,68,69,71,76–78,81,83–100,106–108,110,119,127,128],
- Nonlinear programming (NLP) [66,72,74,79,101,103–105,112,116–118,129],
- Mixed-integer nonlinear programming (MINLP) [25,26,48,50,56,59,64,67,70,73,75,80,102,109,111,114,120–126],

Most of the studies reviewed formulate a mixed-integer linear mathematical problem. This problem involves integer decision variables associated with the hourly import/export of electricity during the established period of time or the state of charge/discharge of the storage systems, among other factors, in addition to continuous variables that represent the values of energy exchanged in the VPP model. The

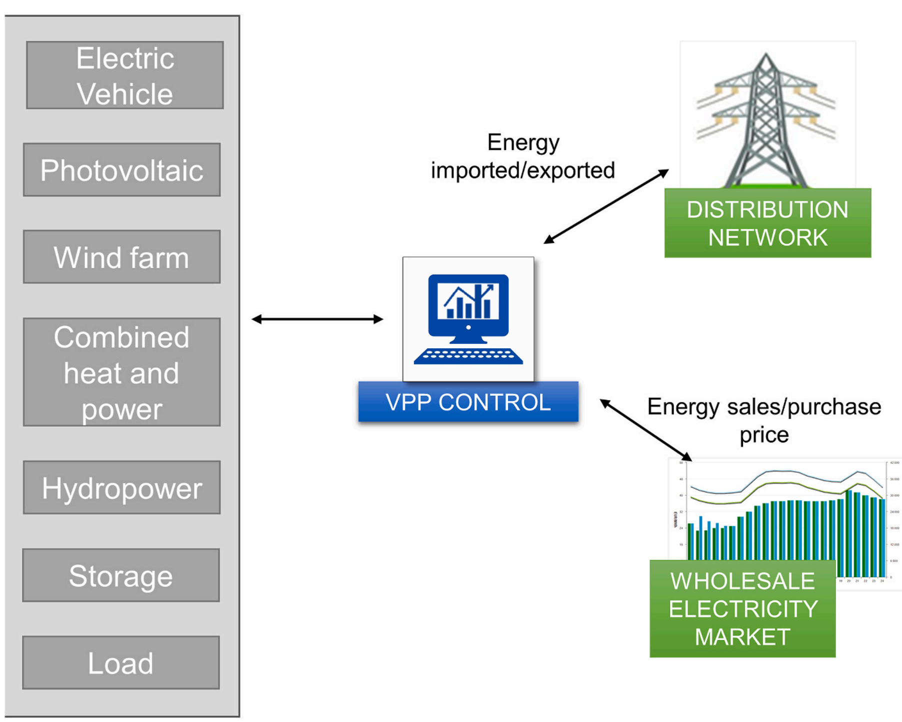

Fig. 1. Diagram of a VPP and its interaction with electricity markets and networks.

Table 1
Summary of advantages and limitations of VPP model types and resolution methods.

	Method	References	Advantages	Limitations
Types of optimization problems	Linear programming	[57,60,65,82,113,115]	Simplicity of implementation	Linear objective function and constraints/Does not allow uncertainty
	Mixed-integer linear programming	[20–24,27–47,49,51–55,58,61–63,68,69,71,76–78,81,83–100,106–108,110,119,127,128]	Simplicity of implementation and obtainment of a unique optimal solution	Does not consider the evolution of the variables, since only linear decision variables can be considered
	Nonlinear programming	[66,72,74,79,101,103–105,112,116–118,129]	More complete model	Difficulty of resolution/Previous use of linearization techniques
	Mixed-integer nonlinear programming	[25,26,48,50,56,59,64,67,70,73,75,80,102,109,111,114,120–126]	More complete and realistic model	High resolution difficulty/Cannot guarantee a global optimal solution
Heuristic methods	Particle swarm optimization	[26,72,78,117,120]	Simplicity of implementation and calculation efficiency	Local optimums
	Genetic algorithms	[56,100,117,124,125]	Flexibility and mode of operation, as they simultaneously determine several solutions	Local optimums
	Big bang big crunch	[51]	Application to complex models	Local optimums
	Imperialist competitive	[54]	Application to complex models	Local optimums
Mathematical methods	Simplex method	[57,60,65,82,113,115]	Ease of implementation	When increasing the number of variables, too many iterations are needed to obtain the optimal solution
	Branch-and-bound method	[20–25,28,29,31,34,35,37–40,43,45,47,52,55,68,69,71,76,81,83–85,87–91,93–99,119]	Convergence to the global optimum of the problem	Memory usage
	Quadratic programming	[49,101,104]	Faster convergence/Convexity	High execution time
	Interior-point method	[77,110]	Application to linear and nonlinear problems with a large number of variables	More efficient for linear problems/Longer processing time for nonlinear problems
	Dynamic programming	[80]	Efficient mode of operation	Inefficient with large models
	Column generation method	[30,32,58,86]	Calculation efficiency in linear problems with a large number of variables	Memory usage
	Game theory	[58,66,67,107,127,128]	Optimal analysis of the strategic behavior of VPP in different electricity markets	When increasing the number of participants, additional techniques should be used to reduce the computation-al load
	Fuzzy simulation	[56,102]	Appropriate for solving multiobjective optimization problems	Difficulty with solving
	Point estimate method	[27,121,123]	High accuracy, computational efficiency, and variable correlation	Mathematical assumptions
	Area-based observe and focus algorithm	[62]	Ability to find the global optimum	Increase in the number of search points
	ADMM and consensus optimization	[53]	Improves convergence ratio and scalability	Complex mathematical formulation

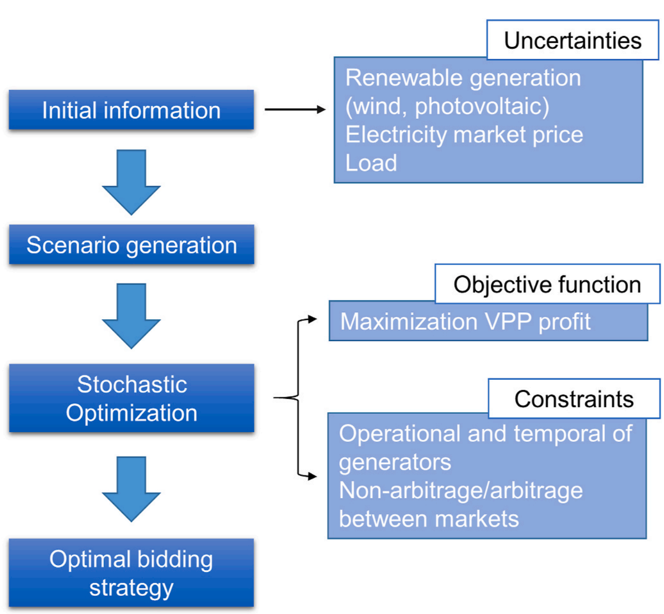

Fig. 2. Methodology for solving for the optimal bidding strategy of a VPP.

simplicity of this problem's implementation is notable, and it has a fast execution time for finding the optimal solution. Currently, the majority of calculation software incorporates efficient solvers to obtain the optimal solution of mixed-integer linear problems. However, some authors formulate the VPP problem with nonlinear constraints, which makes it difficult to solve because the feasible region does not necessarily have to be convex. For this reason, before proceeding to its resolution, the problem is transformed into a mixed-integer linear model using the Karush-Kuhn-Tucker optimality conditions and duality theory. In addition, other articles formulate the model with integer variables and nonlinear constraints, making the problem a mixed-integer nonlinear model that is difficult to solve. Due to the nonlinearity of these problems, they are generally nonconvex, which implies the existence of several local solutions without being able to guarantee an optimal global solution. To obtain an optimal solution, the authors use various problem solving techniques that can be classified mainly into mathematical and heuristic methods. Next, the main advantages and disadvantages of each method will be analyzed in depth.

3.1.1. *Mathematical methods*

Mathematical methods ensure convergence to an optimal solution (if any). For this reason, many authors use these techniques to obtain the optimal management of the energy resources that compose the VPP.

- Simplex method [57,60,65,82,113,115].
- Branch-and-bound technique [20–25,28,29,31,34,35,37–40,43,45,47,52,55,68,69,71,76,81,83–85,87–91,93–99,119].
- Quadratic programming [49,101,104].
- Interior-point method [77,110].
- Dynamic programming [80].
- Column generation and constraint method [30,32,58,86].
- Game theory [58,66,67,107,127,128].
- Fuzzy simulation [56,102].
- Point estimate method [27,121,123].
- Area-based observe and focus algorithm [62].
- The alternating direction method of multipliers (ADMM) and consensus optimization [53].

When solving LP models, the authors mainly use the simplex method, which is the most common method. It offers a wide range of applications due to its easy implementation and computational efficiency, meaning that it requires little time to find an optimal solution.

In contrast, when solving integer programming models, articles fundamentally consider branch-and-bound techniques that implicitly list feasible integer solutions. Important advances have been made in solving MINLP problems through the use of advanced optimization algorithms such as branch-and-bound or heuristic methods. However, some works propose linearizing the model equations before solving them due to the complexity of MINLP, the need for high calculation times, and the difficulty of obtaining an optimal solution.

The branch-and-bound method used in references such as [25,83,93], and [97] provides an intelligent search for the optimal solution. This is done by evaluating the different alternatives based on the value of the integer variables, eliminating the combinations that do not meet certain constraints, and determining the optimal conditions according to their bounds. It facilitates convergence to the global optimum of the problem since it has different strategies for exploring the field of solutions and, thus, is able to significantly limit the search for the optimum, ultimately yielding efficiency. However, this method requires a large use of memory, as each possible solution must be autonomous, which means that it must contain all the information for the branch-and-bound process. This then makes it impossible to have a global structure to build the solution.

Study [80] uses dynamic programming to solve the VPP bidding problem in different electricity markets. The short execution times obtained demonstrate the practical viability of this approach to rebalance decisions in intraday markets. The advantage of this method is its ability to manage discrete variables, constraints, and uncertainty at the level of each subproblem instead of considering all aspects simultaneously in a complete decision model. This method increases the resolution efficiency by avoiding repeating the same calculation several times.

To obtain optimal scheduling for the VPP, the authors of [56] use fuzzy programming and propose the transformation of fuzzy probability constraints in their equivalent forms to improve the calculation efficiency. The aim of this work is to find the optimal balance between economy and reliability in VPP operation. Study [62] uses an iterative procedure based on the area-based observation and focus algorithm, which is divided into two parts. First, this method provides a general description of the search field with possible random solutions. Subsequently, it undergoes a more detailed local search on the best point obtained in the first part of the procedure. This approach reduces the possibility of obtaining a local optimum.

In reality, however, distributed energy resources participate in a cooperative game in electricity markets to maximize the joint operating profit of the VPP. As a result, several studies [67,127,128] use procedures based on cooperative game theory to analyze the influence that each energy resource has on obtaining this profit and propose an appropriate distribution of profits. In contrast, other studies [58,66,107] use procedures based on the theory of noncooperative games, specifically the Stackelberg game. This type of model is applied to study the interaction between the market operator and the VPP operator. This method establishes an optimal two-stage decision process. First, the leader announces his strategy and has an idea about the response action of the follower. In the second stage, the follower performs a receptive strategy to respond to the leader. Once the leader receives this strategy, the final strategy is established.

Game theory is appropriate for analyzing the strategic behavior of VPPs in different electricity markets and competition among different VPPs. However, the information of all participants must be considered. In addition, one must account for the fact that as the number of participants and strategies increases, the degree of mathematical complexity for their resolution also increases.

3.1.2. Heuristic methods

Heuristic methods can provide a good solution to the problem, but they do not necessarily obtain an optimal solution. However, the resolution time is much shorter than in the case of mathematical methods. In addition, another important feature of these methods is their flexibility, as this allows for the incorporation of difficult modeling conditions. Heuristic methods are useful when the problem involves a large number of integer variables in addition to nonlinear constraints, where it is difficult to find an efficient solution using exact mathematical methods. Increasingly, articles have proposed heuristic procedures to solve problems of energy resource optimization in VPPs to either minimize the operating cost or maximize profit. The most common techniques that obtain the best solutions are as follows:

- Particle swarm optimization algorithm (PSO) [26,72,78,117,120].
- Genetic algorithms (GAs) [56,100,117,124,125].

The PSO algorithm is inspired by birds' social behavior in flight. Each particle is characterized by a position and velocity vector that directs its movement in the search space. This movement is guided by the optimal particles in the current moment. This algorithm is simple to implement, as there are few parameters that need adjustment. In addition, it produces an efficient search for the optimal solution with a shorter calculation time and less memory usage. On the other hand, GAs simulate biological evolution and natural selection based on learning, adaptation, and evolution. In each iteration, these algorithms consider a series of starting solutions. The main advantages are their flexibility and mode of operation, as they simultaneously determine several solutions instead of determining them sequentially, as done in common mathematical techniques. In other words, they explore the solution space quickly and intelligently. In addition, they more strongly avoid local optimal solutions even with highly complex problems. However, obtaining appropriate solutions demands that special attention be paid to the selection of the algorithm parameters, such as the population size and mutation rate. For example, if the population size is very small, the algorithm does not adequately explore the entire solution space, which may result in a local optimum.

In contrast, study [51] uses a metaheuristic method based on the big bang big crunch algorithm that seeks to minimize the purchase of electricity from the grid by managing the energy resources of the VPP in unbalanced distribution networks. Study [54] uses the metaheuristic imperialist competitive algorithm to minimize the operational cost of a VPP.

3.1.3. Summary of methods

As previously mentioned, most authors formulate the VPP problem as a mixed-integer linear model, and they mainly use mathematical methods to solve it. The application of branch-and-bound techniques is particularly popular due to their rapid convergence to a single optimal solution. However, the success of applying heuristic methods (approximation algorithms) rests on studying models of great mathematical complexity in a simple way and obtaining sufficiently strong solutions with a reasonable calculation time.

Table 1 summarizes the main advantages and limitations of the optimization problem types and the methods used for VPP model resolution.

3.2. Multiobjective optimization

Studies such as [46,72–75] propose the simultaneous minimization (or maximization) of different influential criteria in the operation of VPPs to achieve the optimal balance between them. As discussed in section 2, the authors of previous studies have proposed different objectives as subfunctions to analyze the multiobjective problem in VPPs. Study [46] seeks to maximize the profit of a VPP and minimize the cost of VPP self-consumption. Other studies, such as [72,74], seek to maximize the profit of a VPP and minimize carbon emissions, while the authors of [73,75] propose maximizing the economic profit of a VPP and minimizing the economic risk of the VPP by participating in electricity markets. In addition, different methods have been used for the appropriate resolution of the problem (see Table 2).

The authors of [73,75] transform the multiobjective model into a single objective problem to solve it by using weight coefficients. They first define a payoff table that decides the attributes for the calculation of the weight coefficients of the different objective functions. Subsequently, they use the fuzzy method to analyze the distance between the value of the objective function and the ideal value. Finally, they determine the optimal weight coefficients to solve the problem and thus reveal the best VPP operation strategy. These weight coefficients indicate the relative importance of each objective, and they are determined by using the entropy weight [73] and rough set [75] methods. Both methods are based on objective data to overcome the shortcomings of subjective methods. The weighting method stands out for its simple implementation of the problem and its efficiency. Study [72] uses an approach based on the Pareto optimum. The real Pareto frontier must be determined, which includes the set of optimal solutions (nondominated solutions) in the objective space. Once the Pareto frontier is generated, the VPP selects the best compromise solution according to the carbon emission constraints and the economic constraints related to the operation in the distribution system. In contrast, study [74] uses the epsilon-constraint method, which basically consists of maintaining an objective and restricting the rest of the objectives to an epsilon value. This method can be applied to convex and nonconvex problems. However, the difficulty with this approach is knowing the appropriate range of values to select the epsilon vector for the objective functions. It also has a high calculation time due to the level of variability required for the epsilon values.

Table 2
Characteristics of multiobjective optimization problems.

Ref.	Objective	Method	Best compromise solution	Characteristics
[46]	Maximizing the profit of the VPP and minimizing the cost of self-consumption of the VPP	Iterative process using CPLEX solver	–	Division of the original problem to make it more manageable
[72]	Maximizing the profit of VPP and minimizing operating emissions	PSO	Fuzzy technique	Reduction of execution time
[73]	Maximizing VPP profit and minimizing operating risk and emissions	Weighting method	Payoff table/ Fuzzy linearization/ Weight calculation	Efficiency and simplicity of implementation
[74]	Maximizing the profit of the VPP and minimizing operating emissions	Augmented epsilon-constraint method	Fuzzy technique	Selection of the appropriate range of epsilon vector values
[75]	Maximizing VPP profit and minimizing operation risk	Weighting method	Payoff table/ Fuzzy linearization/ Weight calculation	Efficiency and simplicity of implementation

4. Participation in electricity markets

Currently, most countries have already implemented processes of liberalization and openness to competition in their respective electricity markets. One reason that liberalization has been promoted is to improve the economic efficiency of the activities of electricity companies, finance new investments in the electricity infrastructure, and especially reduce the final prices of electricity supply. This change in the electricity sector brought about a transformation from a vertical structure, where all activities were integrated, to another organization where generation, transmission, distribution, and retailing operate independently.

At the beginning of liberalization towards the end of the 20th century, the majority of electricity markets were organized around a short-term wholesale market. This involved a large number of buyers and sellers of the system attending and conducting auctions for the purchase and sale of electricity. However, some markets, such as Texas (following the proposals of the Federal Energy Regulatory Commission), Scandinavian countries (NordPool), and the English market (New Electricity Trading Agreements), sought to promote the use of bilateral transactions and avoid all energy being traded in a single pool. Currently, mature electricity markets have both day-ahead markets and forward and futures markets, which allow for diversifying the price risk in the purchase and sale of energy in electricity markets.

In addition, the current energy context characterized by the massive introduction of renewable energy in the power system implies a greater use of the balancing mechanisms of the system due to deviations from the generation program of renewable sources.

An important advantage of VPPs is that they sell energy on behalf of the owners of the distributed energy resources when accessing the wholesale electricity markets and thus increase their joint profit. This section addresses the participation of VPPs in different electricity markets.

4.1. Futures and forward market

The futures market consists of purchase and sale contracts of firm energy for a specified period of time at a fixed price. This market allows for the acquisition of a quantity of energy on a determined date that can be within a week or even years. Futures are typically traded on a standardized exchange, whereas forward markets are self-regulated.

Studies [41–43,47], and [100] propose VPP models that allow energy purchase and sales transactions through futures markets. Participation in this market allows the VPP to avoid the risks derived from the high uncertainty of prices in the day-ahead electricity market. The VPPs presented in studies [42,43], and [100] exploit the arbitrage opportunities between the day-ahead electricity market and the futures market to increase their operating profit.

4.2. Bilateral contracts (PPAs)

Bilateral contracts consist of a direct agreement for the sale of electricity between a power generator and a buyer of that power. Both parties agree on a series of characteristics, such as the price, volume of power delivery, and duration of the contract, in addition to the minimum power to be supplied/consumed. The strong growth of renewable energy sources in recent years has boosted this type of contract intended to avoid price uncertainty and, thus, ensure long-term price stability to make both investment in the construction of the generation plant and the productive process of the consumer profitable. In the reviewed literature, articles [20,22,33,40,42,43,62,69–71,94], and [126] propose a VPP model that must supply part or all of the demand through a bilateral contract in a time horizon of one week. This contract offers a strong opportunity to guarantee VPP income due to the volatility of the market price and possible constraints of the transmission system operator.

4.3. Day-ahead market

The day-ahead market is designed to conduct electricity transactions for each hour of the following day through the presentation of sale and purchase bids by market agents. The VPPs allow generators direct access to the electricity markets for the sale of their production and allow consumers to self-produce energy, the sale of excess energy from generation facilities that they cannot self-consume. At a higher market price, the general trend of generation facilities is to produce the maximum generation available to maximize the operating profit of the VPP due to the sale of surplus energy generated. As a result, research papers incorporate this capacity to participate in the day-ahead electricity market in their VPP models to maximize their operating profit [20–129]. In addition, a flexible electrical system is achieved, encouraging self-consumption and reducing the environmental impact.

Although the VPP generally acts as a price-taker in electricity markets, in some reviewed works, the VPP acts as a price-maker [79,80,82, 84,87,100,103,107,116,118], and [119]. This condition is advantageous given that the bidding decisions can influence the resulting day-ahead electricity market prices for VPPs' own profit.

4.4. Ancillary services market

The main objective of the ancillary services market is to guarantee the security and reliability of the electricity generation and transmission system. The role of ancillary services is to provide the system with the capacity to maintain a balance between generation and demand at all times. With the improvement of the liquidity of ancillary services markets, the participation of VPPs will likely increase considerably, and their economic viability may improve. From a technical perspective, the progressive growth of renewable generation facilities in current power systems can weaken them, as poor management can lead to the collapse of the grid, thereby failing to guarantee the reliability of the electricity supply. As a result, several studies have incorporated the capacity to participate in ancillary services markets into VPP modeling to allow for frequency-power control that guarantees the quality and security of the electricity supply [21,33,37,38,44,61,74,88,90,95,110,118], and [122]. These VPP models also incorporate storage systems, which are essential elements to overcome electricity grid stability problems that may appear due to deviations of renewable energy resources.

4.5. Reserve market

The reserve market is a mechanism that allows additional generation reserves to ensure demand coverage and the security of the electricity supply. Usually, generators that present offers are remunerated at a marginal price. This mechanism is increasingly necessary given the frequency of situations in which reduced margins of power reserves in the electrical system are identified due to the growth of nondispatchable renewable energy (mainly wind and photovoltaic). Several works in the literature reviewed [27,29,30,32,33,57,64,73,86,91,98,119,120,122, 124,125], and [127], propose different methodologies for the VPP to make the optimal decisions in the day-ahead and reserve electricity markets, maximize the economic profit, and ensure adequate levels of security and reliability. According to the results obtained from these studies, the reserve market is more important in periods of maximum demand because a contingency can have a greater impact. In addition, when a greater amount of renewable generation is produced, it is more profitable for the VPP to sell energy in the day-ahead market or recharge the storage systems than to participate in the reserve market. Therefore, the profit of the VPP associated with this market does not necessarily increase. There are electricity markets where the scheduling of energy and reserves is separated, as in the case of the Iberian Electricity Market (Spain), while this scheduling is done together for others, such as the California Independent System Operator (California, USA).

4.6. Intraday market

Intraday markets are designed to adjust the energy traded in the day-ahead market with greater precision, as there is more information than in that session. In these markets, a lower volume of energy is traded than in the day-ahead electricity market. Intraday markets are gaining greater importance due to the increase in renewable energy and its unpredictable nature, making it essential to correct offers and adjust the imbalances in the availability of expected generation. In addition, this market can also be highly useful for the agents that participate in it. For example, if there is a breakdown in a generator group, agents can repurchase the energy that it sold in the day-ahead market session in an intraday session. Studies [36,44,55,59,80,93,95,100,104,106], and [113] include the commercialization of VPP energy in intraday markets to increase profits.

4.7. Real-time balancing market

The real-time balancing market is the last market opportunity for balancing production and consumption. The gate closure of this market typically ranges between five and 30 min before actual energy delivery.

Although intraday markets allow VPPs to adjust the scheduled energy after the day-ahead market, exchange power imbalance may still occur as the dispatch time approaches. Thus, to avoid penalties, VPPs can participate in real-time balancing markets. The objective in the reviewed papers is to minimize the imbalance error and associated cost. In other words, this refers to the difference between the actual electric output and the forecasted output, covered either by the VPP or through the electricity from the balancing market [26,45,58–60,67,70,82–86, 91–93,99,102,103,107–109,111], and [127–129]. Due to the intermittent nature of renewable energy sources, VPP access to these markets is essential to balance generation and consumption.

4.8. Summary of electricity markets in which VPP models participate

Table 3 summarizes the main characteristics of the different electricity markets in which the VPP models reviewed in the literature participate. Fig. 3 graphically depicts the sequence of market types.

In conclusion, the VPP models proposed in the articles reviewed participate in the day-ahead market for the purchase and sale of energy to maximize their operating profit. Due to the integration of distributed energy resources in VPPs, they can participate more actively in electricity markets, as they would have greater difficulties accessing markets individually due to their small capacities.

In recent years, power systems have experienced substantial growth in generation plants with renewable energy. To favor these plants' integration into the electricity system, market mechanisms should be promoted that provide greater flexibility to the electricity system and improve its capacity to cope with the variability and uncertainty of renewable generation. This should ultimately ensure the security of the electricity supply. For this reason, the growing development of ancillary services markets and bilateral contracts is notable.

There is an important current trend regarding the signing of bilateral energy sales contracts by electricity producers with renewable sources. This type of contract represents a strong opportunity for electricity consumers to manage and minimize the risk of high future prices. In addition, these contracts reduce environmental impacts by opting for a long-term and stable renewable source. Moreover, this type of contract allows for the financing of new renewable projects.

Table 3
Main characteristics of the types of markets.

Ref.	Electricity market	Characteristics
[41–43,47,100]	Futures market	Purchase and sales contracts of firm energy for a period of time and fixed price Avoid electricity market price uncertainty
[20,22,33,40,42,43,62,69–71,94,126]	Bilateral contracts	Direct agreement on the sale of electricity between a power generator and the buyer of said energy Avoidance of price uncertainty Long-term price stability to make profitable both the investment in the construction of the generation plant and the production process of the possible consumer
[20–129]	Day-ahead market	Offers of sale and purchase of energy for each hour of the following day Flexibility of the electrical system Greater self-consumption and operating profit
[21,33,37,38,44,61,74,88,90,95,110,118,122]	Ancillary services market	Security and reliability of the electricity generation and transmission system Balance of generation and demand at all times
[27,29,30,32,33,57,64,73,86,91,98,119,120,122,124,125,127]	Reserve market	Management of additional generation reserves to ensure demand coverage and the security of electricity supply
[36,44,55,59,80,93,95,100,104,106,113]	Intraday market	Precise adjustment of the energy traded in the day-ahead market Reduction of imbalance costs
[26,45,58–60,67,70,82–86,91–93,99,102,103,107–109,111,127–129]	Real-time balancing market	Management of deviations between generation and demand Electrical system balance Security of electricity supply

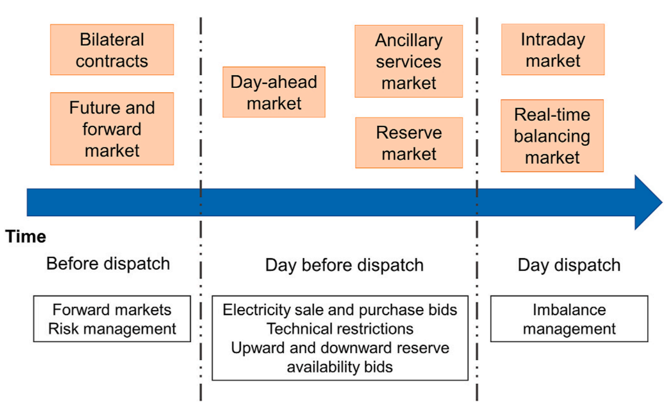

Fig. 3. Sequence of electricity market types.

At the same time, there must be a constant balance between generation and consumption to ensure the stability of the network. Many of the articles reviewed include VPPs' participation in the real-time balancing market to reduce generation deviations and possible subsequent economic penalties.

As a result of electricity market volatility, good risk management of both electricity sales and purchases must adequately combine futures markets, bilateral contracts, and the day-ahead (spot) market. In addition, simultaneous participation in different markets can provide additional profits to VPPs. However, only a few studies reviewed acknowledge this idea, and they have only combined day-ahead and futures markets [42,43], and [100].

5. Real case studies

To validate the efficiency of the mathematical optimization model of a VPP, some papers apply the model to a real case study to analyze the real scope of the implementation of VPPs. This is done through the optimal coordination of power generation and storage sources available to cover a given load at any time during the established study period. In addition, studies have analyzed different electricity markets to clarify their interaction with the model proposed and maximize their operating profit.

Older models applied to a real case study include few components and do not study the impact of storage system integration [40,45]. The authors of [40] use real data from generation facilities of both renewable and conventional origin in addition to data from the electrical demand of Sibenik County, located on the coast of Croatia. Market prices are determined from historical data of the EEX market. Reference [45] proposes a case study of a VPP with residential tariffs and the generation profile of a fixed photovoltaic installation located on the roof of the KU Leuven campus in Belgium. Regarding cogeneration components, this study details the technical data of real models existing in the market. In addition, it uses the energy purchase and sale prices in the day-ahead market of Belpex recorded in 2012.

Other articles include pumped hydrostorage [20,88], as it is a mature technology with an infinite technical life and a fast response capacity. Recent papers have studied the joint management of water and energy [24,25]. The authors of [24,25] apply the VPP model to a large irrigation system located in Aragon (Spain) with their own data of only renewable generation (hydroelectric, self-consumption photovoltaic, wind) and electricity demand. The studies use the hourly prices of the OMIE wholesale electricity market for the purchase and sale of energy in 2017.

The reviewed models mainly incorporate batteries to store renewable energy [21,33,52,60,82,83,86], and [107]. Energy storage is a key factor for managing renewable production and ensuring the stability of the electrical system against the massive introduction of this intermittent production. In these works, the VPP can reduce the risks of volatile market prices and operating risks of stochastic wind and/or photovoltaic generators. Nevertheless, the study periods are quite short, generally spanning a day or week, which allows for minimal analysis of the VPP operation. Study [21] analyzes data related to wind speed, solar radiation, and market prices of the PJM market for the area of Virginia (USA) on a summer day in 2005 to obtain a solution for the proposed model. Similarly, study [86] uses real data on the day-ahead market price, reserve, and real time of the PJM electricity market in July 2017. It also uses data related to the production and installed capacity of the generation facilities. The authors of [52] present a small-scale VPP project in Guizhou (China) that includes a wind farm (WPP), photovoltaic installations (PV), batteries, electric vehicles (EVs), combined heat and power plants (CHP), and a boiler. In addition, this study uses real data on the purchase and sales prices of energy and the operation and maintenance costs of the components. Articles [60,82], and [83] obtain the optimal bidding strategy of a VPP by analyzing historical data on the hourly prices of the electricity market in the area of Massachusetts (USA) for a day in May 2011. They also analyze historical wind production data obtained from the Bishop and Clerk wind farms. Once the wind speed is known, the hourly wind energy production curve is obtained from the power curve provided by the wind turbine manufacturer.

The authors of [33] analyze the feasibility of a VPP based on data from the new engineering campus at the University of Melbourne (Australia). The VPP consists mainly of photovoltaic installations and batteries in addition to controllable loads. The research includes investment costs and fixed and variable operating costs. For market prices, the study accounts for how the VPP participates in various markets, such as electricity, FCAS, and cap contracts. Study [107] uses the electricity market transaction rules of the Electric Reliability Council of Texas (USA) for the optimal operation of a VPP comprising large-scale photovoltaic installations with a storage system.

Note that the optimal management of renewable resources and electricity demand is achieved with the incorporation of storage systems in the VPP model. This produces greater energy autonomy and a better correlation between production curves and electricity demand. In addition, greater economic profit is achieved by participating in electricity markets through purchasing energy at low prices and selling it at high prices. The VPP makes the best decisions that maximize its operating profit. For example, the VPP might buy or sell additional energy in the real-time market or use the storage system to compensate for prediction errors, ensuring compliance with market operations. The incorporation of storage systems reduces both the risk of volatility in the price of the electricity market and the risk of operating renewable resources.

Table 4 summarizes the main characteristics of the VPP model applied to real case studies.

6. Discussion

This section compares the VPP models and their temporal evolution over the last ten years. This review classifies the articles according to several significant criteria, such as the type of problem, resolution methods, and electricity markets. Older articles propose simpler VPP models with fewer components that participate only in the day-ahead market by selling production of the generators. Most articles use a linear or mixed-integer linear mathematical model without high computational complexity [20–24,27–47,83–100], etc. Over time, however, there has been an evolution towards more complete and realistic models.

