COMILLAS
UNIVERSIDAD PONTIFICIA

ICAI

GRADO EN INGENIERÍA EN TECNOLOGÍAS DE INDUSTRIALES

DEGREE'S THESIS

# Modelling cooperative behavior among consumers in the investment decision-making in distributed generation: a theoretical approach

Author: Javier García Blanco

Supervisors: Salvador Doménech Martínez

José Villar Collado

Fco. Alberto Fernández Campos

Madrid

Declaro, bajo mi responsabilidad, que el Proyecto presentado con el título

Modelling cooperative behavior among consumers in the investment decision-making in distributed generation: a theoretical approach

en la ETS de Ingeniería - ICAI de la Universidad Pontificia Comillas en el

curso académico 2020/21 es de mi autoría, original e inédito y

no ha sido presentado con anterioridad a otros efectos.

El Proyecto no es plagio de otro, ni total ni parcialmente y la información que ha sido

tomada de otros documentos está debidamente referenciada.

Fdo.: Javier García Blanco Fecha: 06/07/2021

Autorizada la entrega del proyecto

EL DIRECTOR DEL PROYECTO

Fdo.: Fco. Alberto Campos Fernández Fecha: 06/07/2021

José Villar Collado

Salvador Doménech Martínez

VILLAR COLLADO JOSE - 00818527A
Digitally signed by VILLAR COLLADO JOSE - 00818527A
Date: 2021.07.06 07:41:49 +01'00'

CAMPOS FERNANDEZ FRANCISCO ALBERTO - 11836144E
Firmado digitalmente por CAMPOS FERNANDEZ FRANCISCO ALBERTO - 11836144E
Fecha: 2021.07.06 09:49:23 +02'00'

**AUTORIZACIÓN PARA LA DIGITALIZACIÓN, DEPÓSITO Y DIVULGACIÓN EN RED DE PROYECTOS FIN DE GRADO, FIN DE MÁSTER, TESINAS O MEMORIAS DE BACHILLERATO**

***1º. Declaración de la autoría y acreditación de la misma.***

El autor D. Javier García Blanco DECLARA ser el titular de los derechos de propiedad intelectual de la obra: "Modelling cooperative behavior among consumers in the investment decision-making in distributed generation: a theoretical approach", que ésta es una obra original, y que ostenta la condición de autor en el sentido que otorga la Ley de Propiedad Intelectual.

***2º. Objeto y fines de la cesión.***

Con el fin de dar la máxima difusión a la obra citada a través del Repositorio institucional de la Universidad, el autor **CEDE** a la Universidad Pontificia Comillas, de forma gratuita y no exclusiva, por el máximo plazo legal y con ámbito universal, los derechos de digitalización, de archivo, de reproducción, de distribución y de comunicación pública, incluido el derecho de puesta a disposición electrónica, tal y como se describen en la Ley de Propiedad Intelectual. El derecho de transformación se cede a los únicos efectos de lo dispuesto en la letra a) del apartado siguiente.

***3º. Condiciones de la cesión y acceso***

Sin perjuicio de la titularidad de la obra, que sigue correspondiendo a su autor, la cesión de derechos contemplada en esta licencia habilita para:

a) Transformarla con el fin de adaptarla a cualquier tecnología que permita incorporarla a internet y hacerla accesible; incorporar metadatos para realizar el registro de la obra e incorporar "marcas de agua" o cualquier otro sistema de seguridad o de protección.
b) Reproducirla en un soporte digital para su incorporación a una base de datos electrónica, incluyendo el derecho de reproducir y almacenar la obra en servidores, a los efectos de garantizar su seguridad, conservación y preservar el formato.
c) Comunicarla, por defecto, a través de un archivo institucional abierto, accesible de modo libre y gratuito a través de internet.
d) Cualquier otra forma de acceso (restringido, embargado, cerrado) deberá solicitarse expresamente y obedecer a causas justificadas.
e) Asignar por defecto a estos trabajos una licencia Creative Commons.
f) Asignar por defecto a estos trabajos un HANDLE (URL *persistente)*.

***4º. Derechos del autor.***

El autor, en tanto que titular de una obra tiene derecho a:

a) Que la Universidad identifique claramente su nombre como autor de la misma
b) Comunicar y dar publicidad a la obra en la versión que ceda y en otras posteriores a través de cualquier medio.
c) Solicitar la retirada de la obra del repositorio por causa justificada.
d) Recibir notificación fehaciente de cualquier reclamación que puedan formular terceras personas en relación con la obra y, en particular, de reclamaciones relativas a los derechos de propiedad intelectual sobre ella.

***5º. Deberes del autor.***

El autor se compromete a:

a) Garantizar que el compromiso que adquiere mediante el presente escrito no infringe ningún derecho de terceros, ya sean de propiedad industrial, intelectual o cualquier otro.
b) Garantizar que el contenido de las obras no atenta contra los derechos al honor, a la intimidad y a la imagen de terceros.
c) Asumir toda reclamación o responsabilidad, incluyendo las indemnizaciones por daños, que pudieran ejercitarse contra la Universidad por terceros que vieran infringidos sus derechos e intereses a causa de la cesión.
d) Asumir la responsabilidad en el caso de que las instituciones fueran condenadas por infracción

de derechos derivada de las obras objeto de la cesión.

***6º. Fines y funcionamiento del Repositorio Institucional.***

La obra se pondrá a disposición de los usuarios para que hagan de ella un uso justo y respetuoso con los derechos del autor, según lo permitido por la legislación aplicable, y con fines de estudio, investigación, o cualquier otro fin lícito. Con dicha finalidad, la Universidad asume los siguientes deberes y se reserva las siguientes facultades:

- La Universidad informará a los usuarios del archivo sobre los usos permitidos, y no garantiza ni asume responsabilidad alguna por otras formas en que los usuarios hagan un uso posterior de las obras no conforme con la legislación vigente. El uso posterior, más allá de la copia privada, requerirá que se cite la fuente y se reconozca la autoría, que no se obtenga beneficio comercial, y que no se realicen obras derivadas.
- La Universidad no revisará el contenido de las obras, que en todo caso permanecerá bajo la responsabilidad exclusive del autor y no estará obligada a ejercitar acciones legales en nombre del autor en el supuesto de infracciones a derechos de propiedad intelectual derivados del depósito y archivo de las obras. El autor renuncia a cualquier reclamación frente a la Universidad por las formas no ajustadas a la legislación vigente en que los usuarios hagan uso de las obras.
- La Universidad adoptará las medidas necesarias para la preservación de la obra en un futuro.
- La Universidad se reserva la facultad de retirar la obra, previa notificación al autor, en supuestos suficientemente justificados, o en caso de reclamaciones de terceros.

Madrid, a 6 de Julio de 2021

**ACEPTA**

Fdo. Javier García Blanco

Motivos para solicitar el acceso restringido, cerrado o embargado del trabajo en el Repositorio Institucional:

GRADO EN INGENIERÍA EN TECNOLOGÍAS DE INDUSTRIALES

DEGREE'S THESIS

# Modelling cooperative behavior among consumers in the investment decision-making in distributed generation: a theoretical approach

Author: Javier García Blanco

Supervisors: Salvador Doménech Martínez

José Villar Collado

Fco. Alberto Fernández Campos

Madrid

# Agradecimientos

Me gustaría agradecer el apoyo recibido de mi familia, amigos y novia durante este proyecto. No quiero olvidarme de Salvador, Alberto y José por todos sus consejos, su guía durante el proyecto y su esfuerzo.

# MODELADO DEL COMPORTAMIENTO DE UN AGREGADOR DE DEMANDA EN LA TOMA DE DECISIONES DE INVERSIÓN EN GENERACIÓN DISTRIBUIDA MEDIANTE TEORÍA DE JUEGOS COOPERATIVOS: UN ENFOQUE TEÓRICO

**Autor: García Blanco, Javier.**

Directores: Doménech Martínez, Salvador.
Villar Collado, José.
Fernández Campos, Fco. Alberto.

Entidad Colaboradora: ICAI – Universidad Pontificia Comillas

## RESUMEN DEL PROYECTO

Hay distintas propuestas para modelar el poder de mercado de clientes y generadores de energía, como el Equilibrio de Stackelberg, el Equilibrio de Cournot o el Equilibrio de Variación Conjetural. Este trabajo aporta un nuevo algoritmo para computar las conjeturas de la demanda de manera endógena. Estas conjeturas representan la variación en el precio de la electricidad en caso de una variación en la demanda de un cliente.

**Palabras clave**: Agregador, Conjeturas, Poder de mercado, Sistemas eléctricos

### 1. Introducción

Las fuentes de energía renovable (FER) tienen una penetración cada vez mayor en las redes europeas, tal y como se puede observar en el Gráfico 1. Esto se debe principalmente a los objetivos de neutralidad climática de la UE (Comission, 2021) y a la reducción del coste en las tecnologías de FER (IRENA, 2020).

