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GRADO EN INGENIERÍA DE TECNOLOGÍAS INDUSTRIALES

Trabajo Fin De Grado

Modelling bounded rational behaviour of economic agents in distributed generation investments

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Modelado del comportamiento racional limitado de agentes inversores en generación distribuida

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Entidad Colaboradora: IIT – Instituto de Investigación Tecnológica.

RESUMEN DEL PROYECTO

- *Definición modelo de comportamiento*

Un modelo de comportamiento de los agentes económicos es una herramienta matemática cuyo objetivo es representar, de la forma más veraz posible, el comportamiento de estos agentes en su toma de decisiones. En este proyecto, dicho modelo se utiliza en situaciones en las que algunos agentes (principales los consumidores) toman decisiones de inversión en generación de energía distribuida (GD o, en inglés DG). Esta subsección será explicada con más detalle en la sección 1.

- *Definición GD*

Para ofrecer al lector una base previa de lo que se va a tratar, se va a explicar brevemente (detallado también en la sección 1) qué es la GD. Es un tipo de generación que engloba toda fuente de energía que esté instalada en la red de distribución cerca de un lugar de consumo. Está caracterizada por aportar varios beneficios al sistema como pueden ser: la reducción de pérdidas de energía a través de las redes de transporte, una mayor estabilidad del sistema ya que puede actuar como suministro de reserva de energía, una disminución de los costes de operación (debido a la reducción de pérdidas) y un fomento de la utilización de energías renovables (principales tipos de energía utilizadas en la GD) [1].

- *Objetivos del proyecto*

Ahora que la GD ha sido definida, se explicará más concretamente el objetivo de este proyecto (también detallado en la sección 1 del documento), que consiste en el modelado del comportamiento de agentes inversores en GD. Este objetivo resulta relevante dado que, por ejemplo, ante un escenario de expansión en GD, las GENCOs perderían facturación viéndose obligadas a invertir en otros ámbitos de la compañía como, por ejemplo, el transporte o el almacenamiento de energía, para así poder compensar la falta de facturación.

La inversión en GD podría provocar también que las GENCOs bajen sus precios de oferta para hacerlos más competitivos creando sistemas eléctricos más eficientes, todo ello en un contexto en el que la regulación lo permita. A su vez, las inversiones en GD facilitan la penetración de energía renovable en el sistema dado que la mayoría de las tecnologías de GD (turbinas eólicas, paneles solares o baterías de almacenamiento son algunas de estas tecnologías [1]) generan energías "verdes". A su vez, la GD podría ayudar a la seguridad del sistema apoyando a la reserva en situaciones de desbalance de demanda y oferta [13].

Hoy en día, los modelos de comportamiento de agentes económicos son una de las áreas con mayor importancia dentro de cualquier industria. Permiten evaluar cómo afectan los cambios en las políticas de oferta de las compañías al comportamiento de los agentes (las empresas, los consumidores o el Estado) en un determinado mercado. Gracias a la posibilidad de estudiar dichos efectos, podemos entender las razones que hay detrás de las decisiones tomadas y, de esta forma, llegar a predecir el comportamiento del mercado y de sus agentes de una forma más precisa.

- *Introducción a la teoría de la racionalidad económica*

En concreto, cuando hablamos de decisiones de inversión, las mismas no son tomadas por algunos agentes de manera completamente racional y objetiva. Por poner un ejemplo sencillo, un consumidor normalmente no compra un peine porque sea más o menos bonito, sino porque se quiere peinar con él. En definitiva, se va a comprar el peine que le sea más útil para su pelo obviando las características subjetivas del producto. Eso es utilitarismo. Por ello en este proyecto se utiliza el concepto de agente racional como aquel que maximiza la utilidad (teoría de la racionalidad) esperada en la toma de decisiones [6]. Este concepto será explicado con mayor detalle en la sección 2 de este documento.

La teoría de la racionalidad sugiere que todo agente económico ha de comportarse de manera racional. De la teoría de la racionalidad deriva la racionalidad limitada, en la que se basa nuestro modelo. Esta teoría surgió por la necesidad de estudiar aquellas situaciones en las que el decisor carece del tiempo, de la información y/o de la capacidad de cálculo necesarias [9] para tomar decisiones óptimas. Por ejemplo, el tiempo necesario para tomar una decisión es importante porque el consumidor en la práctica no dedica el tiempo suficiente a estudiar el producto y puede que por ello se pierda la mejor oferta del mercado.

Se puede considerar que los modelos de racionalidad limitada se pueden aplicar a una gran cantidad de temas, pero en nuestro caso, nos centraremos en las inversiones en GD, que han sido representadas en el modelo CEVESA, descrito en [2] , punto de partida de este trabajo. Para ayudar al lector a situarse en un contexto más claro, vamos a explicar resumidamente CEVESA, que a su vez tomó como base el modelo de equilibrio del mercado de [12]. El modelo CEVESA plantea un equilibrio de mercado para estudiar la expansión de GD por parte de consumidores y también de GENCOs. Esto es relevante ya que cualquier variación significativa en las inversiones en GD puede afectar a los beneficios de las GENCOs, tal y como se mencionó anteriormente. En concreto, CEVESA plantea un modelo de equilibrio para la minimización de costes de la GD y la maximización de beneficio de las GENCOS, que puede ser integrado en un problema de optimización equivalente.

- *Posibles mejoras en CEVESA*

Este proyecto replantea el equilibrio de mercado de CEVESA considerando diferentes situaciones subóptimas (secciones 2 y 3 de la memoria) en las que un agente económico se puede encontrar a la hora de tomar una decisión y modelando diferentes tipos de funciones utilidad para cada una de esas situaciones. Para ello se han tomado como base las propuestas descritas en el proyecto europeo "The Penny Project" presentado en [17]. En concreto, se pueden diferenciar tres categorías de sesgos en función de la situación en la que el agente económico toma decisiones, que serán explicadas a continuación:

1. Preferencias no estandarizadas: engloba numerosas funciones de utilidad, de las cuales las más importantes son las basadas en las normas sociales, la inatención racional, el sesgo presente, la aversión al riesgo (o a la pérdida) y la dependencia de la referencia. De estas 5 grandes funciones de utilidad, en este trabajo solo se considerarán las 3 primeras debido a que son las que mejor se adaptan al problema que estamos tratando de modelar y estudiar. La conveniencia de unas funciones sobre otras será explicada con mayor detalle en la sección 4.

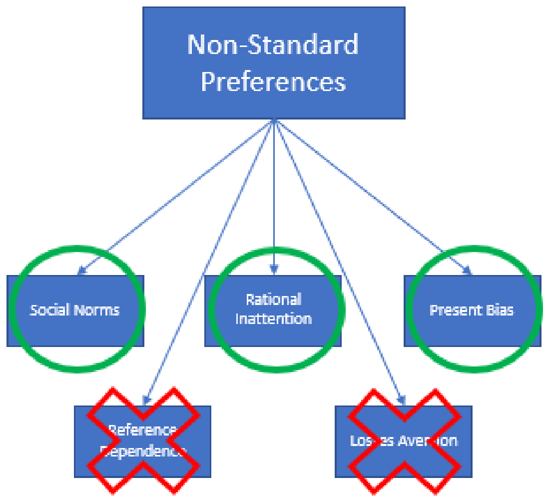

Figura 1. Sesgos más importantes en Preferencias No Estandarizadas.