Fig. 4 shows the participation of the reviewed VPP models in different markets (day-ahead, intraday, futures, ancillary services, reserve, real-time balancing, and bilateral contracts). The most recent models show greater diversity in the types of electricity markets in which VPPs participate. First, this is because the legal regulation of the countries has allowed distributed generation to participate in ancillary services of the electricity system, which was previously reserved for classical power plants. Moreover, the greater maturity of electricity markets encourages consumers and generators to participate more actively in other types of markets, with the objective of obtaining additional profits from their participation in the day-ahead market or in bilateral contracts.

Fig. 5 graphically summarizes the mathematical models used for the optimal management of VPP resources. The figure confirms that most of the reviewed works formulate a mixed-integer mathematical problem with continuous and integer variables. This type of formulation is characteristic of problems regarding the optimal dispatch of resources, wherein decisions are made to produce/not produce, export/import energy, etc. However, in recent years, the complexity of mathematical models has been growing, and more nonlinear problems have been formulated. This is the result of incorporating more realistic approximations of the VPPs and including more complex interactions in the mathematical models between agents and markets. To resolve these models, articles, such as [26,56], and [72], usually use heuristic methods given that they allow greater flexibility and robustness for handling the problem characteristics.

Regarding the composition of the VPP, the most current models already integrate storage systems, EVs, and their interaction with electricity markets to maximize the VPP's operating profit.

Note that increasingly more research has focused on the proposal of multiobjective problems that account not only for economic profits but also for the environment and other aspects [46,72–75]. However, there is an area for improvement here, and other models can be developed to include additional aspects, such as investment costs and more distribution network constraints.

This review's findings indicate that only a few studies consider the ability of arbitrage between day-ahead and futures markets [42,43,100].

Table 4
Characteristics of VPP models applied to real case studies.

Ref.	Components	Location	Technical data	Study period
[20]	Gas turbine/ WPP/PV/Pumped storage hydro	Sibenik County (Croatia)	Gas turbine capacity = 5.67 MW WPP capacity = 9.6 MW PV capacity = 6 MW Pumped storage accumulation = 40 MWh	1 week
[21]	WPP/PV/Diesel/ Microturbine/ Batteries	Virginia (USA)	WPP capacity = 25 kW PV capacity = 12 MW Min/max capacity Diesel generator = 5/30 MW Micro turbine min/max capacity = 5/28 MW 220 V 16 A lithium-ion batteries	1 day
[24, 25]	Hydroelectric/ WPP/PV	Irrigation system in Aragon (Spain)	Hydroelectric capacity = 14.7 MW WPP capacity = 30 MW PV capacity = 15.5 MW Annual demand = 39 MWh	1 year
[33]	PV/Gas generator/ Batteries	New engineering campus of the University of Melbourne (Australia)	PV capacity = 1.1 MW Gas generator capacity range = 0–4 MW Battery capacity range = 0–4 MW Load = 14 MW	1 year
[40]	PV/WPP/Gas turbine	Sibenik County (Croatia)	WPP capacity = 9.6 MW Min/max gas turbine capacity = 2.5/5.67 MW PV capacity = 6 MW	1 week
[45]	PV/CHP/Boiler	KU Leuven Campus (Belgium)	Small PV capacity = 32 kW Boiler efficiency = 90%	1 day
[52]	PV/WPP/CHP/ Boiler/Storage/ EV	Guizhou (China)	WPP capacity = 300 kW PV capacity = 305 kW CHP capacity = 600 kW Boiler capacity = 500 kW Storage capacity = 200 kWh, SOC = 20–80% EV capacity = 324 kWh	1 day
[60]	WPP/Storage	Massachusetts (USA)	WPP capacity = 100 MW Storage capacity = 200 MWh, efficiency = 90%	1 day
[82]	WPP/Storage	Massachusetts (USA)	WPP capacity = 100 MW Storage capacity	1 day

(continued on next page)

Table 4 (*continued*)

Ref.	Components	Location	Technical data	Study period
			= 200 MWh, efficiency = 90%	
[83]	Gas turbine/ WPP/Storage	Massachusetts (USA)	WPP capacity = 100 MW Min/max gas turbine capacity = 20/180 MW Storage capacity = 200 MWh, efficiency = 90% Maximum charge/ discharge capacity = 100 MW	1 day
[86]	PV/Storage/ Flexible load/ Dispatchable generating units	PJM market (USA)	PV capacity = 6 MW Storage charge/discharge capacity = 0.3/ 0.5 MW Flexible load capacity = 2 MW DGUs capacity = 5 MW	1 day
[88]	WPP/Pumped storage hydro/ Gas turbine	Sibenik County (Croatia)	WPP capacity = 9.6 MW Pumped storage hydro capacity = 40 MWh Gas turbine capacity = 5.67 MW	1 day
[107]	PV/Storage/EV	Texas (USA)	PV capacity = 100 MW Battery capacity = 25 MWh, efficiency = 98% Max charge/ discharge capacity = 12.5 MW EV capacity = 70 kWh Max EV charge/ discharge capacity = 10 kW	1 day

This shows how there are still pending challenges related to the modeling of CVPPs, such as the simultaneous consideration of multiple electricity purchase and sales strategies in wholesale markets. In other words, the CVPP models decide how to diversify the risk of the acquisition or sale of energy among the different instruments available: spot market, futures market, PPAs, etc.

The papers reviewed have rarely considered distribution network constraints in VPP operation [64]. More research should be conducted to study the technical and economic viability of electricity exchanges in distribution networks, including the interaction between CVPPs and TVPPs in the model.

Some authors have begun to introduce artificial intelligence techniques for wind generation prediction [62]. Nevertheless, these methods need to be investigated properly. Incorporating artificial intelligence can allow the VPP models to learn to maximize the profit of the operation as they train with more real data, from the perspectives of both demand and the management of VPP energy resources.

VPP models have rarely been applied to real cases, and they include few components [45,60,82]. Future research should focus on the application of the proposed models to real case studies to analyze the integration of new types of agents (storage systems, demand aggregators, etc.) in the framework of current power systems and its contribution to competitive electricity markets.

7. Conclusions

The purpose of this review is to analyze the interaction of VPP models with different types of electricity markets. This article clearly identifies the relevant aspects of the research conducted in this field of study, how the models have evolved in recent years, and the challenges that remain for future research. This review classifies and analyzes 110 papers according to the definition of the main objective, formulation of the model, selection of the solving method, participation in different electricity markets, and application of the proposed VPP model to real case studies. This review evaluates in detail the advantages and disadvantages of each aspect analyzed to provide useful knowledge for further research.

The four main conclusions of this review are as follows:

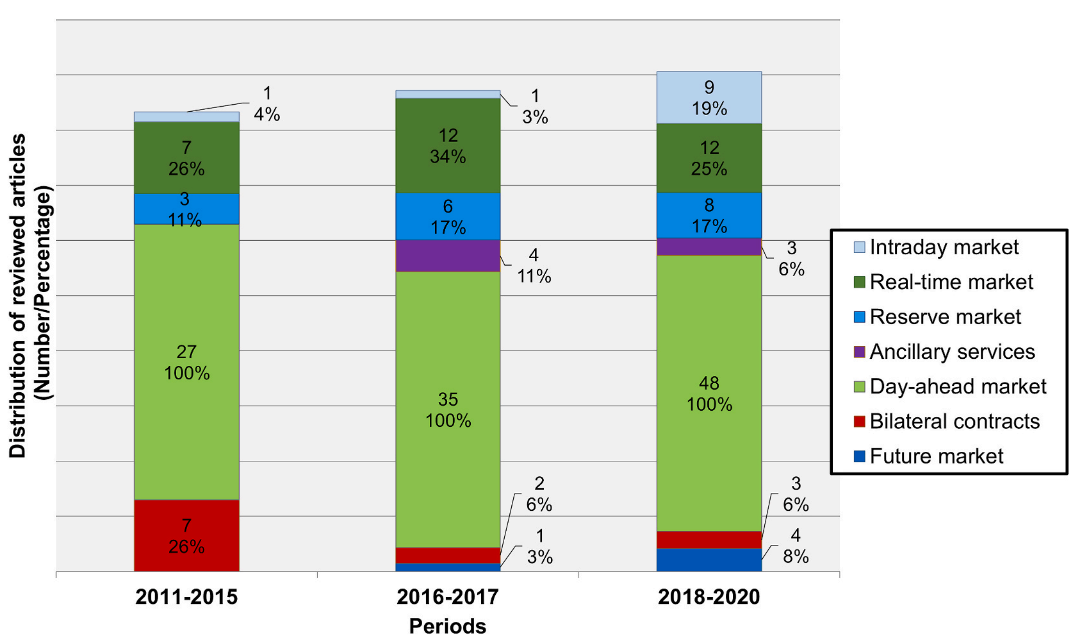

Fig. 4. Distribution of the types of markets included in the VPPs (2011–2020).

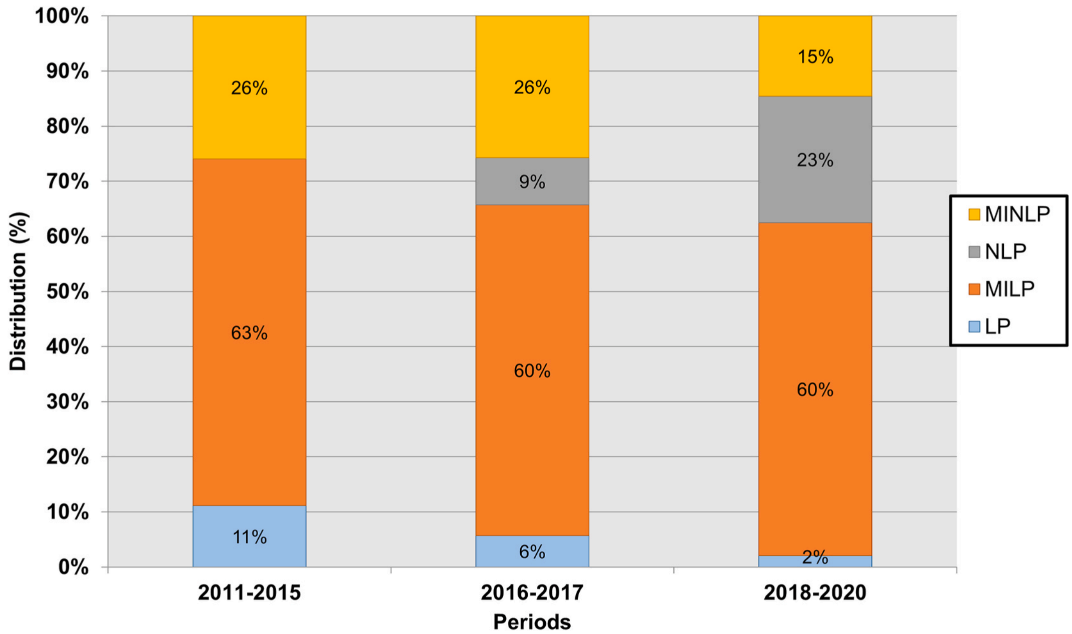

Fig. 5. Distribution of the mathematical models used for VPPs (2011–2020).

- Most of the research has focused on the development of VPP models to achieve optimal control and coordination among the components and thus maximize the operating profit.
- As time has progressed, models have become more complete and complex and include more operating constraints. As a result, more advanced optimization techniques are required to achieve an optimal solution.
- From the perspective of participation in electricity markets, the integration of distributed generation in the VPP has contributed to more active participation in different types of markets. In addition to the day-ahead spot market, recent articles have included bilateral contracts, futures, and balancing markets in the models. This shows how greater profits can be obtained in the operation of VPPs.
- Proposed models have rarely been applied to real cases, such as in industrial processes that require the management of electricity consumption and its own generation facilities.

In addition, the review establishes that there is a paucity of research that uses real-world case studies. Furthermore, the review identifies other pending challenges, such as the combination of multiple VPP electricity purchase and sales strategies and the use of artificial intelligence techniques to provide learning tools for VPP models to anticipate the best decisions.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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A virtual power plant optimal dispatch model with large and small-scale distributed renewable generation

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A B S T R A C T

Volatility and sharp increases in the price of electricity are serious economic problems in the primary sector because they affect modernization investments for irrigation systems in Spain. This paper presents a new virtual power plant (VPP) model that integrates all available full-scale distributed renewable generation technologies. The proposed VPP operates as a single plant in the wholesale electricity market and aims to maximize profit from its operation to meet demand. Two levels of renewable energy integration in the VPP were considered: first, a wind farm and six hydroelectric power plants that inject the generated electricity directly to the distribution network, and second, on-site photovoltaic plants associated with each of the electricity supply points in the system that are designed to prioritize self-consumption. The proposed technical-economic dispatch model was developed as a mixed-integer optimization problem that determines the hourly operation of distributed large-scale renewable generation plants and on-site generation plants. The model was applied to real data from an irrigation system comprising a number of water pumping stations in Aragon (Spain). The results of the VPP model demonstrate the importance of the technical and economic management of all production facilities to significantly reduce grid dependence and final electricity costs.

1. Introduction

Electricity is one of the most costly elements in the operation of an agricultural irrigation water pumping station. Until 2008, the Spanish government set regulated electricity rates, but since then, farming communities have had to purchase electricity from a deregulated market at much higher prices. As a result, the survival of many recently modernized facilities has been threatened due to higher electricity prices; these prices also exhibit volatility and uncertainty throughout the year. Farming communities paid prices above 15 c€/kWh in 2014, compared to an average of 7.7 c€/kWh in 2007. The future of the current scenario of volatility and steep increases in wholesale electricity market pricing is uncertain.

Countries worldwide rely on their energy policy strategies to develop renewable energy to address global warming, reduce their dependence on fossil-fuel-based electricity, improve the security of energy supply and promote industry and development in a region where renewable energy technology is installed. Introducing renewable energy to an increasingly competitive electricity market requires new technologies and operating systems to address new technical and economic challenges arising from the optimal integration of available resources. Smart grids, virtual power plants and digital transformation are keys to this integration.

Most of the studies reviewed in this paper have focused on the growing importance of the management capabilities of different types of virtual power plants. A virtual power plant can be defined as a cluster of distributed generation units, controllable loads and storage systems that are aggregated to operate as a single power plant without the need for a physical connection by direct power lines [1]. In virtual power plants, an energy management system is integral to coordinating power flow between generators, loads and storage. Communication between units may be bidirectional, which means that the virtual power plant (VPP) can send control signals to the components that constitute the virtual plant as well as receive information on the current status of each unit.

The main objective of previous studies has been optimizing the operation of the VPP to maximize profit, using techniques for typical technical and economic dispatch problems, which leads to scheduling different power generation sources [2].

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Nomenclature

Indexes

i	index for number of hours
j	index for pumping stations

Variables

P^i_{exp}	energy exported to the grid (MWh)
P^i_{imp}	energy imported from the grid (MWh)
P^i_W	wind power generated (MW)
P^i_H	hydroelectric power generated (MW)
$P^i_{in\ j}$	energy input from general bus A to a pumping station j (MWh)
$P^i_{out\ j}$	energy output from a pumping station j to general bus A (MWh)
I^i_{exp}	binary variable equal to 1 if energy is delivered to the grid; otherwise, it is equal to 0
I^i_{imp}	binary variable equal to 1 if the pumping station j imports energy from the grid; otherwise, it is equal to 0
$I^i_{in\ j}$	binary variable equal to 1 if energy is received by the pumping station j from general bus A; otherwise, it is equal to 0
$I^i_{out\ j}$	binary variable equal to 1 if energy is delivered from the pumping station j to general bus A; otherwise, it is equal to 0

Data

ρ^i_{exp}	hourly energy sales price (€/MWh)
ρ^i_{imp}	hourly energy purchase price (€/MWh)
f_W	operation and maintenance cost of wind farm technology (€/MWh)
f_H	operation and maintenance cost of hydroelectric technology (€/MWh)
f_{PV}	operation and maintenance cost of photovoltaic technology (€/MWh)
$P^i_{D\ j}$	hourly load of each pumping station j (MW)
$P^i_{PV\ j}$	photovoltaic power generated hourly (MW)
$P^i_{W\ max}$	hourly available wind power generation (MW)
$P^i_{H\ max}$	hourly available hydroelectric power generation (MW)
$P^i_{exp\ max}$	hourly maximum power exported to the grid (MWh)
$P^i_{imp\ max}$	hourly maximum power imported from the grid (MWh)

Researchers have proposed different solving methods for the dispatch problem (see Table 1). In Ref. [3], the problem of optimal energy management has been solved with an imperialist competitive algorithm. The study in Ref. [4] has proposed a fully distributed dispatch algorithm without a centralized controller. The authors of [5] have used a combined optimization method based on interval and deterministic optimization to solve an economic dispatch problem related to VPPs and to manage the uncertainties associated with renewable energy. In Ref. [6], the “Big Bang Big Crunch” optimization method has been used to minimize the annual purchase of electricity in unbalanced distribution networks. Other works have applied stochastic optimization ([7,8]) and non-linear optimization programming ([9,10]). However, the most frequently applied optimization technique has been mixed-integer linear programming since it suits the characteristics of dispatch problems ([11–17]).

One must also consider the economic aspects of the dispatch problem. Virtual power plants can participate in different electricity markets to purchase and sell power. Different approaches can be found in the literature that consider energy markets in relation to VPPs. Reference [11] has maximized the weekly profit of a VPP under long-term bilateral contracts. In Ref. [12], a coalition-forming scheme has been developed for a commercial virtual power plant based on weekly bilateral contracting and futures market as well as day-ahead markets. Reference [13] has used several interregional energy contracts to model a cooperation system among neighbouring VPPs. In Ref. [18], a methodology to coordinate different VPP agents and electricity market operators has been presented.

Electricity can also be purchased and sold in real-time. Several papers have aimed to determine an optimal bidding strategy for a VPP using different optimization methods. In Ref. [19], an optimal offering strategy for a commercial virtual power plant has been obtained by using stochastic optimization. The study in Ref. [7] has provided a combination of adaptive robust and stochastic optimization for VPP models that participate in day-ahead and real-time electricity markets. In Ref. [9], the distributionally robust optimization approach has been proposed to determine the optimal values of parameters for the bidding strategy, such as capacity or cost curve. The authors of [10] have presented a fuzzy optimization technique to address the bidding problem and have achieved lower computation times with this method than with other deterministic and probabilistic methods.

In order to reduce the range of the problem’s uncertainties, some papers have incorporated an initial statistical contribution in which electricity market pricing and renewable power generation intermittency are the most influential variables. Different methods have been proposed to manage the uncertainty of these parameters in VPP scheduling. References [14,19] have considered different demand response programs and have used stochastic programming to manage uncertainty. The point estimate method has been used in Ref. [15], while the studies [7,8] have proposed a stochastic robust optimization method. References such as [16,20] have applied the Conditional Value at Risk (CVaR) method to risk management in the VPP model. Reference [21] has presented a multi-objective programming model that incorporates the uncertainty management and carbon dioxide emissions of VPP. In the mentioned study, the Conditional Value at Risk (CVaR) method and robust optimization theory have been used to model uncertainty. In Ref. [22], a method has been provided for profit allocation among different distributed energy resources that constitute the VPP. This method has been shown to reduce computation time through cooperative game theory methods.

Very few papers have studied and analyzed the virtual power plant concept in real cases. In Ref. [23], the integration of VPPs in the German energy market has been economically assessed, while the study [17] has analyzed the technical-economic impact of the implementation of the VPP concept in the Spanish electricity system. In Ref. [24], the economic feasibility of VPPs in Chongming Island (China) has been studied by calculating the net present value (NPV) and analyzing the life cycle cost.

In summary, the reviewed studies have generally proposed models that do not include all the control variables of the different types of renewable generation. In addition, these models have not

Table 1
Classification of the reviewed VPP studies.

Ref.	Objective	Solving method	Wholesale markets	Uncertainty management	Storage	Case study	Real case study
[3]	Energy management	Imperialist competitive algorithm		✓	✓	✓	
[4]	Profit maximization	ADMM and consensus optimization				✓	
[5]	Economic dispatch	Combined interval and deterministic optimization		✓			✓
[6]	Energy management	Big Bang Big Crunch	✓		✓	✓	
[7]	Bidding strategy	Stochastic adaptive robust optimization	✓	✓			
[8]	Self-scheduling	Stochastic adaptive robust optimization	✓	✓		✓	
[9]	Bidding strategy	Second-order cone program	✓		✓		
[10]	Bidding strategy	MINLP	✓	✓		✓	
[11]	Mid-term dispatch scheduling	MILP	✓	✓	✓	✓	
[12]	Medium term coalition	MILP	✓			✓	
[13]	Interregional cooperation	MILP	✓	✓		✓	
[14]	Electrical/thermal energy scheduling	MILP	✓	✓	✓		
[15]	Electrical/thermal energy scheduling	MILP	✓	✓	✓		
[16]	Risk aversion scheduling	MILP		✓		✓	
[17]	Profit maximization	MILP					✓
[18]	Congestion management	Rolling horizon method	✓	✓		✓	
[19]	Bidding strategy	Mathematical programming model with equilibrium constraints	✓	✓		✓	
[20]	Energy management	MINLP	✓			✓	
[21]	Multi-objective profit maximization/risk minimization/ carbon emissions minimization	Robust optimization		✓			
[22]	Profit allocation	Two-stage stochastic programming/game theory	✓	✓			
[23]	Economic feasibility	Scenario method					✓
[24]	Economic feasibility	NPV/life cycle cost					✓

integrated the management of large- or medium-scale power generation plants (which are mainly designed to export all the electricity produced to the grid) with small-scale photovoltaic self-consumption facilities. Furthermore, the VPP concept has rarely been applied to real cases. These aspects are all considered in our research.

The goal of this paper is to develop a new optimal operation model that incorporates the electricity generation and consumption of irrigation systems. This model incorporates both renewable generation sources and the hourly electricity demand through a virtual power plant mathematical model. As a new feature, the model proposes that the pumping stations' demand is supplied by their own system's power generation sources (for example, wind or hydro) but also by renewable distributed generation sources at each pumping station (photovoltaic), to reduce both its dependence on the grid and the final electricity cost. When necessary, electricity from the grid can be purchased to meet demand. The proposed model is a mixed-integer linear programming model that aims to maximize the profit of the operation of the VPP for each hourly period over one year of study.

In summary, the most innovative contributions of this research are as follows:

- The design of an optimal VPP management model with two levels of integration of renewable energy: on the one hand, wind and hydroelectric power generation injected directly to the grid, and on the other, on-site photovoltaic self-consumption facilities.
- The application of this model to the operation of a power control centre of a 135,000 ha irrigation system in Aragon (Spain) with an electricity consumption of 39 GWh per year and a power generation of 180 GWh per year.

The rest of this article is organized as follows. Section 2 explains the proposed optimal dispatch model. Section 3 details the case study with actual demand and renewable power generation data. Section 4 presents the main results of the model. Next, Section 5 provides a sensitivity analysis of various model parameters. Finally, Section 6 presents the main conclusions of this study.

2. Optimal dispatch model

The irrigation system of Riegos del Alto Aragon, one of the largest in Europe, comprises a group of irrigation communities spanning an area exceeding 135,000 ha and with an annual water consumption of 800 Hm^3. This system is located in Aragon (Spain), where climatic conditions make irrigation a key determinant of production diversification and of labour and land productivity. Therefore, irrigation is a key influencer of farm income and of the living standards of farmers, which is reflected in the territorial distribution of farm employment.

In recent years, irrigation communities in Riegos del Alto Aragon have invested significantly in their own renewable power generation facilities (wind, hydro). These communities are also large consumers of electricity due to their water pumping stations; therefore, it is essential to jointly manage consumption and power generation to reduce energy costs and improve environmental sustainability. This paper proposes the design and implementation of a VPP that incorporates the electricity consumption of pumping stations and power generation plants. The proposed VPP operates as a single plant in the wholesale electricity market and maximizes the profit of the systems involved. Fig. 1 depicts the location of the electricity generation facilities and the irrigated areas of the Riegos del Alto Aragon irrigation system.

The system under study consists of 27 irrigation water pumping stations that are connected to the electric distribution network and have a total annual electricity demand of 39 GWh. This demand is partially supplied by on-site photovoltaic generation facilities, by other sources from within their own generation system or by the purchase of electricity from the electricity market.

This research proposes a mathematical model of optimal hourly dispatch to incorporate the technical and economic management of all the consumption and generation facilities into a VPP model. The mathematical problem of the VPP profit maximization was formulated as a mixed-integer linear programming model. On the one hand, the problem has binary variables associated with the decision to import or export energy in each subsystem for each hour. On the other hand, the optimum values of the power generation and the imported energy were calculated, both at each pumping station and by the system overall. Equations (1)–(13) formulate the objective function and the technical constraints that model the system behaviour.

Hourly demand and renewable electricity generation forecasts are available the day before for the dispatch model, as well as electricity market prices for purchasing and selling energy from the day-ahead market [25]. However, the decision-making process was performed hourly for one year in order to analyze the system operation and the effective generation and demand coupling during the year 2017.

Fig. 2 schematically presents the VPP agents. The electricity generation plants distributed in the region are connected hourly to attempt to meet the pumping station demand. There are two levels for connecting the generated power: (i) the wind farm and the six hydroelectric power plants send the generated electricity directly to the distribution network, and (ii) the on-site photovoltaic plants (PV) are designed to prioritize meeting the demand of each pumping station and inject any surplus power into the distribution network. These self-consumption facilities are obliged to meet first the local demand in accordance with the provisions of article 9.1 of Spanish Law 24/2013 [26]. Fig. 2 presents the load $P^i_{D\,j}$ and produced solar power $P^i_{PV\,j}$, and the input $P^i_{in\,j}$ and output $P^i_{out\,j}$ power in each subsystem. These variables do not represent the power line flows, but rather, the power to connect hourly in the integrated economic VPP model.

If the demand of the pumping stations is not met, energy P^i_{imp} will be purchased from the electricity market by a pass-through contract indexed to the OMIE wholesale market prices of Spain [25]. Conversely, if excess energy P^i_{exp} is produced, it will be sold to the grid each hour at the price stated by the OMIE day-ahead market, minus generation taxes and fees. The model assumes that purchasing and selling energy transactions cannot occur simultaneously (Eq. (6)).

The objective function presented in Eq. (1) maximizes the hourly profit of joint operation of the power generation and consumption facilities of the VPP, expressed as the difference between income and costs of all the system agents. The income results from selling the hourly excess in generated power ($\rho^i_{exp} \cdot P^i_{exp}$) to the electricity market, while the costs are from the power generated hourly by each wind and hydro generation facility ($f_W \cdot P^i_W$, $f_H \cdot P^i_H$), the cost of PV surplus power sent out from the pumping station ($f_{PV} \cdot P^i_{out\,j}$) and the hourly cost of purchasing energy if generation does not meet demand ($\rho^i_{imp} \cdot P^i_{imp}$).

As mentioned above, the PV plants meet the demand of each pumping station first, so the demand supplied by the PV plants does not need to be purchased from the electricity market. Only the cost of the extra energy generated by each PV plant and injected into the distribution network is considered in the dispatch model.

The technical constraints considered for modelling the system are defined below.

The overall power balance of the system that ensures the supply of the demand at all times is stated in Eq. (2). Furthermore, Eq. (3) defines the power balance at each pumping station and ensures that all available photovoltaic power is used every hour.

Eqs. (4) and (5) establish that wind and hydroelectric power generation (P^i_W, P^i_H) must each be equal to or greater than 0 and are limited by their maximum available power.

Next, the constraints related to the energy imported from and exported to the distribution network are presented. The

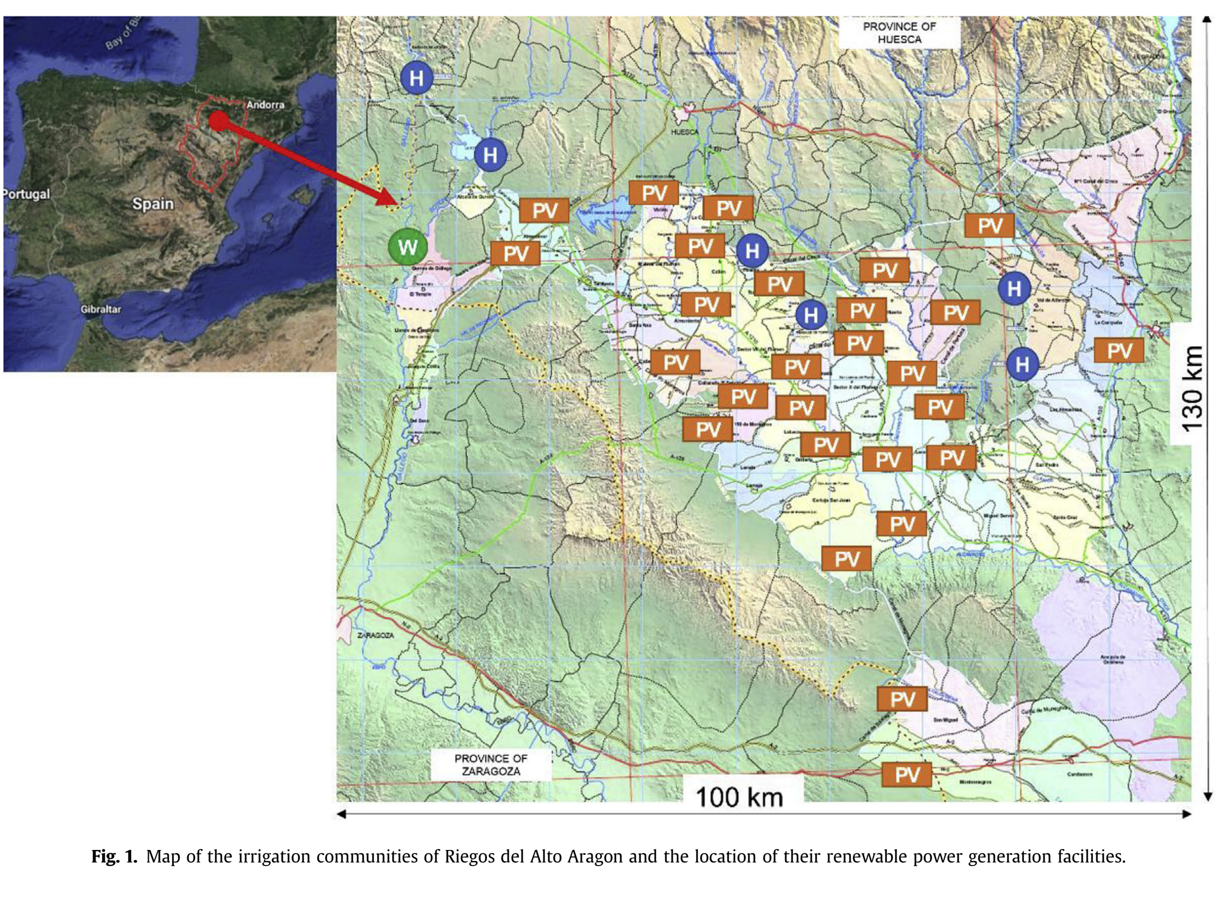

Fig. 1. Map of the irrigation communities of Riegos del Alto Aragon and the location of their renewable power generation facilities.