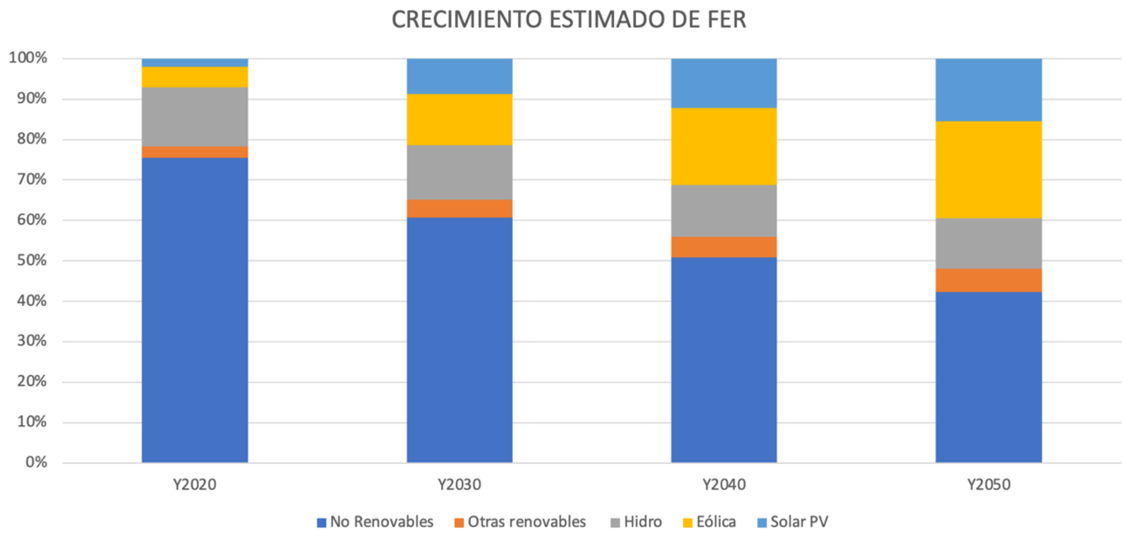



Gráfico 1. Crecimiento estimado de FER (IRENA, 2020)

En el futuro, los servicios de respuesta de la demanda serán clave para integrar las FER, adaptando la demanda a la generación, y no al revés como se hace en el presente. Se necesitarán más modelos de colaboración para gestionar la respuesta de la demanda de forma eficiente. Uno de estos modelos de colaboración es la agregación, proceso en el que grupos de consumidores pueden cooperar para aprovechar las economías de escala, por ejemplo, instalando paneles solares y baterías para una comunidad residencial, en lugar de que cada consumidor tenga su propio equipo (de Almansa, Campos, Doménech, & Villar, 2019).

Estos grupos de consumidores podrían también cooperar con otros agregadores para formar un agregador mayor que actúe como una sola entidad. Este agregador podría ser suficientemente relevante como para ejercer poder de mercado y manipular los precios del mercado. Entender la influencia de los agregadores en el mercado cumple con los Objetivos de Desarrollo Sostenible (ODS) definidos por las Naciones Unidas (United Nations, 2021). En particular, este trabajo está relacionado con los ODS de: "Energía asequible y no contaminante", "Industria, Innovación e Infraestructura", "Ciudades y Comunidades Sostenibles" y "Acción por el clima".

## 2. Definición del proyecto

El principal objetivo de este trabajo es modelar el poder de mercado que pueda ejercer un agregador, utilizando las conjeturas, y realizando una propuesta implementable en el modelo de la expansión de la generación CEVESA. Esto se llevará a cabo siguiendo los pasos que se presentan a continuación:

1. Analizar la literatura relativa al modelado del poder de mercado de los agregadores, con especial énfasis en los enfoques de variación conjetural.

2. Modelar las relaciones de mercado entre los distintos participantes, i.e., consumidores, prosumidores (consumidores con FERs instaladas, que pueden vender su exceso de energía a la red) y compañías de generación.

3. Identificar los parámetros necesarios para obtener las conjeturas y ejecutar CEVESA para probar preliminarmente el algoritmo.

4. Sacar conclusiones y definir el camino a seguir para obtener los resultados finales.

## 3. Descripción del algoritmo

El poder de mercado de un agregador se ha modelado utilizando las conjeturas, que representan el cambio en el precio del mercado si un consumidor/productor cambia su demanda/producción. Las conjeturas se calcularán endógenamente utilizando las siguientes expresiones:

Ec. 1 $$\theta_{i,n}^{D} = \frac{-1}{\sum_{j\neq i} \alpha_{j,n}^{D} + \sum_{e} \alpha_{e,n}^{P}}$$

Ec. 2 $$\theta_{e,n}^{P} = \frac{-1}{\sum_i \alpha_{i,n}^{D} + \sum_{j \neq e} \alpha_{j,n}^{P}}$$

Donde $\alpha_{i,n}^{D}$ y $\alpha_{e,n}^{P}$ son las pendientes de la demanda y de la generación respectivamente. Se propone un algoritmo iterativo para calcular las pendientes de la demanda y la producción.

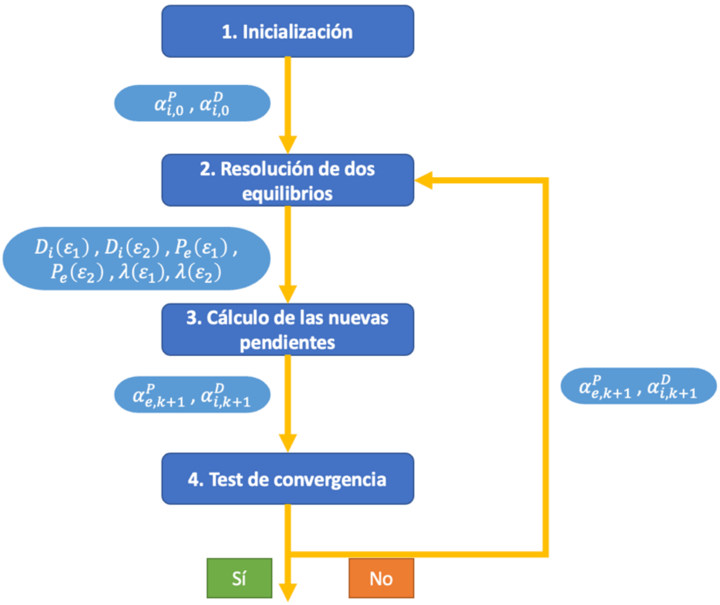



Gráfico 2. Esquema del algoritmo propuesto

En el primer paso del algoritmo propuesto se inicializan las pendientes de la demanda y la producción a valores cercanos al valor esperado, i.e., entre 0 y 5 €/(GWh·MWh). En el segundo paso, se resuelven los equilibrios de dos escenarios infinitesimalmente cercanos ($\varepsilon_1$ y $\varepsilon_2$) para poder aproximar las pendientes de la demanda y la producción. En este trabajo se hicieron cambios en la producción renovable para obtener estos dos escenarios. Del segundo paso se obtendrán: la demanda de cada cliente, la producción de cada generador y el precio marginal. En el tercer paso, se calculan las pendientes, utilizando las salidas del paso anterior, y aproximando las pendientes con la aproximación de primer orden de Taylor. Finalmente, se comprueba la convergencia restando las pendientes de la anterior iteración $\alpha_{e,k}^{P}$ y $\alpha_{i,k}^{D}$ de las pendientes $\alpha_{e,k+1}^{P}$ y $\alpha_{i,k+1}^{D}$ respectivamente. Si el valor absoluto de la resta es menor que la tolerancia fijada, las pendientes habrán convergido, y por tanto las conjeturas podrán ser calculadas. Si no converge, las pendientes obtenidas en esta iteración se introducen en el segundo paso del algoritmo y se vuelve a iterar hasta que converja.

## 4. Resultados

Se ha desarrollado un prototipo del algoritmo propuesto para obtener las conjeturas. Este prototipo se desarrolló utilizando CEVESA (desarrollado por el IIT) para resolver los diferentes equilibrios planteados en el algoritmo. No obstante, quedan pendientes tanto el cálculo automático de ambos equilibrios, como la prueba y depuración sistemática del algoritmo. A continuación, se presentan las dos principales hipótesis que se tomaron y los errores que proporcionaron:

1. Computar las conjeturas basadas en los periodos de día y de noche: se tomó esta hipótesis porque las decisiones que pueden tomar los consumidores en CEVESA son instalar baterías y paneles solares. Por lo tanto, se esperaban valores similares para las conjeturas en cada bloque de horas. El principal problema de esta hipótesis era que la potencia del mercado cambia cada hora, no dependiendo sólo de los periodos diurnos y nocturnos, por lo que el valor de las conjeturas en cada bloque de horas no era similar.

2. Considerar incertidumbre en la producción renovable: eran necesarios dos escenarios infinitesimalmente cercanos para aproximar las pendientes, y el enfoque seguido fue calcular el equilibrio para los escenarios de renovable de dos semanas consecutivas en CEVESA. El principal inconveniente de este enfoque es que la variación entre ambos escenarios podría no ser infinitesimal y, por tanto, arrojar resultados erróneos.

## 5. Conclusiones

Este trabajo propone un método para modelar el poder de mercado de los consumidores a través de las conjeturas de demanda. El algoritmo propuesto permite calcular las conjeturas de demanda y oferta de forma endógena en un proceso flexible.

El trabajo futuro debería estar enfocado en probar este trabajo teórico con diferentes casos de estudio, teniendo en cuenta que:

1. Las conjeturas de cada cliente serán calculadas para cada hora, adaptando CEVESA para usarlo para resolver los dos equilibrios presentes en el algoritmo.

2. Se comprobará la existencia de bloques de horas en los que la conjetura tome valores similares para poder buscar algoritmos más simples.