Considerando las hipótesis que permiten plantear cada una de estas 3 funciones de utilidad (y que tienen que ver con comportamientos subóptimos y subjetivos de los agentes económicos, como por ejemplo aquellos que tienen que ver con modas), en este trabajo se ha adaptado la función de utilidad de los agentes inversores en GD de [2]. A continuación, se describirá la naturaleza de las funciones utilidad seleccionadas:

a. **Normas sociales:** consideran comportamientos subjetivos como la reciprocidad (o mimetismo), la aversión a la similitud y el egoísmo. Por ejemplo, en el caso de las inversiones en GD, el término de mimetismo considera que, si la sociedad empieza a invertir en tecnologías de GD, el agente copiará su comportamiento. En este caso el mimetismo es función de la potencia instalada en GD del sistema estudiado.

b. **Inatención racional:** considera la falta de atención del agente respecto al estudio del producto como inversión, sea por falta de tiempo para tomar la decisión, desconocimiento del producto, escasez de recursos, etc.

c. **Influencia del presente:** estudia la importancia que tienen los costes cercanos al presente frente a los costes que se van a dar en un futuro lejano. El agente común es más reticente a pagar 100 euros en el momento que 120 dentro de 3 años. A esto se le denomina **sesgo presente**.

En este trabajo se han añadido los 2 primeros factores (**normas sociales** e **inatención racional**) a través de una combinación que permite modelar de una forma más precisa una mixtura de comportamientos sociales (el **sesgo presente** ya había sido considerado en [2]). Matemáticamente esta combinación se traduce en la multiplicación de los parámetros que definen cada uno de estos 2 factores.

2. Tomas de decisión no estandarizadas: considera una función heurística que reduce la cantidad total de búsqueda requerida para poder encontrar la decisión óptima, al considerar implícitamente solo un subgrupo de todas las diferentes decisiones posibles.

3. Creencias no estandarizadas: considera el sesgo que tiene el agente a la hora de estimar la probabilidad de diversos escenarios futuros. Añade un parámetro **p**, que modela esa probabilidad mencionada a una función utilidad ya existente. Sin embargo, este parámetro no se ha aplicado a nuestro modelo ya que, debido al carácter del problema que se ha resuelto, es complicado estimar las probabilidades de los distintos escenarios de forma fiable. La inclusión de este fenómeno en nuestro modelo podría ser estudiada en un futuro.

A través de la aplicación de los enfoques anteriores a CEVESA, se ha propuesto un modelo (sección 4) que representa comportamientos con racionalidad limitada en la toma de decisiones de los consumidores que invierten en GD. En los casos estudio (programados mediante General Algebraic Modelling System, GAMS) se han planteado distintos escenarios para los parámetros de los enfoques anteriores a fin de estudiar distintos comportamientos irracionales, a partir de los cuales se han deducido interesantes conclusiones (para más detalle ver la sección 4).

- *Conclusiones de los resultados*

Los resultados obtenidos en la sección 4 dan lugar a una serie de conclusiones:

- Este modelo no estima el coste real de la inversión a realizar, si no que refleja la percepción que el inversor puede tener de dicho coste de acuerdo con sus sesgos.

- Cuanto mayor sea la inatención prestada al producto, mayor es la percepción de los costes. Los agentes no perciben un beneficio en forma de ahorro de costes hasta que se fijan detenidamente en el producto. Por lo tanto, las inversiones en tecnologías de GD decrecen resultando así en una mayor demanda de energía de los clientes de la red al tratar de compensar la falta de auto consumición.

- Cuanto menor sea el egoísmo (los costes de la inversión no influyen en la decisión de invertir) del cliente, mayor serán las inversiones en tecnologías de GD y, por lo tanto, menor la demanda de energía de los clientes a la red.

- *Futuros desarrollos*

La metodología utilizada en este proyecto es un acercamiento aceptable al modelado del comportamiento de los agentes económicos, pero es solo un primer paso para considerar representaciones más completas debido a que:

- **El software de optimización (GAMS) y el enfoque** utilizados en este proyecto limitan el espectro de casos estudio que se pueden similar. En concreto, la dependencia de la aversión (a diferentes comportamientos del resto de agentes) y de la reciprocidad (si el agente se deja influir por tendencias del resto de agentes).

- **No todos los sesgos fueron considerados** resultando así en un modelo menos completo a la hora de modelar determinados comportamientos irracionales.

- El **comportamiento irracional** de las GENCOs no ha sido tenido en cuenta y esto da lugar a un modelo de inversiones menos preciso a la hora de hacer su análisis.

Modeling of the limited rationality behaviour of investment agents in distributed generation

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SUMMARY OF THE PROJECT

- *Behavioural model definition*

A model of behaviour of economic agents is a mathematical tool, whose aim is to represent, in the most truthful way possible, the behaviour of these agents in their decision making. In this project, such model is used in situations in which agents (principally consumers) make investment decisions in distributed generation (DG). This definition will be explained in more detail in section 1.

- *DG definition*

To offer the reader a base for the subjects that will be studied, there will be a brief explanation (also detailed in section 1) of what DG is. It is a type of generation that entails all energy source installed near a place of consumption. It is characterized for adding value to the system, such as: reducing energy losses through the transportation network, a higher system stability since it can act as a supply of energy reserves, a lowering in costs of operation (due to the lower energy losses) and the promotion of renewable energy use (main types of energy used in DG) [1]. This definition will be explained in section 1.

- *Project's objectives*

After defining what DG is, the aim of this project will be presented (also thoroughly detailed in section 1), which is modelling the behaviour of investment agents in DG. This is relevant for many reasons. Take the scenario where there is an expansion on DG. The generating companies (GENCOs) would lose income, having then to invest in other scopes of the company such as the transportation or storage of energy, so as to compensate the loss of income.

The investment in DG could also trigger GENCO's lowering their prices to be more competitive, creating more efficient electric systems (considering a context where regulation allows it). At the same time, investments in DG facilitate renewable energy penetration, since most of DG technologies (wind turbines, solar panels or storage batteries are some examples of these technologies [1]) generate green energy. DG would also help higher the security of the system, helping the reserves in situations of unbalance of offer and demand [13].

Nowadays, behavioural models of economic agents are one of the areas of greatest importance inside any industry. They allow to evaluate how changes in the companies' offer policies affect the behaviour of the agents (companies, consumers or the Government) in each market. Due to the possibility to study said effects, the reasons behind these decisions can be understood, which allows for predicting the market and the agents in a more precise manner. This will be fully explained on section 2 of the memory.

- *Introducing economic rationality theory*

More precisely, when talking about investment decisions, these are not taken by agents in a complete rational and objective way. To illustrate this statement, a simple example can be given. Imagine the reader a consumer who wants to buy a comb. The consumer will not think of the beauty of the comb when deciding what product to buy but choose one that allows him to comb his hair. This is, he will buy a comb depending on how it meets the end of brushing his hair and not on subjective characteristics of the product. This is called utilitarianism. In the case of this product, the consumer is considered a rational agent, since he will maximize utility (rationality theory), as expected in decision making [6]. This concept will be explained in more detail in section 2 of this document.

The rationality theory suggests that every economic agent acts in a rational manner. From the rationality theory derives limited rationality, which the model studied in this project will be based on. This theory rises from the necessity to explain situations where the decision maker lacks the time, information and/or capacity of calculation necessary to make optimal decisions [9]. For example, the time needed to make a decision is important because, in practice, the consumer does not spend enough time studying the product and may therefore miss out the best offer in the market.

Limited rationality models can be applied to a wide variety of issues, but the main object of study in this project will be investments in DG, represented following the CEVESA model described in [2], starting point of this project. To help the reader situate himself on a clearer context, CEVESA will be briefly explained, which, in turn, is based on the model of market equilibrium presented in [12]. CEVESA poses a market equilibrium to study the expansion of DG due to consumers and also GENCOs. This is relevant since any significant variation in DG investments can alter the profits of GENCOs, as mentioned before. In particular, in CEVESA an equilibrium model is proposed where costs for DG are minimized and benefits for GENCOs are maximized, and that is possible to be integrated as a problem of equivalent optimization.

- *Possible improvements for CEVESA*

This project rethinks the equilibrium of the market described in CEVESA by considering different situations (detailed in sections 2 and 3) below optimal conditions where an economic agent may find itself at the time of making decisions and modelling these situations through different types of utility functions. To achieve this, the proposals described in the European project "The Penny Project" (presented in [17]) have been taken as basis. Three bias categories can be differentiated depending on the situation given at the time of the decision making:

1. Non-standardized preferences: includes numerous utility functions, out of which the most important ones are those based on the society norms, the rational inattention, the present bias, the risk aversion (or loss) and the dependency on reference. Out of these 5 utility functions, in this work piece only the first three ones will be considered, due to their adaptability to the problem we are trying to model and study. The convenience of some functions over others will be explained in greater detail in section 5.