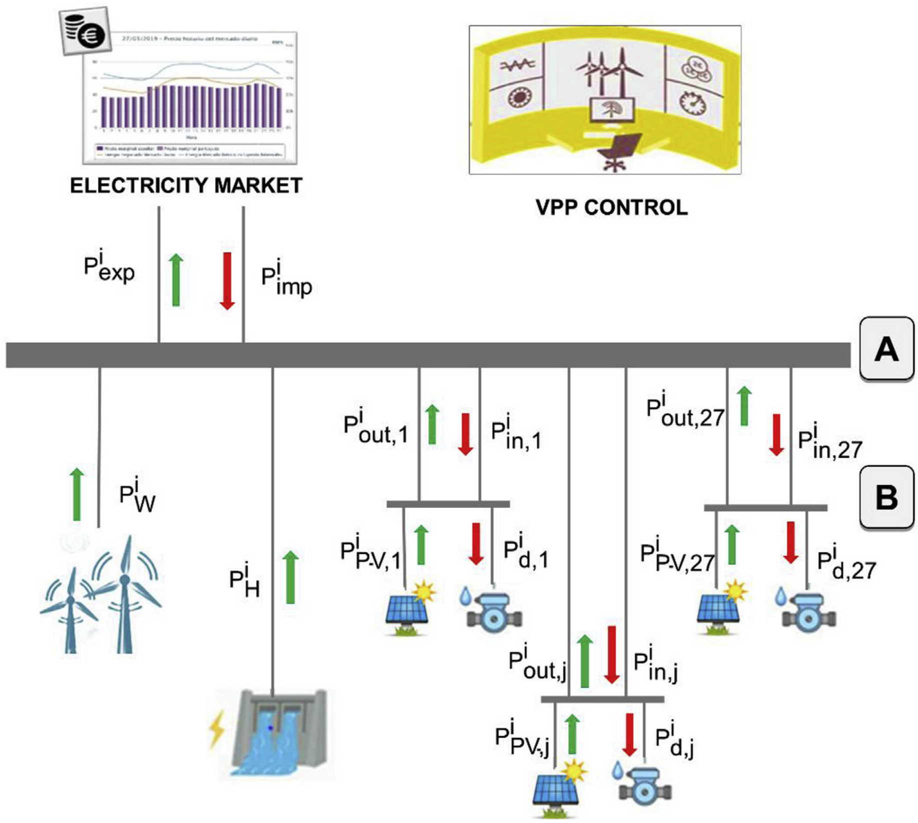

Fig. 2. Agents involved in the proposed VPP.

transactions of purchasing and selling energy in the electricity market cannot occur simultaneously every hour; therefore, Eq. (6) states that the sum of the integer decision variables (I^i_{imp}, I^i_{exp}) must be less than or equal to 1. The limits of energy imported from the grid are defined by Eq. (7); the minimum value must be greater than or equal to 0, while the maximum value depends on the product of the maximum demand of the system (Eq. (9)) and the associated integer variable. If energy is imported, $I^i_{imp} = 1$, and the imported energy will be less than or equal to the maximum demand, $P^i_{imp\ max}$. A similar situation exists for energy exported to the grid (Eqs. (8) and (10)). The maximum system energy that can be generated, and therefore exported to the grid, $P^i_{exp\ max}$, is stated in Eq. (10).

Lastly, the constraints related to the photovoltaic generation plants in each pumping station were established. Electricity can only be exchanged in one direction between a subsystem B and the virtual bus of system A each hour (that is, it can only be imported from A to B or exported from B to A (see Fig. 2)); As stated by Eq. (11), the sum of the integer decision variables ($I^i_{out\ j}$, $I^i_{in\ j}$) must be less than or equal to 1. The limits of the energy output of each pumping station is indicated by Eq. (12); it must be greater than or equal to 0, and the upper limit depends on the integer decision variables $I^i_{out\ j}$ and $I^i_{in\ j}$. If energy is delivered to the general bus A, $I^i_{out\ j} = 1$, and the upper limit of the energy output of each pumping station will correspond to the available hourly photovoltaic power generated. Otherwise, if the energy is received, $I^i_{in\ j} = 1$, and the maximum value of the energy input of the pumping station will coincide with its hourly demand (Eq. (13)).

- Objective function

$$max\left\{\sum_{i=1}^{8760}\left(\rho^i_{exp}\cdot P^i_{exp} - \rho^i_{imp}\cdot P^i_{imp} - f_W\cdot P^i_W - f_H\cdot P^i_H - \sum_{j=1}^{27} f_{PV}\cdot P^i_{out\ j}\right)\right\} \quad (1)$$

- Constraints

$$P^i_{imp} - P^i_{exp} + P^i_W + P^i_H = -\sum_{j=1}^{27} P^i_{out\ j} + \sum_{j=1}^{27} P^i_{in\ j} \quad (i = 1..8760) \quad (2)$$

$$P^i_{out\ j} - P^i_{in\ j} = P^i_{PV\ j} - P^i_{Dj} \quad (j = 1..27,\ i = 1..8760) \quad (3)$$

$$0 \le P^i_W \le P^i_{W\ max} \quad (4)$$

$$0 \le P^i_H \le P^i_{H\ max} \quad (5)$$

$$I^i_{imp} + I^i_{exp} \le 1 \quad (6)$$

$$0 \le P^i_{imp} \le I^i_{imp}\cdot P^i_{imp\ max} \quad (7)$$

$$0 \le P^i_{exp} \le I^i_{exp}\cdot P^i_{exp\ max} \quad (8)$$

$$P^i_{imp\ max} = \sum_{j=1}^{27} P^i_{D\ j} \tag{9}$$

$$P^i_{exp\ max} = P^i_{W\ max} + P^i_{H\ max} + \sum_{j=1}^{27} P^i_{PV\ j} \tag{10}$$

$$I^i_{outj} + I^i_{inj} \leq 1 \tag{11}$$

$$0 \leq P^i_{out\ j} \leq I^i_{out\ j} \cdot P^i_{PV\ j} \tag{12}$$

$$0 \leq P^i_{in\ j} \leq I^i_{in\ j} \cdot P^i_{D\ j} \tag{13}$$

As indicated by the equations of the formulated optimization problem, the model is of a mixed-integer linear programming type (MILP) because there are decision variables related to the import or export of electricity and continuous variables for the values of energy exchanged. An appropriate solving method involves obtaining the optimal management of energy resources integrated into a VPP, as seen in Section 1. The integer variables are used to carry out the decision-making process for each hourly period during a year. Thus, an optimal hourly solution to the problem can be obtained. MATLAB software was used to solve the mathematical problem because its optimization toolbox includes an efficient solver for mixed-integer linear programming (MILP). The computation time was 6.64 min for the dispatch problem of 8760 h using a computer with an Intel®Core i7 processor, 2.5 GHz CPU and 12 GB of RAM.

3. Case study: data

3.1. Demand

The hourly load curves of the pumping stations in 2017 are available for integrating demand into the VPP dispatch model. Electricity consumption is highly seasonal since the area's crop irrigation season mainly occurs during the summer months (see Fig. 3).

Table 2 presents the electricity consumption per year for each pumping station. The total annual consumption of the analyzed system was 39 GWh.

The final cost of electricity to a consumer in Spain is the sum of the cost of generating electricity in the wholesale market plus the cost of access tariffs for grid use and other minor fees.

The irrigation communities are under a six-period access tariff contract, meaning there are six different periods with different grid usage costs that depend on the month and time of day. Period P1 is the most expensive and period P6 is the cheapest; therefore, the irrigation communities try to minimize consumption in period 1 and concentrate it in cheaper periods. Fig. 4 shows the distribution of the different periods of the time-of-use access tariffs throughout the year.

Table 3 presents the distribution of electricity consumption for each of the six periods of the high voltage access tariffs. An analysis of the energy distribution indicates that most electricity consumption occurs in period P6 when the energy price is lower; this corresponds to nights, weekends and the month of August.

3.2. Hydroelectric generation

The system has six hydroelectric power plants, geographically scattered throughout the region, with a total output power of 14.7 MW. These plants use dammed water and water flowing through channels to produce electricity. Table 4 describes the power distribution of each hydroelectric power plant. The hourly hydropower generation data are available for 2017. Fig. 5 depicts the monthly generation of the system's six hydroelectric plants.

As indicated in Fig. 5, only one plant operates for the whole year because its dam is fed by a river. The remaining five plants generate power mainly during the irrigation season, when there is an increased amount of water flowing through the transport channels. Table 5 describes the distribution of generated power by pricing period. The total amount of energy generated by the hydropower plants is 48.9 GWh/year.

As previously stated, 60% of the power generation occurs during period P6. However, 80% of the yearly pumping station demand is concentrated in the hours of the same pricing period, P6; therefore, a complete temporal match between hydropower generation and power demand does not exist.

3.3. Wind farm

The system has a wind farm consisting of nine wind turbines with an installed capacity of 30 MW. The hourly generation data of the wind farm are available. Fig. 6 visualizes the power generated per month.

Table 6 presents the power generation distribution by pricing period. Again, the largest power generation occurs during period P6, which is relevant for system power management because it coincides with the period of highest consumption by the irrigation communities.

3.4. Distributed photovoltaic generation

Each pumping station has a self-consumption photovoltaic (PV) system. The total installed PV capacity is 15.5 MW. Table 7 lists the installed capacity of each pumping station. Fig. 7 presents the total power generation of the 27 PV plants for each of the 24 h of every day over the 365 days of study.

As expected, power generation is concentrated in the hours when there is solar radiation, and the maximum generation values are obtained between 12:00 and 17:00.

Additionally, Table 8 presents the distribution of the energy generated by pricing period. The highest power generation occurs in period P6, but this amount is less than that of the wind farm and the hydropower plants.

3.5. Generation costs

This research considered variable generation costs, including the renewable technologies' operating and maintenance costs that determine the study model behaviour (see Table 9).

3.6. Cost of purchasing electricity

The demand of the pumping stations is met first by on-site photovoltaic plants and secondly by the system generators. In the event that the generation does not fully meet the demand, additional energy P^i_{imp} will be purchased from the electricity market through an indexed contract. In the standard format of a pass-through electricity supply contract, the calculation of the hourly price of purchasing electricity ρ^i_{imp} must incorporate other terms in addition to the energy price term of the OMIE day-ahead market (see Eq. (14)).

$$\rho^i_{imp}(€ / MWh) = \Big[\Big(C^i_{OMIE} + C^i_{const} + C^i_{procSO} + C^i_{int} + C^i_{cap} + C_{MO}$$

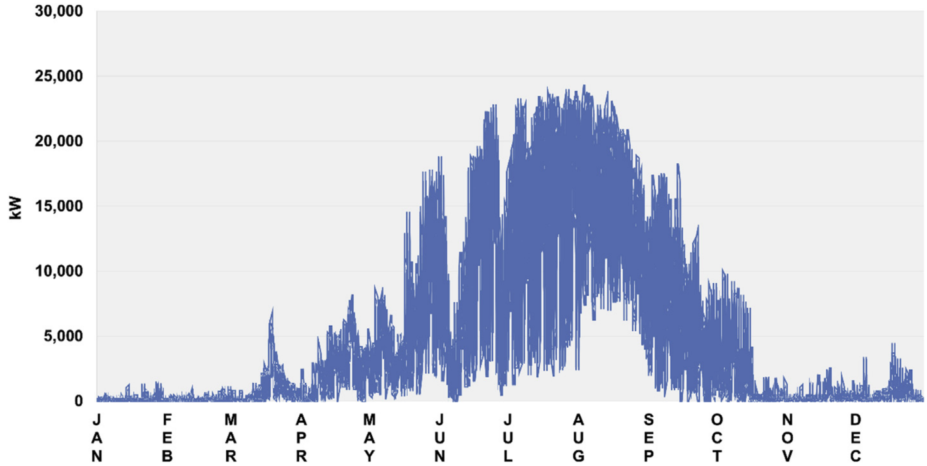

Fig. 3. Annual demand curve of the irrigation communities under study.

Table 2
Annual electricity consumption of the pumping stations.

Pumping station	Energy (MWh)	Pumping station	Energy (MWh)
PS1	746	**PS15**	450
PS2	2223	**PS16**	622
PS3	965	**PS17**	3732
PS4	4419	**PS18**	278
PS5	2112	**PS19**	656
PS6	2555	**PS20**	900
PS7	843	**PS21**	1615
PS8	530	**PS22**	1592
PS9	2036	**PS23**	2688
PS10	284	**PS24**	2014
PS11	1011	**PS25**	1053
PS12	1282	**PS26**	192
PS13	1045	**PS27**	801
PS14	2361		
Total energy (MWh)		**39,003**	

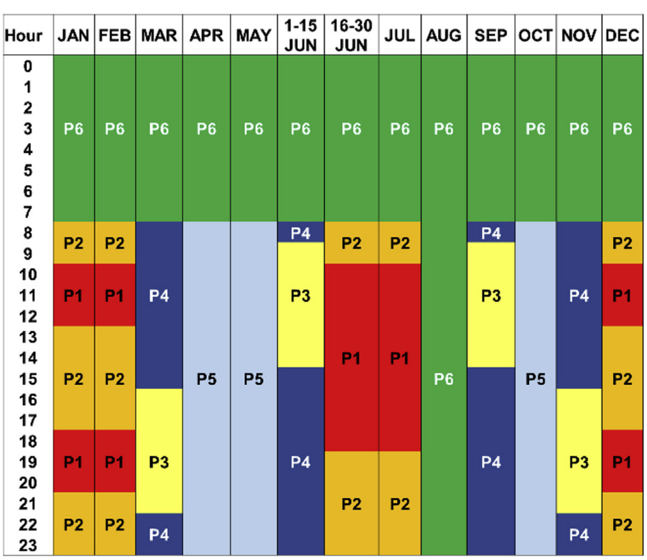

Fig. 4. Time-of-use access tariff schedule.

$$+ C_{SO}\Big) \cdot \Big(1 + k^i_{loss}\Big) \cdot Cf\Big] + Fee + NT^i \qquad (14)$$

The terms of Eq. (14) are defined as follows:

Table 3
Electricity consumption distribution by pricing period.

Period	Energy consumed (MWh)	Percentage (%)
P1	1124	2.88%
P2	2432	6.23%
P3	405	1.04%
P4	1334	3.42%
P5	1676	4.30%
P6	32,032	82.13%
Total energy (MWh)	**39,003**	**100.00%**

Table 4
Installed capacity of the hydroelectric facilities.

Hydroelectric power plant	Installed capacity (MW)
H1	4.4
H2	0.9
H3	1.2
H4	1.1
H5	5.0
H6	2.1
Total power (MW)	**14.7**

- C^i_{OMIE}: hourly electricity price from the OMIE day-ahead market
- C^i_{const}: hourly technical constraints on the market price
- C^i_{procSO}: hourly market price of ancillary services of the system operator
- C^i_{int}: interruptible service cost
- C^i_{cap}: capacity cost
- C_{MO}: market operator cost
- C_{SO}: system operator cost
- k^i_{loss}: grid loss coefficient
- Cf: coefficient that varies according to the supplier (usually from 1.15 to 1.18)
- Fee: management cost that depends on the supplier
- NT^i: regulated energy term for the grid access tariff

3.7. Income from selling electricity

In the proposed model, surplus energy generated in the system is sold at the marginal hourly price recorded by the OMIE wholesale market during 2017. The generation tax (7%) and the generation grid access tariff (0.5 €/MWh) are considered in the final energy sales price (see Eq. (15)).

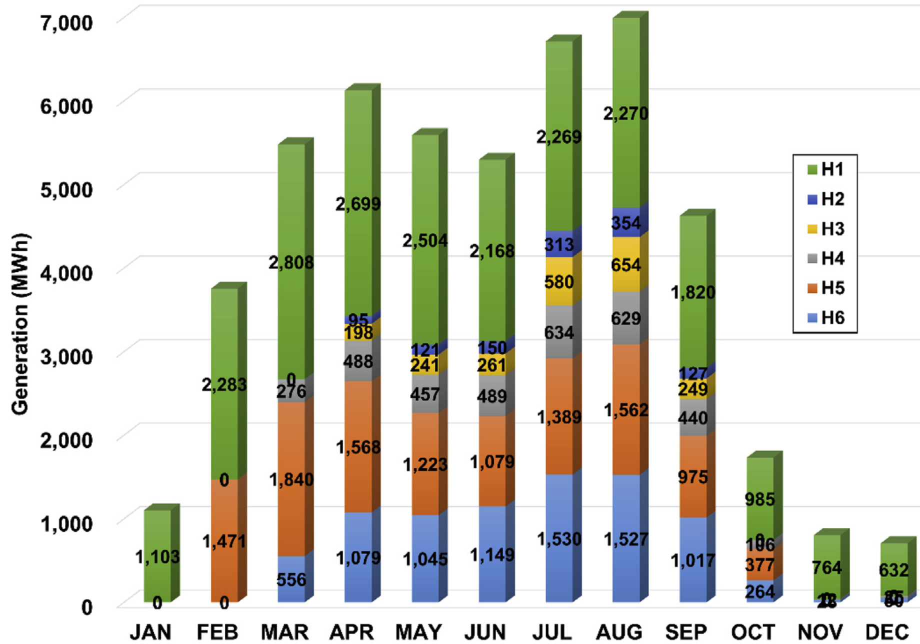

Fig. 5. Monthly power generation of the hydropower plants.

Table 5
Distribution of hydropower generation by pricing period.

Periods	Energy produced (MWh)	Percentage (%)
P1	3206	6.55%
P2	3841	7.85%
P3	2416	4.94%
P4	4007	8.19%
P5	6239	12.75%
P6	29,226	59.72%
Total energy(MWh)	**48,934**	**100.00**%

Table 6
Distribution of wind power generation by pricing period.

Period	Energy produced (MWh)	Percentage (%)
P1	6806	6.50%
P2	10,684	10.20%
P3	4879	4.66%
P4	9224	8.81%
P5	10,014	9.56%
P6	63,096	60.26%
Total energy (MWh)	**104,703**	**100.00**%

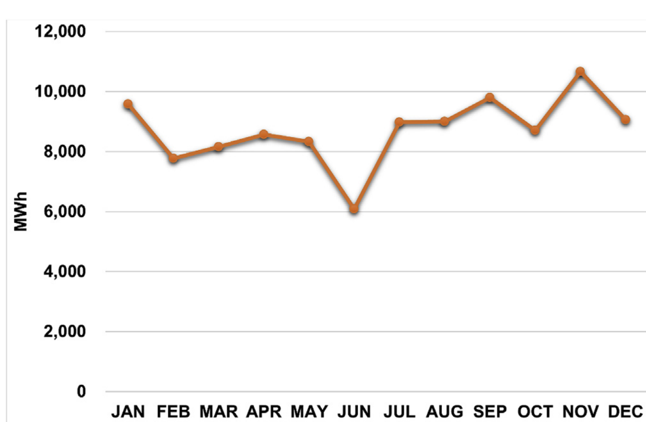

Fig. 6. Wind power generation per month.

$$\rho^{i}_{exp}\ (€/MWh) = \left[C^{i}_{OMIE}\cdot(1-0.07)-0.5\right] \tag{15}$$

4. Case study: results

The optimization model, which maximizes the hourly profit generated by the system, calculates the optimum value of 114 variables over the 8760 h of a year. The main optimization problem variables are those related to the power generated by each of the technologies included in the model and the amount of energy imported or exported hourly, both at each pumping station and by the whole system overall. In addition, the model includes 56 integer variables that have a value of 0 or 1 depending on the most profitable option for the system every hour.

Fig. 8 displays the hourly results obtained to meet the demand of all pumping stations for a week in July, which is typically the month of maximum annual demand.

In the optimal VPP solution for the hours in July, hydropower generation remains almost constant, since hydroelectric plants depend on water flow into the irrigation communities through the supply channels, and in this month the pumping stations are in full operation.

In contrast, the variability of wind power generation is apparent and leads to some full demand coverage situations but also to some periods with a lower contribution to the energy system. When maximum wind power generation is reached, there is no need to buy electricity from the grid, and excess power is exported to the grid; conversely, if wind power generation decreases, the system usually needs to purchase energy from the grid to meet demand.

Lastly, according to the design specifications, the photovoltaic plant's power is self-consumed as much as possible. However, energy consumption patterns are different for each pumping station, and the on-site photovoltaic generation does not perfectly match

Table 7
Installed capacity of photovoltaic facilities.

Pumping station	Installed PV capacity (kW)	Pumping station	Installed PV capacity (kW)
PS1	325	**PS15**	575
PS2	700	**PS16**	230
PS3	300	**PS17**	1005
PS4	975	**PS18**	230
PS5	941	**PS19**	255
PS6	1106	**PS20**	350
PS7	367	**PS21**	750
PS8	301	**PS22**	750
PS9	1000	**PS23**	715
PS10	225	**PS24**	815
PS11	400	**PS25**	445
PS12	420	**PS26**	877
PS13	230	**PS27**	585
PS14	600		
Total power (MW)		**15.5**	

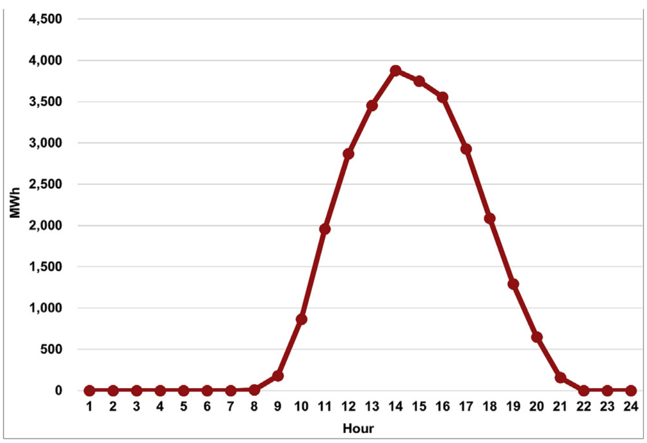

Fig. 7. Total energy generated by the photovoltaic plants.

Table 8
Distribution of the total photovoltaic generation by pricing period.

Period	Energy generated (MWh)	Percentage (%)
P1	3874	14.02%
P2	2473	8.95%
P3	2057	7.44%
P4	3099	11.21%
P5	5588	20.21%
P6	10,553	38.17%
Total energy (MWh)	**27,645**	**100.00%**

Table 9
Operating and maintenance costs of renewable technologies [27,28].

TECHNOLOGY	OPERATING AND MAINTENANCE COSTS (€/MWh)
Wind	$f_W = 16.49$
Hydroelectric	$f_H = 16.19$
Distributed photovoltaic	$f_{PV} = 7.40$

the load profile of each pumping station. For that reason, some of the stations obtain very small self-consumption rates since they barely connect their pumps during the day when there is substantial photovoltaic generation, while other pumping stations reach self-consumption percentages of around 50%. In the winter months, there is almost no demand, and solar generation is exported to the grid; therefore, the system income increases due to the sale of surplus power.

Fig. 9 shows the optimal power generated monthly by each technology included in the model. As expected, the hydropower plants produce electricity according to the seasonality of the water flowing through the transport channels to the pumping stations, that is, generation is more concentrated in months of the irrigation season. The variation in the electricity generated by the photovoltaic plants follows the typical solar irradiance cycle during the year. However, wind energy production exhibits greater variability than solar energy production due to its stochastic nature, as later discussed in Section 5.2.

Fig. 9 also demonstrates that the demand follows a seasonal pattern and is mainly concentrated in the summer months. However, for the overall system, monthly production is greater than monthly demand throughout the year.

Furthermore, a very high percentage of the available wind and hydroelectric power production is scheduled (98.98% and 99.53%, respectively) (Table 10), but for some hours it is more profitable to purchase energy from the electricity market instead of generating it using renewable power generation plants (see Fig. 11). Electricity production from on-site photovoltaic plants reaches 100% since these plants produce energy whenever the solar resource is available. This information illustrates the usefulness of the optimal dispatch model in maximizing the profit of an integrated VPP operation.

Fig. 10 depicts the monthly generation costs of each technology as well as the income from the sale of surplus power to the electricity market. As indicated, the income throughout the year is greater than the system costs. In the months when the system demand is minimal, surplus power is generated, and high income results from its sale. Conversely, in the irrigation season months, self-consumption increases, and energy must be purchased from the electricity market (C_{imp}) to meet demand, resulting in higher costs.

The pumping station demand is entirely met by the power generation plants for 8247 h per year (see Fig. 11). In addition, the power plants produce no power for 36 h a year. During those hours it is necessary to purchase all the energy required from the electricity market to meet demand, a situation that occurs most often during the peak demand summer months (see C_{imp} in Fig. 10).

Table 11 presents the main results obtained, in terms of both energy and cost. The power generation plants cover 94.6% of the annual pumping station demand, which considerably reduces the dependence on the grid and aids system sustainability. The remaining 5.4% of demand is purchased from the electricity market either because there is not enough internal generation in the VPP or because purchasing energy is more profitable.

From the results in Table 11, an annual average generation cost of

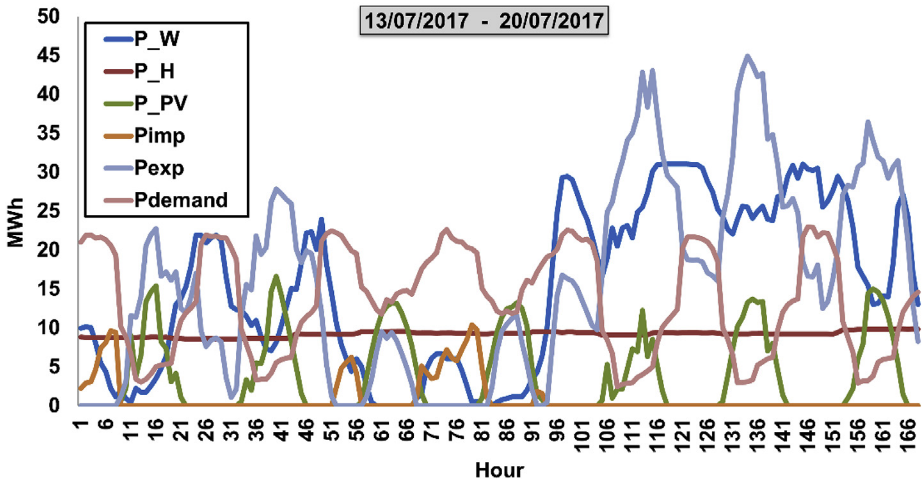

Fig. 8. Hourly optimum results for a week in July.

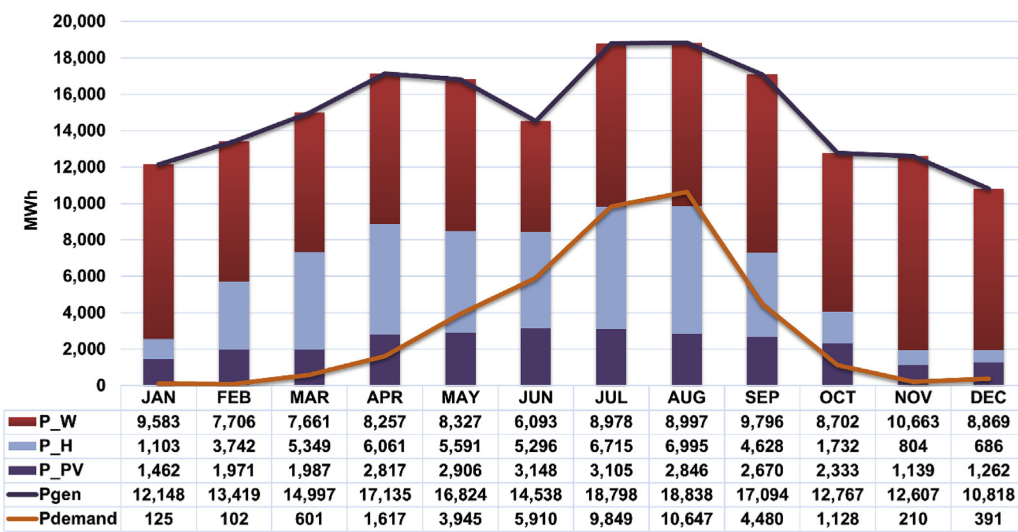

Fig. 9. Monthly aggregation of optimal hourly power generation.

the electricity production of 15.01 €/MWh can be calculated. The annual average remuneration obtained from the sale of electricity is 47.67 €/MWh, and the average cost of the electricity purchase is 58.65 €/MWh. As explained in Section 3, the purchase cost is the sum of the wholesale market price and the network access tariffs.

For the system to maximize its profit, the electricity generation must occur at the same time as consumption, that is, the quantity of energy produced must match the energy demand as closely as possible. However, it depends not only on the available generation resources but also on whether the generation costs are competitive compared to the prices set in the day-ahead electricity market.

5. Sensitivity analysis

This section presents a sensitivity analysis of various model parameters to evaluate their corresponding economic impact on the VPP.

5.1. Wholesale electricity market prices

This section analyzes the sensitivity of the optimal dispatch model in different electricity market price scenarios. Variation in these prices affects both the income from the sale of surplus generation to the wholesale market and the costs of purchasing energy

Table 10
Percentage of annual demand supplied by the system's generators and scheduled generation of each technology.

	Energy production (MWh)	Demand coverage (%)	Scheduled generation (%)
P_W	103,634	54.5%	98.98%
P_H	48,703	25.6%	99.53%
P_{PV}	27,645	14.5%	100.00%
TOTAL	179,982	94.6%	

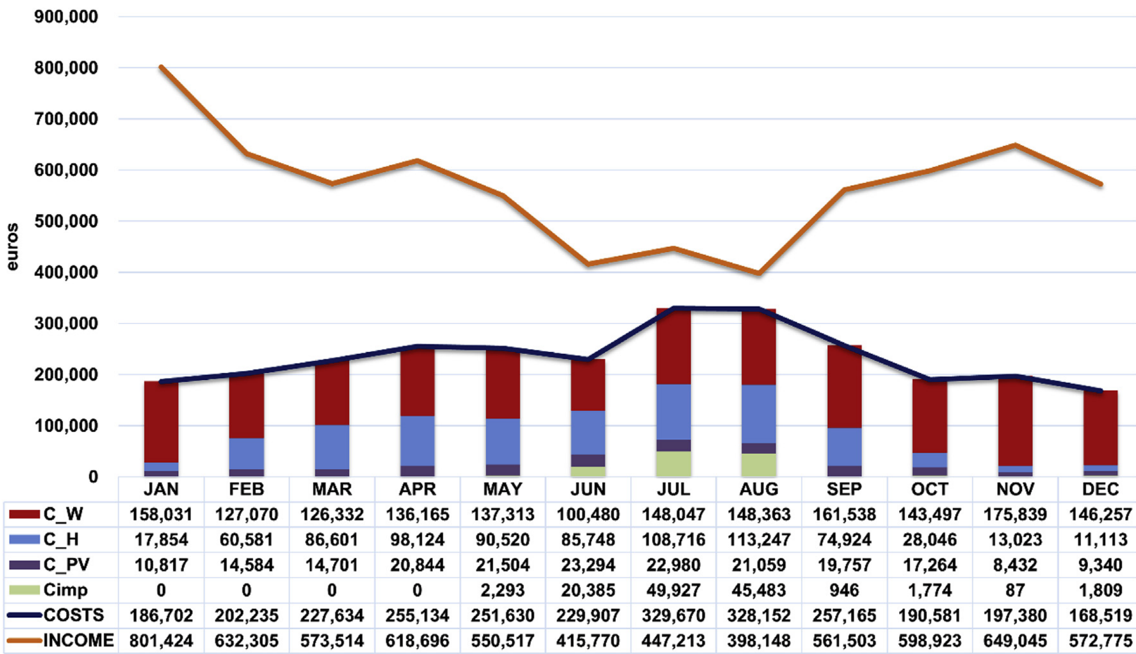

Fig. 10. Monthly costs and income.

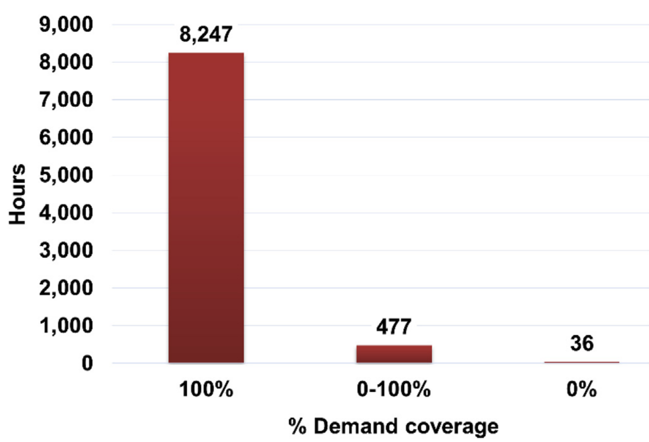

Fig. 11. Number of hours and percentage of demand supplied by the VPP.

during certain months of the year. Using the OMIE average 2017 wholesale market price in Spain as a reference, between 2006 and 2017 there are differences that range from −40% to +20% of the 2017 price [25,29]. Six scenarios of sensitivity analysis have been performed for market prices ranging from −40% to +20%.