3. Se buscarán otras fuentes de incertidumbre para plantear la robustez.

## 6. Referencias

Comission. (2021). *National Energy and Climate Plans.*

de Almansa, M., Campos, F. A., Doménech, S., & Villar, J. (2019). Residential DER Cooperative Investments. *2019 16th International Conference on the European Energy Market (EEM).*

IRENA. (2020). *Global Renewable Outlook.*

IRENA. (2020). *Renewable Power Generation Costs in 2019.*

United Nations. (2021). *SDGS*. Obtenido de https://sdgs.un.org/es/goals

# MODELLING COOPERATIVE BEHAVIOR AMONG CONSUMERS IN THE INVESTMEN DECISION-MAKING IN DISTRIBUTED GENERATION: A THEORETICAL APPROACH

**Author: García Blanco, Javier**
Supervisors: Doménech Martínez, Salvador.
Villar Collado, José.
Fernández Campos, Fco. Alberto.
Collaborating Entity: ICAI – Universidad Pontificia Comillas

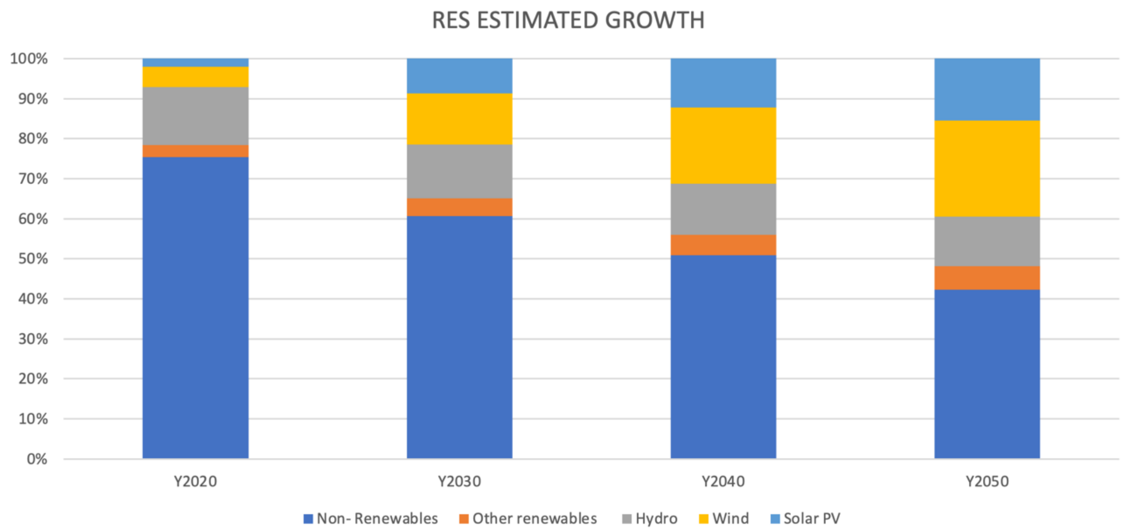
## ABSTRACT

There are different proposals to model the market power of customers and power generators, such as Stackelberg Equilibria, Cournot Equilibria or Conjectural Variational Equilibria. This paper provides a new algorithm to compute demand conjectures endogenously. These conjectures represent the variation in the price of electricity in case of a variation in a customer's demand.

**Keywords**: Aggregator, Conjectures, Market power, Electric systems

### 1. Introduction

Renewable energy sources (RES) have an increasing penetration (as can be observed in Graph 1) in the European grids, primary because the EU's objectives for climate neutrality (Comission, 2021) and the reduction in the price of RES technologies (IRENA, 2020).




Graph 1. European estimated growth of RES (IRENA, 2020)

In the future, demand response services will be key to integrate the RES, by adapting the demand to the generation, and not the other way around as it is done in the present. More collaborative models will be needed to handle demand response efficiently. One of these collaborative models is aggregation, in which groups of consumers can cooperate to take advantage of economies of scale, e.g., installing solar panels and batteries for a residential community, instead of each consumer its own equipment (de Almansa, Campos, Doménech, & Villar, 2019).

These consumer groups could also cooperate with other aggregators to form a bigger aggregator that acts as a single entity. This aggregator could be relevant enough to exercise market power and manipulate the market prices. Understanding the influence of aggregators in the market complies with the Sustainable Development Goals (SDG) defined by the United Nations (United Nations, 2021). In particular, this work is related to the "Affordable and Clean Energy", "Climate Action", "Sustainable Cities and Communities" and "Industry, Innovation and Infrastructure" SDGs.

## 2. Project definition

The main aim of this project is to model the market power of aggregators, using conjectures, and making a proposal implantable in CEVESA, an expansion of the generation model. This will be done by following the next steps:

1. Analyze the literature regarding the modelling of market power of aggregators, with special emphasis on conjectural variation approaches.
2. Model the market relations between the different players, i.e., consumers, prosumers (consumers with RES installed, that can sell their surplus of energy) and generation companies.
3. Identify the parameters needed to obtain the conjectures and execute CEVESA for preliminary testing the algorithm.
4. Drawing conclusions and defining the path to follow in order to obtain final results.

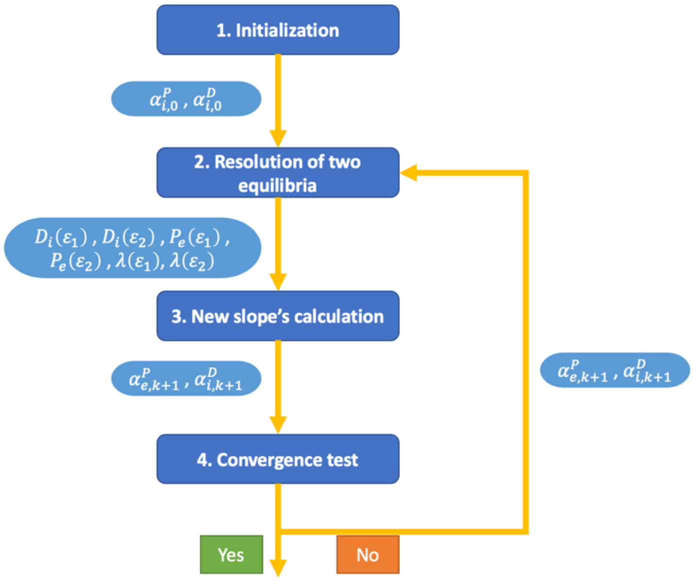
## 3. Description of the algorithm

The market power of an aggregator has been modelled using conjectures, which represent the change in the market price if a consumer/producer changes its demand/production. The conjectures will be endogenously calculated using the following expressions:

Eq. 1 $$\theta_{i,n}^{D} = \frac{-1}{\sum_{j\neq i}\alpha_{j,n}^{D} + \sum_{e}\alpha_{e,n}^{P}}$$

Eq. 2 $$\theta_{e,n}^{P} = \frac{-1}{\sum_{i}\alpha_{i,n}^{D} + \sum_{j\neq e}\alpha_{j,n}^{P}}$$

Where $\alpha_{i,n}^{D}$ and $\alpha_{e,n}^{P}$ are the demand and production slopes respectively. An iterative algorithm is proposed to compute the demand and production slopes.




Graph 2. Proposed algorithm scheme

In the first step of the algorithm the supply and demand slopes are initialized to values that are proximate to the expected values, i.e., between 0 to 5 €/(GWh·MWh). In the second step, the equilibria of two infinitesimally proximate scenarios ($\varepsilon_1$ and $\varepsilon_2$) are solved to approximate the demand and supply slopes. In this work, these two scenarios were obtained by changing the renewable production. From the second step it is obtained: the demand of each client, the production of each generator and the marginal price. In the third step, the slopes are calculated, using the output of the previous step, by approximating them with a first-order Taylor approximation. Finally, the convergence is tested by subtracting the slopes of the previous iteration $\alpha_{e,k}^{P}$ and $\alpha_{i,k}^{D}$ from the slopes $\alpha_{e,k+1}^{P}$ and $\alpha_{i,k+1}^{D}$ respectively. If the absolute value of the subtraction is less than the fixed tolerance, the slopes converge, and therefore the conjectures can be computed. If it does not converge, the obtained slopes in the last iteration are introduced in the second step, and another iteration is carried out until it converges.

## 4. Results

A prototype of the proposed algorithm was developed to obtain the conjectures. This prototype was developed using the tool CEVESA for solving the different equilibria set out in the algorithm, although an automatic computation of both equilibria and systematic test and debug of the algorithm are still pending. The two main hypothesis that were taken and provided errors are presented below:

1. Computing the conjectures based on the day and night periods: this hypothesis was taken because the decisions that consumers can make in CEVESA are to install batteries and solar panels. Therefore, similar values were expected for the conjectures on each block of hours. The main problem with this assumption was that the market power changes every hour, not depending only on the day and night periods, so the value of the conjectures in each block of hours was not similar.

2. Considering uncertainty in renewable energy production: two infinitesimal close scenarios were needed to approximate the slopes, and the followed approach was to compute the renewable scenario of two different consecutive weeks in CEVESA. The main drawback of this approach is that the variation between both scenarios could be not infinitesimal, and hence give erroneous results.

## 5. Conclusions

This project proposes a method to model the market power of consumers via the demand conjectures. The proposed algorithm allows to calculate the demand and supply conjectures endogenously in a flexible process.

The future work should be focused in testing this theoretical work with different cases studies considering that:

1. The conjectures of each client will be computed hourly, adapting CEVESA to use it to solve the two equilibria.

2. The existence of blocks of hours in which the conjecture takes similar values will be checked to search for simpler algorithms.

3. Robustness against other sources of uncertainty will be checked.

## 6. References

Comission. (2021). *National Energy and Climate Plans.*

de Almansa, M., Campos, F. A., Doménech, S., & Villar, J. (2019). Residential DER Cooperative Investments. *2019 16th International Conference on the European Energy Market (EEM)*.

IRENA. (2020). *Global Renewable Outlook.*

IRENA. (2020). *Renewable Power Generation Costs in 2019.*

United Nations. (2021). *SDGS*. Retrieved from https://sdgs.un.org/es/goals

# *Memory's index*

# *Tables Index*

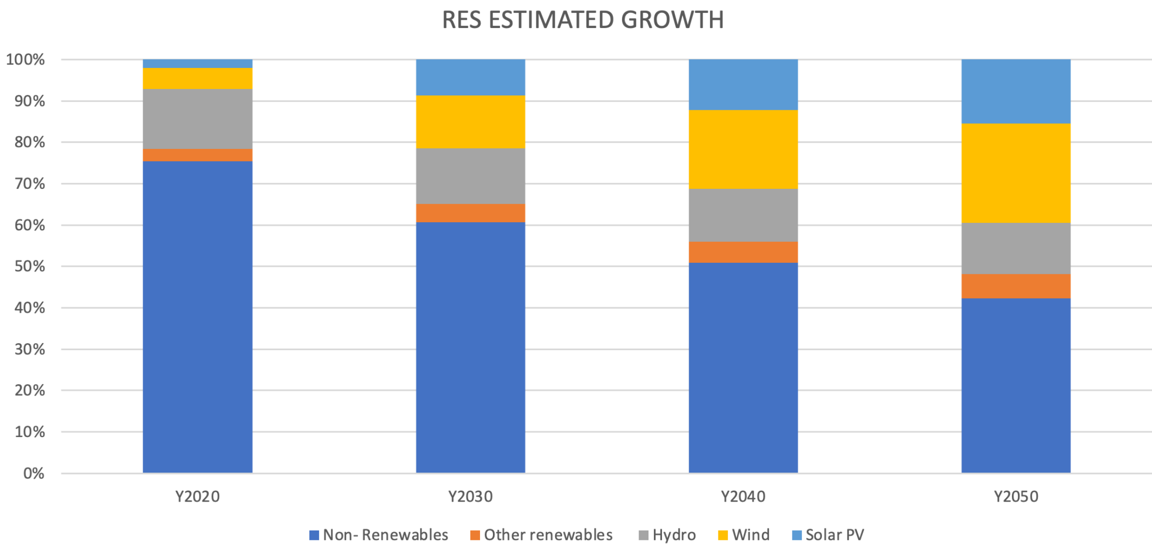


# *Graphs Index*

# Chapter 1. INTRODUCTION

## *1.1 CONTEXT*

The different renewable energy sources (RES) have an increasing penetration in the European and Spanish grids due to the EU's objectives for climate neutrality (Comission, 2021), and the fact that RES technologies are becoming more affordable (IRENA, 2020).