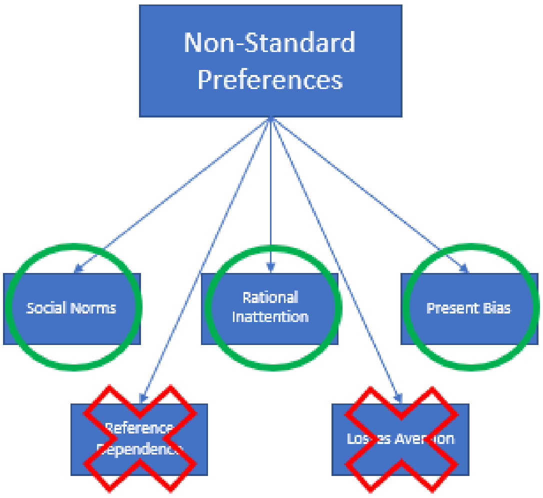

Figure 1. Non-Standard Preferences most important biases.

Considering the hypothesis that allow each of these 3 functions to be explained (and that relate to suboptimal and subjective behaviours of the economical agents, such as those related to passing trends), in this project utility function found in [2] has been adapted. Next comes a description of the nature of the utility functions selected:

   a. **Social norms:** they consider subjective behaviours such as reciprocity (or mimicry), the aversion to similarity and greed. For example, in the case of DG investments, the term of mimicry considers that, if society starts to invest in

DG technologies, the agent will copy its behaviour. In this case, mimicry is a function of the power installed in DG of the studied system.

b. Rational intention: considers the absence of attention of the agent with respect to the study of the product as an investment, may it be due to lack of time for taking the decision, no knowledge of the product, shortage of resources, etc.

c. Influence of the present: studies the importance that costs near the present have versus those in a distant future. The common agent is more reticent to pay 100 euros in the moment than 120 in 3 years' time. This is known as **present bias**.

In this piece of work the two first factors (**social norms** and **rational inattention**) have been added through a combination that allows modelling to be more precise regarding a mixture of social behaviours (**present bias** had already been included in [2]). Mathematically, this combination translates as the multiplication of these parameters defining each of the two factors.

2. Non-standardized decision making: considers a heuristic function that reduces the total amount of search needed to find the optimal decision, by implicitly considering only one subgroup of the different possible decisions.

3. Non-standardized beliefs: considers the bias that the decision-making agent has when estimating the probability of different future scenarios. It adds a parameter p, that models the afore-mentioned probability to an already existing utility function. Nonetheless, this parameter has not been applied to this project's model since, due to the essence of the problem solved, it is complicated to estimate the probabilities of the different scenarios reliably. Including this phenomenon in the model could be an option to stud in the future.

Through the application of the approaches before CEVESA, a model has been proposed (section 3), which represents behaviours of limited rationale in consumers' decision making when investing in DG. In the case studies (programmed on General Algebraic Modelling System, GAMS), different scenarios have been proposed for the parameters of the previous approaches, so as to study various irrational behaviours, through which interesting conclusions have been obtained (more details in section 5).

- *Results conclusions*

The results obtained in section 5 leads us to the following conclusions:

- This new model does not estimate the real cost of the investment to make, but it reflects the perception the investor might have of such a cost depending on his bias.

- The higher the inattention to the product, the higher the perception of the costs is. The agents do not perceive the benefit in form of costs' savings until they focus in detail on the product. Therefore, the investments will decrease resulting in a higher demand to the network by clients in order to compensate the energy missed by auto consumption.

- The lower the self-interest (the price of the investment does not influence the decision) of the client, the higher the investments in DG technologies are and the lower the demand to the network by clients is.

- *Future developments*

The methodology used in this project is an acceptable approach to the modelling of economic agents behaviour, but is only the first step to consider more complete representations due to the facts that:

- The **optimisation software used (GAMS) and the approach taken** limit the spectrum of study cases as a result of the dependency of aversion (to different behaviours of the rest of the agents) and reciprocity (whether the agent is influenced by the actions taken by the rest of the agents) to the installed power *p*.

- **Not all the biases were considered** resulting in a less complete irrational behaviour model.

- The **irrational behaviour of the GENCOs** was not considered and this results in a less precise investments behaviour analysis.

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Acronyms

GENCO – Generation Company

GD – Generación Distribuida

DG – Distributed generation

IIT – Instituto de Investigación Tecnológica

GAMS - General Algebraic Modelling System

aversion – behindness aversion

SELF – self-interest

rec - reciprocity

INAT_IC – rational inattention for installation costs

INAT_TP – rational inattention for contracted power

CX – sector of clients X

Nomenclature

Indexes

y - years

g – GENCO

c – consumer/client

t – technology

h - hour

t – generation unit

Parameters

$VC_{t,g,y}$ - term that models the variation of the cost of CG for a GENCO [€/MWh]

$TC_{c,y}$ - volumetric buying term [€/MWh]

$IC_{t,g,y}$ - cost of investment [€/MW]

$TP_{c,y}$ - power term tariff [€/MW]

$TV_{c,y}$ - volumetric selling term [€/MWh]

Variables

$\lambda_{h,y}$ – market price [€/MWh]

$q_{t,h,y}$ – generated power [MWh]

$p_{t,g,y}$ – the installed power [MW]

$cp_{c,y}$ - customer's, c, contracted power [MW]

$dq_{c,h,y}$ - energy demanded [MWh]

$eq_{c,h,y}$ – energy injected to the grid [MWh]

1 INTRODUCTION

1.1 Behavioural model definition

A behavioural model of economic agents is a mathematical tool with the objective of representing, as accurately as possible, how these agents behave when facing a decision. In our project, this model will be applied to situations where these agents have to make a decision related to investments in DG. In this way it will be possible to introduce changes in some of the parameters that give shape to our model and to evaluate the impact that those variations of the parameters have on the results obtained in order to model more precisely the DG expansion.

1.2 DG definition

To introduce the reader in the matter that is going to be discussed, first, the concept of DG will be explained briefly. This is a type of generation that is characterised for being installed in the distribution network next or near a load. Besides, it is also characterised for providing the system with a lot of benefits, for example: energy losses reduction through the high voltage network, a higher stability of the system because it can perform as a supply of energy reserve, a diminishing of the operation costs (related to the energy losses reduction) and an improvement of the usage of renewable energy resources (main types of energy used in DG) [1].

1.3 Main objective

The main objective of this work is the analysis of the modelling of different irrational behaviours of consumers when making investment in DG. The different irrational behaviour patterns have been formulated and implemented using GAMS in an existing equilibrium model described in [2] that represents the operations and investment decisions of GENCOs in centralized energy generation and the corresponding of the consumers when investing in DG. This equilibrium model models the MIBEL (Mercado Ibérico de Electricidad) and the expansion of the energy generation.

To achieve this objective, a set of study cases of situations of investment in DG have been assessed when considering different behaviours that are far from a strictly rational behaviour.

This memory includes a description of the state of art of the problem solved (section 2), the proposed methodology (section 3) followed (section 4), and the main conclusions (section 5) that have be drawn from the results of the study cases.

2 STATE OF THE ART

Nowadays, behavioural models of economic agents are one of the areas with the most importance inside almost any industry as, for example, in the healthcare industry [3], in the marketing industry [4] or in the food industry [5]. The use of these models is very helpful because they are a tool that makes easier the analysis and posterior comprehension of economic agents' behaviours. They allow us to evaluate how the effects of the changes in the offer policies of the companies affect the behaviour of the different economic agents (the generation companies – GENCOs-, the consumers or the Government). The study of these effects, the reasons behind a decision of purchase or supply can be understood, and, in this way, it will be possible to forecast the behaviour of any market in a more precise way.