Table 12 describes the evolution of the annual generation, import and export of power in relation to the variation in the average electricity market price. Energy imported from the grid remains constant since it is difficult to compete against renewable power generation costs, even when electricity market prices drop by 40%. However, when the market price increases, generation and surplus power sales increase slightly (0.2%) because the price paid by the market renders power generation more profitable. Conversely, when the market price drops, power generation decreases between the reference case and the OMIE -40% case (−1.6%) because generating power is not as profitable if the power is sold at a price below the generation cost.

Fig. 12 presents the evolution of system costs and income depending on the electricity market price. In general, the income is greater than system costs for all cases analyzed and always yields a positive operating profit. Changes in electricity market prices have a greater impact on income because they are directly related to the power sales price set by the market, while costs barely change with decreases or increases in the OMIE market price. For example, in the OMIE +20% case, income increases by 20% compared to the 2017 reference case and 61% compared to the OMIE -40% case; however, costs only increase 1% and 4% for each case, respectively.

Table 11
Optimal annual results of the VPP.

	Energy (MWh)	Demand coverage (%)	Costs/Income (€)
P_{demand}	39,003	100%	
P_{gen}	179,982		−2,702,004
P_{exp}	143,071		6,819,833
P_{imp}	2092	5.4%	−122,704
$P_{self\text{-}cons}$	36,912	94.6%	
Total cost			−2,824,708
Total income			6,819,833

Fig. 13 represents the optimal scheduling of power generation according to the variation in electricity market prices. The photovoltaic energy always reaches 100% due to design specifications. The wind and hydropower generation curves follow a similar trend, but wind energy is used less than hydropower in all the cases studied. This disparity arises mainly because wind power has a higher generation cost; furthermore, the hours of hydroelectric generation and the hours of demand are more similar than those of wind power. Fig. 13 also demonstrates that as market prices increase, producing more electricity with the wind farm and hydropower plants becomes increasingly profitable.

5.2. Wind power generation

Wind power technology has the greatest influence on the VPP model. Section 4 validated the model with actual production data from the wind farm in 2017, and this section studies the influence of other wind power generation profiles on the model. For this

Table 12
Evolution of the annual generation, import and export of power according to OMIE prices.

	OMIE −40%	OMIE −30%	OMIE −20%	OMIE −10%	**OMIE ref**	OMIE +10%	OMIE +20%
P_{gen} (MWh)	177,069	178,861	179,720	179,853	179,982	180,144	180,306
P_{imp} (MWh)	2092	2092	2092	2092	2092	2092	2092
P_{exp} (MWh)	140,157	141,949	142,808	142,941	143,071	143,232	143,394

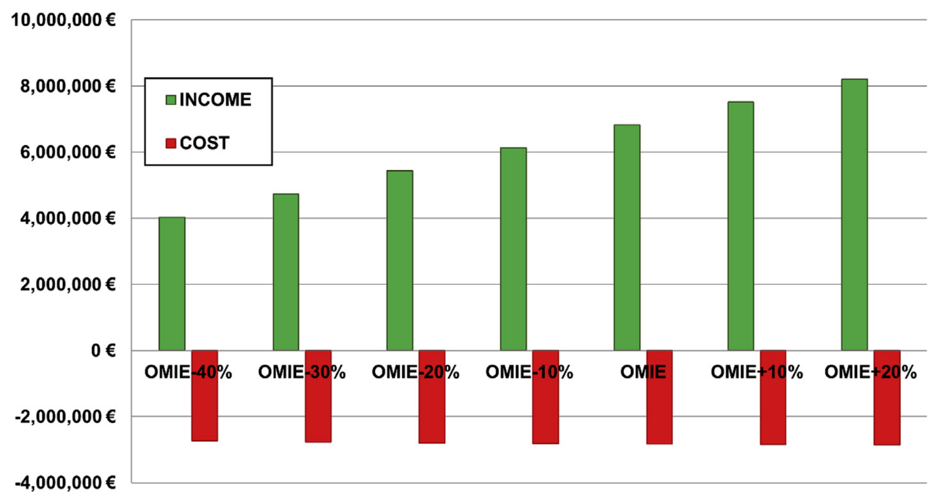

Fig. 12. Evolution of annual system cost and income versus OMIE day-ahead market prices.

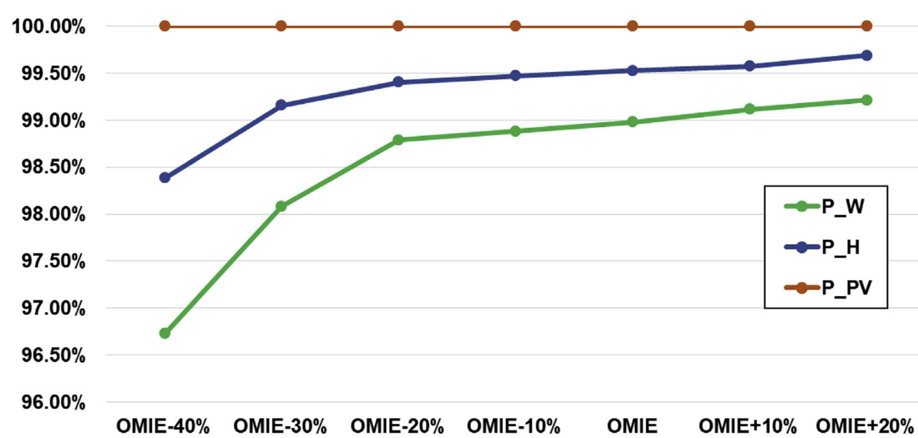

Fig. 13. Optimal power production of each generation technology for different market prices.

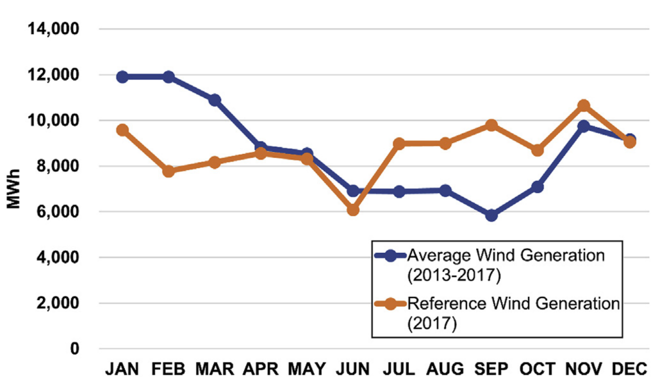

Fig. 14. Monthly wind power generation.

sensitivity analysis, the 2013–2017 average monthly generation in Spain was applied to the hourly generation profile used in Section 4 (see Fig. 14).

The new wind power generation values were applied to the VPP optimal dispatch model. Tables 13 and 14 present the main results obtained by changing wind power generation. As a result of wind power generation reduction in the highest-demand months of the irrigation communities (May to September), power import from the grid increases and causes a slight decrease in the use of wind power (−0.22%) and a small increase in system costs (+0.93%). However, the income increases due to excess generation in lower-demand months (+0.73%), and a higher operating profit is achieved compared to the base case in Section 4 (+0.59%). These results demonstrate that the seasonal variations in wind generation do not excessively influence the economic profit of the VPP model.

Table 13
Percentage of annual demand supplied by system generators and scheduled generation of each technology, compared with previous results from Table 10.

	Energy (MWh)	Demand coverage (%)	Demand coverage Δ	Scheduled generation (%)	Scheduled generation Δ
P_W	103,407	53.7%	−1.47%	98.76%	−0.22%
P_H	48,703	25.3%	−1.17%	99.53%	–
P_{PV}	27,645	14.4%	−0.69%	100.00%	–

Table 14
Optimal annual results depending on the annual wind power generation profile, compared with previous results from Table 11.

	Energy (MWh)	Demand coverage (%)	Costs/Income (€)	Δ
P_{demand}	39,003	100%		
P_{gen}	179,755		−2,698,256	−0.14%
P_{exp}	143,359		6,869,826	+0.73%
P_{imp}	2608	6.7%	−152,986	+19.79%
$P_{self\text{-}cons}$	36,396	93.3%		
Costs			−2,851,242	+0.93%
Income			6,869,826	+0.73%

6. Conclusions

The development of new power management tools for irrigation systems is essential to improve farm profitability. In addition, the adoption of distributed generation in power systems and the development of more competitive electricity markets require new operation models to optimally integrate the available resources. The proposed technical-economic dispatch model supports VPP management, which is essential for such integration.

With the available renewable-source power generation facilities in the Riegos del Alto Aragon irrigation system, the VPP is able to meet almost 95% of the demand, greatly reducing the system's dependence on the grid and the final cost of power supply. Power is purchased from the electricity market when the hours or quantities of generation and consumption do not match or when purchasing energy is more profitable than generating it with internal renewable-source generation plants. In the latter case, wind and hydroelectric power generation are not 100% scheduled, while photovoltaic generation is completely utilized due to the model design.

A sensitivity analysis of the impact of changes in the wholesale electricity market price on the optimal dispatch model of the VPP was performed. Higher electricity market prices yield higher income from the energy exported to the grid, and increasing power generation and sale to the wholesale electricity market is more profitable. However, a variation in the annual wind power generation profile only slightly changes the results.

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Article

Water-Energy Management for Demand Charges and Energy Cost Optimization of a Pumping Stations System under a Renewable Virtual Power Plant Model

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Abstract: The effects of climate change seriously affect agriculture at different latitudes of the planet because periods of drought are intensifying and the availability of water for agricultural irrigation is reducing. In addition, the energy cost associated with pumping water has increased notably in recent years due to, among other reasons, the maximum demand charges that are applied annually according to the contracted demand in each facility. Therefore, very efficient management of both water resources and energy resources is required. This article proposes the integration of water-energy management in a virtual power plant (VPP) model for the optimization of energy costs and maximum demand charges. For the development of the model, a problem related to the optimal operation of electricity generation and demand resources arises, which is formulated as a nonlinear mixed-integer programming model (MINLP). The objective is to maximize the annual operating profit of the VPP. It is worth mentioning that the model is applied to a large irrigation system using real data on consumption and power generation, exclusively renewable. In addition, different scenarios are analyzed to evaluate the variability of the operating profit of the VPP with and without intraday demand management as well as the influence of the wholesale electricity market price on the model. In view of the results obtained, the model that integrates the management of the water-energy binomial increases the self-consumption of renewable energy and saves electricity supply costs.

Keywords: virtual power plant; water-energy management; optimization; demand charges; renewable generation

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1. Introduction

Since 1998, the Spanish electricity market has been liberalized, which means that both the generation of electricity and the purchase of energy by consumers are open to competition. Liberalization seeks to achieve greater efficiency in investments and operation of electrical systems and thus reduce costs and increase the quality and reliability of electricity supply. In this current legal framework of the electricity sector, all consumers, in addition to paying for the purchase of energy in the hourly production market, are obliged to pay some charges (network access fees) for the use of transportation and distribution, regulated by the Spanish government. This scheme of liberalization of the electricity sector is the same as that followed in all developed countries.

The access charges collect revenue to cover the costs of the regulated activities of transport and distribution of electricity and revenue for other regulated costs of the electricity system. The access tariffs are divided into two terms: an annual charge for the contracted demand (€/kW) and an hourly charge for the energy consumed (€/kWh).

In the agricultural irrigation sector, energy costs are a serious problem for the economic sustainability of farms that require electricity to propel water to the fields. In addition, in some regions, the electricity consumption of the irrigation communities has a very seasonal profile, since irrigation occurs mainly during five months of the year, around the summer. However, the legislation requires that the contracting of electric power be maintained for a period of twelve months, without the option of reducing it in the months of lower consumption, which causes a considerable increase in this fixed cost until reaching 40% of the final price of electricity.

In recent years, irrigation communities have developed strategies to minimize energy costs, among others, by investing in electricity production facilities with renewable sources, thus contributing to the reduction of the environmental impact of the energy consumed. On the other hand, the availability of water supply is not always guaranteed as it depends on changing climatic factors. Rainfall is irregularly distributed over the years, so the water reserves available in the reservoirs do not always satisfy all needs. Therefore, efficient management of water and energy resources is essential to achieve sustainable irrigated agriculture. In this context, where it is necessary to supply electricity for the water pumping stations but also have their own power generation facilities, the virtual power plant model is a good tool for the optimal integrated management of all available resources.

According to Reference [1], the concept of a virtual power plant (VPP) combines different small-sized distributed generation units that operate as a single conventional power plant in the electricity market, responding in the same way to the competencies of the individual operation. For the active control of VPPs, the massive introduction of ICT technologies, with smart meters, wireless connections, and control centers, among others, is fundamental [2]. The VPP allows the joint management and optimization of energy consumption and generation, in addition to reducing possible network interruptions and improving operational decision-making. There are two categories of VPPs: technical virtual power plants (TVPPs) and commercial virtual power plants (CVPPs). On the one hand, TVPP provides support services to the management of the transmission system to ensure both the voltage and frequency levels of the system and the quality of the electricity supply. On the other hand, CVPP optimizes the generation of distributed energy and the consumption of demand response sources. In addition, it has the ability to participate in the wholesale electricity markets of purchase and sale of energy in real time [3]. The CVPP model primarily seeks to maximize VPP income and minimize its operating cost. Thus, this type of VPP determines the optimal hourly energy generation and the optimal bidding strategy in different electricity markets. It is important to point out that the influence of the power distribution network is not taken into account for CVPP modeling [4,5].

The integration of renewable energy sources into the distribution network is a great challenge for the operation of the electrical system. Nowadays, countries are focused on achieving energy independence and security of electricity supply, as well as competitiveness and technological development. References [6,7] study the types of VPPs, communication technologies, and reliability in solving the optimal VPP management problem. In Reference [8], the main benefits and challenges of the implementation of smart grid technology are analyzed from the point of view of demand management, distributed generation, or measurement and communication systems. Similarly, in Reference [9], the challenges of the implementation of VPP technology in the electrical system are described, as well as the projects that have been carried out of VPPs. From a technical point of view, the widespread applicability of VPPs presents challenges in the management and communication among the components, since it is required for the development of ICT infrastructures and real-time monitoring systems for the optimal control of distributed energy resources. On the other hand, from an economic point of view, market mechanisms should be promoted to facilitate flexibility and the introduction of distributed energy resources to electricity markets, which may favor the implementation of VPPs in the most immediate future [10,11]. References [12,13] evaluate the impact of different sources of distributed generation on the price of various electricity markets in Europe.

As a result of the intermittency of renewable energy, some articles [14,15] include pumped storage in the VPP model to obtain more flexible operation and maximize its operating profit. Thereby, the incorporation of storage systems into a VPP allows optimal management of energy resources and demand in addition to guaranteeing the security and reliability of the electrical system.

Many studies in the literature have as their main objective the maximization of the operating profit of VPPs through the use of various optimization methods. Within the mathematical optimization methods, mixed-integer linear programming stands out [16–21], nonlinear programming [22–25], point estimate method (PEM) [26], or quadratic programming [27]. In contrast, other authors propose heuristic methods to obtain the optimal management of VPP resources [28,29]. However, these methods increase the resolution time, in addition to sometimes obtaining local solutions instead of a globally optimal solution. On the other hand, several researchers consider at the same time the impact that electricity market prices may have on VPP for the resolution of this type of problem. In Reference [30], a probabilistic model for the management of electrical and thermal energy of a VPP that participates in the daily market and electricity reserve is presented, while work [31] uses a combination of stochastic and robust optimization to model the uncertainties. Other articles include long-term bilateral contracts for selling energy [32,33]. Reference [18] studies two risk management approaches to address the variability of profit due to electricity market price uncertainties, Conditional Value at Risk (CVaR), and Second-Order Stochastic Dominance Constraints (SSD), while the authors of Reference [26] use the Point Estimate Method. The studies [17,32] use the concept of CVaR to model and optimize risk in the wholesale market, describing the advantages of this method over others, such as its convexity, which facilitates the implementation of optimization algorithms. It is worth mentioning that other studies, such as References [19,34,35], include demand response programs that provide greater flexibility to the system in addition to more efficient use of resources.

From the point of view of the direct participation of the VPP in different electricity markets to maximize its profit, several works propose different methodologies to decide the optimal bidding strategy of the VPP and reduce prediction errors and, thus, avoid the costs of deviations. References [36–38], among others, use stochastic optimization methods, while studies such as Reference [39] use robust programming models. The authors in References [40,41] propose the combination of robust and stochastic optimization for the resolution of this type of VPP problem.

On the other hand, from the perspective of the applicability of VPP models to real cases, articles [42,43] propose economic studies of VPPs in the German electricity market through an analysis based on scenarios and models. Recently, the authors of Reference [21] developed an optimal technical-economic dispatch model for a VPP that participates in the wholesale electricity market. The model is applied to a large irrigation system in Aragon (Spain) with electricity generation and demand of 200 GWh per year.

In conclusion, previous studies do not include demand costs in the formulation of the VPP model. In addition, no real cases of VPP have been found that analyze the management of water and energy resources together. Our study focuses mainly on these gaps in the literature.

As a consequence of the increase in energy costs and problems of water availability, the main objective of this article is the integration of the management of the water-energy binomial under the approach of a virtual power plant model by optimizing the costs of power and energy. This approach belongs to the CVPP type of virtual power plant. The proposed model is a mixed-integer nonlinear programming model (MINLP) that aims us to maximize the annual operating profit of a VPP that participates in the wholesale electricity market through optimal planning of the annual contracted electricity demand and hourly power generation resources. Additionally, as a result, the optimal hourly schedule for the operation of the pumping stations will be obtained.

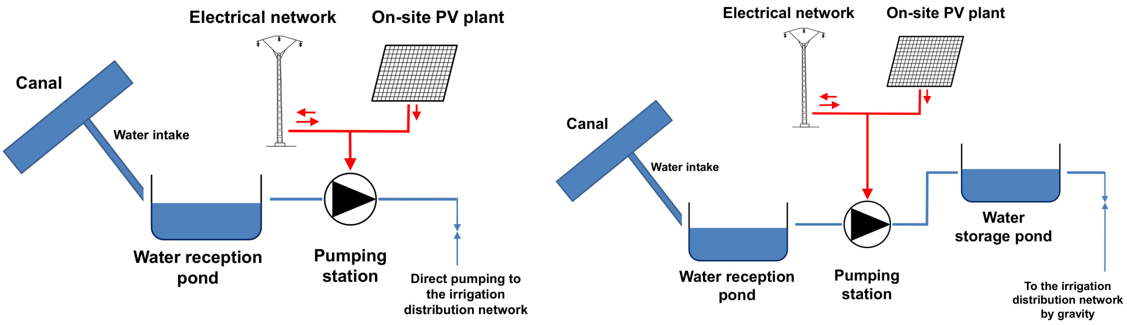
The rest of the article is divided as follows: Section 2 describes the problem and next, Section 3 presents the proposed mathematical model. Section 4 analyzes the results obtained, and subsequently, Section 5 evaluates the influence of the electricity market price on the model. Finally, Section 6 summarizes the main conclusions drawn from this research.

2. Problem Statement

The high energy cost together with the uncertainty about the availability of water resources to meet the demand creates a risk to the economic viability of the water supply and distribution facilities for irrigation since energy has become the main cost factor of m^3 of water for farmers in many regions. In this context, the efficient joint management of energy and water in agricultural operations is essential to minimize energy costs.

In relation to water management, during the irrigation campaign, the irrigation communities request the necessary flow for each day. The existence of internal regulation ponds is essential to adapt to the availability of the resource and the water demand over time.

Irrigation communities follow different pumping strategies. On the one hand, there are pumping stations that collect water from canals at one or more points, temporarily storing it in reception ponds for gravity irrigation or by direct pumping. Other communities, however, have a water storage pond, which allows for temporarily storing a quantity of water that satisfies the irrigation in the following days. In this case, the water is taken from the regulation canals to a water reception pond, and from there, the water is raised by means of a pumping station to the water storage pond. From the water storage pond, the water is distributed by gravity to the different irrigated areas (see Figure 1).



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

Figure 1. Scheme of operation of pumping stations: (**a**)direct pumping; (**b**) with water storage pond.

The real study system consists of 27 pumping stations connected to the electricity distribution network, with a high-voltage access tariff of six periods. The hourly demand for electricity is manageable in 10 of the pumping stations, since they have storage for the efficient management of water in a water storage pond, while for the rest of the pumping stations the hourly demand for electricity is known (direct pumping). We refer to the first 10 pumping stations as manageable, since they are able to schedule the water pumping during the hours of a day while satisfying the daily irrigation needs (see Figure 1b), whereas the other 17 pumping stations are considered unmanageable as they must meet the required water demand for irrigation each hour (see Figure 1a). It should be noted that the 27 pumping stations act as a single entity that participates in the OMIE electricity market, allowing the contracting of a single maximum power in each pricing period.

On the other hand, from the point of view of power generation, the study system consists of a wind farm and six hydroelectric plants that evacuate their production to the region's electricity grids and 27 self-consumption photovoltaic plants located next to the pumping stations. First, these self-consumption photovoltaic plants should meet the local demand of each pumping station. Subsequently, in the case of excess generation, PV plants will export the rest of the energy produced to the distribution network. Figure 2 shows the energy flow of the proposed VPP model. Each subsystem (B) consists of a pumping station connected both to the grid and to a self-consumption PV plant. On the other hand, the global system (A) receives the energy flow from the wind farm and hydroelectric plants, and also from the subsystems. The actual data of the study system are shown in Appendix A.

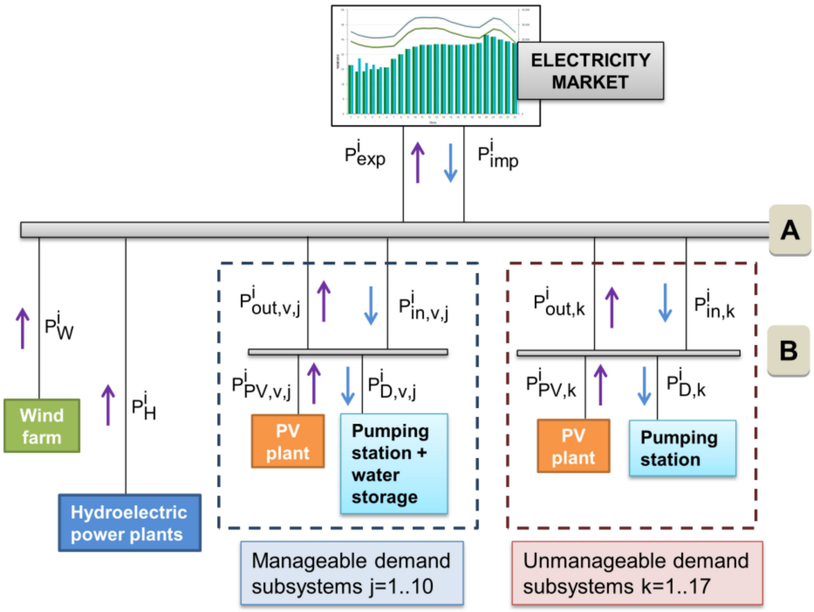


Figure 2. Energy flow diagram of the proposed VPP.

As introduced in Section 1, this work aims to develop a mathematical model to maximize the operating profit of a VPP for a whole year by optimizing the annual contracted demand of the hourly management of water consumption and electricity from the pumping stations and from the electricity production resources. The VPP participates in the OMIE wholesale electricity market for the purchase and sale of electricity in real time.

3. Mathematical Model

The optimization model is a problem with 80 continuous variables and 63 integers in each hour. The optimization model returns, in each hour, the optimal values of the binary integer variables for decision making in the problem:

- import/export of energy from the global system (I^i_{imp}/I^i_{exp})
- import/export of energy from each pumping station with self-consumption ($I^i_{in,k}$, $I^i_{in,v,j}/I^i_{out,k}$, $I^i_{out,v,j}$)
- excess power (I^i_{exc}) The model also returns, in each hour, the optimal hourly values of:
- production of electricity from its own sources with renewable energy: hydroelectric, wind, photovoltaic (P^i_W, P^i_H, $P^i_{PV,k}$, $P^i_{PV,v,j}$)
- energy imported/exported from the global system (P^i_{imp}/P^i_{exp}) and subsystems ($P^i_{in,k}$, $P^i_{in,v,j}/P^i_{out,k}$, $P^i_{out,v,j}$)
- hourly electricity demand in each pumping station with water storage ($P^i_{D,v,j}$)

In addition, the annual optimal values of the contracted demand are obtained in each pricing period ($P_{c,p}$).

As highlighted in Section 1, an important novelty of this work is the integration of water management with energy, as well as the optimization of the annual contracted demand to minimize energy costs. In this way, a more complete and realistic exploitation model is offered for the study system.

Next, the terms that make up the objective function and the constraints that the variables of the problem must meet are presented.

- Objective function

The calculation of the optimization of the operating profit of the VPP is performed by formulating an objective function composed of the difference between income and costs of the study system (Equation (6)).

On the one hand, the objective function expresses the costs of producing electricity from renewable sources:

$$f_W \cdot P^i_{W,z} - f_H \cdot P^i_{H,z} - f_{PV} \cdot \sum_{k=1}^{17} P^i_{out,k,z} - f_{PV} \cdot \sum_{j=1}^{10} P^i_{out,v,j,z} \tag{1}$$

In addition, the acquisition of energy is also allowed ($P^i_{imp,z}$) at the hourly price of the wholesale electricity market ($\rho^i_{imp,z}$) when there is no energy available in the system to meet the demand or if it is more economically profitable:

$$\rho^i_{imp,z} \cdot P^i_{imp,z}. \tag{2}$$

On the other hand, the objective function also includes the costs of contracted demand in each pricing period, which are obtained as a product of the price of the power term of the access tariff $f_{power,p}$ (Table 1) by the annual contracted demand in each period ($P_{c,p}$).

$$f_{power,p} \cdot P_{c,p} \tag{3}$$

Finally, the charges for excess demand are added, as indicated in Spanish legislation [44].

$$\sum_{p=1}^{6} K_p \cdot K_{ex} \cdot \sqrt{\sum_{i=1}^{n} 4 \cdot \left(exc^i_{r,p}\right)^2} \tag{4}$$

Table 1. Data on demand charges [44,45].

Period	$f_{power,p}$ (€/kW-year)	K_p
P1	39.139427	1
P2	19.586654	0.5
P3	14.334178	0.37
P4	14.334178	0.37
P5	14.334178	0.37
P6	6.540177	0.17

The imputed cost using the formula of Equation (4) occurs only when the net power demand at the evacuation point of the pumping stations ($P^i_{in,total}$) exceeds the contracted demand in any hourly period. The excess power is calculated monthly and every quarter of an hour. In this case, it has been assumed that the same value is obtained for each quarter of an hour. K_p is a dimensionless constant whose value depends on the pricing period, while K_{ex} is a constant whose value is 1.4064 €/kW. Table 1 shows the prices of the annual power term for the high-voltage access tariff of six periods ($f_{power,p}$), as well as the values of the coefficient K_p for the calculation of excess demand charges.

On the other hand, the income of the system comes only from selling surplus energy to the electricity market ($P^i_{exp,z}$) at the hourly market price, resulting in daily auctions organized by the Spanish wholesale market operator OMIE ($\rho^i_{exp,z}$).

$$\rho^i_{exp,z} \cdot P^i_{exp,z} \tag{5}$$

In this way, the mathematical optimization problem, whose objective function is formulated in Equation (6), calculates both the optimal hourly dispatch of the virtual power plant over 365 days of the year and the optimal annual contracted demands.

$$\max\left[\begin{array}{c}\sum_{z=1}^{365}\sum_{i=1}^{24}\left(\rho^i_{exp,z}\cdot P^i_{exp,z}-\rho^i_{imp,z}\cdot P^i_{imp,z}-f_W\cdot P^i_{W,z}-f_H\cdot P^i_{H,z}-f_{PV}\cdot\sum_{k=1}^{17}P^i_{out,k,z}-f_{PV}\cdot\sum_{j=1}^{10}P^i_{out,v,j,z}\right)\\ -\left(\sum_{p=1}^{6}f_{power,p}\cdot P_{c,p}\right)-\sum_{m=jan}^{dec}\left(\sum_{p=1}^{6}K_p\cdot K_{ex}\cdot\sqrt{\sum_{i=1}^{n}4\cdot\left(exc^i_{r,p}\right)^2}\right)_m\\ (i=1\ldots 24,\ z=1\ldots 365,\ j=1\ldots 10,\ k=1..17,\ p=1\ldots 6)\end{array}\right] \quad (6)$$

- Constraints

Equations (7)–(9) show the energy balances of the global system (A) and of each subsystem (B) (see Figure 2). As regards demand management, Equation (10) indicates the fulfillment of daily demand, while Equation (11) limits the hourly demand in each of the pumping stations with water storage.

$$P^i_{imp}-P^i_{exp}+P^i_W+P^i_H=-\sum_{j=1}^{10}P^i_{out,v,j}-\sum_{k=1}^{17}P^i_{out,k}+\sum_{j=1}^{10}P^i_{in,v,j}+\sum_{k=1}^{17}P^i_{in,k} \quad (7)$$

$$P^i_{out,v,j}-P^i_{in,v,j}=P^i_{PV,v,j}-P^i_{D,v,j}\ (j=1\ldots 10) \quad (8)$$

$$P^i_{out,k}-P^i_{in,k}=P^i_{PV,k}-P^i_{D,k}\ (k=1\ldots 17) \quad (9)$$

$$P^z_{D,total,j}=\sum_{i=1}^{24}P^i_{D,v,j} \quad (10)$$

$$0\le P^i_{D,v,j}\le P^i_{D,lim,j}. \quad (11)$$

The variables of wind and hydroelectric generation can vary between 0 and a maximum value defined according to the availability of renewable resources, as shown by Equations (12) and (13).

$$0\le P^i_W\le P^i_{W,\ max} \quad (12)$$

$$0\le P^i_H\le P^i_{H,\ max}. \quad (13)$$

The model supports both the purchase and sale of energy to the electricity market according to the optimal economic situation in each hourly period, but both operations can never occur at the same time (Equation (14)). Equations (15)–(18) establish the variation range of the energy import and export variables to the distribution network.

$$I^i_{imp}+I^i_{exp}\le 1 \quad (14)$$

$$0\le P^i_{imp}\le I^i_{imp}\cdot P^i_{imp,max} \quad (15)$$

$$P^i_{imp,max}=\sum_{k=1}^{17}P^i_{D,k}+\sum_{j=1}^{10}P^i_{D,lim,j} \quad (16)$$

$$0\le P^i_{exp}\le I^i_{exp}\cdot P^i_{exp,max} \quad (17)$$

$$P^i_{exp,max}=P^i_W+P^i_H+\sum_{k=1}^{17}P^i_{PV,k}+\sum_{j=1}^{10}P^i_{PV,v,j} \quad (18)$$

Regarding the pumping stations with photovoltaic self-consumption, Equations (19)–(22) show the range of variation of the incoming/outgoing energy in each of them. Equations (23)–(24) prevent the export and acquisition of energy from the pumping stations from occurring simultaneously.

$$0 \leq P^{i}_{in,k} \leq P^{i}_{D,k} \cdot I^{i}_{in,k} \tag{19}$$

$$0 \leq P^{i}_{out,k} \leq P^{i}_{PV,k} \cdot I^{i}_{out,k} \tag{20}$$

$$0 \leq P^{i}_{in,v,j} \leq P^{i}_{D,lim,j} \cdot I^{i}_{in,v,j} \tag{21}$$

$$0 \leq P^{i}_{out,v,j} \leq P^{i}_{PV,v,j} \cdot I^{i}_{out,v,j} \tag{22}$$

$$I^{i}_{in,v,j} + I^{i}_{out,v,j} \leq 1 \tag{23}$$

$$I^{i}_{in,k} + I^{i}_{out,k} \leq 1. \tag{24}$$

In regard to the optimization of demand charges, Equation (25) limits the maximum demand contracted in each pricing period. In high voltage charges, legislation requires that the demand contracted in a pricing period ($P_{c,(p+1)}$) must always be greater than or equal to the demand contracted in the previous pricing period ($P_{c,p}$) [44]. Equations (26)–(29) set the restrictions for the billing of excess power. A variable is defined ($exc^{i}_{r,p}$) that will only consider the excess power when the power demanded in the system ($P^{i}_{in,total}$) in each hour of the period p exceeds the demand contracted in that period. In order to make this decision, a binary variable (I^{i}_{exc}) will take a value equal to 1 when excess power occurs; otherwise, it will take a value equal to 0. The parameter M represents the positive upper bound of the excess power restriction, $\left(exc^{i}_{p}\right)$, while parameter m is its negative lower bound.

$$P_{c,p} \leq P_{c,p+1} \ (p = 1..6) \tag{25}$$

$$exc^{i}_{p} = \left(P^{i}_{in,total} - P_{c,p}\right) \tag{26}$$

$$m \cdot \left(1 - I^{i}_{exc}\right) \leq exc^{i}_{p} \leq M \cdot I^{i}_{exc} \tag{27}$$

$$exc^{i}_{r,p} = exc^{i}_{p} \cdot I^{i}_{exc} \tag{28}$$

$$P^{i}_{in,total} = \sum_{k=1}^{17} P^{i}_{in,k} + \sum_{j=1}^{10} P^{i}_{in,v,j} \tag{29}$$

According to the characteristics of the optimization problem described above, it is of type mixed-integer nonlinear because integer variables and nonlinear constraints are defined in the model.