Graph 1. Estimated Growth of RES in Europe (IRENA, 2020)

A prosumer is a grid user who can produce electricity for self-consumption and can inject and sell its surplus to the grid. Prosumers can aggregate to make collective decisions, being able to perform demand response to reduce their costs (Fang, et al., 2020). The penetration of prosumers in the grid is also crucial for RES integration by providing local and global flexibility to the system to help to solve balancing issues and grid constraints. Prosumers can provide this flexibility by managing their consumption, in some cases, with storage facilities. Depending on the regulatory framework, this flexibility could be provided in commercial energy markets such as intraday markets or regulated reserve and grid constraint markets managed by systems operators. In (BOE, 2020), the Spanish government is trying to include these prosumers in the market, e.g., by reducing the minimum power needed to participate in the wholesale electricity market, allowing more participants to offer their services.

The article (Castagneto Gissey, Subkhankulova, Dodds, & Barret, 2019) highlights the importance of distributed resources for the power system. It studies the effect in the system of an aggregator with energy storage resources. It states that if the aggregated participants were coordinated with the aim of generating at peak periods and consuming at valley periods, they would reduce their costs and would provide flexibility to the system. In addition, this leads to reduced electricity prices for the rest of consumers in the system. According to (Kirschen, 2003), small consumers will only modify their demand if they can benefit from it, and this will only occur if they are exposed to variable electricity prices and can participate in flexibility markets. Dynamic tariffs generally offer this possibility, being the most common implicit real time pricing and time of use. Big prosumers that are allowed to participate in the wholesale market would be also likely to change their demand or generation in order to benefit from price-fluctuations. Since the electricity price depends on both generation and load, these prosumers would be able to modify the price by curtailing or rising their load and by withholding or producing more energy.

## *1.2 MOTIVATION*

One of the strategic objectives of many companies and industries for the following years is to become emissions neutral. To achieve that objective, power-intensive industries are installing renewable energy plants in their facilities or signing power purchase agreements with renewable generation plants. This will change the traditional consumer position, as they will become not only consumers but also generators. According to (Ramyar, Liu, & Chen, 2020) the percentage of prosumers is expected to increase in the future, and in some cases these prosumers or their aggregations can be large enough to influence the price. The study of how large prosumers may behave is very relevant, especially to understand how the markets may behave in the future.

With that purpose of understanding the behavior of prosumers, (de Almansa, Campos, Doménech, & Villar, 2019) proposes an energy-sharing model in a residential community. Said work uses cooperative game theory to study the efficiency of cooperation compared to the individual non-cooperative decisions of its members. This work is a continuation of that work, with focus on market power. In particular, the aim of this thesis is to theoretically model strategic prosumers and how they interact with other market-players in an electricity market, assuming that they have enough market-power to influence the market price.

## *1.3 ALIGNMENT WITH THE SUSTAINABLE DEVELOPMENT GOALS:*

The United Nations (UN) adopted the Sustainable Development Goals (SDG) in 2015 (United Nations, 2021). The aim of the SDGs is to guide the nations to achieve peace and prosperity for both the people and the Earth, through 17 objectives:


Graph 2. Sustainable Development Goals (UNESCO, 2021)

This work contributes in a tangent way to the SDGs 7, 9, 11 and 13:

1. The "Affordable and Clean Energy" SDG is related to this work as the understanding of the market power of an aggregator is an important step to prevent anti-competitive practices which could influence the price of energy, making it less affordable.

2. This work is also related to the "Climate Action" SDG because aggregators will be key to integrate RES via demand response services. Hence modeling the aggregators market power allows to better organize the deployment of RES, contributing to this SDG.

3. The "Sustainable Cities and Communities" SDG is also related to this work. Aggregators can be composed of residential communities, understanding how these will behave is relevant to design the future and adapt the current cities and communities.

4. Finally, the "Industry, Innovation and Infrastructure" is related to this work because some of the players that are more prone to install RES are industry players. In some industries (e.g., metalworking) electricity costs are a high percentage of the costs of operation (Moya & Boulamanti, 2016), so these players have a bigger motivation to install RES. Hence, understanding how to model their market-power will also help to design and adapt these industries.

# Chapter 2. STATE OF THE ART

Several papers have tackled demand aggregation and how big prosumers interact with the wholesale market. Most papers assume that the prosumers cannot influence the market price (so they are price-takers).

For instance, (Martin Zepter, Lüth, Crespo del Granado, & Egging, 2018) studies how prosumers take part in peer-to-peer trading (P2P) and how being able to buy and sell energy in the wholesale market affects their electricity bill, assuming that the prosumers do not have market power. It concludes that prosumers are key to integrate distributed energy resources and to lower the electricity price. It leaves as future work the study of how price-making prosumers would affect the model. (Tushar, Yuen, & Nahid, 2020) proposes a cooperative Stackelberg game to address the interaction between a centralized agent (managing a centralize power system, CPS) and prosumers, being the objective of both types of players to shave demand peaks. This work presents a methodology to reduce the demand peak as one of the possible approaches for demand response. However, the thesis does not study how these interactions affect the price.

(Saez-Gallego & Morales, 2017) analyses how a broadcasted price from the CPS can affect a prosumer's consumption or production. It considers price responsive loads and different risk thresholds. It analyses historical data from a power system with three different risk models, providing an analytical solution to the retailer's bidding problem. This work offers another way to model the interaction of prosumers with the market, but it does not model the market power of the prosumer. (Calvillo, Sanchez-Miralles, Villar, & Martin, 2016) analyses the impact on consumers' price of an aggregator that plans its bids using residual demand curves. It concludes that the economic benefits increase up to 50 % when installing distributed energy resources systems and managing load.

There are different approaches to analyse the effect prosumers have on the market. The literature agrees that the main common outcomes that these aggregations have on the wholesale market are:

- The decrease in prosumers' costs.
- The integration of renewable sources.
- The increase of the market power that prosumers can exercise.

## *2.1 THE DECREASE IN PROSUMERS' COSTS*

The main driver for consumers to install renewable energy facilities and become prosumers is to reduce their electricity bill. This objective is accomplished on the long run by consuming less energy from the grid and even selling their surplus if there is any.

(Kirschen, 2003) studies the relationships between consumers and prosumers with an electricity market, addressing the economic characteristics of the electricity demand of the consumers. It highlights that consumers that face a large electricity bill, compared to their total costs, are more likely to change their demand curve to benefit from lower electricity prices. Moreover, in order to offer demand services, prosumers need to purchase and install metering and control systems. The purchase of these metering systems is only profitable if the prosumer trades a large amount of energy. The paper concludes that demand-side participation in the system economically benefit the consumers that take part by curtailing their costs.

(Lu, Lü, & Leng, 2019) presents a two-leader and two-follower Nash-Stackelberg game, modelling the transaction mechanism among retailers and consumers who participate in demand response. It shows that by participating in demand response, consumers are able to reduce their expenses, and the retailers are able to increase their revenue. (Li, Wan, Yuan, & Song, 2019) poses the scenario of a power system that is able to efficiently integrate distributed energy resources. It defines a strategy for demand response considering load fluctuations and grid price waving. The retailer, which set the price, buys energy from the grid and from prosumers, and then sells it to end-users. Prosumers, consumers and energy storage systems are able to provide demand response services in this framework. The paper also provides a case study that shows that when participating coordinated by the retailer in demand response, end-users are able to reduce their costs. (Brunix, Pandzic, Le Cadre, & Delarue, 2020) analyses the relationships between an aggregator of the demand and demand response providers, and between the aggregator and the day-ahead market. It models the first as a Stackelberg game where the aggregator is the leader, and it analyses the latter as a bilevel optimization problem. The paper finally applies the model to a case-study, concluding that consumers that accept to be controlled by the aggregator manage to reduce their energy bill 0.7 €/MWh on average.

## 2.2 *THE INTEGRATION OF RENEWABLE SOURCES*

Renewable sources have the inconvenience of uncertainty, as the renewable production depends on meteorological variables. The more penetration of renewable resources, the more uncertainty is introduced into the system. Traditionally the regulation has been done from the production side, but renewable sources do not always allow the regulation. Therefore, in a future with more renewable generation, it will become crucial for the demand to take part in regulation, i.e., demand response services.

Prosumers will be key in providing demand response services and will do it more efficiently by aggregating. According to (Spodniak, Ollikka, & Honkapuro, 2021), the increasing penetration of RES will cause larger deviations between the forecasted power supply and the actual power generation, which means that balancing services and the intraday markets will become more important. (Niu, Tian, & Yue, 2020) also remarks the importance of flexibility measures for including a higher percentage of renewable energy in the electricity mix. It focuses on a distributed power system performing demand response to provide flexibility to the market. (Braun, 2009) analyses a real case of a Virtual Power Plant (VPP). It studies how the VPP is able to aggregate the distributed generation resources creating a single operating profile. This allows a better management of the intermittent resources, integrating them efficiently into the electricity grid. According to (Mashhour & Moghaddas-Tafreshi, 2011) distributed resources are not visible to the system due to the "fit and forget" approach when it comes to their installation. A VPP is analysed to aggregate distributed energy resources. The case-study shows that via a VPP distributed energy resources are able to provide system supports and security activities.