2.1 Economic Rationality Theory

Unfortunately, the decisions of the economic agents are not completely rational. In order to explain those irrational behaviours, first, the concept of rational agent needs to be introduced: it is the one that maximizes the expected utility (utilitarianism theory) in a decision [6]. For example, a rational consumer usually does not buy a comb because it is more or less beautiful, but because he wants something to comb his hair. In conclusion, he is going to buy the comb most useful for that task. That is utilitarianism. The main actors (agents) of this model are consumption agents that demand an installation of DG in their factories or homes for different reasons and whose behaviour wants to be modelled.

2.1.1 Bounded Rationality Theory

In this idea it is based the theory of economic rationality. It suggests that any economic agent must behave rationally, this is, following the utilitarianism theory [7]. From the rationality theory originates the bounded rationality theory. This theory will be the source from which we obtain the various utility functions that are applied to the model described in [2] and that models the behaviour of the economic agents. There are various economists of prestige like Herbert Simon [8], a social sciences theorist and American economist of the 20th Century, that defended and took part actively in the development of this theory. The bounded rationality theory emerged due to the necessity to study situations in which the decider lacked from the time, the information and or the capacity of calculus necessary [9] to take the optimal decision. For example, the time needed to take a decision is important because if the consumer does not take enough time analysing the existing products, he may miss the best offer in the market. In summary, the bounded rationality theory is based on being completely objective with the product that the consumer is considering buying in order to minimize the costs or maximize the profits and disregard subjective characteristics of the product that lead to higher costs as how beautiful the product is.

It may be considered that the bounded rationality models can be applied to diverse subjects of discussion like the games of two players [10] based on the prisoner dilemma [11], but for our specific situation, the focus will be targeted on the model [2] already explained in the introduction section. This model will be based in the mathematic calculations of other papers and projects that will help us obtain an equilibrium model of the market [12]. To situate the reader in a clearer context, the model of [2] is explained in the sequel.

The most important application of [2] is to represent the investment decisions taken by both the DG consumers and the GENCOs . This is critical because the rising of investments in DG by final consumers affects directly the incomes in the energy sector. The GENCOs start to turn over lower quantities of money and they see themselves forced to compensate from another businesses of the company, for example, by reducing the cost of production, transportation or energy storage. In order to study these effects, an equilibrium model is proposed in [2] to study distributed and centralized DG expansion planning.

The investment in DG could also trigger GENCO's lowering their prices to be more competitive, creating more efficient electric systems (considering a context where existing regulation allows it). Simultaneously, investments in DG facilitate renewable energy penetration, since most of DG technologies (turbines, solar panels or storage batteries are some examples of these technologies [1]) generate green energy. DG would also help increase the security of the system, helping the reserves in situations of unbalance of offer and demand [13].

2.1.2 Other theories

As well as basing our model on bounded rationality [14], two other theories (experimental economy and behavioural economy) were approached with the intention to complement the first one and in which we have tried to base this work too. Unfortunately, these theories are more complicated to put on practice on model [2] because they deal with qualitative characteristics of the product as how beautiful is the object.

- <u>Experimental economy</u>: it is based on the product design. It exploits characteristics that attract the economic agent. Everyone has different tastes and modelling mathematically those subjective characteristics is quite complicated and the reason why it is so difficult to implement. Besides, it is complex to apply because its ultimate goal is to obtain economic parameters from experiments, which has not been carried out in this work. That's the reason why the experimental economy theory will not be given too much importance.

- Behavioural economy: it is a mix between the two theories mentioned previously: the former, the bounded rationality theory that contributes with the theory of utilitarianism (objective part); and the latter, the experimental economy theory (subjective part) that models economic parameters by experimenting different situations. This theory analyses all the possible aspects of human behaviour but focusing sometimes too much on specific decisions and the reasons behind them. Therefore maximizing or minimizing the utility function is not a matter of special analysis.

There exists a last theory called flexible-bounded rationality [14] that complements the theory of bounded rationality. This theory distinguishes itself from the first in that it makes use of equations and data from study cases to model behaviour and, through the use of AI (Artificial Intelligence) and statistics, it obtains a model that can forecast more precisely the results of future possible situations. It will not be applied to our model because we are not making use of AI. Moreover, the model we use is a fundamental model that does not use statistics to train the outputs.

2.2 Comprehension of Model [2]

In order to better understand the model in [2], some of its equations are going to be explained. As it has been mentioned, in this model, an equilibrium between GENCOs profit maximization and consumers cost minimization is proposed. These two optimization criteria liked by the demand and generation balance constraint are integrated in a unique optimization model that is mathematically equivalent to the mentioned equilibrium model.

2.2.1 GENCOs profits maximization

In first place, the profits maximization for the GENCOs is explained. This maximization is per agent and every agent simultaneously. The goal of this optimization is to maximize the total profits of each GENCO g, considering variables of energy production and installation.

$$\max \left\{ \begin{array}{c} \sum_{t,h,y} \begin{pmatrix} \lambda_{h,y} \cdot q_{t,h,y} \\ -VC_{t,g,y} \cdot q_{t,g,h,y} \end{pmatrix} \\ -\sum_{t,y} IC_{t,g,y} \cdot p_{t,g,y} \end{array} \right\}, \forall g \qquad (1)$$

Each one of these terms is going to be briefly explained but, in case the reader wants more precise information, he should head to the paper we have been referring to [2]. In the optimization:

$\lambda_{h,y} \cdot q_{t,h,y}$: the incomes from selling energy [€].

$VC_{t,g,y} \cdot q_{t,g,h,y}$: represents a term that helps the equilibrium formula be more precise in terms of profits [€].

$\sum_{t,y} IC_{t,g,y} \cdot p_{t,g,y}$: represents total costs of investment in a generation unit, *t*, by a GENCO, g [€].

2.2.2 Clients costs minimization

The next step is the costs minimization of each consumer that must be solved similar to the previous optimization, per agent (client) and simultaneously. Total costs of each client *c*, considering the variables of energy installation, energy demand and energy injection into the grid, are computed.

$$\min \left\{ \begin{matrix} \sum_{y} TP_{c,y} \cdot cp_{c,y} + \sum_{t,y} IC_{t,c,y} \cdot p_{t,c,y} \\ + \sum_{h,y} \begin{pmatrix} (\lambda_{h,y} + TV_{c,y}) \cdot dq_{c,h,y} \\ -(\lambda_{h,y} - TC_{c,y}) \cdot eq_{c,h,y} \end{pmatrix} \end{matrix} \right\}, \forall c \tag{2}$$

$\sum_{y} TP_{c,y} \cdot cp_{c,y}$: this term represents the costs of having a certain amount of power contracted [€].

$\sum_{t,y} IC_{t,c,y} \cdot p_{t,c,y}$: represents total costs of investment in a *t* by a *c* [€].

$(\lambda_{h,y} + TV_{c,y}) \cdot dq_{c,h,y}$: this term represents the final cost of the energy demanded by *c* from the grid [€].

$(\lambda_{h,y} - TC_{c,y}) \cdot eq_{c,h,y}$: this term represents the profits resulting of the energy injected by the *c* into the grid [€].

2.2.3 Integrated optimization model equivalent to the equilibrium model

Finally, optimizations in (1) and (2) are integrated in [2] to achieve the optimization model described in (3). The equivalence proof is complex, and it is described in detail in the annex of [2].

$$\min \left(\sum_g \left\{ \sum_{h,y} \left(\begin{array}{c} \sum_t VC_{t,g,y} \cdot q_{t,g,h,y} \\ +\theta_{g,h,y} \cdot 0.5 \cdot \left(\sum_t q_{t,g,h,y} \right)^2 \end{array} \right) + \sum_{t,y} IC_{t,g,y} \cdot p_{t,g,y} \right\} \atop + \atop \sum_c \left\{ \begin{array}{c} \sum_y TP_{t,c,y} \cdot cp_{t,c,y} + \sum_{t,y} IC_{t,c,y} \cdot p_{t,c,y} \\ + \sum_{h,y} \left[\begin{array}{c} TV_{c,y} \cdot dq_{c,h,y} + TC_{c,y} \cdot eq_{c,h,y} \\ +\theta_{c,h,y} \cdot 0.5 \cdot \left(eq_{c,h,y} - dq_{c,h,y} \right)^2 \end{array} \right] \end{array} \right\} \right) \qquad (3)$$

All the terms in (3) have been previously described but two, those that consider the conjectural variations $\theta_{g,h,y}$ and $\theta_{c,h,y}$ (both in €/MWh^2) of the price with GENCOs and clients productions, respectively. These conjectural variations help model the price-response of the market (see [15] for more details).