For the resolution of the proposed problem, LINGO was used, a calculation software suitable for modeling and solving nonlinear mathematical optimization problems efficiently [46]. This software uses the branch-and-bound method [47] to favor obtaining a global optimal solution and, thus, avoid local optimal solutions. This technique allows us to implicitly enumerate all possible combinations of integer variables. Upper and lower bounds of the value of the objective function are generated, which are approximated to each other. This process fundamentally consists of dividing the total set of feasible solutions into smaller subsets of solutions to facilitate the search for a global optimum. The execution of the model ends when it is not possible to make further divisions of the problem, or the difference between the lower and upper bound of the target value is less than a pre-established tolerance. This method allows the optimal selection of the next subset so that valid solutions are found more efficiently.

It is worth mentioning that LINGO allows us to develop a model in a similar way to the standard mathematical notation. In addition, this software can integrate a large amount of data into the model from external spreadsheets to facilitate data management. According to the formulation of the problem, LINGO invokes the appropriate internal solver to search for the optimal solution to the proposed model. Once it determines the optimal solution (if any), it provides a solution report with general information about the model and the values for all variables. For our problem, LINGO returned a globally optimal solution. As expected, being a nonlinear model with a large number of variables, this optimization procedure required a long computation time. The calculation time of each case was 630 min, using a computer with an Intel® Core i7 processor, 3.00 GHz CPU and 16 GB of RAM.

4. Case Study

4.1. Data

The model proposed in Section 3 was applied to a real case study, consisting of different energy infrastructures, with both consumption and electricity generation assets. The system consisted of 27 water pumping stations for agricultural irrigation, located in a dispersed manner in a geographical area of 135,000 hectares in Spain, which consumed annual electricity of 39 GWh, according to real data recorded in 2017 (see Figure 3).

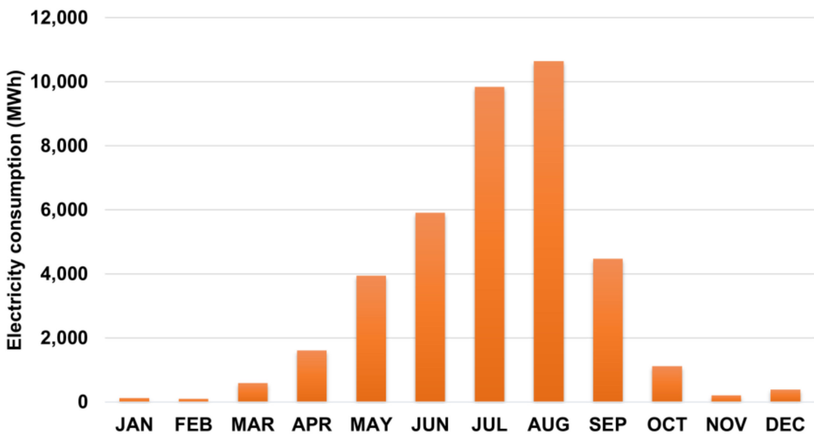


Figure 3. Annual electricity demand.

The system integrated different renewable electricity generation units, both hydroelectric and wind and photovoltaic, with a total installed capacity of 60.2 MW. Table 2 shows the total data of the demand and the generation facilities, as well as the production costs that have been considered in the model. See Appendix A for a more detailed description of the data used here.

Table 2. Global data on demand, generation and production costs.

	Total Installed Capacity (MW)	Total Energy (MWh)	Operating and Maintenance Cost (€/MWh)
Demand	-	39,003	-
Hydropower generation	14.7	48,934	16.19
Wind power generation	30	104,703	16.49
hotovoltaic generation	15.5	27,645	7.40

In the case study, the hourly prices of the Spanish wholesale electricity market in 2017 were published by the market operator OMIE [48].

4.2. Results and Discussion

The mathematical problem of nonlinear mixed-integer programming allows us to optimize the cost of the system and to calculate as a result the optimal hourly value of 143 variables of the model during each hour of a year. It should be noted that six variables were of the integer type, associated with the optimal annual contracted demand in each pricing period, and 57 variables are of binary integer type, taking a value of 0 or 1, associated with the decisions to import or export electricity in the different subsystems and in the joint system. These variables allow the decision to obtain the optimal economic exploitation of the system, minimizing the cost in each hourly period. Figure 4 presents the results of the optimal dispatch for a day in June. As can be seen, the VPP purchases the necessary energy in the electricity market when it cannot deliver the requested demand with its own sources of renewable generation.

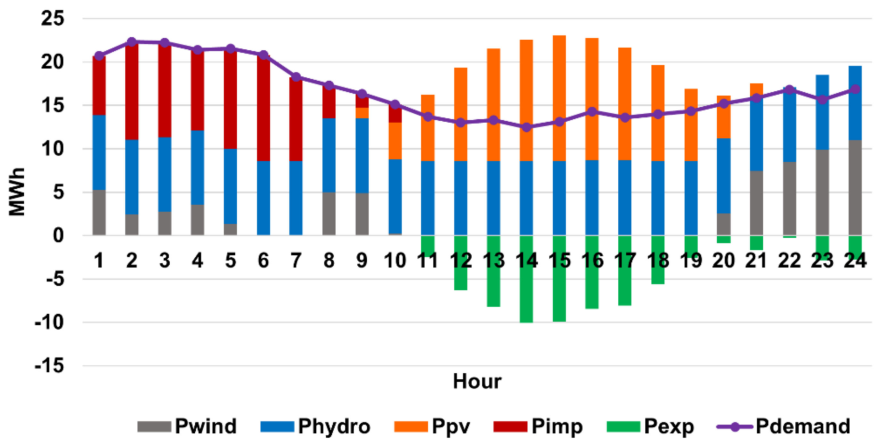


Figure 4. Results of optimal dispatch for a day in June (24/06/2017).

The main parameters for the analysis of the results obtained are the electricity values, such as generation, import and export of the system, and the hourly distribution of the manageable demand of the pumping stations. In addition, the costs of the energy consumed and the demand recorded will be analyzed according to the optimal contracted demand in each pricing period. Pricing periods are distributed across the year as they are established by the regulation of network access tariffs (see Table 3).

Table 3. Number of hours of the regulated access tariff of six periods.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
P1	132	120	-	-	-	88	168	-	-	-	-	114	622
P2	220	200	-	-	-	88	168	-	-	-	-	190	866
P3	-	-	138	-	-	66	-	-	120	-	120	-	444
P4	-	-	230	-	-	110	-	-	200	-	200	-	740
P5	-	-	-	320	368	-	-	-	-	352	-	-	1040
P6	392	352	376	400	376	368	408	744	400	392	400	440	5048
Total	744	672	744	720	744	720	744	744	720	744	720	744	8760

In order to evaluate the results obtained from the proposed model, the problem was initially solved considering the data of the electrical demand to be satisfied at each hour in each pumping station, without considering the possible intraday management of the demand of some pumping stations. In other words, in this first case study (case 1), the demand is known every hour, and therefore, it is not a variable to be optimized. Table 4 shows the distribution of demand according to the month and pricing period without taking into account the demand management in the model.

Table 4. Distribution of the electrical demand of the system without management of the hourly demand (MWh).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
P1	13	10	-	-	-	316	754	-	-	-	-	30	1124
P2	23	18	-	-	-	613	1724	-	-	-	-	54	2432
P3	-	-	57	-	-	129	-	-	197	-	23	-	405
P4	-	-	91	-	-	392	-	-	808	-	42	-	1334
P5	-	-	-	378	1111	-	-	-	-	187	-	-	1676
P6	88	74	452	1239	2834	4459	7372	10,647	3475	941	145	307	32,032
Total	125	102	601	1617	3945	5910	9849	10,647	4480	1128	210	391	39,003

On the other hand, Table 5 shows the results in the case of the system with manageable intraday demand proposed in this article. Comparing both tables and analyzing the results in the months of greatest demand (mainly June and July), it is observed that, in the case of the system with intraday demand management (see Table 5), there is a large increase in consumption in period 1, and lighter, in periods 3 and 4, corresponding to the hours with the highest solar radiation. This is caused by the greater self-consumption of photovoltaic power by the system. By favoring self-consumption, there is more efficient management of demand throughout the hourly periods of access tariffs, decreasing consumption in period 6, which has a lower cost but corresponds mainly to night hours where all available production resources cannot be taken advantage of.

Table 5. Distribution of the electrical demand of the system with intraday management of the hourly demand (MWh).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
P1	6	7	-	-	-	533	1289	-	-	-	-	24	1858
P2	12	13	-	-	-	617	1669	-	-	-	-	47	2358
P3	-	-	50	-	-	183	-	-	313	-	15	-	562
P4	-	-	64	-	-	415	-	-	930	-	32	-	1442
P5	-	-	-	392	1265	-	-	-	-	296	-	-	1952
P6	107	82	486	1225	2681	4162	6891	10,647	3236	832	162	320	30,832
Total	125	102	601	1617	3945	5910	9849	10,647	4480	1128	210	391	39,003

Figure 5 represents the values reflected in the previous tables from a more graphic point of view for the annual demand according to the pricing periods, observing for the case with manageable demand an increase of 65.62% in the demand of period 1 and a decrease of the demand of period 6. Conversely, in the months of lower demand, consumption slightly increases in the cheaper periods, thus minimizing energy costs. In short, intraday demand management adapts the consumption curve of pumping stations to the generation curve of renewable energy sources, since the most efficient VPP is that in which self-consumption is closest to 100%. In this case, it is possible to cover 99.64% of the annual demand through the self-consumption of the electricity generation itself (Table 6). The remaining 0.36% of annual demand corresponds to hours where the cost of generation is less competitive than the cost of acquiring electricity in the electricity market.

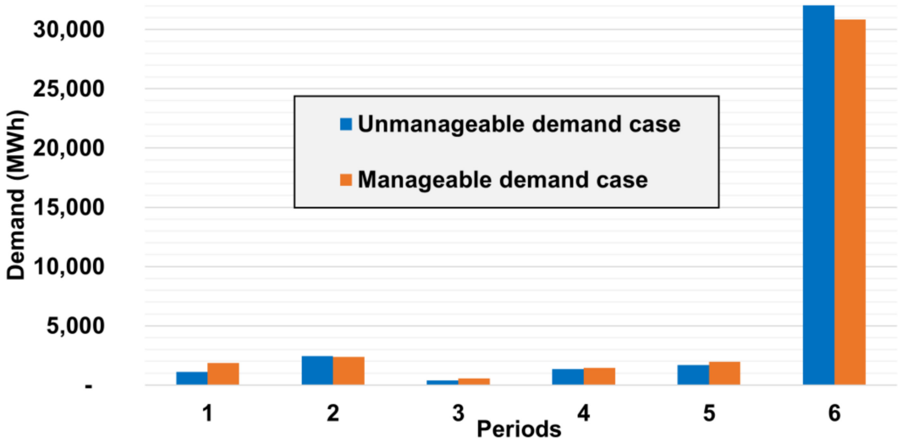


Figure 5. Evolution of the annual demand of cases with and without intraday demand management.

Table 6. Comparison of annual production, export and import results with and without demand management.

CASES	P_{PV} (MWh)	P_H (MWh)	P_W (MWh)	P_{exp} (MWh)	P_{imp} (MWh)	P_D (MWh)	Demand coverage
Case 1 (unmanageable demand)	27,645	48,703	103,634	143,071	2092	39,003	94.60%
Case 2 (manageable demand)	27,645	48,699	103,634	141,116	140	39,003	99.64%

Regarding the production results, it is verified that a higher percentage of energy produced is self-consumed thanks to intraday management. As shown in Table 6, the demand is covered with the same production as in the case without manageable demand, but reducing the imported power (P_{imp}) considerably and slightly reducing the exported power (P_{exp}). Therefore, it is shown that it is more efficient to self-consume than to export, whenever possible, achieving in this situation that the VPP is able to cover 99.64% of its demand with its own generation compared to 94.60% without intraday management.

From the analysis of the results obtained associated with the optimal contracted demand in each pricing period (see Tables 3 and 7), it is observed that with the proposed demand management model, it is possible to reduce the peaks of maximum demand and flatten the curve of daily demand. In this way, the maximum contracted demand annually in the most expensive hourly periods is reduced, as well as the excess power, and, consequently, the operating profit of the VPP is increased (see Table 8). It is worth remembering that the contracted demand values in each of the six pricing periods must be maintained by law for one year.

Table 7. Comparison of optimal contracted demand in each pricing period with and without intraday demand management.

CASES	P1 (kW)	P2 (kW)	P3 (kW)	P4 (kW)	P5 (kW)	P6 (kW)
Case 1 (unmanageable demand)	859	1447	1447	2178	2299	22,075
Case 2 (manageable demand)	548	1022	1022	1575	1807	24,852

Table 8. Comparison of annual results of costs and income with and without intraday demand management.

	Case 1 (Unmanageable Demand)	Case 2 (Manageable Demand)
R_{exp} (€)	6,819,763	6,760,377
C_{prod} (€)	2,775,854	2,644,919
C_{power} (€)	291,252	266,812
C_{exc} (€)	403,612	392,589
Operating profit (€)	3,349,045	3,456,057
R_{exp} Δ	-	0.87%
C_{prod} Δ	-	−4.72%
C_{power} Δ	-	−8.39%
C_{exc} Δ	-	−2.73%
Profit Δ	-	3.20%

The maximum demand contracted in period 6 is much higher than the rest of the contracted powers since the irrigation communities of the analyzed system concentrate on average 80% of their consumption in this period. Period 6 includes 5048 annual hours, which include, among others, those corresponding to the entire month of August (Table 3). In this month, there is a high demand for energy along with the lower cost of acquiring electricity. For this reason, the intraday demand management strategy allows us to reduce the contracted demand in the most expensive periods while increasing in period 6. In this way, the contracted demand is better adjusted to the demand of the facilities and, as a consequence, excess power is reduced.

Table 8 compares the results of the income and costs of the case studies. According to the demand charges, in both cases, the costs for excesses in the contracted demand are higher than the costs per fixed power term. This is because the power needs have a seasonal variation in the farms since a high power is needed to pump the water in the months of the irrigation season (May to September) and a minimum power the rest of the year. However, the obligation to contract electric power throughout the year and the high cost of the fixed term of annual power make it profitable to contract a lower electric power than the maximum demanded annually even at the cost of assuming a cost of the penalty for excess power.

In view of the results of the integration of intraday demand management in the model, there is a reduction in the production cost (−4.72%), the fixed cost of contracted demand (−8.39%) and the cost of power excesses (−2.73%). Income also decreases, but to a much lesser extent (−0.87%), and as a consequence, the operating profit of VPP increases (3.20%). This trend can be seen in a more graphic way in Figure 7. In addition, as seen in Table 6, less energy is exported to the grid (−1.37%), although income is not reduced in the same proportion (−0.87%), which means that a better economic performance is obtained from selling exported power.

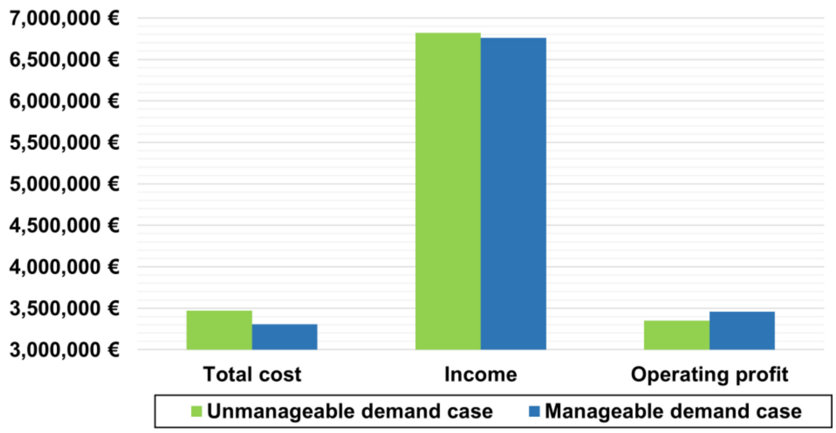


Figure 6. Evolution of annual costs and income of the case studies.

5. Analysis of the Influence of the Electricity Market Price

In addition to solving the models with and without intraday demand management, other scenarios were studied to evaluate the influence of the Spanish wholesale electricity market OMIE on the proposed model. As a reference, the prices of the wholesale electricity market of 2017 have been taken, while in order to determine the variations that are applied to these prices, a historical study of the evolution of the average price of electricity in the last ten years was carried out. For this analysis, the most extreme cases were considered, obtaining a percentage difference of +10% and −30% with respect to the average price of the year 2017.

Regarding the results of power generation, export and import (see Table 9), for case studies 1.3 and 2.3 with a lower price in the electricity market, the production of available power decreases, since it is more profitable to stop producing to export, to continue generating to sell energy at a price lower than the cost of generation. The opposite occurs when the price of the electricity market increases. The main differences are observed in the amount of power imported from the grid since for cases of unmanageable demand (cases 1.1, 1.2, 1.3), it remains constant in the face of possible changes in the price of the electricity market. Generation costs remain more competitive than the energy purchase price set by the electricity market even when the market price is reduced by 30%. In addition, in these cases, energy balances must be satisfied, and demand must be met at all times.

Table 9. Annual results of power generation, export and import of all cases studied.

CASES		P_{PV} (MWh)	P_H (MWh)	P_W (MWh)	P_{exp} (MWh)	P_{imp} (MWh)	P_D (MWh)	Demand coverage
Case 1 (unmanageable demand)	**Case 1.1** (OMIE ref)	27,645	48,703	103,634	143,071	2092	39,003	94.60%
	Case 1.2 (OMIE +10%)	27,645	48,725	103,774	143,232	2092	39,003	94.60%
	Case 1.3 (OMIE −30%)	27,645	48,521	102,695	141,949	2092	39,003	94.60%
Case 2 (manageable demand)	**Case 2.1** (OMIE ref)	27,645	48,699	103,634	141,116	140	39,003	99.64%
	Case 2.2 (OMIE +10%)	27,645	48,722	103,774	141,279	141	39,003	99.64%
	Case 2.3 (OMIE −30%)	27,645	48,516	102,702	139,982	122	39,003	99.69%

However, for the cases with intraday demand management (cases 2.1, 2.2, 2.3), it is observed that, for the situation of a low market price (case 2.3), the system tends to self-consume as much as possible and avoid exporting power to the distribution network. It should be remembered that the model always seeks to maximize the percentage of self-consumed power and import the least amount of power possible from the grid, so for a reduction of 30% of the market price, the power imported from the grid decreases by 12.85%. Flexibility in demand allows for more efficient management of renewable resources and reduces energy dependence. Despite the intraday demand management, in all the cases studied, the VPP is not able to completely cover its demand with renewable energy sources, since in some hours of analysis, the energy balance cannot be met by any technology generation due to technical production constraints, or it is more economical to purchase power from the electricity market.

On the other hand, Table 10 shows the results of the optimal contracted demand in the face of variations in the electricity market price. As expected, when the demand is known (cases 1.1, 1.2, 1.3), the values do not vary, since it must be remembered that in this case, the demand is a condition to be satisfied in each hour and, therefore, is not a variable to be optimized. However, intraday demand management (cases 2.1, 2.2, 2.3) optimizes contracting for each market situation. As shown in Table 9, at a lower OMIE market price (case 2.3), demand and available production resources are managed more efficiently, increasing self-consumption as much as possible, which causes period 6 to be slightly reduced, and as a consequence, the maximum demand contracted in this period is also reduced. As will be seen later in the economic results shown in Table 11, this situation causes a decrease of 0.72% in the costs of the power term, although an increase of 2.31% in the power excesses. However, due to the seasonality of demand in irrigation and high power costs, it is necessary to find the economic balance between both terms, and it is generally more profitable to minimize the contracted demands and incur costs due to excess power.

Table 10. Optimal demand contracted in each pricing period of all case studies.

CASES		P1 (kW)	P2 (kW)	P3 (kW)	P4 (kW)	P5 (kW)	P6 (kW)
Case 1 (unmanageable demand)	**Case 1.1** (OMIE ref)	859	1447	1447	2178	2299	22,075
	Case 1.2 (OMIE +10%)	859	1447	1447	2178	2299	22,075
	Case 1.3 (OMIE −30%)	859	1447	1447	2178	2299	22,075
Case 2 (manageable demand)	**Case 2.1** (OMIE ref)	548	1022	1022	1575	1807	24,852
	Case 2.2 (OMIE +10%)	548	1000	1000	1547	1817	25,038
	Case 2.3 (OMIE −30%)	548	1008	1008	1627	1790	24,510

Table 11. Annual results, income and costs of all case studies.

	Case 1 (Unmanageable Demand)			**Case 2 (Manageable Demand)**		
	Case 1.1 (OMIE ref)	**Case 1.2** (OMIE +10%)	**Case 1.3** (OMIE −30%)	**Case 2.1** (OMIE ref)	**Case 2.2** (OMIE +10%)	**Case 2.3** (OMIE −30%)
R_{exp} (€)	6,819,763	7,511,725	4,735,724	6,760,377	7,447,771	4,689,484
C_{prod} (€)	2,775,854	2,789,113	2,725,618	2,644,919	2,649,604	2,618,743
C_{power} (€)	291,252	291,252	291,252	266,812	267,303	264,881
C_{exc} (€)	403,612	403,612	403,612	392,589	400,093	401,655
Operating profit (€)	3,349,045	4,027,748	1,315,242	3,456,057	4,130,771	1,404,205
R_{exp} Δ	-	10.15%	−30.56%	-	10.17%	−30.63%
C_{prod} Δ	-	0.38%	−1.45%	-	0.18%	-0.99%
C_{power} Δ	-	-	-	-	0.18%	-0.72%
C_{exc} Δ	-	-	-	-	1.91%	2.31%
Profit Δ	-	20.27%	−60.73%	-	19.52%	−59.37%

Regarding the income of the system, it is observed that by increasing the price of the OMIE electricity market, the general trend is to increase the income of the system due to the increase in energy production for its subsequent export to the grid at a higher selling price, see Table 11 and Figure 6. On the other hand, regarding the costs of the system, the influence of intraday demand management is fundamentally appreciated in the production costs with a variation of 0.18%, −0.99% with respect to the cases +10% OMIE and −30% OMIE, respectively, percentages lower than those obtained for cases of unmanageable demand (0.38%, −1.45%, respectively), since the model always tends to seek the optimal value of energy self-consumed, by virtue of which it manages the demand and consequently the optimal profit.

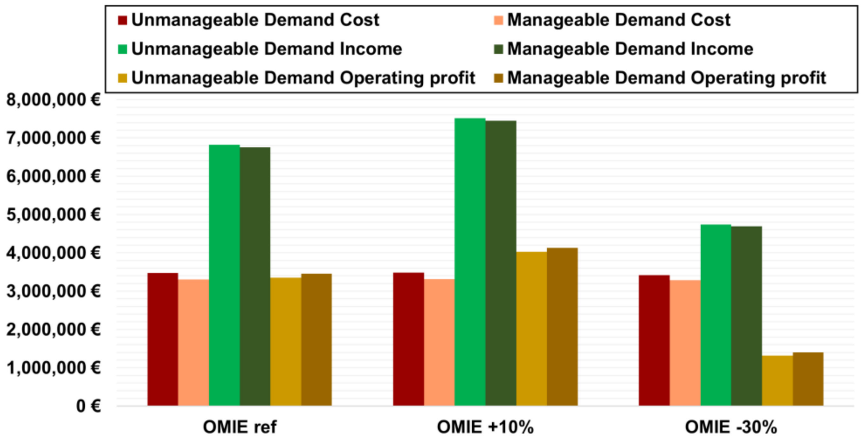


Figure 7. Evolution of annual costs and income of the system with and without intraday demand management.

6. Conclusions

Improving the competitiveness of farms requires the development of new innovative strategies for water and energy management. The availability of natural resources to produce sustainable electricity is being used in irrigation communities to promote new investments that make the supply of electricity to water pumping stations more economically and environmentally sustainable. The model proposed in this study of the virtual power plant (VPP), with the integration of the joint management of water and energy, covers up to 99.64% of the electricity demand with its own renewable energy sources.

The analysis of the results shows that it is more economically efficient to self-consume as much electricity as possible and avoid exporting energy to the grid. As a consequence, the consumption curve of the pumping stations adapts to the curve of electricity generation with renewables, provided that the generation costs are more competitive against the purchase price of energy in the electricity market. In addition, it is possible to increase the use of electricity production with renewable energy and reduce the peaks of maximum demand, thus increasing the operating profit of the VPP by reducing the maximum demand contracted annually in the hourly periods with higher energy costs.

This approach may be useful not only for the case presented in this research, but also for other cases of distributed power generation sources, which are not necessarily connected on-site to the load but belong to the same owner or a joint venture that would benefit from working together as a single operator in the electricity market. In particular, the proposed model could be applied to a group of industrial companies where electricity and other supplies (water, heat) must be managed together with their own power generation resources, even if those electricity production facilities are spread over a large geographical area. Further research should also address the new paradigms of demand response aggregation and energy communities that can be modeled under a virtual power plant scheme.

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Nomenclature

Indexes	
i	index for number of hours
p	index for pricing periods
n	index for number of hours exceeding the maximum contracted demand
m	index for number of months
z	index for number of days
j	index for pumping stations with manageable demand
k	index for pumping stations with unmanageable demand
Data	
ρ^i_{exp}	hourly price for selling energy $\left(\frac{€}{\text{MWh}}\right)$
ρ^i_{imp}	hourly price for purchasing energy $\left(\frac{€}{\text{MWh}}\right)$
f_W	wind technology operation and maintenance cost $\left(\frac{€}{\text{MWh}}\right)$
f_H	hydroelectric technology operation and maintenance cost $\left(\frac{€}{\text{MWh}}\right)$
f_{PV}	photovoltaic technology operation and maintenance cost $\left(\frac{€}{\text{MWh}}\right)$
$f_{power,p}$	price of the annual power term according to pricing period p $\left(\frac{€}{\text{kW-year}}\right)$
$P^i_{D,k}$	hourly demand of each pumping station k (MW)
$P^z_{D,total,j}$	daily demand of each pumping station j (MW)
$P^i_{D,lim,j}$	maximum hourly demand of each pumping station j (MW)
$P^i_{PV}/P^i_{PV,v}$	hourly power from photovoltaic generation (MW)
$P^i_{W,\ max}$	maximum available hourly power from wind generation (MW)
$P^i_{H,\ max}$	maximum available hourly power from hydroelectric generation (MW)
$P^i_{exp,max}$	maximum hourly power exported from the global system (MWh)
$P^i_{imp,max}$	maximum hourly power imported from the global system (MWh)
K_p	constant of excess power according to pricing period p
K_{ex}	excess power factor (€/kW)
Variables	
P^i_{exp}	hourly power exported from the global system (MWh)
P^i_{imp}	hourly power imported from the global system (MWh)
P^i_W	hourly power from wind generation (MW)
P^i_H	hourly power from hydroelectric generation (MW)
$P^i_{in,k}/P^i_{in,v,j}$	hourly power imported from subsystems k/j (MWh)
$P^i_{out,k}/P^i_{out,v,j}$	hourly power exported from subsystems k/j (MWh)
$P^i_{D,v,j}$	hourly demand in each pumping station with water storage j (MW)
I^i_{exp}	binary variable equal to 1 if power is exported from the global system; otherwise, it will be equal to 0
I^i_{imp}	binary variable equal to 1 if power is imported to the global system and, otherwise, it will be equal to 0
$I^i_{in,k}/I^i_{in,v,j}$	binary variable equal to 1 if power is imported to the pumping stations k/j and, otherwise, it will be equal to 0
$I^i_{out,k}/I^i_{out,v,j}$	binary variable equal to 1 if power is exported from pumping stations k/j and, otherwise, it will be equal to 0
$P_{c,p}$	demand contracted in each pricing period p (p = 1.6) (kW)
$exc^i_{r,p}$	positive excess power in each pricing period p (p = 1.6) (kW)
exc^i_p	excess power in each pricing period p (p = 1.6) (kW)
I^i_{exc}	binary variable equal to 1 if excess power is produced; otherwise, it will be equal to 0
$P^i_{in,total}$	total hourly incoming power from the general bus to pumping stations (kWh)

Appendix A

Table A1 shows the electricity consumption during 2017 of the 27 pumping stations that make up the study system.

Table A1. Power consumed annually from each pumping station.

Pumping Station	Electricity Consumption (MWh)	Pumping Station	Electricity Consumption (MWh)	Pumping Station	Electricity Consumption (MWh)
1	746	10	284	19	656
2	2223	11	1011	20	900
3	965	12	1282	21	1615
4	4419	13	1045	22	1592
5	2112	14	2361	23	2688
6	2555	15	450	24	2014
7	843	16	622	25	1053
8	530	17	3732	26	192
9	2036	18	278	27	801
Total electricity consumption (GWh)				**39**	

Table A2 shows the installed power of the hydroelectric plants that make up the study system.

Table A2. Installed capacity of hydroelectric plants (MW).

Hydroelectric Power Plant	Installed Capacity
1	4.4
2	0.9
3	1.2
4	1.1
5	5.0
6	2.1
Total capacity	**14.7**

Table A3 shows the power of the self-consumption photovoltaic installation in each of the pumping stations.

Table A3. Installed power of the self-consumption photovoltaic installations.

Pumping Station	Installed PV Capacity (kW)	Pumping Station	Installed pv Capacity (kw)	Pumping Station	Installed PV Capacity (kW)
1	325	**10**	225	**19**	255
2	700	**11**	400	**20**	350
3	300	**12**	420	**21**	750
4	975	**13**	230	**22**	750
5	941	**14**	600	**23**	715
6	1106	**15**	575	**24**	815
7	367	**16**	230	**25**	445
8	301	**17**	1005	**26**	877
9	1000	**18**	230	**27**	585
Total installed capacity (MW)				**15.5**	

Table A4 shows the most detailed data of the renewable generation facilities according to the hourly periods of the contracted access charge.