## *2.3 INCREASE OF THE MARKET POWER THAT PROSUMERS CAN EXERCISE*

In the Spanish electricity market, there are some generator players that can influence the price by curtailing their production to obtain bigger benefits. In the demand side individual consumers do not have the size to influence the price. However, aggregators with a considerable size compared to the wholesale demand could be able to manipulate the market prices by reducing or increasing their demand. If the aggregator does not have a preference to consume at any hour, or the cost of electricity is very relevant to its activities, the fact of reducing the price would increase the utility of its demand.

(Sharma, Bhakar, & Tiwari, 2014) considers windmill aggregators. These aggregators are considered strategic power producers in the day-ahead market. It uses Cournot game theory to represent the strategic behaviour of the aggregator and it assumes that the aggregator can withhold energy to modify the market's price. It compares a base case where the aggregator offers the forecasted generation with a case where three strategic aggregators offer generation to maximize their profits. The results show that by offering the optimal amount of energy strategic aggregators are able to increase the utility of their production, rising their profits by 5 to 10 per cent. (Ruhi, Dvijotham, Chen, & Wierman, 2018) studies how much can profit a strategic aggregator from reducing its generation offers and its demand response to the wholesale market. It states that, by offering strategic energy production or demand, aggregators are able to significantly reduce their costs when consuming energy, and increase their benefits when selling energy, increasing the utility of both their generation and demand. It concludes that the larger the aggregator is, the higher the profit it obtains. The profit for curtailing also increases with its generation capacity, meaning that larger aggregators have larger incentives to manipulate the price. Similarly, (Ramyar, Liu, & Chen, 2020) studies an aggregate of prosumers that try to maximize their profit by buying, selling, and storing energy. In order to simplify the problem, and since the considered generation market is perfectly competitive, it assumes that all generators are owned by a single firm. It concludes that even though the prosumer has the ability to change the wholesale market price, it will not change its position from selling to buying energy. In fact, the prosumer will only change the amount bought or sold.

(Kardakos, Simoglou, & Bakirtzis, 2016) addresses the optimal bidding strategy problem faced by a commercial virtual power plant (CVPP). The CVPP comprises distributed energy resources, batteries and electricity consumers. It presents a bi-level model comprised by the CVPP and the independent system operator. The VPP's profit maximization problem is considered the upper level, and the independent system operator's market clearing problem the lower level. The model is applied to a case-study that compare a scenario with no coordination from the CVPP, another with coordination and a last one with coordination but the CVPP acting as price-maker. The results from the case-study show a 5% average increase in profit when the CVPP acts in coordination and a 3% more benefit when acting as price-makers.

The following table summarises the state of the art described in this section:

| WORK | PROBLEM DEFINITION | RESOLUTION METHOD | MAIN CONCLUSION |
|---|---|---|---|
| (Brunix, Pandzic, Le Cadre, & Delarue, 2020) | Bilevel optimization problem between aggregator and day-ahead market. | Stackelberg game between aggregator and controllable DR providers. | Consumers reduce their energy bill by 0.72 €/day on average. |
| (Kardakos, Simoglou, & Bakirtzis, 2016) | Addresses optimal bidding strategy of a commercial virtual power plant acting as a price-maker. | It models the aggregator as a Virtual Power Plant. | By coordination from the CVPP they obtain a 5% more profit in a case study. |
| (Mashhour & Moghaddas-Tafreshi, 2011) | Addresses optimal bidding strategy of a commercial virtual power plant | It models clients as Virtual Power Plants. | DG is not visible to the system so centralized generation capacities must be retained to perform support and security activities. |
| (Fang, et al., 2020) | How an aggregator can coordinate large-scale car charging of electric vehicles to minimize its costs. | It proposes an aggregator-based demand response mechanism. | The participation of the aggregator in peak regulation can reduce the total system costs. |
| (Castagneto Gissey, Subkhankulova, Dodds, & Barret, 2019) | How centralized & decentralized resources affect electricity prices under different scenarios. | It uses an agent-based model to compute the equilibrium. | If prosumers produced during peak periods (or used demand response), prices would lower. |
| (Martin Zepter, Lüth, Crespo del Granado, & Egging, 2018) | How being able to trade P2P and trade in the wholesale market affects prosumers electricity bill. | It considers that prosumers are price-takers. | Peer-to-peer trading allows prosumers to reduce their electricity costs. |
| (Tushar, Yuen, & Nahid, 2020) | How centralized power system interacts with prosumers to shave the peak. | It proposes a cooperative Stackelberg game. | Prosumers are better by forming coalitions. |

| | | | |
|---|---|---|---|
| (Saez-Gallego & Morales, 2017) | It analyses the effect of risk tolerance on prosumers' outcome. | Formulates a stochastic programming model under risk aversion. | Under a risk aversion model allows the retailer to bid optimally. |
| (Sharma, Bhakar, & Tiwari, 2014) | It studies how wind power producers could increase their profit through strategic bidding. | Cournot game-theory to represent strategic behavior of producers. | Wind producers can increase their profit through strategic bidding. |
| (Ruhi, Dvijotham, Chen, & Wierman, 2018) | Quantifies the opportunities for price manipulation depending on the size of the aggregator. | It approximates the network with a radial one, allowing this to apply specific algorithms. | Significant increases in profit can be achieved via strategic curtailment in the real-time market. |
| (Ramyar, Liu, & Chen, 2020) | How being a strategic player can influence the decisions of the prosumer and how these decisions would differ from a non-strategic position. | It simplifies the problem by assuming that the other generators are price-takers. | Even though prosumers can manage to manipulate the wholesale price, it probably would not influence in his position. |
| (Yazdani-Damavandi, Neyestani, Shafie-khah, Contreras, & Catalao, 2018) | How a multi-energy player (MEP) deals with the wholesale electricity market. | Models the strategic behavior of the MEP as a bi-level decision-making problem. | The MEP manages to increase the total efficiency of the system. |
| (Chen, Olama, Rajpurohit, Dong, & Xue) | Model the electricity pricing strategy between a distribution system operator and load aggregators. | Stackelberg game approach between players. | Optimal prices can be obtained by changing the power the leader of the game has. |
| (Contreras-Ocana, Ortega-Vazquez, & Zhang, 2019) | It studies the aggregators' effect on system welfare. | It uses Nash bargaining theory. | Shows that storage units are likely to cooperate in the long-term. |
| (Parvania, Shahidehpour, & Fotuhi-Firuzabad, 2013) | How to model the strategies for the energy markets. | Considers aggregators as price-takers. | It presents an optimization framework for demand response. |

| | | | |
|---|---|---|---|
| (Calvillo, Sanchez-Miralles, Villar, & Martin, 2016) | It studies a price-maker aggregator, modelling its impact on the market. | Analyses the residual demand curves to bid optimally. | By being able to influence price the aggregator can increase its economic benefit. |

Table 1. State of the art

The main conclusions that can be extracted from the table above are:

1. Most of the works do not consider the aggregator's ability to modify the price, limiting the study to a price-taking situation.

2. The Stackelberg approach is only useful if there is a clear leader and follower. In a situation in which multiple players have market power the Stackelberg approach does not allow the modelling because there is not a leader and followers.

3. To best of the author's knowledge, the conjecture approach has been used to model the generator's market power, but this approach has not been applied to the represent prosumers' market power.

# Chapter 3. THESIS DEFINITION

## *3.1 JUSTIFICATION*

There are different approaches regarding the equilibria to model the electricity markets as can be seen in the previous table, being the most popular ones Stackelberg equilibria (SE), Cournot equilibria (CE), supply function equilibria (SFE), conjectural variation equilibria (CVE) and conjectured supply function equilibria (CSFE).

SE considers one player as a leader and the rest of the players as followers. The leader takes into account the reaction of the followers to make its decisions, but the followers do not consider neither the other followers' reactions nor the leader's reaction.

CE approaches the problem by considering that the electricity producers and consumers consider the other players' decisions and make their decisions to maximize their profits (Borenstein, Bushnell, & Knittel, 1997). This approach is easier to compute that the others, but one player does not take into account the reaction of the other players against the changes on its own strategy. The players' behaviors are represented by the quantities they produce or consume.

SFE approaches the equilibrium by representing player's behavior by their supply functions (Rudkevich, 2003). In the case of the clients, they will be represented by their demand function (consumption curves). A differential equation's system needs to be solved, which leads to a heavy computational task, therefore, it will not be used for this work.

CVE considers the competitors reaction to model the equilibrium. The reactions are modelled through the conjectures, which represent the influence the output of that firm has on the market price (Lopez de Haro, Sanchez Martin, de la Hoz, & Fernandez Caro, 2007). This approach is complex to execute because of the difficulty of endogenously estimating the conjectures.

CSFE is a mix of SFE and CVE. Finding this equilibrium does not involve solving differential equations and allows the conjecture to be computed endogenously. In this thesis CVE have been assumed for modeling both the supply and the demand conjectures, knowing that there is little literature regarding the calculation of the demand conjectures. The main contribution of this work is to provide an algorithm to endogenously estimate such conjectures. The steps that will be followed to achieve this objective are:

1. Literature analysis on how aggregators' market power is modelled, with special emphasis on CVE approaches.
2. Model the market relations which will be composed by consumers, prosumers and generation companies.
3. Identify and obtain the parameters needed to obtain the conjectures.
4. Propose a novel algorithm to endogenously estimate such conjectures.