2.3 **The Penny Project**

Equation (3) is modified according the model created by "The Penny" European project, see [16]. This project studies the different situations in which an individual can find himself when making a decision and models different utility functions for each one of those situations. This project starts by defining a general equation for the individual's decisions:

$$\max_{x_y{}^i \in X^i} \sum_{y=0}^{Y} \delta^y \cdot \sum_{s \in S} p(s_y) \cdot U(x_i{}^y | s_y) \qquad (4)$$

y: year of the investment
X^i: Set of decision variables, [units of the decision]
δ^y: discount factor, $0 \leq \delta^y \leq 1$, [dimensionless]
$p(s_y)$: probability of each state s_y to happen, $0 \leq \mathrm{p}(\mathrm{s_y}) \leq 1$, [dimensionless]
$x_i{}^y$: decision variable, [units of the decision]
$U(x_i{}^y|s_y)$: Utility Function (positive or negative), [€]

Due to the nature of the problem, it is difficult to estimate the probabilities of the different scenarios reliably. For this reason, this work assumes that the problem is deterministic and therefore (the stochastic model could be studied in the future):

$$\max_{x_y{}^i \in X^i} \sum_{y=0}^{Y} \delta \cdot \sum_{s \in S} U(x_i{}^y | s_t) \tag{5}$$

Utility $U(x_i{}^y | s_t)$ is particularly noteworthy, as it does not represent the actual cost of the investment that the agents have to undertake, but the cost they perceive they will have to assume. It is a function of both the actual cost and a series of utility functions that measure a variety of possible biases the agent may suffer from, as will be further shown in section 4.

On the article [16] a distinction is made for three different categories of biases. These categories represent the deviations of economic agents when doing rational calculation and they are the following: non-standard preferences, they refer to elements that form part of the utility function; non-standard decision making, concerns the set of possible decisions; and non-standard beliefs, takes into account the part of the decisions where probabilities need to be considered.

2.3.1 Non-standard preferences category

This is the main category that is going to be used as a support for our final utility function. There are a lot of examples of utility functions for this category and here the five most important are going to be explained: social norms, rational inattention, loss or risk aversion, reference dependence and present bias (or status quo bias).

2.3.1.1 Social Norms Bias (or Preferences)

Belonging to the non-standard preferences bias category, this bias [17] covers the situations where an economic agent is influenced by what society (or the other agents) may think of his actions and the personality of that agent. In a "two-player game" where one could be a consumer and the other one a GENCO, the utility functions to be maximized are.

$$U_A = \pi_A \cdot (\rho \cdot r + \sigma \cdot s + \theta \cdot q); U_B = \pi_B \cdot (1 - \rho \cdot r - \sigma \cdot s - \theta \cdot q) \tag{6}$$

ρ: aversion, $-1 \leq \rho \leq 1$, [dimensionless]

σ: selfishness (self-interest) or charity (opposite point of view), $-1 \leq \sigma \leq 1$, [dimensionless]

θ: reciprocity, $-1 \leq \theta \leq 1$, [dimensionless]

π_A / π_B: each of the players' payoff in the game (positive or negative), [units of the payoff received]

Each player has a specific payoff assigned by either π_A (GENCO) or π_B (consumer), and, multiplied by the social coefficients represented by ρ, σ and θ, the total losses or gains of the two-player system is obtained. The parameters *r, s,* and *q* are binary variables used to include or exclude the effect of the social coefficients.

The parameter ρ (aversion) represents the aversion of a player to a particular decision taken by the other player. There exists two types of aversions: similarity aversion and behindness aversion. The former represents the reluctance of the investor to follow trends. For example, if a great part of society is buying a new brand of shoes, the investor will not make the same decision of investment due to the fact he does not want to follow trends. On the other hand, the latter aversion considers the fear of the investor of being left behind. For example, if a new product is launched to the market, this investor will make an economic effort to buy it in order not to be "updated". In this project only similarity aversion will be studied. The convenience of ignoring the behindness aversion effect will be justified in section 3, Equation (27.1).

The parameter σ, selfishness, represents the level of self-interest of a player when making a decision. Concretely, it represents how much a player is focused on their own profit or their own minimization of the total costs. The more self-interested player B is, the lower the value of the parameter σ is. As it will be explained later on section 3, only player B will be considered.

Finally, the parameter θ (reciprocity) represents the mutual dependence between the two players. If one player decides to be reciprocal, the other will tend to be reciprocal too. The more reciprocal a player is, the higher the value of the parameter θ is. This parameter is quite similar to the behindness aversion one. The difference lies in that while the reciprocity parameter represents the situations where an agent copies other agents behaviours' (if they invest, he invests), the behindness aversion represents the desire of the agent, *c*, to have all the latest updates. For example, it represents the same desire that a technology geek feels when a new phone comes to the market, he does not want to be old-fashioned, as it has been explained previously.

Some of the values that have been used in social preferences models are the following (also taken from [17]):

		Variables and Restrictions			
		Restrictions	ρ	σ	θ
	Self-Interest	$\rho = \sigma = \theta = 0$	0	0	0
	Altruism	$\rho = \sigma$ & $\theta = 0$	0.212	0.212	0
	Behindness Aversion	$\rho = \theta = 0$	0	0.118	0

Model Situations	Charity	$\sigma = \theta = 0$	0.422	0	0
	Difference Aversion	$\theta = 0$	0.422	-0.14	0
	Reciprocal Charity	$\sigma = 0$	0.425	0	-0.089
	Social Welfare	-	0.424	0.023	-0.111

Table 1. Typical values for the social norms utility function.

Table 1 describes different situations that "The Penny Project" has studied and from which it has obtained the values used on the model. For example, when the three parameters of the utility function are zero, the payoff (the profits) of player B (consumer) are maximized creating a self-interest situation.

2.3.1.2 Rational Inattention Bias

Belonging to the non-standard decision making bias category, this bias [18] [19] covers the situations where the individual presents a lack of sufficient study of a product before taking the decision of investing in it. This usually happens because the individuals try to simplify complex decisions by eliminating some of the features of the product as they have a strong preference over some of the product features or because they underweight aspects of the product that are not salient.

In order to model this behaviour, a parameter is created to measure the level of attention that each economic agent gives to each of the terms (qualities, costs, etc) that belong to the utility function.

$$\widehat{U} = U + (1 - \theta) \cdot o \tag{7}$$

$\widehat{U}$: real value of the product from the perspective of the consumer, $\widehat{V} \geq 0$, [€]
U: real value of some qualities of the product (totally attended), $v \geq 0$, [€]
θ: inattention parameter, $0 \leq \theta \leq 1$, [dimensionless]
o: benefits or costs that are being unattended or insufficiently attended (positive or negative), [€]

The parameter of inattention is only applied to some of the variables of the utility function as it was mentioned before. The individual may have preferences over one of the features of the product and he leaves some of the other features unattended or insufficiently attended. For example, an individual can buy a refrigerator because he sees that it is huge and he is going to have a lot of space for all his food, but at the same time he is not taking attention to the motor inside of it. If that motor is really bad quality, he will have to change it and the cost of changing it is higher than the difference of paying a little bit more for a better refrigerator. Sometimes, when making a decision, important features of a product are not taken into account because of this inattention and it makes the investor lose a lot of money or buy a product that is not as good as another.