Table A4. Annual generation data according to hourly periods (MWh).

Period	Hydropower Generation	Wind Power Generation	Photovoltaic Generation
P1	3206	6806	3874
P2	3841	10,684	2473
P3	2416	4879	2057
P4	4007	9224	3099
P5	6239	10,014	5588
P6	29,226	63,096	10,553
Total generation	48,934	104,703	27,645

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Optimal short-term water-energy dispatch for pumping stations with grid-connected photovoltaic self-generation

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ABSTRACT

Increases in the energy costs of irrigation water pumping facilities puts the economic sustainability of recent investments in the modernization of farms at risk. To address this problem, it is essential to apply renewable technologies for the production of electricity, and photovoltaic energy is particularly attractive due to its lower cost and recent technological advances. The aim of this research is to develop a mathematical techno-economic dispatch model that optimizes the hourly schedule of pumping equipment subject to electrical and hydraulic constraints to minimize the weekly operating costs of a real pumping station. The resulting model is formulated as a mixed-integer nonlinear programming problem that determines the optimal hourly combination of pumping equipment and available resources to meet water and energy needs. The proposed model comprises fixed and variable speed pumps, a grid-connected photovoltaic plant, and two water ponds for internal regulation and storage. The results verify that the combination of self-consumption photovoltaic facilities and variable speed drives make it possible to maximize the percentage of self-consumed energy up to 99.41% during the month with the highest demand for water. In this case, the pumping station reduces its energy costs by 21.56%, in addition to improving water management.

1. Introduction

Irrigation water pumping facilities consume large amounts of electricity in addition to representing complex water management systems. Generally, energy consumption represents more than 90% of the total costs, while the initial investment cost of pumping equipment rarely represents more than 5% of the total costs during its life cycle (Karassik et al., 2001; Yates and Weybourne, 2001). The other 5% corresponds to maintenance of the equipment.

In recent years, irrigation facilities have focused on modernization. To this end, different solutions have been implemented to expand the use of water resources through pressure irrigation systems (aspersion, drip) replacing traditional gravity irrigation systems. There have also been advances in elements associated with these systems that enable automated water regulation, such as reception ponds, storage ponds, variable speed drives, and starters. By modernizing irrigation systems, it is possible to considerably reduce losses due to evaporation and infiltration and thus to better manage resources; however, modernization also implies an increase in energy needs because greater pressure is required compared to traditional systems.

At the same time, all countries have encouraged the implementation of renewable generation facilities to address the effects of climate change and increases in energy pricing. Pumping stations not only seek to maximize the use of available water for irrigation but also to improve their energy efficiency. Thus, many irrigation communities have begun to invest in photovoltaic self-consumption plants for irrigation water pumping in order to exploit energy incentives. Renewable production facilities can help maintain the economic sustainability of the heavy investments made by farmers to modernize their farms and allow still-pending projects to be completed. In global economic terms, the expansion of self-consumption allows for greater presence of renewables in the electricity market, with a foreseeable reduction in wholesale energy prices. In technical terms, self-consumption reduces losses in electrical grids by producing part of the electricity in the same place it is consumed. The application of these renewable technologies for electricity production must consider the coupling of electricity production with the electricity demand of the pumping stations as well as the technical limitations of pumping and storage hydraulic facilities.

Focusing on the design of pumping stations Guyer (2012) provides guidelines for determining the appropriate sizing of system components such as pumps, variable frequency drives, flow meters, pipes, and valves.

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Nomenclature

Indexes

h	number of hours
i	number of fixed-speed pumps
j	number of variable-speed pumps

Data

N_h	study time period
N_{FP}	total number of fixed-speed pumps
N_{VP}	total number of variable-speed pumps
ρ^h_{exp}	hourly price of energy sale $\left(\frac{€}{kWh}\right)$
ρ^h_{imp}	hourly price of energy purchase $\left(\frac{€}{kWh}\right)$
P^h_{PV}	hourly power from photovoltaic generation (kW)
$P^h_{exp_{max}}$	maximum hourly energy exported to the grid (kWh)
$P^h_{imp_{max}}$	maximum hourly energy imported from the grid (kWh)
$V^h_{pond_{st,max}}$	maximum volume of the storage pond (m^3)
$V^h_{pond_{st,min}}$	minimum volume of the storage pond (m^3)
$Q^h_{VP_j,max}$	maximum hourly flow rate of variable-speed pump j $\left(\frac{m^3}{h}\right)$
$Q^h_{VP_j,min}$	minimum hourly flow rate of variable-speed pump j $\left(\frac{m^3}{h}\right)$
Q^h_D	hourly flow rate of irrigation demand $\left(\frac{m^3}{h}\right)$
Q^h_{req}	requested hourly flow rate reaching the reception pond $\left(\frac{m^3}{h}\right)$
P^h_c	power contracted according to tariff period (kW)
$V^h_{pond_{rec,max}}$	maximum volume of the reception pond (m^3)
$V^h_{pond_{rec,min}}$	minimum volume of the reception pond (m^3)
$Q^h_{FP_i,rated}$	rated flow of an operating fixed-speed pump i $\left(\frac{m^3}{h}\right)$
$P^h_{FP_i,rated}$	rated power of an operating fixed-speed pump i (kW)
$P^h_{VP_j,max}$	maximum power of the variable-speed pump j (kW)
k_{start}	start-up cost of fixed-speed pumps i (€)
k_{VP}	constant for power-flow ratio of variable-speed pumps j

Variables

P^h_{exp}	hourly energy exported to the grid (kWh)
P^h_{imp}	hourly energy imported from the grid (kWh)
I^h_{exp}	binary variable equal to 1 if energy is exported from the pumping station; otherwise, it is equal to 0
I^h_{imp}	binary variable equal to 1 if energy is imported to the pumping station; otherwise, it is equal to 0
$I^h_{FP_i}$	binary variable equal to 1 if the fixed-speed pump i is running; otherwise, it is equal to 0
$I^h_{VP_j}$	binary variable equal to 1 if the variable-speed pump j is running; otherwise, it is equal to 0
$Q^h_{FP_i}$	hourly flow rate of fixed-speed pump i $\left(\frac{m^3}{h}\right)$
$Q^h_{VP_j}$	hourly flow rate of variable-speed pump j $\left(\frac{m^3}{h}\right)$
$V^h_{pond_{st}}$	hourly volume of the storage pond (m^3)
$V^h_{pond_{rec}}$	hourly volume of the reception pond (m^3)
$P^h_{FP_i}$	power of fixed-speed pump i (kWh)
$P^h_{VP_j}$	power of variable-speed pump j (kWh)
$I^h_{start_i}$	binary variable equal to 1 if pump i begins to function; otherwise, it is equal to 0
$C^h_{start_i}$	hourly start-up cost of pump i (€)
C^h_{start,r_i}	actual hourly start-up cost of pump i (€)

Another contribution on the design phase (Pulido-Calvo and Gutiérrez-Estrada, 2006) centers the research on the annual depreciation costs of pumps and reservoirs and the operation schedule in an optimization model.

In relation to energy efficiency, Tarjuelo et al. (2015) review the technical aspects of the modernization process of pumping stations. They analyze the management of irrigation systems and conclude that water efficiency improves but energy demand and investment costs increase. Brati et al. (2018) evaluate different solutions for improving the energy efficiency of pressurized irrigation systems, verifying that the factors that most influence system efficiency are the types of pump and electric motor, operating conditions, and dimensions of special elements such as valves, hydrants, and pipes. Sharu and Ab Razak (2020) focus on the different parameters that affect hydraulic performance in drip irrigation systems, such as the coefficient of uniformity or variation.

Most of the reviewed studies aim to minimize pump operating costs and use different mathematical methods, particularly integer programming (Galindo et al., 2017; Reca et al., 2015; Zhuan and Xia, 2013) or heuristic methods based on genetic algorithms (Alonso Campos et al., 2020; De Ocampo and Dadios, 2017; Rasoulzadeh-Gharibdousti et al., 2011). In (Galindo et al., 2017), the model consists of two stages: first, water distribution is scheduled by minimizing electricity prices, and second, the pumps are scheduled for maximum efficiency. Zhuan and Xia (2013) propose a dynamic scheduling model for the optimal operation configuration of a pumping station with several pumps. In (Reca et al., 2015), mathematical model also includes evaporation water losses. Additionally, Rasoulzadeh-Gharibdousti et al. (2011) include the annualized investment cost of a water pumping system in Iran. The approach used to combine nonlinear programming and heuristic methods provides rapid convergence and ease of use to obtain optimal solutions to complex problems. De Ocampo and Dadios (2017) study the influence of several optimization parameters in genetic algorithm (population size and mutation function) to obtain the most optimal solution for operating cost minimization. Alonso Campos et al. (2020) include the surplus power penalty in operating costs while minimizing the pressure required for each hydrant. Tricarico et al. (2014) propose a methodology for a multi-objective model for water distribution systems that seeks to optimize the operating costs of the pumps, the pressure necessary, and the income derived from pumps operating as turbines for energy recovery.

Regarding the incorporation of photovoltaic facilities in irrigation systems, Li et al. (2017) present a comprehensive review focusing on components, parameters that affect performance, optimization methods, and applications. Almeida et al. (2018) establish a method for selecting solar pumps that operate at a variable frequency. Narvarte et al. (2019) present a methodology that defines the number of solar panels required for large irrigation systems to avoid losses in photovoltaic energy production, such as motor voltage, grid voltage, or temperature. Campana et al. (2015) include the investment costs of a photovoltaic plant in their optimization model.

Regarding the management of irrigation water, the storage pond is an important component, and some research focuses on its optimization to minimize the operating costs of pumping facilities. For instance, Al-Ani and Habibi (2013) aim to optimize the operation of a pumping station and reservoir capacity through a heuristic method. Furthermore, Kim et al. (2006) highlight that the strategy of pumping water to a storage reservoir results in more continuous pumping, higher efficiency, and lower energy costs. However, the reservoir must be close to the pumping station to ensure minimal friction losses in the pipes and to avoid increasing energy requirements and thus total costs.

Other studies analyze effective water management from economic and environmental viewpoints through the study of sectorization in irrigation network design and the incorporation of pumps with variable speed drives (Fernández García et al., 2014). Results show significant energy savings while also guaranteeing service pressure in the hydrants. Soonthornnapha (2017) studies the optimal scheduling of several variable-speed pumps in a water distribution system in Thailand. Córcoles et al. (2016) propose a methodology for calculating optimal pressure and thus minimizing the energy consumed by the pumping station. They demonstrate that the installation of variable pressure regulation elements in the pumping system improves the system's energy efficiency. Recently, Cimorelli et al. (2020) analyze the application of two pump scheduling strategies in water distribution systems based on fixed-speed pumps and variable speed drives from technical and economic perspectives. Occasionally, the economic savings of using variable speed drives do not compensate for the start-up costs of the drives, especially in low-power pumping stations. However, from an environmental perspective, it is possible to significantly increase energy savings and reduce carbon dioxide emissions.

Lima et al. (2018) and Lima et al. (2019) propose a tool that simulates an irrigation network to minimize energy costs and considers the distribution of the crops as well as their water requirements. Additionally, different irrigation strategies are studied.

Based on the literature reviewed, the proposed models are overly simplistic since they do not include self-consumption photovoltaic generation facilities or the joint management of water demand and electricity consumption. In addition, these models do not take into account the filling and emptying strategies of the reception and storage ponds or the other hydraulic and electrical constraints applied to a real irrigation water pumping system. To overcome these gaps, this study focuses on addressing the challenge of joint management of water and energy consumption in water pumping facilities. The goal of this paper is the development of a new mathematical model for optimal hourly scheduling of the pumps in a real water pumping system with photovoltaic self-consumption. The proposed model is a mixed-integer nonlinear programming model that aims to minimize operating costs for a week depending on solar availability, the water levels of the ponds, and the hourly cost of the electricity required to meet water demand.

The main contributions of this article are summarized as follows:

- The development of a new optimal techno-economic dispatch model that obtains the optimal pumping schedule to satisfy irrigation needs at a minimum cost.
- The integration of different types of pumps (fixed and variable speed), a grid-connected photovoltaic self-consumption plant, and two water ponds (reception and storage) in the proposed model.
- The application of this model to the operation of a real pumping station.

The article is structured as follows: Section 2 explains the mathematical techno-economic dispatch model. Section 3 describes the real case study and analyzes the results obtained from the application of the model. Section 4 presents different case studies varying the demand in the model. Finally, Section 5 presents the main conclusions of this study.

2. Mathematical model

Irrigation communities use different strategies for pumping and storing water. Some allow direct pumping for irrigation and simultaneous pumping to a storage pond for further use of water; others do not have a storage pond and therefore have a more limited capacity to manage water resources or are subject to hydraulic limitations against using all the pumping power. In pumping stations, it is common to incorporate pumps with a variable speed drive, which allows precise regulation of the flow rates supplied by the pump according to needs at each instant. As a result, its operation is fully optimized, thereby achieving great energy savings. As discussed in Section 1, due to current energy incentives in many countries, irrigation communities are beginning to invest in the implementation of grid-connected photovoltaic facilities that help to achieve the economic, energy, and environmental balance of pumping stations. Generally, if a pumping station is unable to meet irrigation demand by its own photovoltaic production plant, energy can be acquired from the grid at a fixed price determined by the tariff period. When surpluses of photovoltaic generation occur, energy can be exported to the grid in exchange for remuneration.

Thus, the need to integrate energy and water management in irrigation pumping facilities to improve efficiency, reduce operating costs, and improve farms' economic viability is evident. This research therefore aims to develop a short-term techno-economic dispatch model to obtain the optimal irrigation water pumping schedule over 1 week at minimum operating costs of a pumping station with photovoltaic self-consumption. The proposed model must meet the facility's water irrigation demand as well as its electrical and hydraulic constraints (see Fig. 1). For this reason, the system purchases energy from the grid if the photovoltaic generation is not enough to meet demand. Otherwise, if power surpluses are produced, these are injected into the distribution network. It is worth mentioning that hourly water demand and photovoltaic generation forecasts are available for the dispatch model, in addition to prices for selling surplus energy to the day-ahead electricity market (OMIE, 2020).

The variables are defined every hour for a week for the proposed model and are classified according to their type as follows:

Binary variables (0,1) for decision-making in this model:

- import from or export energy to the grid in the pumping station (I^h_{imp}, I^h_{exp})
- operating status for each fixed or variable pump of the system ($I^h_{FP_i}$, $I^h_{VP_j}$)
- start-up of the fixed-speed pumps ($I^h_{start_i}$)

Integer variables:

- power of the fixed-speed pumps ($P^h_{FP_i}$)

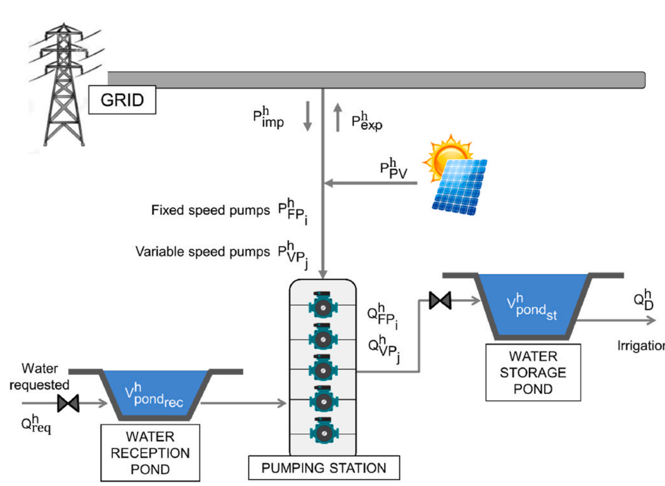

Fig. 1. Diagram of the techno-economic dispatch model.

- flow rate of the fixed-speed pumps ($Q^h_{FP_i}$)

Continuous variables:

- power of the variable-speed pumps ($P^h_{VP_j}$)
- flow rate of the variable-speed pumps ($Q^h_{VP_j}$)
- amount of energy imported from or exported to the grid in the pumping station (P^h_{imp}, P^h_{exp}).
- volume of water in the reception and storage ponds ($V^h_{pond_{rec}}$, $V^h_{pond_{st}}$)

2.1. Objective function

Once the variables of the problem are defined, Equation (1) presents the objective function to be optimized, which includes both the operating costs of the pumping equipment and the income derived from the sale of surplus photovoltaic production ($\rho^h_{exp} \cdot P^h_{exp}$). The sale price is only subject to the hourly price established by the wholesale electricity market. Regarding the costs of the system, in addition to the costs of purchasing energy from the grid ($\rho^h_{imp} \cdot P^h_{imp}$), start-up costs of fixed-speed pumps are considered (C^h_{start,r_i}). The continuous starting and stopping of the pumps is very inefficient because it can lead to instabilities in the hydraulic system and wear out the electric motors and pumps.

$$min(Cost) = \sum_{h=1}^{N_h} \left(\rho^h_{imp} \cdot P^h_{imp} - \rho^h_{exp} \cdot P^h_{exp} + \sum_{i=1}^{N_{FP}} C^h_{start,r_i} \right) \tag{1}$$

2.2. Constraints

The hydraulic and electrical constraints of the optimization model are described below.

Equation (2) shows the energy balance in the pumping system to meet hourly energy needs. As energy inputs into the pumping system, photovoltaic generation and energy imported from the grid are considered. Conversely, the energy consumed from the pumps and the energy exported to the grid are considered system outputs. Equations (3) and (4) establish the lower and upper limits of imported (P^h_{imp}) or exported (P^h_{exp}) energy of the pumping station during each hour. The upper limits are conditioned by the value of the integer decision variables (I^h_{imp}, I^h_{exp}). If photovoltaic generation (P^h_{PV}) is greater than the demand of the system, this implies that $I^h_{exp} = 1$ and $I^h_{imp} = 0$, so the system will export the excess production to the distribution network. In the opposite case where photovoltaic production is lower, $I^h_{exp} = 0$ and $I^h_{imp} = 1$, so the system will purchase energy from the grid to meet the required demand. In addition, the system can also neither import nor export energy, so the integer decision variables, I^h_{imp}, I^h_{exp}, will be equal to 0. Equation (5) imposes that the energy imported from the grid each hour cannot exceed the contracted power (P^h_c) in each tariff period to avoid economic penalties for surplus power. Equation (6) requires the maximum hourly amount of energy exported to the grid to be determined by available photovoltaic generation. It is worth mentioning that the hourly operations of importing from and exporting energy to the grid cannot occur simultaneously, so the sum of the binary variables (I^h_{imp}, I^h_{exp}) must be less than or equal to 1, as stated in Equation (7).

Regarding pump power, Equation (8) defines the behavior of fixed-speed pumps ($P^h_{FP_i}$). These pumps are characterized by an all-or-nothing operating mode, that is, when a pump of this type is operating, the power corresponds to its rated power, but otherwise its value is zero. Equation (9) expresses the power of the variable-speed pumps. The application of the affinity laws of pumps relates flow and power to rotational speed (Soonthornnapha, 2017). Flow rate decreases proportionally when the rotational speed of the pump shaft decreases, while absorbed power is proportional to the cube of the rotational speed. According to these relationships, an equation is obtained that links the absorbed power ($P^h_{VP_j}$) and flow rate ($Q^h_{VP_j}$) of the pump for any pump speed. In Equation (10), the constant k_{VP} is defined, which represents the known pump operating point at nominal frequency (f_{nom}).

For the characterization of the pumping equipment, it is assumed that the hydraulic head does not change because the losses due to friction and accessories of the system are so small they can be neglected. Pipes are usually sized with sufficiently large diameters to achieve efficient water transport and distribution systems (Perpiñan Lamigueiro, 2012). Moreover, ponds are built with large surfaces to maintain the height of the water sheet without great variations. On the other hand, according to Sârbu and Borza (1998), variations in performance when modifying the rotational speed of the pump can be mostly neglected for large pumps if the speed variation does not exceed 33% of the pump's nominal speed; therefore, this model considers this approximation.

Equations (11) and (12) establish the activation sequence of the fixed-speed and variable-speed pumps of the system, respectively, as it may be necessary to work with more or fewer pumps according to water demand. The binary variables $I^h_{FP_i}$ *and* $I^h_{VP_j}$ determine if the fixed-speed and variable-speed pumps run every hour.

Equation (13) shows the calculation of the corresponding water level for each hour of the reception pond ($V^h_{pond_{rec}}$). Q^h_{req} is the requested hourly flow rate to reach the reception pond of the pumping station from the water transport channels of the system. Equation (14) expresses the hourly water level of the storage pond ($V^h_{pond_{st}}$). Q^h_D represents the hourly flow rate of irrigation demand. Equation (15) expresses the total hourly flow pumped by the pumping system ($Q^h_{pump,total}$). Equations (16) and (17) indicate the upper and lower capacity limits of the reception pond and storage pond, respectively. The level of the ponds should be the same at the beginning and end of the study period (Equation (18)). The upper and lower limits of the water flows capable of passing through fixed and variable pumps of the system are defined in Equations (19) and (20), respectively.

Finally, Equations (21) and (22) determine the start-up costs of fixed-speed pumps since discontinuous operation of the pumps should be avoided. A variable (C^h_{start,r_i}) is defined that considers the costs of starting a pump, and a binary variable ($I^h_{start_i}$) is defined to make this decision. This binary variable takes a value equal to 1 if a pump starts working and otherwise remains 0. Equation (23) indicates that the start-up cost ($C^h_{start_i}$) is bound at the upper limit by means of a positive dimension (M) and at its lower limit by a negative dimension (m). k_{start} is a constant corresponding to the start-up cost of a pump.

$$P^h_{imp} - P^h_{exp} = \sum_{i=1}^{N_{FP}} P^h_{FP_i} + \sum_{j=1}^{N_{VP}} P^h_{VP_j} - P^h_{PV} \tag{2}$$

$$0 \le P^h_{imp} \le P^h_{imp_{max}} \cdot I^h_{imp} \tag{3}$$

$$0 \le P^h_{exp} \le P^h_{exp_{max}} \cdot I^h_{exp} \tag{4}$$

$$P^h_{imp_{max}} = P^h_c \tag{5}$$

$$P^h_{exp_{max}} = P^h_{PV} \tag{6}$$

$$I^h_{imp} + I^h_{exp} \le 1 \tag{7}$$

$$P^h_{FP_i} = P^h_{FP_i,rated} \cdot I^h_{FP_i} \tag{8}$$

$$P^h_{VP_j} = k_{VP} \cdot \left(Q^h_{VP_j} \right)^3 \tag{9}$$

$$k_{VP} = \frac{P_{VP_j}\left(f_{nom}\right)}{Q^3_{VP_j}\left(f_{nom}\right)} \tag{10}$$

$$I^h_{FP_{i+1}} + \left(1 - I^h_{FP_i}\right) \leq 1 \tag{11}$$

$$I^h_{VP_{j+1}} + \left(1 - I^h_{VP_j}\right) \leq 1 \tag{12}$$

$$V^h_{pond_{rec}} = V^{h-1}_{pond_{rec}} + Q^h_{req} - Q^h_{pump,total} \tag{13}$$

$$V^h_{pond_{st}} = V^{h-1}_{pond_{st}} - Q^h_D + Q^h_{pump,total} \tag{14}$$

$$Q^h_{pump,total} = \sum_{i=1}^{N_{FP}} Q^h_{FP_i} + \sum_{j=1}^{N_{VP}} Q^h_{VP_j} \tag{15}$$

$$V^h_{pond_{rec,min}} \leq V^h_{pond_{rec}} \leq V^h_{pond_{rec,max}} \tag{16}$$

$$V^h_{pond_{st,min}} \leq V^h_{pond_{st}} \leq V^h_{pond_{st,max}} \tag{17}$$

$$V^h_{pond_{st}}\left(0\right) = V^h_{pond_{st}}\left(N_h\right) \tag{18}$$

$$Q^h_{FP_i} = Q^h_{FP_i,rated} \cdot I^h_{FP_i} \tag{19}$$

$$Q^h_{VP_j,min} \cdot I^h_{VP_j} \leq Q^h_{VP_j} \leq Q^h_{VP_j,max} \cdot I^h_{VP_j} \tag{20}$$

$$C^h_{start,r_i} = C^h_{start_i} \cdot I^h_{start_i} \tag{21}$$

$$C^h_{start_i} = k_{start} \cdot \left(I^h_{FP_i} - I^{h-1}_{FP_i}\right) \tag{22}$$

$$m \cdot \left(1 - I^h_{start_i}\right) \leq C^h_{start_i} \leq M \cdot I^h_{start_i} \tag{23}$$

The mathematical optimization problem is a mixed-integer nonlinear programming type (MINLP) problem, which proposes the best possible combination of pumping equipment and available resources every hour to meet water and energy needs for a week. In recent years, new methods and software for resolving complex problems on small and large scales have been developed. This study used GAMS®, a powerful software program that allows the modeling, analysis, and optimization of various types of mathematical models with a large number of equations and variables (linear, nonlinear, or mixed-integer), in addition to providing a wide variety of solvers (Corporation, 2013). Bonami et al. (2008) and Kronqvist et al. (2019) compare different optimization algorithms; this study used BONMIN-HYB due to its robustness and high efficiency. This method is based on a hybrid external approach that uses branching and cutting techniques for the resolution of the proposed mixed-integer nonlinear model with a runtime of 5 h 35 min using a computer with an Intel® Core i7 processor, 3.00 GHz CPU, and 16 GB of RAM. The optimization process followed by the aforementioned solver consists of solving the relaxation of nonlinear subproblems in additional nodes of the tree as well as performing local searches in the nodes, which guarantees an optimal solution to the problem (Bonami et al., 2008).

3. Case study

3.1. Baseline data

The pumping station analyzed in this article is located in the province of Huesca (Spain) and irrigates an area of approximately 2800 ha, for which it has five parallel pumps that all work to deliver water from the reception pond to the storage pond (see Fig. 1). Four of the five pumps are fixed-speed pumps of 400 kW rated power. The fifth is a 400 kW pump equipped with a variable-speed drive to efficiently adapt the flow to the required demand. In addition, the pumping station has a 1.5 MW photovoltaic plant to reduce energy costs and the environmental impact of the agricultural sector. Pumping systems often have a lifespan of 15–20 years, while photovoltaic panels can reach up to 25 years.

The main components of the analyzed pumping station consist of the following (see Fig. 2):

- Photovoltaic modules (3334) that capture solar radiation and convert it into energy for the pumping system. The photovoltaic modules of the pumping station are fixed on the ground and therefore do not require much maintenance.
- Six DC-AC inverters that allow the photovoltaic energy produced to be injected into the pumping station or into the grid through the conversion of the direct current (DC) generated by the photovoltaic modules into alternating current (AC) for power line frequency.
- One variable frequency drive (VFD) that allows the pump to be started and stopped smoothly and adapts the flow to irrigation demand by modifying the rotation frequency of the electric motor.
- Four starters in fixed-speed pumps that allow control of the three phases of the asynchronous motor by regulating the voltage and current during starting and stopping, thus providing effective control of the torque.
- Five centrifugal pumps that transform mechanical energy into hydraulic energy and are responsible for driving water through the pipes. The characteristic curves of these pumps allow the flow to be related to the head generated and the power absorbed. The affinity laws determine the behavior of the pumps according to the speed of rotation. Each pump is driven by a three-phase asynchronous motor.

The control method of the variable frequency drive is based on voltage-frequency control. This strategy consists of maintaining a constant ratio between the supply voltage and frequency of the power supplied to the motor as the frequency is varied to regulate the motor's rotation speed. The VFD uses the pulse-width modulation (PWM) technique to construct a specific AC sine wave; this technique requires switching the inverter power devices (transistors or Insulated Gate Bipolar Transistors) on and off many times to generate the proper RMS voltage levels.

On the other hand, the control strategy of the inverter is based on the maximum power point tracking (MPPT) that enables the best performance of the solar panels as it seeks to exploit the maximum available power at all times.

The technical specifications of the motor-pump and variable frequency drive are indicated in Tables 1 and 2, respectively.

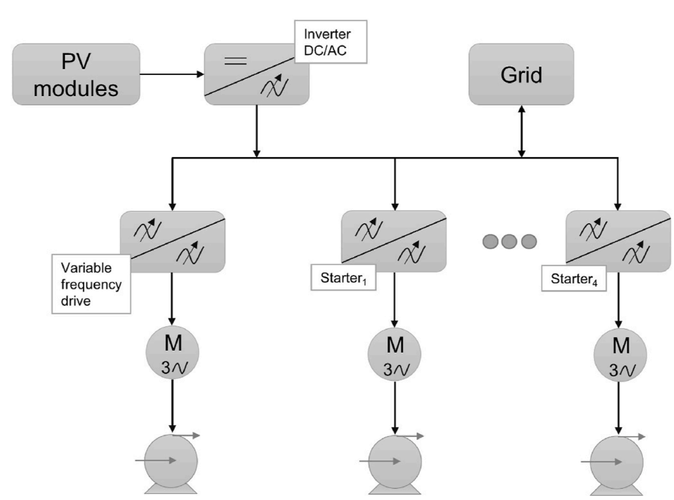

Fig. 2. Block diagram of the pumping station.

Table 1
Technical specifications of motor and pump (ABB, 2020).

Pump model	**STR 400/10/480**
Manufacturer	Sulzer
Rated flow (m^3/h)	1967
Head (m)	54.2
Motor type	ABB M3BP 355MLA 4
Power (kW)	400
Rated voltage (V)	690
Rated current (A)	409
Rated speed (rpm)	1489
Torque (Nm)	2565
Number of poles	4

Table 2
Technical specifications of variable frequency drive (Rockwell Automation, 2020).

Model	PowerFlex 755 AC Drive
Manufacturer	Rockwell Automation
Output current (A)	415
Voltage rating (V)	690
Power (kW)	450 Light Duty
	400 Normal Duty
	355 Heavy Duty

Fig. 3 shows the seasonality of the electricity consumption of the pumping station in 2019, with the beginning and end of the irrigation season clearly seen through the higher consumption from May to September.

This irrigation community has contracted a high-voltage electricity tariff at a fixed-price for six periods. In other words, the energy retailer and the consumer reach an agreement on a single kWh price for each of the tariff periods throughout the year. The irrigation community studied concentrates its energy consumption in period 6, which is associated with the lowest energy costs, corresponding to night hours and weekend hours throughout the year (see Fig. 4). Therefore, this system plans the operation of the pumps to maximize their use during these hours. The rest of the hours are associated with different periods according to the month of the year and have higher energy costs. It should be noted that the installation of a self-consumption photovoltaic plant in the system increases the number of pumping hours in the remaining hours of the day. In addition, the months of maximum solar radiation coincide with the months of greatest irrigation demand (May to September), which supports that a large amount of the photovoltaic energy produced can be self-consumed.

Table 3 shows the distribution of annual electricity consumption according to the tariff period, providing details of electricity prices and the power contracted in each period. The power contracted in period 6 covers the system's needs, while energy use during the most expensive periods is avoided and minimum power is contracted for the auxiliary services of the pumping station.

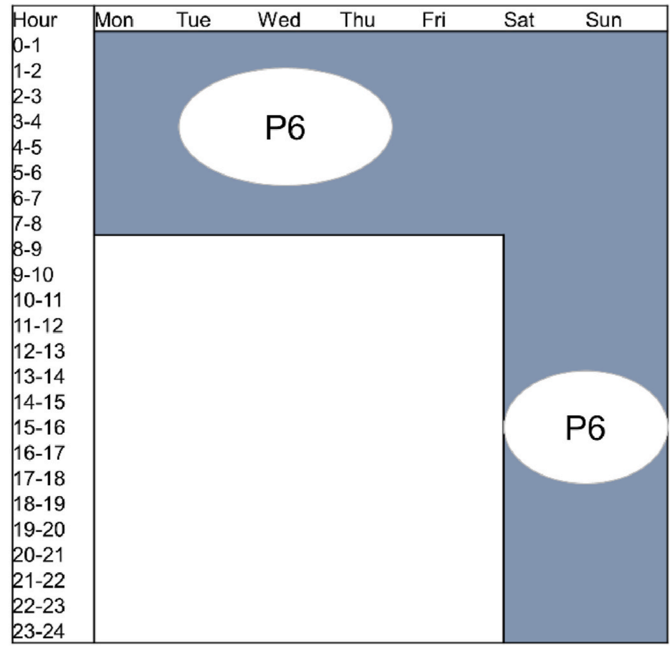

Fig. 4. Hourly distribution for period 6 of the electricity tariff.