# Chapter 4. MODEL DESCRIPTION AND RESOLUTION METHODOLOGY

## NOMENCLATURE

### *Indexes:*

$i$ - client

$e$ - generator

$h$ - hour to compute the conjectures

$t$ - generation unit

### *Parameters (in capital letters):*

$TP_i$ - power term of client $i$

$TV_i$ - variable term of client $i$ when it consumes energy

$TC_i$ - variable term of client $i$ when it injects energy

$VC_{t,e}$ - variable cost of production of unit $t$ of producer $e$

$IC_{t,i-e}$ - investment costs of client/producer $i$/ $e$

$D_{i,0}$ - inelastic term of the demand

$P_{e,0}$ - inelastic term of the production

$\tau$ - Convergence tolerance

***Variables (in lower or Greek letters):***

$d_i$ - demand of client $i$

$p_e$ - production of generator $e$

$d_{i,k}$ - demand of client $i$ for iteration $k$

$p_{e,k}$ - production of generator $e$ for iteration $k$

$\lambda$ - marginal market price

$\lambda_k$ - marginal market price for iteration $k$

$\theta_e^P$ - production's conjecture of generator $e$

$\theta_i^D$ - demand's conjecture of client $i$

$\alpha_i^D$ - demand's slope of client $i$

$\alpha_e^P$ - production's slope of producer $e$

$\alpha_{i,k}^D$ - demand's slope of client $i$ for iteration $k$

$\alpha_{e,k}^P$ - production's slope of producer $e$ for iteration $k$

$c_i$ - marginal cost of client $i$

$cp_i$ - contracted power of customer $i$

$ip_i, ip_e$ - installed power of client/producer $i$/ $e$

$\delta_{D,i}$ - binary variable that takes 1 if client $i$ injects energy to the grid

## *4.1 MODEL FORMULATION*

### 4.1.1 CONJECTURES' COMPUTATION AND HYPOTHESIS

The objective of this section is to define the expressions that will allow to compute the conjectures, which are defined as follows:

*Eq. 1* $$\theta_i^D = -\frac{\partial \lambda}{\partial d_i}$$

*Eq. 2* $$\theta_e^P = \frac{\partial \lambda}{\partial p_e}$$

In the electricity market there needs to be an equilibrium between the generated and consumed energy to avoid power unbalances, which lead to unbalances in the frequency and can cause damage in the electrical equipment and system shutdowns. Therefore, the energy production will be considered always equal to the energy demand.

*Eq. 3* $$d(\lambda) = p(\lambda)$$

$$\rightarrow d_i + d_{-i} = p_e + p_{-e}$$

$$\rightarrow d_i = p_e + p_{-e} - d_{-i}$$

$$\rightarrow p_e = d_i + d_{-i} - p_{-e}$$

Where $d_{-i}$ represents the demand of all the clients except client $i$ and $p_{-e}$ represents the production of all the generators except generator $e$.

*Eq. 3* is derived with respect to $\lambda$ to obtain the expression of the demand conjecture:

*Eq. 4*
$$\frac{\partial d_i}{\partial \lambda} = \frac{\partial p}{\partial \lambda} - \sum_{j \neq i} \frac{\partial d_j}{\partial \lambda}$$

Being $p$ the total production. By substituting in *Eq. 4* the definition of the conjecture provided in *Eq. 1* the following equation can be obtained:

*Eq. 5*
$$\frac{\partial d_i}{\partial \lambda} = -\frac{1}{\theta_i^D} = \frac{\partial p}{\partial \lambda} - \sum_{j \neq i} \frac{\partial d_j}{\partial \lambda}$$

$$\rightarrow \theta_i^D = \frac{1}{\sum_{j \neq i} \left(\frac{\partial d_j}{\partial \lambda}\right) - \frac{\partial \sum_e p_e}{\partial \lambda}}$$

The same steps can be followed to calculate the production conjecture. *Eq. 3* is derived with respect to $\lambda$ to obtain the expression of the production conjecture:

*Eq. 6*
$$\frac{\partial p_e}{\partial \lambda} = \frac{\partial d}{\partial \lambda} - \sum_{j \neq e} \frac{\partial p_j}{\partial \lambda}$$

Being $d$ the total production. The definition of the production conjecture (*Eq. 2*) is substituted in the previous equation:

*Eq. 7*

$$\frac{\partial p_e}{\partial \lambda} = \frac{1}{\theta_e^P} = \frac{\partial d}{\partial \lambda} - \sum_{j \neq e} \frac{\partial p_j}{\partial \lambda}$$

$$\rightarrow \theta_e^P = \frac{1}{\sum_i \left(\frac{\partial d_i}{\partial \lambda}\right) - \frac{\partial \sum_{j \neq e} p_j}{\partial \lambda}}$$

Knowing that the equations of the production and demand with respect to $\lambda$ of each generator/consumer are:

*Eq. 8*

$$d_i = D_{i,0} - \alpha_i^D \cdot \lambda$$

*Eq. 9*

$$p_e = P_{e,0} + \alpha_e^P \cdot \lambda$$

The higher is $\lambda$ in *Eq. 8*, the lower the demand will be, therefore:

*Eq. 10*

$$\alpha_i^D = -\frac{\partial d_i}{\partial \lambda}$$

On the other hand, on *Eq. 9* the higher is $\lambda$, the higher the production will be, therefore:

*Eq. 11*

$$\alpha_e^P = \frac{\partial p_e}{\partial \lambda}$$

In an hourly model the conjectures, and demand and supply slopes will depend on each hour. Hence, the conjectures are defined for every hour $h$. The equations obtained by substituting

*Eq. 10* and *Eq. 11* in *Eq. 5* and *Eq. 7* are the conjectures for hour $h$ for each client $i$ and generator $e$ in the equilibrium:

*Eq. 12*

$$\theta_{i,h}^{D} = \frac{-1}{\sum_{j \neq i} \alpha_{j,h}^{D} + \sum_{e} \alpha_{e,h}^{P}}$$

$$\theta_{e,h}^{P} = \frac{-1}{\sum_{i} \alpha_{i,h}^{D} + \sum_{j \neq e} \alpha_{j,h}^{P}}$$

It can be observed that both conjectures are calculated as a function of the slope of the generators curve of the production and the demand curve of the clients.

### 4.1.2 CVE EQUILIBRIUM CONSTRAINTS AND CONJECTURES ENDOGENOUS

Aggregators act most of the time as consumers, this means that if they make strategic decisions, they will minimize their costs, which are defined as follows:

*Eq. 13*

$$c_i(d_i, d_{-i}) = TP_i \cdot cp_i(d_i) + \lambda \cdot d_i + TV_i \cdot d_i$$

The term $cp_i(D_i)$ is only different from 0 in the hour of the year in which $D_i$ is maximum.

In order for $C_i$ to be minimum, its derivative in the equilibrium with respect to $D_i$ must be equal to 0:

$$\frac{\partial c_i}{\partial d_i} = TP_i + \lambda + \frac{\partial \lambda}{\partial d_i} \cdot d_i + TV_i = 0$$

$$\rightarrow \lambda = -\left(TP_i + \frac{\partial \lambda}{\partial D_i} \cdot d_i + TV_i\right)$$

The definition of the conjecture (*Eq. 1*) is introduced in the previous equation, obtaining an expression for $\lambda$ that depends on the conjecture. The following system of equations models the single-bus CVE:

*Eq. 14*

$$\lambda = \theta_i^D \cdot d_i - TP_i - TV_i = \frac{-1}{\sum_{j \neq i} \alpha_j^D + \sum_e \alpha_e^P} \cdot d_i - TP_i - TV_i \qquad \forall i$$

$$\sum_e p_e = \sum_i d_i$$

The system of equations *Eq. 14* leads to multiple results, as it has more variables than equations.

### 4.1.3 ROBUSTNESS AGAINST PRODUCTION OF RENEWABLE ENERGY

According to (Martinez-Anido & Hodge, 2016) variable wind resources can shift the production curve, changing electricity prices. Similar to the reasoning of (Klemper & Meyer, 1989), where the supply curves are considered robust against uncertainty in the demand, in this work the demand curves of the clients and the supply curves of the generators will be considered robust towards variations in renewable production as a hypothesis. Per definition a derivative can be approximated by two proximate values. Two infinitesimally close renewable production scenarios are considered to approximate the derivatives of the slopes, and hence be able to calculate the conjecture.

More specifically, the total energy production is divided into renewable production ($R$) and not renewable production ($NR$):

$$\sum_e p_e = \sum_{e\epsilon R} p_e + \sum_{e\epsilon NR} p_e$$

The two infinitesimally close production scenarios ($\varepsilon_1$ and $\varepsilon_2$) that are going to be considered are:

*Eq. 15*

$$P_R(\varepsilon_1) = P_R - \frac{\Delta P_R}{2}$$

$$P_R(\varepsilon_2) = P_R + \frac{\Delta P_R}{2}$$

Being $P_R$ the renewable production. The demand of each client in each scenario can be approximated by the Taylor series of the demand:

*Eq. 16* $$d_i(\varepsilon_1) = d_i(\lambda - h_1) = d_i(\lambda) - \frac{\partial d_i(\lambda)}{\partial \lambda} \cdot h_1 + \frac{\partial d_i^2(\lambda)}{\partial \lambda^2} \cdot \frac{h_1^2}{2} - K_1$$

*Eq. 17* $$d_i(\varepsilon_2) = d_i(\lambda + h_2) = d_i(\lambda) + \frac{\partial d_i(\lambda)}{\partial \lambda} \cdot h_2 + \frac{\partial d_i^2(\lambda)}{\partial \lambda^2} \cdot \frac{h_2^2}{2} + K_2$$

$K_1$ and $K_2$ are Taylor's third and higher degree terms, and $h_1$ equals $\lambda - \lambda(\varepsilon_1)$ and $h_2$ equals $\lambda(\varepsilon_2) - \lambda$.