2.3.1.3 Loss Aversion Bias

Belonging to the non-standard preferences bias category, the loss aversion bias ([20]) is used to measure how individuals use to be more afraid of loss risks over gain risks. Studies show that losses are more penalized than gains and that is why this bias is represented as a utility function defined by a discontinuous function. The terms of the utility function that represent losses will have a different function adding importance to these ones, than those that represent gains which stay as they are.

$$\max_{x_y{}^i \in X^i} \sum_{y=0}^{Y} \delta^y \cdot \sum_{s \in S} p(s_y) \cdot \left[U(x_i{}^y | s_t, y_c(x_i{}^y) > y_c(E \cdot x_i{}^y) + V(x_i{}^y | s_y, y_c(x_i{}^y) < y_c(E \cdot x_i{}^y))\right] \quad (8)$$

y: year of the investment

X^i: Set of decision variables, [units of the decision]

$x_i{}^y$: decision variable, [units of the decision]

δ^y: discount factor, $0 \leq \delta^y \leq 1$, [dimensionless]

$y_c(x_i{}^y)$: benefits an investor believes he will make in an investment opportunity(positive or negative), [€]

$y_c(E \cdot x_i{}^y)$: turnover that the investor would expect (*E)* as the minimum to not lose money in an investment opportunity ("reference value") (positive or negative), [€]

$p(s_y)$: probability of each state s_t to happen, $0 \leq \mathrm{p}(\mathrm{s_y}) \leq 1$, [dimensionless]

$U(x_i{}^y|s_y)$: Utility Function if $y_c(x_i{}^y) > y_c(E \cdot x_i{}^y)$ (positive or negative), [€]

$V(x_i{}^y|s_y)$: Utility Function if $y_c(x_i{}^y) < y_c(E \cdot x_i{}^y)$ (positive or negative), [€]

2.3.1.4 Present Bias

Belonging to the non-standard preferences bias category, the present bias [22] suggests that consumers are usually more influenced by the close present costs or savings (for example, installation costs) rather than by the future ones (for example, renewing working material 10 years from now). This bias is modelled by adding a discount factor to the terms that represent future costs. The resultant utility function would be the following:

$$\max_{x_y{}^i \in X^i} -I_x{}^0 - \sum_{y=1}^{Y} \delta^y \cdot \widehat{c_x} \quad (9)$$

y: year of the investment

X^i: Set of decision variables, [units of the decision]

$x_i{}^y$: decision variable, [units of the decision]

δ^y: discount factor, $0 \leq \delta^y \leq 1$, [dimensionless]

$I_x{}^0$: investment costs in the year 0, $I_x{}^0 > 0$, [€]

$\widehat{c_x}$: perceived future costs during the lifetime of the investment, $\widehat{c_x} > 0$, [€]

Formula (9) represents the costs of an investment during the life of the product. It can be appreciated that the only terms of the formula affected by the discount factor are the ones that take place during or after the first year ($t \geq 1$). This makes the investment costs (taking place in year 0) gain weight in the utility function by representing the unconscious influence of the present costs. The discount factor can either be constant through the duration of the investment or variable. If the user chooses to have a variable discount factor, the following equation can be applied to simplify the final formula used to calculate the discount factor for each one of the years of the investment.

$$\sum_{y=1}^{Y} \delta^y = \delta \cdot \frac{1-\delta^Y}{1-\delta} \tag{10}$$

The application of equation (12) to (11) leads to the following simplified formula representing the present bias:

$$\max_{x_y{}^i \in X^i} -I_x{}^0 - \delta \cdot \frac{1-\delta^Y}{1-\delta} \cdot \widehat{c_x} \tag{11}$$

2.3.1.5 Reference Dependence Bias

Belonging to the non-standard preferences bias category, the reference dependence bias [21] compares the costs or qualities of a product with a utility reference value that acts as a satisfaction meter. It helps the consumer see if the product that he is going to invest in is better or worse than the reference level that he determined previously as a satisfaction level (reference point). It is directly related to the loss aversion bias and the present bias because it takes into account a reference point from where to start to have profits (loss aversion) and the timing of the election (present bias). The formula would be the following:

$$\max_{x_y{}^i \in X^i} \sum_{y=0}^{Y} \delta^y \cdot [U(x_i{}^y) - adj(\|y_c(x_i{}^y) - y_c(x_0{}^y)\|)] \tag{12}$$

y: year of the investment

X^i: Set of decision variables, [units of the decision]

$x_i{}^y$: decision variable, [units of the decision]

δ^y: discount factor, $0 \leq \delta^y \leq 1$, [dimensionless]

$y_c(x_i{}^y)$: value that the consumer ends up "paying" (positive or negative), [€]

$y_c(x_0{}^y)$: reference value from which the consumer would start considering that a higher value is a loss (positive or negative), [€]

$U(x_i{}^y|s_y)$: value of the product (positive or negative), [€]

Equation (12) represents the utility function with the value $U(x_i{}^y)$ of the product minus an adjustment cost function $adj(\|y_c(x_i{}^y) - y_c(x_0{}^y)\|)$ that represents the distancing from the reference point. Even though these last two categories are reasonable by their own, they are directly related, and it results that there is a simpler way to model the loss aversion and the reference dependence by combining (8) and (12). The result is a discontinuous function that gives more importance to the losses and that is directly affected by a reference point:

$$\max \sum_i p_i \cdot v(x_i|r) \quad where\ v(x_i|r) = \begin{cases} x - r & if\ x \geq r \\ \lambda \cdot (x - r) & if\ x \leq r \end{cases}, \qquad \lambda > 1 \quad (13)$$

p_i: probability of a hypothetical situation to happen, $0 \leq p_i \leq 1$, [dimensionless]

$v(x_i|r)$: utility function (positive or negative), [€]

x_i: value, cost or quality of the product measured, [€]

r: reference point, [€]

λ: loss aversion parameter, $\lambda > 1$, [dimensionless]

The maximization (10) works in the following way: first, there is a probability term that predicts the possibility for each situation to happen. For example, it is used to determine the probability of a situation where a consumer has bought a product for two times the value that he was first thinking of investing. This probability is lower than the one given for the situation where he has paid one and a half times the reference value he had in mind. Then, a utility function subtracts the value of the reference point to the value of the cost or quality of the product in mind. Finally, if the subtraction has a negative value, a loss aversion parameter is applied in order to make that value weigh more in our final decision (making it a higher negative value). Obviously, the maximization term could always be changed for a minimization term in case costs were considered instead of profits. In that case, the loss aversion parameter would be applied to subtractions which result is positive meaning higher costs than expected.

2.3.2 Non-standard decision making category

This bias substitutes the utility function for a heuristic function. This heuristic function could be using a small subset of all the different solutions, or, in rarely occasions, it could also stay as a simple modified utility function. This category is not considered due to the fact that, in order to model the behaviour of economic agents, a mathematical application is needed, and this category does not provide one.

2.3.3 Non-standard beliefs category

It represents the probability of different states to happen. It adds the parameter p mentioned in equation (4). Some errors [16] come up when introducing it like for example: overconfidence, the law of small numbers or the projection-bias (related to the status quo bias seen in the non-standard preferences):

1. Overconfidence is the lack of self-control. Even though you have experienced an error in the past and it completely changes the probabilities of it happening again, there is something that is not considered in these probabilities, the self-control. It has a really big impact on people's decisions because people tend to act based on their guts, on their instinct as they have low self-control.

2. The law of small numbers can be applied, for example, to gambling situations (gambler's fallacy). If a number has been repeated several times in the roulette, the individual is going to gamble against it because he thinks that is almost impossible for it to fall again, even though that the roulette starts again with the same probabilities as in the previous rounds.

3. The projection-bias makes the user give a value to the probabilities based on this present conditions. The decision maker never knows if he is going to change of preferences in a future, so he does not know if those probabilities are correctly estimated for a future situation so that is where the error resides. Directly related to section 3.3.1.5.