Table 3
Electrical data of the pumping station.

Period	Electricity consumption (MWh)	Electricity Price (€/MWh)	Power contracted (kW)
1	8.088	116.5	50
2	10.184	107	50
3	4.063	94	50
4	7.488	87	50
5	11.041	73.5	50
6	2688.280	59.4	2000

Tables 4 and 5 show the technical data of the reception and storage ponds as well as the pumps of the studied system. In water pumping facilities, pumps rarely work below 35 Hz due to decreases in pressure in

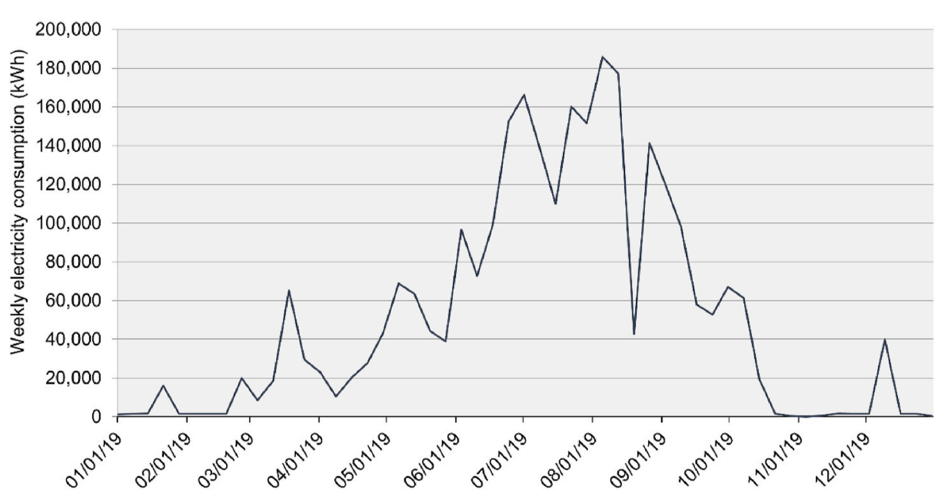

Fig. 3. Weekly electricity consumption in 2019.

Table 4
Technical data of the reception pond and storage pond of the pumping station.

Ponds	Minimum volume	Maximum volume
Reception pond (m^3)	75,000	155,000
Storage pond (m^3)	200,000	280,000

Table 5
Technical data of the pumping station pumps at different variable-speed drive frequencies.

Type	Number of pumps	Rated power 50 Hz (kW)	Rated flow 50 Hz (m^3/h)	Power 35 Hz (kW)	Flow rate 35 Hz (m^3/h)
Fixed-speed	4	400	1967	–	–
Variable-speed	1	400	1967	137.2	1377

the pump when speed is reduced. In addition, in this variation range, performance remains constant under changes in pump speed (Sârbu and Borza, 1998). In this situation, the pump only requires 1/3 of the initial power for the drive, demonstrating the great efficiency of using variable speed drives for flow regulation in these facilities.

Regarding the costs of the study pumping station, Table 6 indicates the initial cost of each of the main components of the system, and Table 7 includes the annual maintenance costs, which are highly variable depending on the year.

3.2. Results and discussion

The mixed-integer nonlinear hourly dispatch problem minimizes the operating costs of a pumping station with photovoltaic self-consumption through the optimal technical and economic management of water and energy to meet the required water demand. As a result, the optimal number of pumps of each type (fixed- and variable-speed) is determined, along with their respective values of power and flow, water levels of the reception and storage ponds, and the amount of imported electricity and electricity exported to the grid for each hour during the 168 h of a week.

To illustrate the operation of the proposed model, a week in July is analyzed, since it is the month with the highest demand for water and energy in the pumping station.

Fig. 5a represents the optimal hourly energy results to meet demand (see Fig. 5b) for one week. The greatest number of pumps in operation to meet the necessary water demand occurs at night or on weekends or at all hours during period 6 since these periods correspond to the lowest energy purchase price. It should be noted that the pumping strategy of this system during period 6 is to use energy acquired from the grid and to therefore maintain the minimum contracted power in the remaining tariff periods so as not to incur penalties for surpluses of power (see Table 3). At the end of the second day of the study week, the water storage pond reaches capacity, with a value of 276,667 m^3 (the maximum limit is 280,000 m^3). For the first few hours of the next day, water is only pumped with the variable-speed pump, with the fixed-speed pumps used only rarely and at specific times, leading to a peak in the pumped power of the system (hour 52; see Fig. 5b).

Table 6
Cost of each component of the pumping station.

Components	Unit	Unit price (€)	Total cost (€)
Photovoltaic modules 450 W	3334	90	300,060
Inverter	6	3250	19,500
Centrifugal pump and motor	5	36,250	181,250
Variable frequency drive	1	40,000	40,000
Starter	4	5000	20,000
Valves, filters, flow meters	–	–	1,200,000

Table 7
Annual maintenance costs of the pumping station.

Maintenance items	Annual cost (€)
Mechanical	
Bearings	3650
Electrical	
Labor and travel	3100
Motors	10,000
Transformers	2800
Annual inspection of the electrical installation	2350
Capacitor bank	2750
Other (electric equipment, automation)	3000

At the same time, the photovoltaic plant allows for more pumping hours by exploiting available solar energy as long as the upper and lower water levels of the ponds and the technical limits of the pumps are fulfilled. Thus, the system seeks to adapt at all times to the maximum production power of the photovoltaic plant. This system configuration reduces weekly costs by 21.56% compared to the system without a photovoltaic self-consumption plant. Fig. 6 depicts solar radiation within the study week. The first five days are clear-sky days with a clean sinusoidal curve, reaching a maximum production value at 12:00 a.m. However, the sixth day corresponds to a cloudy day with large fluctuations in irradiance, so less power is used. Finally, there are sparse clouds on the last day, resulting in some punctual irregularity in irradiance.

The irrigation system configuration of this pumping station with reception and storage ponds improves regulation so that it is possible to pump during low-cost hourly periods and to have on-demand irrigation in any hour period, including on cloudy days with low solar production. Fig. 7 shows the evolution of the optimal water levels of the ponds during a week of July. These levels simultaneously guarantee pumped water reaching the reception pond as well as the supply of water for agricultural irrigation from the storage pond.

Table 8 presents the hourly results for one day to allow detailed analysis of the optimal water and energy management of the pumping station. Based on the results, the use of a variable speed drive is essential for pumping water through solar panels because it varies the speed of the pump according to the power available in the photovoltaic generator. In this way, the maximum use of solar radiation for water pumping is achieved. The higher the irradiance is, the higher the output frequency and therefore the higher the pump speed, which translates into a higher pumping flow. The variable speed drive acts as if pumps of many powers were activated according to the needs required in each moment. Regarding fixed-speed pumps, they are activated according to system demand and are grouped to prevent the pumps from starting and stopping constantly, which would reduce the lifespan of the pumps and consume more electricity. Energy from the grid is purchased at night when energy costs are lowest to meet the irrigation demand and satisfy the constraints of the maximum imported power model of the network according to the contracted power in each hourly period, maintaining the water levels of the ponds within the capacity limits.

Fig. 8 depicts the results of the variable pump speed and flow rate for the day analyzed in Table 8. Pump flow is proportional to pump speed, according to the affinity laws. As noted, fixed-speed pumps operate on an all-or-nothing basis, so they always run at nominal speed, in this case 1489 rpm, providing their rated flow of 1967 m^3/h. Regarding the hydraulic head, it is assumed that this remains constant because friction losses are neglected and the surface of the water ponds is so large that the height of the water sheet is constant, as explained in Section 2. Hence, the hydraulic head is approximately 54.2 m.

Water is supplied to the pumping station from the water transport channels of the system between 0 and 8 h. Irrigation of agricultural fields also occurs at night for agronomic reasons; that is, between 0 and 8 h, water is moved from the storage pond to meet the irrigation demand. Consequently, although water is pumped from the reception pond

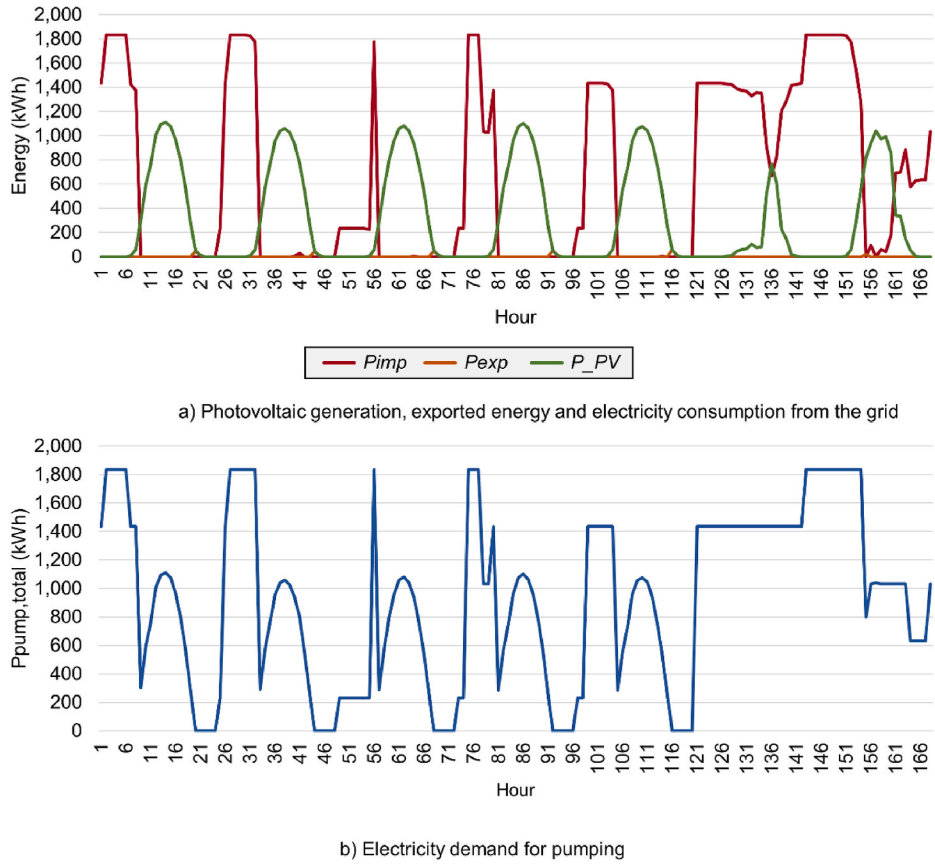

Fig. 5. Results of optimal hourly energy in July (07/15/2019–07/21/2019).

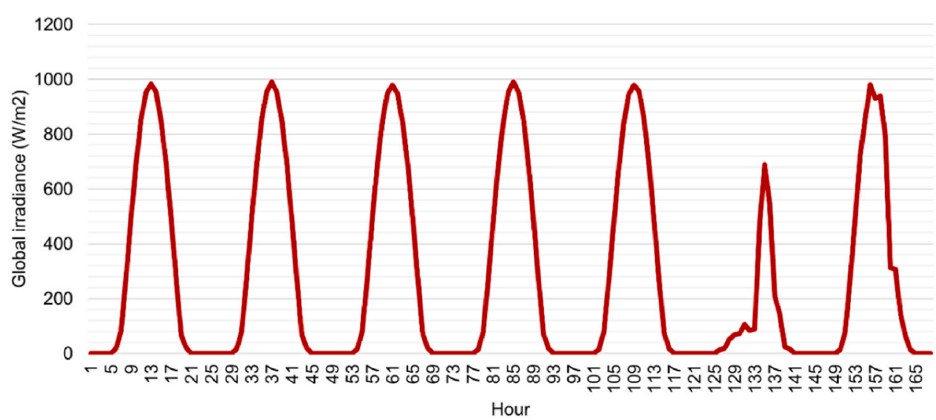

Fig. 6. Solar radiation during the study week.

to the storage pond in this hourly period, the reception pond is filled while the storage pond is emptied until both ponds are close to the maximum and minimum capacities, respectively. However, during the daytime, the water pumped using photovoltaic solar energy is stored in the storage pond for further use in irrigation.

Within this case study, the system can self-consume practically all the photovoltaic energy produced (99.41%) and increase the number of hours of water pumping in the different tariff periods. Only in the hours of very low solar radiation, when photovoltaic production is less than the minimum power capable of absorbing the variable-speed pump, does the system choose to sell that energy to the grid in exchange for remuneration.

In economic terms, for each kWh self-consumed, the pumping station saves the variable cost of electricity needed to pump the water to the storage pond, which is much higher than the income it can receive for each kWh of surplus energy because it only receives the price of energy in the wholesale market.

In conclusion, it is more economically profitable to self-consume as much as possible and to avoid exporting energy to the grid, even if income can be gained from the sale of electricity.

4. Analysis of scenarios

To illustrate the behavior of the model, three typical weeks during the irrigation season with different meteorological conditions and water demand are studied. In general, most crops increase their water requirements as solar irradiance increases, so there is a strong correlation between water needs and the production of photovoltaic energy to pump

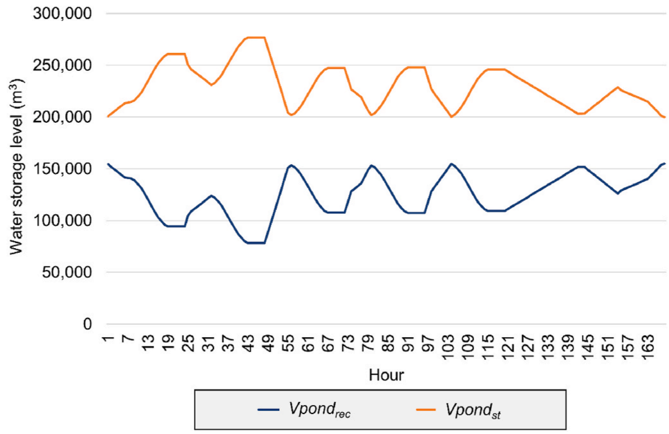

Fig. 7. Evolution of the optimal water levels of the ponds during one study week.

water.

Case 1. One week in April representative of the beginning of the irrigation season.

Case 2. One week in July during which there is the greatest demand for water. This case illustrates the operation of the model in Section 3.

Case 3. One week in September representative of the end of the irrigation season.

Table 9 compares the optimal weekly results obtained for each of the case studies. It shows that for all the case studies, the model trend is the same: to maximize the amount of self-consumed energy, by virtue of which the model decides the optimal scheduling of the pumping equipment and facilities, thereby minimizing the sale of surplus photovoltaic generation to the grid.

In Case 1, where the demand for irrigation is lower, using the hours of greatest solar radiation for pumping water is almost sufficient to meet water demand, so the amount of energy purchased from the grid is much lower compared to the rest of the cases. In addition, the amount of energy exported to the grid increases (3942 kWh), since there are several

Table 8
Optimal hourly results for a study day in July.

hour	P_{FP} (kW)	P_{VP} (kW)	$P_{pump,\ total}$ (kW)	Q_{FP} (m^3)	Q_{VP} (m^3)	$Q_{pump,\ total}$ (m^3)	Q_{req} (m^3)	Q_D (m^3)	$V_{pond_{rec}}$ (m^3)	$V_{pond_{st}}$ (m^3)	P_{PV} (kW)	P_{exp} (kW)	P_{imp} (kW)
1	–	234	234	–	1644	1644	12000	12000	117991	237009	–	–	233
2	–	234	234	–	1644	1644	12000	12000	128347	226653	–	–	233
3	1600	234	1834	7868	1644	9512	12000	12000	130835	224165	–	–	1833
4	1600	234	1834	7868	1644	9512	12000	12000	133323	221677	–	–	1833
5	1600	234	1834	7868	1644	9512	12000	12000	135811	219189	–	–	1833
6	800	234	1034	3934	1644	5578	12000	12000	142233	212767	–	–	1033
7	800	234	1034	3934	1644	5578	12000	12000	148655	206345	7	–	1027
8	1200	234	1434	5901	1644	7545	12000	12000	153110	201890	59	–	1375
9	–	286	286	–	1760	1760	–	–	151350	203650	286	–	–
10	400	167	567	1967	1470	3437	–	–	147913	207087	567	–	–
11	400	349	749	1967	1880	3847	–	–	144066	210934	749	–	–
12	800	167	967	3934	1471	5405	–	–	138661	216339	967	–	–
13	800	274	1074	3934	1735	5669	–	–	132992	222008	1074	–	–
14	800	302	1102	3934	1792	5726	–	–	127266	227734	1102	–	–
15	800	262	1062	3934	1709	5643	–	–	121623	233377	1062	–	–
16	800	158	958	3934	1443	5377	–	–	116246	238754	958	–	–
17	400	377	777	1967	1928	3895	–	–	112351	242649	777	–	–
18	400	148	548	1967	1413	3380	–	–	108971	246029	548	–	–
19	–	268	268	–	1720	1720	–	–	107251	247749	268	–	–
20	–	–	–	–	–	–	–	–	107251	247749	49	49	–
21	–	–	–	–	–	–	–	–	107251	247749	9	9	–
22	–	–	–	–	–	–	–	–	107251	247749	–	–	–
23	–	–	–	–	–	–	–	–	107251	247749	–	–	–
24	–	–	–	–	–	–	–	–	107251	247749	–	–	–

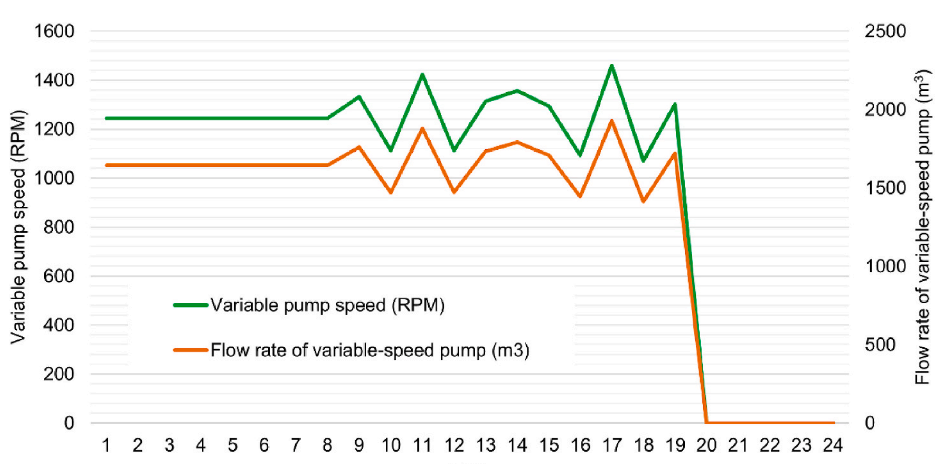

Fig. 8. Results of the variable pump speed and flow rate for a study day in July.

Table 9
Optimal weekly results of the three case studies.

Case	1	2	3
$Q_{pump,total}$ (m^3)	373,152	834,240	601,440
$P_{pump,total}$ (kWh)	58,580	156,004	107,304
P_{PV} (kWh)	45,402	52,404	46,322
P_{imp} (kWh)	17,120	103,909	61,562
P_{exp} (kWh)	3942	309	580
%self-consumption	91.32	99.41	98.75
kWh/m^3	0.1569	0.1870	0.1784
Total cost (€)	1033	6193	3670
Total income (€)	221	16	23
€/m^3	0.0028	0.0074	0.0061

hours when the solar radiation is less than the minimum power that the pump with a variable speed drive is able to absorb; as a result, these surpluses of energy are sold to the grid in exchange for remuneration. For this reason, the percentage of self-consumed energy with respect to the energy generated is 91.32%, which is slightly lower than the value obtained in the other case studies. On the other hand, in Cases 2 and 3, where the water demand is quite high, it is possible to self-consume nearly all the energy generated, 99.41% and 98.75%, respectively. However, in these cases, the pumping station needs to buy a greater amount of energy from the grid during the cheapest hours because it is not able to cover demand even with the maximum use of available photovoltaic production. As indicated in Table 9, the highest amount of self-consumed energy, 52,095 kWh, is achieved in Case 2. The maximum production of photovoltaic energy, 52,404 kWh, is almost reached, and thus the system almost entirely avoids exporting energy to the grid. However, the system still needs to buy a large amount of energy from the grid, 103,909 kWh, to satisfy the irrigation demand.

Table 9 also includes the ratio of energy consumed per volume of water, which is frequently used in the analysis of water pumping. The highest value obtained corresponds to Case 2 with a value of 0.1870 kWh/m^3, indicating that a greater number of fixed-speed pumps are operating, especially during night hours and weekends, to meet the irrigation demand in its entirety. In contrast, Case 1 presents the lowest ratio, 0.1569 kWh/m^3, because when a lower demand is required, the fixed-speed pumps rarely operate. In essence, the pump with a variable speed drive is the only pump operating during the week in Case 1 because it can adequately adjust the flow to the needs demanded by the system by modifying the rotational speed of the pump. In this case, it must operate for many hours in below-nominal flow conditions so that, by reducing the working frequency, energy consumption is also reduced, thereby fostering greater energy efficiency. This analysis is represented graphically in Fig. 9, which compares the number of hours the different pumps are operating for the case studies.

As illustrated in Fig. 9, in Case 1, the variable pump works 139 h during the week, while the fixed pumps work 83 h. Comparing the operating hours of the pumps in Cases 1 and 2, the fixed pumps work significantly fewer hours in Case 1 due to the lower pumping demand. However, the number of hours that the variable-speed pump works remains practically constant in Cases 1 to 3 because by regulating the flow rate supplied by the pump, there is an energy saving in the system, and the use of this pump is always more efficient.

5. Conclusion

The efficient use of energy and water constitutes a great challenge for irrigation from both the environmental and economic perspectives. To address this challenge, this study develops a mathematical model of hourly techno-economic dispatch to minimize the operating costs of several pumps with fixed and variable speeds over a week. In addition, the model integrates a self-consumption photovoltaic power plant and obtains optimal management of the pumping equipment and facilities that make up a real irrigation system.

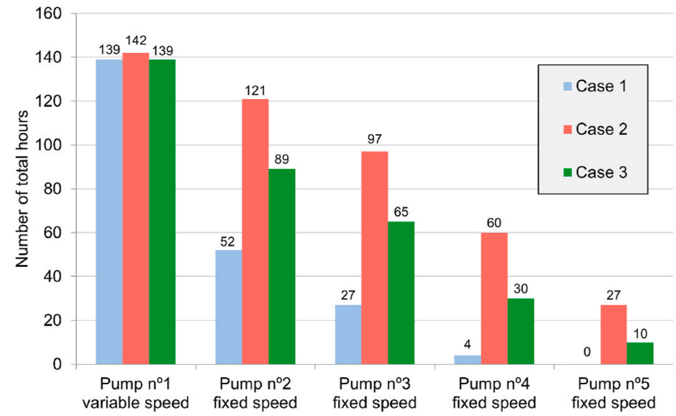

Fig. 9. Comparison of the number of pumping hours during one week for the three case studies.

The analysis of the results in different real cases verifies that the most economically profitable situation for the proposed model is to maximize self-consumption and minimize the surplus energy generated by the photovoltaic plant. In the case study of highest demand, 99.41% self-consumption is reached, but the water pumping system still has to purchase energy from the grid to meet the irrigation demand. In addition, the worst ratio of energy consumed per volume of water (0.1870 kWh/m^3) is obtained, since it is necessary that most of the fixed-speed pumps operate at night to satisfy water demand. During the daytime, the variable-speed pump continuously adjusts its power according to solar availability and irrigation needs to meet the irrigation demand and maintain the water levels of the ponds within their capacity limits. In contrast, in the case study of lowest demand, hardly any pumps work at night because a large part of the irrigation demand is satisfied with the use of solar production (91.32% self-consumption), and surpluses are sold to the grid. The best ratio of energy consumed per volume of water (0.1569 kWh/m^3) is obtained in this case because the variable-speed pump is practically the only pump operating, which increases the system's efficiency.

In short, the model proposed in this research offers a good strategy for efficiently managing water and energy consumption by using renewable energy to completely or partially meet demand in pumping facilities, and applying this model can contribute to improving the competitiveness and viability of agricultural operations.

CRediT authorship contribution statement

Natalia Naval: Conceptualization, Methodology, Software, Formal analysis, Writing – original draft, Writing – review & editing. **Jose M. Yusta:** Conceptualization, Methodology, Validation, Writing – original draft, Writing – review & editing, Supervision, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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3. Metodología

La metodología utilizada para conseguir los objetivos propuestos en esta tesis es la siguiente:

1. Revisión bibliográfica de los modelos existentes de operación conjunta de grupos de producción y consumo de energía no interconectados físicamente.
2. Revisión bibliográfica de técnicas de optimización y herramientas computacionales más apropiadas para la resolución de este tipo de problema.
3. Revisión bibliográfica de los modelos de plantas virtuales de energía con interacción con mercados eléctricos.

   El primer artículo, "*Virtual power plant models and electricity markets – A review*", se centra en profundidad en este tema, clasificando y evaluando los trabajos publicados en función del objetivo del problema, formulación del modelo y métodos de resolución, los mercados eléctricos donde participa la VPP y la aplicabilidad del modelo a casos reales de estudio.

4. Revisión de estrategias para el bombeo de agua en las comunidades de regantes (bombeo directo, bombeo a balsa, bombeo solar con apoyo de la red eléctrica, etc).
5. Estudio del comportamiento de bombas centrífugas en paralelo tanto con velocidad fija como velocidad variable.
6. Propuesta de modelos de despacho técnico-económico para la operación óptima de las instalaciones de generación renovable y consumo de electricidad en sistemas de bombeo de agua. Según la complejidad de los modelos, se definen distintos tipos de problemas de optimización como de tipo lineal mixto-entero (MILP) y no lineal mixto-entero (MINLP). Todos los modelos propuestos incluyen variables continuas y variables de tipo entero que toman valor 0 o 1 en función de la mejor alternativa económica para el sistema.
7. Formulación de la función objetivo (maximizar el beneficio de operación o minimización de los costes) junto con las restricciones técnicas (eléctricas e hidráulicas) que modelan el comportamiento del sistema. El proceso de toma de decisiones se realiza para cada hora a lo largo del periodo de cálculo que se establezca (semanal o anual).

   El segundo artículo, "*A virtual power plant optimal dispatch model with large and small-scale distributed renewable generation*", establece la función objetivo (ecuación 1) que maximiza el beneficio de operación de las instalaciones de producción y consumo de energía integradas en la VPP como la diferencia entre los ingresos y costes de todos los agentes del sistema. Los ingresos proceden de la venta horaria al mercado eléctrico de los excesos de energía producidos, mientras que los costes corresponden a la energía horaria producida en cada instalación de generación renovable (eólica, hidroeléctrica y fotovoltaica de autoconsumo) y al coste horario de compra de energía en caso que la producción propia no satisfaga la demanda.

$$\max\left\{\sum_{i=1}^{8760}\left(\rho_{exp}^{i}\cdot P_{exp}^{i}-\rho_{imp}^{i}\cdot P_{imp}^{i}-f_{W}\cdot P_{W}^{i}-f_{H}\cdot P_{H}^{i}-\sum_{j=1}^{27}f_{PV}\cdot P_{out,j}^{i}\right)\right\} \quad (1)$$

El tercer artículo, "*Water-Energy Management for Demand Charges and Energy Cost Optimization of a Pumping Stations System under a Renewable Virtual Power Plant Model*", expresa la función objetivo (ecuación 2) que maximiza el beneficio de operación de la VPP como la diferencia entre los ingresos y costes de todos los agentes del sistema. Los ingresos proceden únicamente de la venta de los excedentes de energía al mercado eléctrico al precio horario del mercado que resulta en las subastas diarias organizadas por el operador del mercado mayorista español OMIE. Los costes del sistema están asociados a los costes de producción de electricidad de origen renovable (eólica, hidroeléctrica y fotovoltaica de autoconsumo asociada a cada estación de bombeo), la adquisición de energía al precio horario del mercado eléctrico mayorista cuando no haya energía disponible en el sistema para cubrir la demanda, los costes de demanda contratada en cada periodo tarifario y los cargos por excesos de demanda.

$$\max\left[\sum_{z=1}^{365}\sum_{i=1}^{24}\left(\rho_{exp,z}^{i}\cdot P_{exp,z}^{i}-\rho_{imp,z}^{i}\cdot P_{imp,z}^{i}-f_{W}\cdot P_{W,z}^{i}-f_{H}\cdot P_{H,z}^{i}-f_{PV}\cdot\sum_{k=1}^{17}P_{out,k,z}^{i}-f_{PV}\cdot\sum_{j=1}^{10}P_{out,v,j,z}^{i}\right) -\left(\sum_{p=1}^{6}f_{power,p}\cdot P_{c,p}\right)-\sum_{m=jan}^{dec}\left(\sum_{p=1}^{6}K_{p}\cdot K_{ex}\cdot\sqrt{\sum_{i=1}^{n}4\cdot\left(exc_{r,p}^{i}\right)^{2}}\right)_{m}\right] \quad (2)$$

El cuarto artículo, "*Optimal short-term water-energy dispatch for pumping stations with grid-connected photovoltaic self-generation*", presenta la función objetivo (ecuación 3) que minimiza los costes de operación de un sistema de bombeo de agua con autoconsumo fotovoltaico como la diferencia de costes e ingresos. Del mismo modo que en los modelos propuestos en los artículos previos, los ingresos derivados de los excedentes de producción fotovoltaica únicamente están sujetos al precio horario establecido por el mercado mayorista de electricidad. Los costes del sistema incluyen los costes de compra de energía de la red eléctrica y los costes de arranque de las bombas de velocidad fija, ya que el arranque y parada continuo de las bombas es muy ineficiente, provocando inestabilidades del sistema hidráulico y desgaste de los motores eléctricos y las bombas.

$$\min(\text{Cost}) = \sum_{h=1}^{N_h} (\rho_{imp}^{h} \cdot P_{imp}^{h} - \rho_{exp}^{h} \cdot P_{exp}^{h} + \sum_{i=1}^{N_{FP}} C_{start,r_i}^{h}) \quad (3)$$

8. Según el tipo de problema identificado, selección de distintas herramientas computacionales para una resolución eficiente.

Para la resolución del modelo lineal mixto-entero propuesto en el segundo artículo con 58 variables continuas y 56 binarias para cada hora durante un año, se utiliza el software Matlab® ya que su caja de herramientas incluye un *solver* eficiente para resolver este tipo de problemas.

Por otra parte, para la resolución del problema no lineal mixto-entero propuesto en el tercer artículo con 80 variables continuas, 57 binarias y 6 enteras en cada hora durante un año, se utiliza el software de cálculo LINGO® que es adecuado para el modelado y resolución de problemas de optimización no lineal de forma eficiente. De acuerdo con la formulación del problema, LINGO invoca al *solver* interno más adecuado para buscar eficientemente la solución óptima al modelo propuesto. Este software utiliza el método *Branch-and-Bound* para favorecer la obtención de una solución óptima global y, así, evitar los óptimos locales. Esta técnica permite enumerar implícitamente todas las combinaciones posibles de las variables enteras. Se generan cotas superiores e inferiores del valor de la función objetivo, las cuales se van aproximando entre sí. Este proceso consiste fundamentalmente en la división del conjunto total de soluciones factibles en subconjuntos más pequeños de soluciones para facilitar la búsqueda de un óptimo global. La ejecución del modelo finaliza cuando no es posible realizar más divisiones del problema, o bien, la diferencia entre la cota inferior y superior del valor objetivo es menor que una tolerancia preestablecida.