$\lambda$ is considered a continuous function around the equilibrium (Rodriguez, Villar, Campos, & Diaz, 2012), therefore it can be stated that:

$$\lim_{\Delta P_R \to 0} h_1\,(\Delta P_R) = 0$$

$$\lim_{\Delta P_R \to 0} h_2\,(\Delta P_R) = 0$$

Following this reasoning, by subtracting *Eq. 16* from *Eq. 17* and neglecting the second and higher order derivatives the following equation is obtained:

*Eq. 18* $$d_i(\varepsilon_2) - d_i(\varepsilon_1) \approx \frac{\partial d_i(\lambda)}{\partial \lambda} \cdot (h_1 + h_2)$$

The terms of *Eq. 18* are reorganized to obtain *Eq. 19*:

$$\frac{\partial d_i}{\partial \lambda} = -\alpha_i^D \approx \frac{d_i(\varepsilon_2) - d_i(\varepsilon_1)}{h_2 + h_1} = \frac{d_i(\varepsilon_2) - d_i(\varepsilon_1)}{\lambda(\varepsilon_2) - \lambda(\varepsilon_1)}$$

*Eq. 19*

A similar approximation can be made regarding the supply function's slope (Diaz, Villar, Campos, & Rodriguez, 2011):

*Eq. 20*

$$\frac{\partial p_e}{\partial \lambda} = \alpha_e^P \approx \frac{p_e(\varepsilon_2) - p_e(\varepsilon_1)}{\lambda(\varepsilon_2) - \lambda(\varepsilon_1)}$$

Then the conjecture can be obtained by solving the following system of equilibrium equations:

*Eq. 21*

$$\lambda = \theta_i^D \cdot d_i - TP_i - TV_i = \frac{-1}{\sum_{j \neq i} \alpha_j^D + \sum_e \alpha_e^P} \cdot d_i - TP_i - TV_i \qquad \forall i, \forall \varepsilon$$

$$\sum_e p_e(\varepsilon) = \sum_i d_i(\varepsilon) \qquad \forall \varepsilon$$

$$-\alpha_i^D \approx \frac{d_i(\varepsilon_2) - d_i(\varepsilon_1)}{\lambda(\varepsilon_2) - \lambda(\varepsilon_1)} \qquad \forall i$$

$$\alpha_e^P \approx \frac{p_e(\varepsilon_2) - p_e(\varepsilon_1)}{\lambda(\varepsilon_2) - \lambda(\varepsilon_1)} \qquad \forall e$$

It is a non-linear system of equations, therefore the following algorithm is proposed where the values of the conjectures in each iteration are fixed for a linear representation.

## *4.2 EQUIVALENT OPTIMIZATION PROBLEM WHEN CONJECTURES ARE KNOWN*

Assuming that the conjectures are known, the next quadratic optimization problem can be solved for finding the two equilibria defined based on the two first equations of *Eq. 21* (see (Domenech, Campos, Villar, & Rivier, 2020) for the proof):

*Eq. 22*

$$min\left(\sum_e\left(\sum_h\left(\sum_t VC_{t,e}\cdot p_{t,e,h}+\theta^P_{e,h}\cdot 0.5\cdot\left(\sum_t p_{t,e,h}\right)^2\right)+\sum_t IC_{t,e}\cdot ip_{t,e}\right)\right.$$
$$+\sum_i\left(TP_i\cdot cp_i+\sum_t IC_{t,i}\cdot ip_{t,i}\right.$$
$$\left.\left.+\sum_h\left(TC_i\cdot d_{i,h}\cdot\delta_{i,d}+TV_i\cdot d_{i,h}\cdot\left(1-\delta_{i,d}\right)+\theta^D_{i,h}\cdot 0.5\cdot d^2_{i,h}\right)\right)\right)$$

$$\sum_e p_e(\varepsilon)=\sum_i d_i(\varepsilon)\qquad \forall\varepsilon$$

Where $\delta_{i,d}$ is a binary variable that takes 1 if client $i$ injects energy to the grid. This variable has been introduced to consider different tariffs when the prosumer injects energy to the grid ($TC_i$) and when it consumes energy from the grid ($TV_i$).

## *4.3 PROPOSED ALGORITHM*

### 4.3.1 INITIALIZATION

The slopes $\alpha^P_{e,k=0}$ and $\alpha^D_{i,k=0}$ are initialized with arbitrary values and the two renewable production scenarios are defined (*Eq. 15*).

### 4.3.2 RESOLUTION OF TWO EQUILIBRIA

As explained in the section "Robustness against Production of Renewable Energy", the supply and demand slopes can be obtained from the production (or demand) of each player and the price of two infinitesimally close scenarios. Therefore, it is necessary to resolve those two equilibria. Since the slopes are known in this step, the conjectures are also known. Therefore, according to the previous section (Equivalent optimization problem when Conjectures are known), the two equilibria can be resolved by applying the equivalent optimization problem of *Eq. 22*.

The output obtained from this step and needed for computing the slopes is: the demand for each client in each scenario ($d_{i,k}(\varepsilon_1)$ and $d_{i,k}(\varepsilon_2)$), the production for each generator in each scenario ($p_{e,k}(\varepsilon_1)$ and $p_{e,k}(\varepsilon_2)$) and the marginal price for each scenario ($\lambda_k(\varepsilon_1)$ and $\lambda_k(\varepsilon_2)$).

### 4.3.3 CALCULATION OF THE NEW SLOPES

Using the data obtained in the previous step, the slopes of the residual demand curve and the residual supply curve ($\alpha^D_{i,k+1}$ and $\alpha^P_{e,k+1}$) can be computed through *Eq. 19* and *Eq. 20*, obtaining the result for each client and producer. With the slopes of both clients and generators the demand and production conjectures can be computed using *Eq. 12*.

### 4.3.4 CONVERGENCE TEST

Being $k$ the number of the iteration and $\tau$ the established tolerance, it is checked if $\left|\alpha^D_{i,k+1} - \alpha^D_{i,k}\right| > \tau$ and if $\left|\alpha^P_{e,k+1} - \alpha^P_{e,k}\right| > \tau$. In case the previous statement is true, the algorithm is executed again from the second step (Resolution of Two Equilibria) with the value of the new slopes. Otherwise, the model converges, and the values of $\alpha_{i,k+1}$ will be the final values and the final equilibrium will be computed:

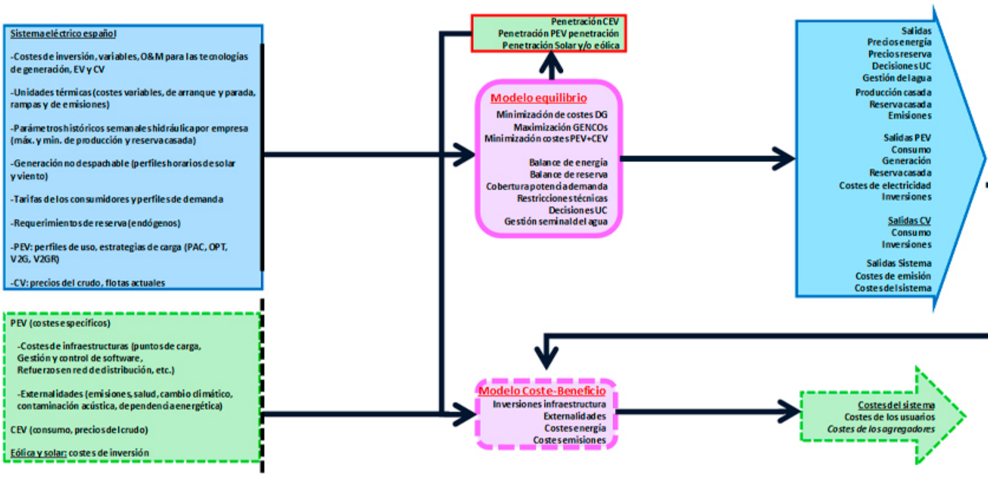
$$min\left(\sum_e\left(\sum_h\left(\sum_t VC_{t,e}\cdot p_{t,e,h}+\theta^P_{e,h}\cdot 0.5\cdot\left(\sum_t p_{t,e,h}\right)^2\right)+\sum_t IC_{t,e}\cdot ip_{t,e}\right)\right.$$
$$+\sum_i\left(TP_i\cdot cp_i+\sum_t IC_{t,i}\cdot ip_{t,i}\right.$$
$$\left.\left.+\sum_h\left(TV_i\cdot d_{i,h}\cdot\delta_{i,d}+TV_i\cdot d_{i,h}\cdot\left(1-\delta_{i,d}\right)+\theta^D_{i,h}\cdot 0.5\cdot d^2_{i,h}\right)\right)\right)$$

$$\textstyle\sum_e p_e=\sum_i d_i$$

# Chapter 5. RESULTS

During this work a prototype of the proposed algorithm was developed to obtain the conjectures. This prototype was developed using the tool CEVESA for solving the different equilibria set out in the algorithm, although an automatic computation of both equilibria is still pending.

CEVESA is a dynamic model for the planification of the expansion of electrical system of the Iberian Peninsula. It considers the investments made by both investors and consumers. It is implemented in GAMS, and CPLEX is used to compute the equilibria. A brief scheme explaining the inputs and outputs of CEVESA is presented in the following image:




Graph 3. Scheme of the CEVESA model (IIT, 2018)

However, a prototype of CEVESA for its use in the proposed algorithm is pending systematic test and debug to find errors and adjust resolution hypotheses. Also, the transversal equations have an impact on the conjectures, and are not considered as it is a simplification.

Some hypotheses were taken and provided errors. The two principal hypotheses are presented below:

1. Computation of conjectures based on the day and night periods: since the decision consumers can make in CEVESA model is to install solar panels and batteries, the hypothesis was to calculate for every client a conjecture for the period in which there is light, and other conjecture for the night period, expecting similar values for the conjecture in these two blocks. This generalization did not provide the expected results. The main reason was that the market power of the consumers changes every hour and not only depending on the solar production.

2. Considering uncertainty in renewable energy: two infinitesimal close production changes were needed to approximate the demand and supply slopes. The followed approach was to suppose uncertainty in the renewable energy production. The proposed variation in the renewable energy was to compute the renewable scenario of two different consecutive weeks. The main drawback of this approach is that the variation between both scenarios could be not infinitesimal, and hence give erroneous results.

Based on the hypothesis taken in this work, possible lines of research for the commercial implementation of the proposed algorithm will be provided in the Future Work section.