These drawbacks have led to this parameter not being implemented in this work

2.4 Other approaches

In addition to all these bias approaches that provide different utility functions, other theories might be considered:

- **Preference rankings**, [23]: this theory proposes that agents decide according to an importance order that is given to all the possible solutions that have been conceived. They may take into account the utility of each of those solutions, but they give an importance factor to each one of them that is what finally makes them decide for one.

- **More knowledge not necessarily positive,** [24]: there are also other ideas that suggest that having all the possible information in hand does not have to lead to better decisions. The reason for this is that, sometimes, too much information can lead people to take into account multiple qualities of the product that are not necessary when taking a decision, especially from the utilitarianism point of view. For example, usually no one would buy a golf ball for the number of holes that it has on its surface and that means that this information is, usually, unnecessary.

Constrained equilibrium model: this theory [25] establishes conditions that restrict the bounded rationality model, like the restriction of possible solutions, or equations that define the model more precisely, for example by representing the subjective behaviour of the agent. This work applies the “satisficing” theory [26] or, as known more commonly, the “Aspiration Level Theory” [27] to the problem of GD investment decision. This theory suggests a series of alternatives and when the economic agent accomplishes a sufficient level of utility or performance for one of them, he has to stop searching for better solutions (as Herbert Simon proposes in [28]).

Thanks to this model that has been created, it will be possible to model the bounded rational (or irrational depending on the point of view of the reader) behaviours of the economic DG agents while trying to maximize their benefits when taking a decision. Specifically, the attention will be pointed to behavioural models focused on the costs minimization of the economic agent in DG investments. This process lets us simulate distinct situations by changing certain parameters that are considered inputs in those analysis.

3 PROPOSED METHODOLOGY

This section is going to discuss the application of what has been found on research papers, articles and scientific magazines with the purpose of perfectionating the model in [2] so as to achieve an improved model that depicts more precisely the behaviour of economic agents when investing in DG technologies. All this information has been explained in section 2 (State of Art).

3.1 Considered Applicable Bias for the Project's Model

As it was carefully detailed in section 2, there are different categories of biases to apply to our model. In this project, only the ones that are considered to influence the most an economic agent when making a decision involving investments in DG have been chosen. More specifically, out of the five different bias categories that were described (social norms, rational inattention, loss aversion, reference dependence and present bias) only three of them are going to be applied: social norms, rational inattention and present bias.

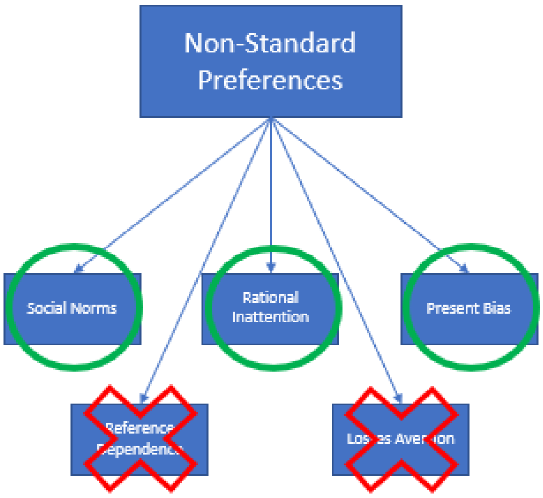


Figure 1. Non-Standard Preferences most important biases.

The reason behind this decision is the following. While loss aversion and reference dependence approaches are mutually related and they both use references variables, the other three categories that were chosen do not. A reference term could be added to the utility function of these biases, but it would significantly increment, probably unnecessarily. As a matter of cautious, it is proposed that these two biases approaches will be considered as future line of research.

In particular, social norms, rational inattention and present bias categories will only be applied to the DG terms of the clients' objective function (equation (2)). The reason behind this decision is that the objective of this project is to analyse the effects that varying the perceived DG costs have only on the client investments.

3.1.1 Social Norms Bias

As previously seen in equation (6), with this bias approach the different behaviours that an economic agent may experience when trying to decide whether to invest in a product are represented by three parameters:

- "Aversion" (ρ), or aversion to follow the trend dictated by the rest of society.
- "Self-interest" (σ) of the economic agent, or how much does the agent disregard the needs of a society or of the neighbours of a community as opposed to their own needs.
- "Reciprocity" (θ), a parameter that represents how the economic agent behaves in relation to the way other economic agents have behaved previously. If the rest of society is doing something good for the rest of the players of it, the individual will be more prompt to act like them.

These terms are fully explained with examples in the State of Art section.

Equation (6) is designed to be applied in a "two player game". As the behaviour of one of the economic agents (the consumers) is being studied, while society is not being considered, the formula has to be modified. One of the two utility functions (U_A) must be eliminated from the formula in order to study the turnover that the clients would have if they behaved irrationally. To simplify the formula, the terms 'r', 's' and 'q' have been set equal to 1. This decision is equivalent to considering the effect of the social coefficients to be always in place.

Equation (6) is then further simplified by uniting all the social coefficients into a single term $S\_soc_{t,c,y}$ resulting in equation (14).

$$S\_soc_{t,c,y} = \left(1 - \rho_{t,c,y} - \sigma_y - \theta_{t,c,y}\right) = \left(1 - \left(aversion\left(p_{t,c,y}\right) + SELF_y + rec\left(p_{t,c,y}\right)\right)\right) \quad (14)$$

$S\_soc_{t,c,y}$: social coefficient

$\rho_{t,c,y} = aversion(p_{t,c,y})$: aversion variable that varies in function of the installed power, $-1 \leq aversion(p_{t,c,y}) \leq 1$

$\sigma_y = SELF_y$: self-interest parameter, $0 \leq SELF_y \leq 1$

$\theta_{t,c,y} = rec(p_{t,c,y})$: reciprocity variable that varies in function of the installed power, $-1 \leq rec(p_{t,c,y}) \leq 1$

The term $S\_soc_{\,t,c,y}$ serves as a form of scaling factor to determine the perceived cost. Thus, higher $S\_soc_{\,t,c,y}$ values, imply a perceived cost that is greater than the actual cost. This is caused by negative values of the social coefficients $(\rho_{t,c,y}, \theta_{t,c,y})$ and low values of the social coefficient σ_y, which denote low reciprocity, high self-interest and similitude aversion. Lower $S\_soc_{\,t,c,y}$ values would in turn cause the perceived cost to be lower than its actual counterpart. This results from positive values of the social coefficients, which reflect the opposite behaviours to those described above.

With the intention to assign a value to each of these parameters, first, a situation to model will be chosen, for example, "Reciprocal Charity" and then a value will be assigned to each parameter. The values and situations will be based on Table 1. Those values will change as a function of the year of investment considered. For example, if during any given year of the timeframe considered a higher value of the variable power installed was obtained in comparison to the previous year, the perceived costs to the investors are lower, due to reciprocity. This means that people are becoming "greener" and more prompt to invest in DG technologies. This is reflected in the parameters with an increase of the variable θ (the more reciprocal an agent is, the higher the value of θ becomes). These changes in the values make the consumers perceive a lower cost of the investment and, therefore, increase their interest in it.