Por último, para la resolución del problema no lineal mixto-entero propuesto en el cuarto artículo con 14 variables continuas, 8 variables enteras y 11 binarias en cada hora durante una semana, se utiliza GAMS® que es un potente software que permite el modelado, análisis y optimización de diversos tipos de modelos matemáticos con un gran número de ecuaciones y variables con una amplia variedad de *solvers*. En este caso, se eligió BONMIN-HYB por su robustez y la gran eficiencia de resolución. Este método está basado en una aproximación externa híbrida fundamentada en las técnicas de ramificación y corte que resuelve la relajación de subproblemas no lineales en nodos adicionales del árbol además de realizar búsquedas locales en los nodos, lo que garantiza la obtención de una solución óptima del problema.

9. Casos de estudio para la validación de los modelos propuestos.
10. Minería de datos horarios de producción de energía renovable, demanda de energía eléctrica y agua, costes de operación de las tecnologías de generación y los equipos de bombeo, precios horarios de compra y venta del mercado eléctrico.
11. Estudio de análisis de sensibilidad de los parámetros con mayor influencia en los modelos, particularmente de los precios de compra y venta del mercado eléctrico, y la producción de los recursos renovables.
12. Aplicación de los modelos propuestos a sistemas reales de regadío con recursos de producción renovable.

En el segundo y tercer artículo, los modelos desarrollados se aplican a un gran sistema de regadío en Aragón (España) con un consumo de energía eléctrica anual de 39 GWh y una producción de 180 GWh.

El sistema de regadío consta de seis centrales hidroeléctricas geográficamente dispersas en la región con una potencia total de 14,7 MW, un parque eólico de 30 MW y 27 plantas de generación fotovoltaica en modalidad de autoconsumo asociadas a cada estación de bombeo con una potencia total instalada de 15,5 MW.

Por otro lado, el modelo propuesto en el cuarto artículo se aplica a una estación de bombeo de agua para riego con autoconsumo fotovoltaico en la provincia de Huesca (Aragón) con un consumo de electricidad anual de 2750 MWh y una producción fotovoltaica de 2260 MWh.

4. Discusión y conclusiones finales

Dada la penetración de la generación distribuida en los sistemas eléctricos, la introducción masiva de tecnologías TIC y el progreso de los mercados eléctricos competitivos, se están desarrollando nuevas herramientas de gestión integrada de los recursos energéticos, destacando las plantas virtuales de energía. Estas herramientas pueden ayudar a hacer frente a la creciente escasez de agua, debida a los periodos cada vez más frecuentes y prolongados de sequía, y a una mayor demanda asociada al desarrollo industrial. Este problema afecta en mayor medida a la agricultura de regadío, puesto que en cada campaña de riego existe una gran incertidumbre acerca de la disponibilidad de agua, lo que puede provocar una mala planificación de los cultivos y no poder satisfacer las demandas de los mercados.

En primer lugar, resulta evidente la necesidad de recopilar y sintetizar los conceptos tratados sobre este tema en la literatura, examinar la tendencia de las investigaciones, organizar y evaluar los trabajos previos, así como identificar nuevas líneas de investigación. Por otra parte, también es esencial el desarrollo de nuevos modelos de despacho técnico-económico con integración de la gestión conjunta de energía y agua y su aplicación a sistemas reales, todo lo cual no se ha abordado en investigaciones previas.

El primer artículo clasifica y evalúa los trabajos publicados en los últimos años sobre el modelado de plantas virtuales de energía con participación en distintos tipos de mercados eléctricos. La clasificación se realiza en función de los criterios más relevantes para el modelado, tales como el objetivo del problema, el tipo de problema matemático y método de resolución, los tipos de mercados eléctricos y la aplicabilidad del modelo a casos reales de estudio. La mayoría de las investigaciones en esta área de conocimiento han desarrollado modelos de VPP para conseguir un control y coordinación óptimas entre sus componentes y maximizar su beneficio de operación. Los modelos más recientes son más completos, incorporando más restricciones de operación, pero necesitando también técnicas de optimización más avanzadas para obtener una solución óptima. Además, estos modelos incluyen la participación de la VPP en los mercados de futuros, contratos bilaterales y/o mercados de tiempo real, consiguiendo mayores beneficios de operación. Como consecuencia de la volatilidad del mercado eléctrico y la gestión de riesgos en el suministro de energía eléctrica, la mejor forma de comprar y vender electricidad es diversificar riesgos combinando adecuadamente los mercados de futuro, los contratos bilaterales y el mercado spot.

Asimismo, ha habido una creciente propuesta de problemas de optimización multi-objetivo para una gestión más realista de las VPPs puesto que hay que tener en cuenta que los problemas en el mundo real en general involucran más de un objetivo a la vez, y el continuo desarrollo de técnicas más eficientes para su resolución facilita que cada vez más autores estudien el modelado de este tipo de problemas con más variables.

A partir del primer trabajo, se concluye que todavía quedan varias líneas de investigación para mejorar y ampliar el conocimiento en esta área de estudio, entre las que destaca la aplicación simultánea de varias estrategias de compra-venta de energía de la planta virtual de energía en los distintos mercados energéticos, además de la utilización de técnicas de inteligencia artificial con el fin de proporcionar al modelo de VPP un método de aprendizaje capaz de garantizar un margen de anticipación en sus decisiones.

Posteriormente, para analizar el alcance real de la gestión de energía de acuerdo al diseño y operación de una planta virtual de energía, el segundo trabajo desarrolla y aplica un nuevo modelo matemático de despacho horario técnico-económico a un gran sistema energético real de bombeo de agua para riego agrícola con recursos de producción renovable centralizada (centrales hidroeléctricas y un parque eólico), plantas de autoconsumo fotovoltaico asociadas a cada estación de bombeo y demanda eléctrica. Para evaluar la validez y robustez del modelo propuesto, se aplica a un año entero y se utilizan datos reales horarios de demanda, generación, precios de compra y venta de energía, así como los costes de generación de cada una de las energías de producción instaladas. A partir de los resultados obtenidos, se demuestra que, gracias a las instalaciones de producción de electricidad con fuentes renovables disponibles en el sistema de regadío real de estudio, la VPP propuesta puede satisfacer casi un 95% su demanda, reduciendo la dependencia de las redes eléctricas y el coste final de suministro eléctrico. El resto de la demanda se satisface mediante la adquisición de energía en el mercado eléctrico, ya que hay momentos donde las horas o cantidades de generación y consumo no coinciden, o bien, cuando resulta más rentable la compra de energía en vez de producirla mediante las plantas propias de generación renovable. Además, a partir del análisis de sensibilidad del modelo ante variaciones del precio del mercado eléctrico mayorista, se verifica que, a precios más elevados en el mercado eléctrico, los ingresos por la energía vertida a la red serían mayores, ya que resultaría más rentable aumentar la producción y, por tanto, su venta al mercado eléctrico. Por otro lado, la energía importada de la red permanece constante ante estas variaciones, ya que es difícil competir contra los costes de generación de las energías renovables aun cuando el precio del mercado eléctrico disminuya un 40%.

Como continuación de este segundo artículo y para afrontar el complejo reto de gestión eficiente del binomio agua-energía en las instalaciones de bombeo de agua, el tercer artículo desarrolla y aplica un nuevo modelo de despacho horario con la integración de los recursos energéticos e hídricos para la optimización de los costes de energía y de los cargos por demanda máxima en un gran sistema de regadío para un año entero. Al tratarse de un modelo no lineal y con un gran número de variables continuas y enteras, la obtención de soluciones óptimas requiere un elevado tiempo de cálculo.

El modelo propuesto de planta virtual de energía con la gestión conjunta de agua y energía, permite cubrir hasta el 99,64% de la demanda eléctrica con las instalaciones propias de generación renovable. Tras el análisis de resultados, se demuestra que es más eficiente económicamente autoconsumir la máxima cantidad posible de electricidad y evitar exportar energía a la red eléctrica, aun recibiendo por ello una remuneración económica. Como consecuencia, la curva de consumo de las estaciones de bombeo se adapta a la curva de generación eléctrica con renovables, siempre que los costes de generación sean más competitivos frente al precio de compra de energía en el mercado eléctrico. Además, se consigue incrementar la utilización de la producción de electricidad con energías renovables y reducir los picos de demanda máxima, y así aumentar el beneficio operativo de la VPP mediante la reducción de la potencia contratada anualmente en los periodos horarios con mayor coste energético.

Por último, la aplicación de fuentes de energía renovable debe considerar el acoplamiento de la producción de electricidad con la demanda de energía eléctrica de las estaciones de bombeo y contemplar las limitaciones técnicas de las instalaciones hidráulicas de bombeo, almacenamiento y distribución del agua. Por tanto, el cuarto trabajo propone el desarrollo de un modelo matemático de despacho con gestión técnica y económica para obtener la programación horaria óptima de los equipos de bombeo, minimizando los costes de operación de una estación real de bombeo de agua con autoconsumo fotovoltaico, sujeto a las restricciones eléctricas e hidráulicas de los sistemas de bombeo, y garantizando la demanda de riego.

A partir del análisis de resultados, al igual que se comprobó en los anteriores trabajos, la situación más rentable económicamente para el modelo propuesto es maximizar el autoconsumo y minimizar el excedente de energía que puede generar la planta fotovoltaica. Esto es debido a que, en términos económicos, por cada kWh autoconsumido la estación de bombeo se ahorra el coste variable de la electricidad necesaria para el bombeo del agua a la balsa de almacenamiento, que es mucho mayor que el ingreso que puede percibir por cada kWh de excedente de energía, ya que en este caso recibe únicamente el precio de la energía en el mercado mayorista.

Además, se comprueba que el uso de un variador de velocidad es imprescindible para el bombeo de agua mediante paneles solares, puesto que hace variar la velocidad de la bomba para trabajar con potencia variable en función de la potencia disponible en el generador fotovoltaico. Como consecuencia, se consigue el máximo aprovechamiento de la radiación solar para el bombeo de agua. A mayor irradiancia se obtiene una mayor frecuencia de salida en el variador y, por tanto, una mayor velocidad de la bomba, lo que se traduce en un mayor caudal de bombeo. El variador de velocidad actúa como si se dispusiera de bombas de muchas potencias según las necesidades que se requieran en cada momento. Respecto a las bombas de velocidad constante, se observa que se van poniendo en funcionamiento según las necesidades de demanda del sistema, y se agrupan para evitar que las bombas arranquen y paren constantemente, ya que esto reduce la vida útil de las bombas y produce un mayor consumo eléctrico. La compra de energía de la red se produce en las horas nocturnas con el menor coste de energía para cumplir la demanda de riego y satisfacer las restricciones del modelo de potencia máxima importada de la red en función de la potencia contratada en cada periodo horario, manteniendo los niveles de agua de las balsas dentro de los límites de capacidad.

Respecto a la estrategia de bombeo, la configuración de sistema de riego con balsa de captación y balsa de copa permite disponer de una mayor regulación del sistema de riego, por lo que se consigue bombear en periodos horarios de bajo coste de energía y disponer de la posibilidad de riego a demanda en cualquier periodo horario, aun cuando aparezcan días nublados con baja producción solar.

Gracias a la combinación de instalaciones de autoconsumo fotovoltaico y variadores de velocidad se consigue maximizar el porcentaje de energía autoconsumida hasta un 99,41% durante el mes de mayor demanda de agua. En este caso, los costes energéticos de la estación de bombeo son reducidos un 21,56%, además de mejorar la gestión del agua. La instalación fotovoltaica permite aumentar las horas de bombeo, mediante el aprovechamiento de la energía solar disponible, siempre y cuando se puedan cumplir también los niveles superior e inferior de las balsas de agua, así como los límites técnicos de las bombas. Por tanto, el sistema busca adaptarse en cada momento a la potencia máxima de producción de la instalación fotovoltaica. Únicamente en las horas de muy baja radiación solar, cuando la producción fotovoltaica obtenida es menor que la potencia mínima que es capaz de absorber la bomba con variador de velocidad, el sistema opta por vender esa energía a la red a cambio de unos ingresos adicionales.

En definitiva, esta tesis doctoral pone de manifiesto la importancia de desarrollar estrategias de gestión óptima de fuentes de generación eléctrica renovable e infraestructuras de agua para minimizar los costes energéticos y mejorar la eficiencia energética. Las plantas virtuales de energía aparecen como un instrumento de utilidad para los sistemas de energía, ya que permiten optimizar la integración de la creciente producción renovable, dotar al sistema de mayor flexibilidad y acceder a los mismos mercados eléctricos que las grandes centrales tradicionales. Así, las plantas virtuales de energía eliminan barreras para maximizar la integración de las energías renovables en la red eléctrica. Además, los modelos de explotación que vinculan la gestión de la energía con la gestión del agua propuestos en esta investigación pueden contribuir a mejorar significativamente la competitividad, así como la sostenibilidad económica, energética y ambiental de las explotaciones agrícolas de regadío.

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Anexos

Los anexos recogen el factor de impacto y áreas temáticas correspondientes a las publicaciones que componen esta tesis doctoral.

Además, se incluye la justificación de la contribución del doctorando en cada uno de los trabajos publicados.

Anexo A. Renewable and Sustainable Energy Reviews

Fuente: Web of Science - Journal Citation Reports – Thomshon Reuters

RENEWABLE & SUSTAINABLE ENERGY REVIEWS

ISSN
1364-0321

EISSN
1879-0690

JCR ABBREVIATION
RENEW SUST ENERG REV

ISO ABBREVIATION
Renew. Sust. Energ. Rev.

Journal information

EDITION
Science Citation Index Expanded (SCIE)

CATEGORY
GREEN & SUSTAINABLE SCIENCE & TECHNOLOGY - SCIE
ENERGY & FUELS - SCIE

LANGUAGES	REGION	1ST ELECTRONIC JCR YEAR
English	USA	2001

Publisher information

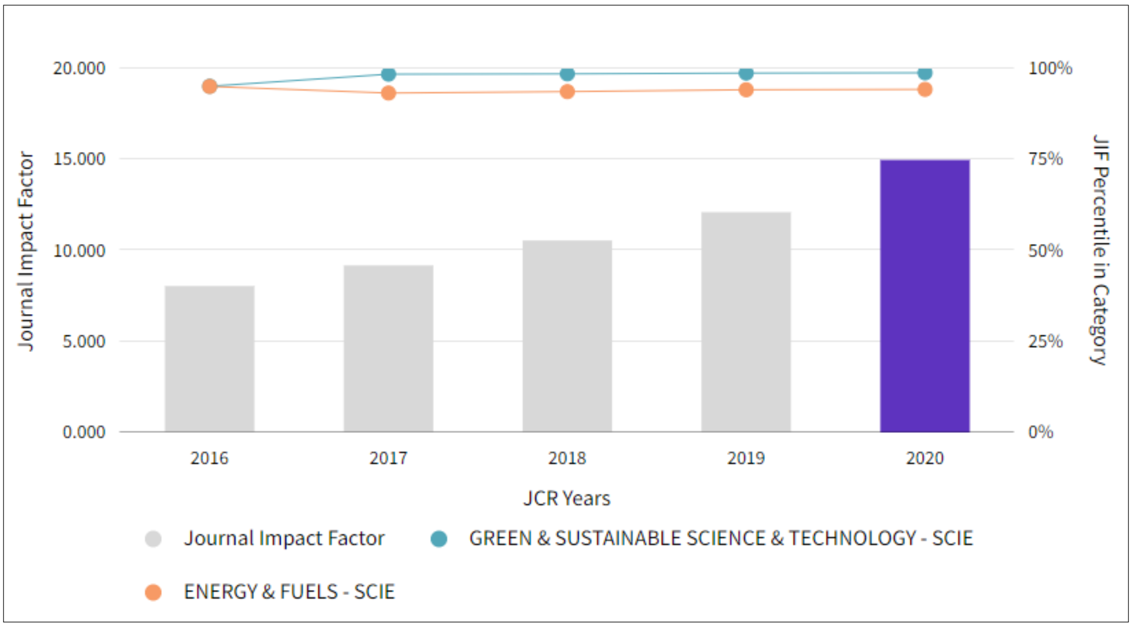
PUBLISHER	ADDRESS	PUBLICATION FREQUENCY
PERGAMON-ELSEVIER SCIENCE LTD	THE BOULEVARD, LANGFORD LANE, KIDLINGTON, OXFORD OX5 1GB, ENGLAND	21 issues/year

CATEGORY
ENERGY & FUELS
7/114

JCR YEAR	JIF RANK	JIF QUARTILE	JIF PERCENTILE
2020	7/114	Q1	94.30
2019	7/112	Q1	94.20
2018	7/103	Q1	93.69
2017	7/97	Q1	93.30
2016	5/92	Q1	95.11

CATEGORY
GREEN & SUSTAINABLE SCIENCE & TECHNOLOGY
1/44

JCR YEAR	JIF RANK	JIF QUARTILE	JIF PERCENTILE
2020	1/44	Q1	98.86
2019	1/41	Q1	98.78
2018	1/35	Q1	98.57
2017	1/33	Q1	98.48
2016	2/31	Q1	95.16



Anexo B. Renewable Energy

Fuente: Web of Science - Journal Citation Reports – Thomshon Reuters

RENEWABLE ENERGY

ISSN
0960-1481

EISSN
1879-0682

JCR ABBREVIATION
RENEW ENERG

ISO ABBREVIATION
Renew. Energy

Journal information

EDITION
Science Citation Index Expanded (SCIE)

CATEGORY
GREEN & SUSTAINABLE SCIENCE & TECHNOLOGY - SCIE
ENERGY & FUELS - SCIE

LANGUAGES	REGION	1ST ELECTRONIC JCR YEAR
English	ENGLAND	1997

Publisher information

PUBLISHER	ADDRESS	PUBLICATION FREQUENCY
PERGAMON-ELSEVIER SCIENCE LTD	THE BOULEVARD, LANGFORD LANE, KIDLINGTON, OXFORD OX5 1GB, ENGLAND	15 issues/year

EDITION
Science Citation Index Expanded (SCIE)

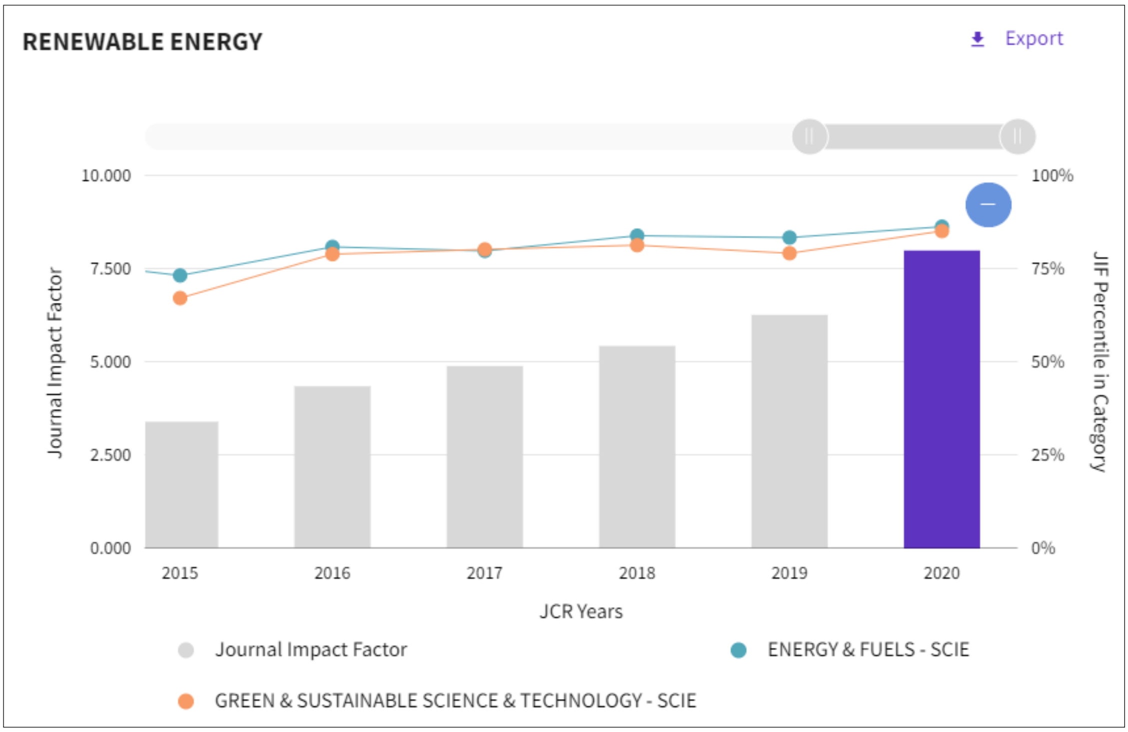
CATEGORY
GREEN & SUSTAINABLE SCIENCE & TECHNOLOGY
7/44

JCR YEAR	JIF RANK	JIF QUARTILE	JIF PERCENTILE
2020	7/44	Q1	85.23
2019	9/41	Q1	79.27
2018	7/35	Q1	81.43
2017	7/33	Q1	80.30
2016	7/31	Q1	79.03

EDITION
Science Citation Index Expanded (SCIE)

CATEGORY
ENERGY & FUELS
16/114

JCR YEAR	JIF RANK	JIF QUARTILE	JIF PERCENTILE
2020	16/114	Q1	86.40
2019	19/112	Q1	83.48
2018	17/103	Q1	83.98
2017	20/97	Q1	79.90
2016	18/92	Q1	80.98



Anexo C. Energies

Fuente: Web of Science - Journal Citation Reports – Thomshon Reuters

Energies

Open Access since 2008

ISSN
N/A

EISSN
1996-1073

JCR ABBREVIATION
ENERGIES

ISO ABBREVIATION
Energies

Journal information

EDITION
Science Citation Index Expanded (SCIE)

CATEGORY
ENERGY & FUELS - SCIE

LANGUAGES	REGION	1ST ELECTRONIC JCR YEAR
English	SWITZERLAND	2010

Publisher information

PUBLISHER	ADDRESS	PUBLICATION FREQUENCY
MDPI	ST ALBAN-ANLAGE 66, CH-4052 BASEL, SWITZERLAND	24 issues/year

EDITION

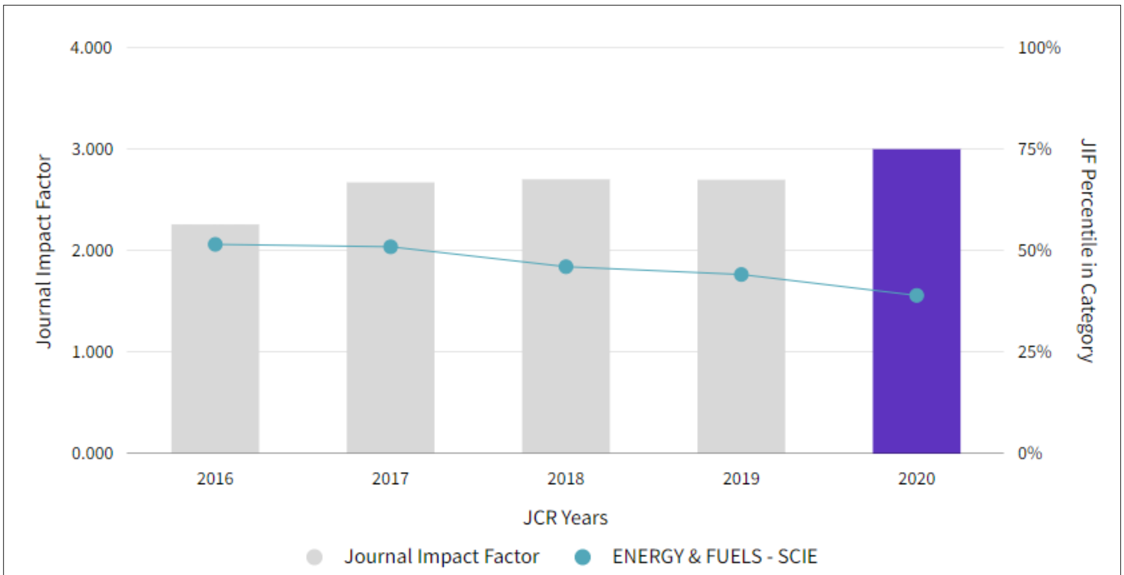
Science Citation Index Expanded (SCIE)

CATEGORY

ENERGY & FUELS

70/114

JCR YEAR	JIF RANK	JIF QUARTILE	JIF PERCENTILE
2020	70/114	Q3	39.04
2019	63/112	Q3	44.20
2018	56/103	Q3	46.12
2017	48/97	Q2	51.03
2016	45/92	Q2	51.63



Anexo D. Journal of Cleaner Production

Fuente: Web of Science - Journal Citation Reports – Thomshon Reuters

JOURNAL OF CLEANER PRODUCTION

ISSN
0959-6526

EISSN
1879-1786

JCR ABBREVIATION
J CLEAN PROD

ISO ABBREVIATION
J. Clean Prod.

Journal information

EDITION
Science Citation Index Expanded (SCIE)

CATEGORY
GREEN & SUSTAINABLE SCIENCE & TECHNOLOGY - SCIE
ENGINEERING, ENVIRONMENTAL - SCIE
ENVIRONMENTAL SCIENCES - SCIE

LANGUAGES	REGION	1ST ELECTRONIC JCR YEAR
English	USA	2004

Publisher information

PUBLISHER	ADDRESS	PUBLICATION FREQUENCY
ELSEVIER SCI LTD	THE BOULEVARD, LANGFORD LANE, KIDLINGTON, OXFORD OX5 1GB, OXON, ENGLAND	30 issues/year

EDITION
Science Citation Index Expanded (SCIE)

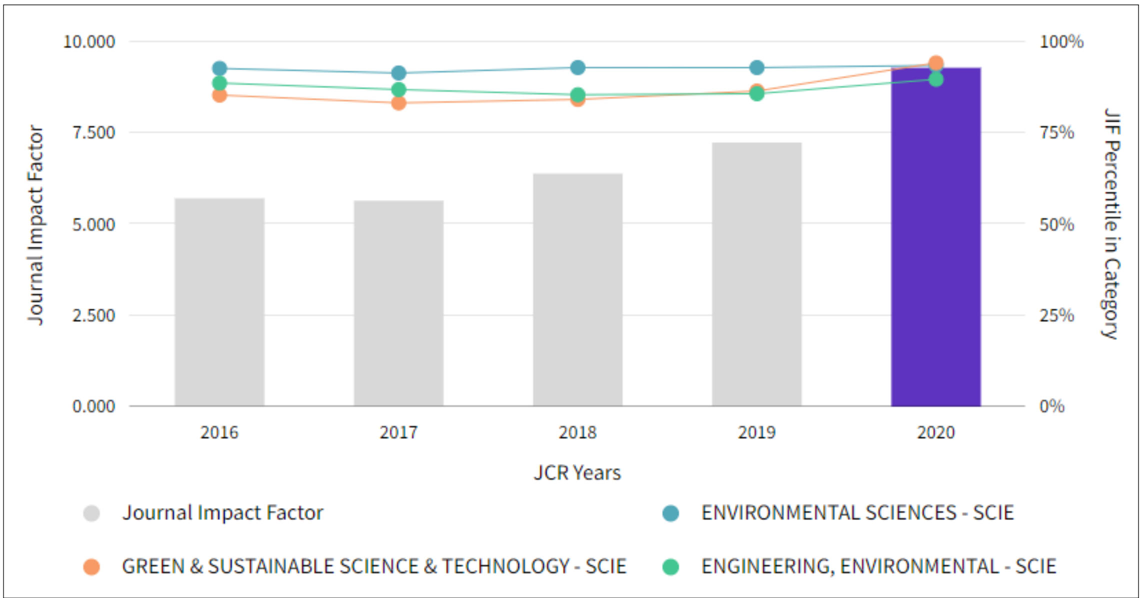
CATEGORY
GREEN & SUSTAINABLE SCIENCE & TECHNOLOGY
3/44

JCR YEAR	JIF RANK	JIF QUARTILE	JIF PERCENTILE
2020	3/44	Q1	94.32
2019	6/41	Q1	86.59
2018	6/35	Q1	84.29
2017	6/33	Q1	83.33
2016	5/31	Q1	85.48

EDITION
Science Citation Index Expanded (SCIE)

CATEGORY
ENGINEERING, ENVIRONMENTAL
6/54

JCR YEAR	JIF RANK	JIF QUARTILE	JIF PERCENTILE
2020	6/54	Q1	89.81
2019	8/53	Q1	85.85
2018	8/52	Q1	85.58
2017	7/50	Q1	87.00
2016	6/49	Q1	88.78



Anexo E. Justificación de contribución del doctorando

E.1. Virtual power plant models and electricity markets – A review

Mis contribuciones en este artículo son las siguientes:

1. Exhaustiva búsqueda de artículos en diferentes bases de datos y revistas que incluyan la interacción de modelos de plantas virtuales de energía y mercados eléctricos.
2. Selección de los artículos en función de diversos factores, como el tema y novedad, así como su publicación en revistas indexadas.
3. Clasificación de los artículos en función del objetivo del problema, métodos de resolución, tipos de mercados eléctricos y aplicación a casos reales de estudio.
4. Participación en el planteamiento y objetivo del artículo.
5. Participación en la redacción del artículo.
6. Participación en la discusión de los artículos revisados y obtención de las principales conclusiones e identificación de los desafíos pendientes en este campo de estudio.

E.2. A virtual power plant optimal dispatch model with large and small-scale distributed renewable generation

Mis contribuciones en este artículo son las siguientes:

1. Revisión completa del estado del arte del modelado matemático de la operación conjunta de grupos de producción y consumo de energía no interconectados físicamente.
2. Programación en el software Matlab® de todas las ecuaciones que simulan el modelo de planta virtual de energía propuesto.
3. Participación en el planteamiento y objetivo del artículo.
4. Participación en la definición de los casos de estudio para la validación del modelo, realización de los cálculos y análisis de resultados.
5. Participación en la redacción del artículo.
6. Participación en la obtención de las principales conclusiones.

E.3. Water-Energy Management for Demand Charges and Energy Cost Optimization of a Pumping Stations System under a Renewable Virtual Power Plant Model

Mis contribuciones en este artículo son las siguientes:

1. Revisión completa del estado del arte del modelado matemático de la operación conjunta de grupos de producción y consumo de energía no interconectados físicamente además de la gestión de agua en estaciones de bombeo.

2. Investigación de las técnicas de resolución y herramientas computacionales adecuadas al tipo de problema identificado.
3. Participación en la caracterización del problema matemático de despacho técnico-económico bajo enfoque de planta virtual de energía.
4. Programación en el software Lingo® de todas las ecuaciones que simulan el modelo de planta virtual de energía propuesto.
5. Participación en el planteamiento y objetivo del artículo.
6. Participación en la definición de los casos de estudio para la validación del modelo, realización de los cálculos y análisis de resultados.
7. Participación en la redacción del artículo.
8. Participación en la obtención de las principales conclusiones.

E.4. Optimal short-term water-energy dispatch for pumping stations with grid-connected photovoltaic self-generation

Mis contribuciones en este artículo son las siguientes:

1. Revisión completa del estado del arte del modelado matemático de la operación de sistemas de bombeo de agua.
2. Estudio del comportamiento de bombas centrífugas de velocidad fija y velocidad variable en paralelo.
3. Revisión de las técnicas de optimización más apropiadas para la resolución del tipo de problema identificado de forma eficiente.
4. Participación en la caracterización del problema matemático de despacho técnico-económico de un sistema de bombeo de agua con generación fotovoltaica de autoconsumo.
5. Programación en el software GAMS® de todas las ecuaciones que simulan el modelo de despacho técnico-económico a corto plazo propuesto.
6. Participación en el planteamiento y objetivo del artículo.
7. Participación en la definición de los casos de estudio para la validación del modelo, realización de los cálculos y análisis de resultados.
8. Participación en la redacción del artículo.
9. Participación en la obtención de las principales conclusiones.