# Chapter 6. CONCLUSIONS

In this project, the market power of an aggregator has been modelled using demand's variational conjecture, which has been endogenously calculated. The main contributions of this work are:

1. An extensive analysis on the current state of the art: providing the directions to model the market power of prosumers in the most computing-effective manner, concluding that this is achieved by using a conjectured demand function equilibrium.

2. A method to model the market power of the consumers through the conjectures. This method is useful to study how a consumer can affect the wholesale electricity price by changing its demand. Unlike Stackelberg or Cournot demand equilibria, this approach allows to compute the reactions of all the players.

3. An algorithm to endogenously compute the demand conjecture. The conjectures are calculated by solving the equilibria for two infinitesimally close scenarios. The main advantage of the proposed algorithm is that it does not depend on statistical estimations of the conjecture, which are dependent on changes in regulation or in the grid structure.

4. A new algorithm to compute both demand and supply conjectures in a flexible process. Because the two equilibria needed to calculate the slopes are solved simultaneously by optimization, more constraints (technical and economical) can easily be added to the minimization problem. Hence, the main advantage of the proposed algorithm, is that it offers the possibility of adding more constraints in an easy manner, which makes the algorithm very flexible and easier to scale.

5. A source of uncertainty to compute the conjectures: the renewable energy production was introduced as the source of uncertainty to apply the proposed algorithm. Unlike other approaches, such as the variation in the total demand, this source of uncertainty can be used to calculate both the demand and supply slopes, and therefore both conjectures.

# Chapter 7. FUTURE WORK

The future work should be focused in testing this theoretical work with different cases studies considering that:

1. Conjectures of each client and generator will be computed hourly. CEVESA will be adapted and used to solve each equilibrium around the renewable generation uncertainty as explained in the Proposed Algorithm Section.

2. After obtaining the conjectures for every hour, it will be checked the existence of blocks of hours in which the conjecture takes similar values. In case these are found, new simpler algorithms will be searched to reduce the computing intensity of the process.

3. In this work the approach followed has been the robustness towards the production of renewable energy. However, the robustness could be against other sources of uncertainty. Another proposed source of uncertainty would be the renewable energy per client.

4. The real residual demand curves in the electricity markets depend on the production of a generator or on the demand of a client. Therefore, to calculate the conjectures it would make sense to suppress the intertemporal restrictions of the model. In the preliminary executions of the model, it was checked that due to these restrictions the conjecture did not have the correct sign and that the algorithm do not converge.

# Chapter 8. BIBLIOGRAPHY

BOE. (2020). *Boletín Oficial del Estado*. Retrieved from https://www.boe.es/buscar/act.php?id=BOE-A-2020-17278

Borenstein, S., Bushnell, J., & Knittel, C. (1997). A Cournot-Nash Equilibrium Analysis of the New Jersey Electricity Market.

Braun, M. (2009). Virtual power plants in real applications: Pilot demonstrations in Spain and England as part of the european project FENIX.

Brunix, K., Pandzic, H., Le Cadre, H., & Delarue, E. (2020, 3). On the Interaction Between Aggregators, Electricity Markets and Residential Demand Response Providers. *IEEE Transactions on Power Systems, 35*(2), 840-852.

Calvillo, C., Sanchez-Miralles, A., Villar, J., & Martin, F. (2016). Optimal planning and operation of aggregated distributed energy resources with market participation. *Applied Energy, 182*, 340-357.

Castagneto Gissey, G., Subkhankulova, D., Dodds, P., & Barret, M. (2019, 2 1). *Value of energy storage aggregation to the electricity system*. Retrieved from Science Direct: https://www.sciencedirect.com/science/article/pii/S0301421519300655

Chen, Y., Olama, M., Rajpurohit, T., Dong, J., & Xue, Y. (n.d.). Game-Theoretic Approach for Electricity Pricing between Distribution System Operator and Load Aggregators.

Comission. (2021). *National Energy and Climate Plans.*

Contreras-Ocana, J., Ortega-Vazquez, M., & Zhang, B. (2019, 3). Participation of an Energy Storage Aggregator in Electricity Markets. *IEEE Transactions on Smart Grid, 10*(2), 1171-1183.

de Almansa, M., Campos, F. A., Doménech, S., & Villar, J. (2019). Residential DER Cooperative Investments. *2019 16th International Conference on the European Energy Market (EEM)*.

Diaz, C., Villar, J., Campos, A., & Rodriguez, M. (2011). *A new Algorithm to compute Conjectured Supply Function Equilibrium in Electricity Markets.* ELSEVIER.

Domenech, S., Campos, A., Villar, J., & Rivier, M. (2020). An equilibrium approach for modeling centralized and behind-the-meter distributed generation expansion. *Electric Power Systems Research*.

Fang, C., Zhao, X., Xu, Q., Feng, D., Wang, H., & Zhou, Y. (2020, 10). Aggregator-based demand response mechanism for electric vehicles participating in peak regulation in valley time of receiving-end power grid. *Global Energy Interconnection, 3*(5), 453-463.

IIT. (2018). *IIT*. Retrieved from https://www.iit.comillas.edu/technology-offer/cevesa

IRENA. (2020). *Global Renewable Outlook.*

IRENA. (2020). *Renewable Power Generation Costs in 2019.*

Kardakos, E., Simoglou, C., & Bakirtzis, A. (2016, 3). Optimal Offering Strategy of a Virtual Power Plant: A Stochastic Bi-Level Approach. *IEEE Transactions on Smart Grid, 7*(2).

Kirschen, D. S. (2003, 5). Demand-side view of electricity markets. *IEEE Transactions on Power Systems, 18*(2), 520-527.

Klemper, P., & Meyer, M. (1989). Supply Function Equilibria in Oligopoly under Uncertainty. *Econometrica, 57*(6), 1243-1277.

Li, B., Wan, C., Yuan, K., & Song, Y. (2019). Demand response for integrating distributed energy resources in transactive energy system. *Energy Procedia, 158*, 6645-6651.

Lin, W., Yunfei, M., Jia, H., Yu, X., Pu, T., & Chen, N. (2019). Game-theory based trading analysis between distribution network operator and multi-microgrids. *Energy Procedia, 158*, 3387-3392.

Lopez de Haro, S., Sanchez Martin, P., de la Hoz, J., & Fernandez Caro, J. (2007). Estimating conjectural variations for electricity market models. *European Journal of Operational Research, 181*, 1322-1338.

Lu, Q., Lü, S., & Leng, Y. (2019). A Nash-Stackelberg game approach in regional energy market considering users' integrated demand response. *Energy, 175*, 456-470.

Martin Zepter, J., Lüth, A., Crespo del Granado, P., & Egging, R. (2018). Prosumer integration in wholesale electricity markets: Synergies of peer-to-peer trade and residential storage. *Energy & Buildings 184*, 163-176.

Martinez-Anido, C. B., & Hodge, B. (2016). The impacto of wind power on electricity prices. *Renewable Energy*(94), 474-487.

Mashhour, E., & Moghaddas-Tafreshi, S. M. (2011, 5). Bidding Strategy of Virtual Power Plant for Participating in Energy and Spinning Reserve Markets. *IEEE Transactions on Power Systems, 26*(2), 949-956.

Moradipari, A., Silva, C., & Alizadeh, M. (2018). Learning to Dynamically Price Electricity Demand Based on Multi-armed Bandits. *IEEE.*

Moya, J., & Boulamanti, A. (2016). *Production costs from energy-intensive industries in the EU and third countries.* European Comission.

Niu, J., Tian, Z., & Yue, L. (2020). Implementation of a price-driven demand response in a distributed energy system with multi-energy flexibility measures. *Energy Conversion and Management, 208.*

Odegaard, S., Tomasgard, A., & Fleten, S.-E. (2016). Prosumer bidding and scheduling in electricity markets. *Energy, 94*, 828-843.

Parvania, M., Shahidehpour, M., & Fotuhi-Firuzabad, M. (2013, 12). Optimal Demand Response Aggregation in Wholesale Electricity Markets. *IEEE Transactions on Smart Grid, 4*(4), 1957-1965.

Ramyar, S., Liu, A. L., & Chen, Y. (2020, 3). Power market model in presence of strategic prosumers. *IEEE Transactions on Power Systems, 35*(2), 898-908.

Rodriguez, M. A., Villar, J., Campos, A., & Diaz, C. (2012). Endogenous computation of conjectured supply functions with network contraints. *Electric Power System Research*, 117-126.

Rudkevich, A. (2003). Supply Function Equilibrium: Theory and Applications.

Ruhi, N. A., Dvijotham, K., Chen, N., & Wierman, A. (2018). Opportunities for price manipulation by aggregators in electricity markets. *IEEE Transactions on Smart Grid, 9*(6), 5687-5698.

Saez-Gallego, J., & Morales, J. M. (2017). Optimal price-energy demand bids for aggregate price-responsive loads. *IEEE Transactions on Smart Grids*, 1-9.

Sharma, K. C., Bhakar, R., & Tiwari, H. (2014). Strategic bidding for wind power producers in electricity markets. *Energy Conversion and Management, 86*, 259-267.

Spodniak, P., Ollikka, K., & Honkapuro, S. (2021). The impact of wind power and electricity demand on the relevance of different short-term electricity markets: The Nordic case. *Applied Energy, 283*, 1-21.

Tushar, W., Yuen, C., & Nahid, A.-M. (2020, 3). Grid influenced peer-to-peer energy trading. *IEEE Transactions on Smart Grids, 11*(2), 1407-1418.

UNESCO. (2021). *UNESCO*. Retrieved from https://es.unesco.org/sdgs

United Nations. (2021). *SDGS*. Retrieved from https://sdgs.un.org/es/goals

Yazdani-Damavandi, M., Neyestani, N., Shafie-khah, M., Contreras, J., & Catalao, J. (2018, 1). Strategic Behaviour of Multi-Energy Players in Electricity Markets as Aggregators of Demand Side Resources Using a Bi-Level Approach. *IEEE Transactions on Power Systems, 33*(1), 397-411.