As it has been mentioned before, the variables 'aversion' and 'rec' have been assumed linearly dependent on the power installations. This is the reason why the dependency of these biases on $p_{t,c,y}$ has not been considered to affect the $cp_{c,y}$. As described on the nomenclature section, $cp_{c,y}$ considers the energy generation per unit, *t*, and not the installed power. The relation will be described in (15) and (16):

$$aversion(p_{t,c,y}) = ma \cdot p_{t,c,y} + ba \tag{15}$$

ma: slope of the aversion function [dimensionless/MW], $-\infty \leq ma \leq \infty$
ba: intercept of the aversion function [dimensionless], $-1 \leq ba \leq 1$

From our knowledge of the DG market, it can be estimated that the DG power installed in a single year will vary between 0 and 100 GW, while the aversion factor will go from -0.2 to -0.5 at most. Given the linear dependency of the aversion factor on the installed power, we will use these extreme points to determine the slope and intercept of said dependency.

$$\begin{Bmatrix} p_{t,c,y} = 0\ MW \ \rightarrow -0.2 = ma \cdot 0 + ba = ba \\ p_{t,c,y} = 100000\ MW \rightarrow -0.5 = ma \cdot 100000 - 0.2 \rightarrow ma = -3 \cdot 10^{-6} \end{Bmatrix}$$

Therefore:

$$aversion(p_{t,c,y}) = -3 \cdot 10^{-6} \cdot p_{t,c,y} - 0.2$$

ba = -0.2

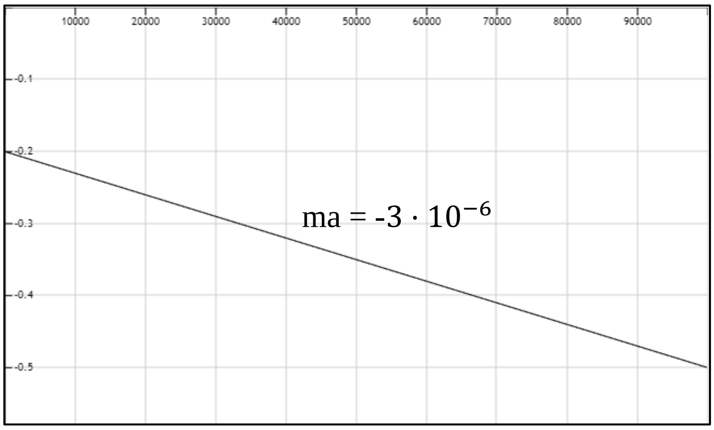


Figure 2. Installed Power p(MW) -horizontal axis- vs. Aversion ρ(dimensionless) -vertical axis-.

Assuming also linearity in the reciprocity factor leads to:

$$rec(p_{t,c,y}) = mr \cdot p_{t,c,y} + br \tag{16}$$

mr: slope of the reciprocity function [1/MW], $0 \leq mr \leq \infty$
br: intercept of the reciprocity function [dimensionless], $0 \leq br \leq 1$

A similar procedure to the one employed for determining the slope and intercept of the aversion factor is used for the reciprocity factor. In this case, we consider that reciprocity will vary from 0.05 to 0.2.

$$\left\{ \begin{array}{c} p_{t,c,y} = 0\ MW \rightarrow 0.05 = mr \cdot 0 + br = br \\ p_{t,c,y} = 100000\ MW \rightarrow 0.2 = mr \cdot 100000 + 0.05 \rightarrow mr = 1.5 \cdot 10^{-6}\ [1/MW] \end{array} \right\}$$

Therefore:

$$rec(p_{t,c,y}) = 1.5 \cdot 10^{-6} \cdot p_{t,c,y} + 0.05$$

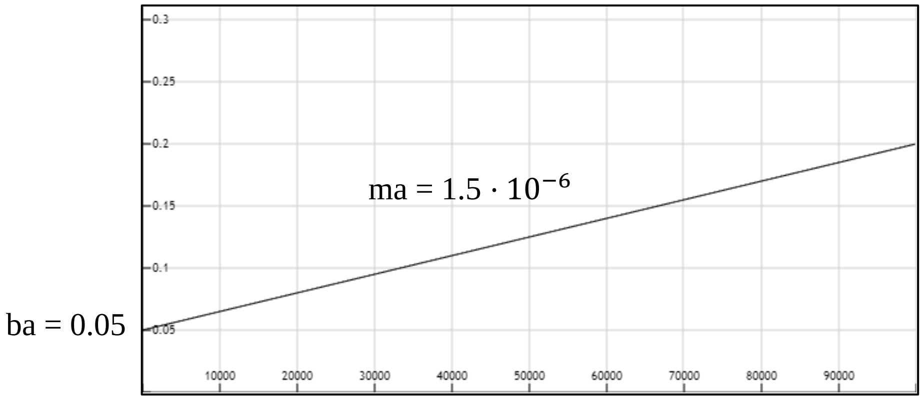


Figure 3. Installed Power (MW) vs. Reciprocity (dimensionless)

The values assigned for the intercepts *ba* and *br* will depend on the scenario simulated. These values are based on the ones displayed on Table 1 and they are obtained in [17] from real life experiments.

The clients' minimization objective function considering only the social norms bias would be the one shown in equation (17).

$$min \left\{ \begin{array}{c} \sum_{t,y} \left(1 - \left(AVERSION_y + SELF_y + REC_y\right)\right) \cdot TP_{c,y} \cdot cp_{c,y} \\ + \sum_{t,y} \left(1 - \left(aversion(p_{t,c,y}) + SELF_y + rec(p_{t,c,y})\right)\right) \cdot IC_{t,c,y} \cdot p_{t,c,y} \\ + \sum_{h,y} \begin{pmatrix} (\lambda_{h,y} + TV_{c,y}) \cdot dq_{c,h,y} \\ -(\lambda_{h,y} - TC_{c,y}) \cdot eq_{c,h,y} \end{pmatrix} \end{array} \right\}, \forall c \qquad (17)$$

3.1.2 Rational Inattention Bias

This category of bias is used to model the situations in which an economic agent lacks the necessary information to make an optimal decision regarding an investment in a product. This lack of information may be the result of not having the calculation resources (for example, programs to determine the installation costs), the data or the time sufficient.

In order to model this problem, a parameter has been added that multiplies the terms of the clients' objective function that are not easy to be measured: the installation costs. This parameter will make those costs have a lower value than originally and, in consequence, it will simulate the unwise decisions that economic agents make when they do not have the sufficient information of a product. If the consumer oversees any information of the product, he will be disregarding some of the important costs related to it and he will end up having a cheaper perception of that product. This will lead to a higher interest in the investment than if he had all the available information and that is the reason why the inattention coefficient will have a value lower than 1. In conclusion, the more unattended the product, the cheaper the perception of the costs and the higher the investments in the product.

As in the previous bias category (social norms), this coefficient will be applied only to DG consumers and specifically on the installation costs and the contracted power costs. The reason is the same as in the last coefficient: the simulated scenarios concern investments in DG technologies and those are the terms that only matter to the clients.

In addition, this parameter will depend on the duration of the investment (as it happened with the social norms parameters). During the investment, the clients will be gaining resources, information or experience and will be able to predict the costs more precisely making the absolute value of the inattention parameter diminish progressively. For example, this change can also be seen in other markets as the real-state one. Nowadays more and more apps have appeared that offer all the information imaginable. This change will be represented with an "information discount" parameter that will be discounting each year a percentage of the value (equal to more attention). This percentage will be fixed at 2% that is a value that was considered acceptable to represent this effect.

With all this known, the rational inattention bias is described by the following equation:

$$RI_{c,y} = \left(1 - \theta_{c,y}\right) = \left(1 - INAT_{CENT\,c,y}\right) \tag{18}$$

The previous equation will be applied to (2) obtaining the following optimization:

$$min \left\{ \begin{array}{c} \sum_{y} INAT_{TP\,c,y} \cdot TP_{c,y} \cdot cp_{c,y} \\ + \sum_{t,y} INAT_{IC\,c,y} \cdot IC_{t,c,y} \cdot p_{t,c,y} \\ + \sum_{h,y} \begin{pmatrix} (\lambda_{h,y} + TV_{c,y}) \cdot dq_{c,h,y} \\ -(\lambda_{h,y} - TC_{c,y}) \cdot eq_{c,h,y} \end{pmatrix} \end{array} \right\}, \forall c \tag{19}$$

$INAT\_IC_{c,y}$: inattention to installation costs, $0 < INAT\_IC_{c,y} < 1$, [dimensionless]
$INAT\_TP_{c,y}$: inattention to the power term tariff, $0 < INAT\_TP_{c,y} < 1$, [dimensionless]

In the case of equation (19), the explanation for the irrational behaviour of the agents is the inattention they give to the product while on (17) only the social behaviour affects.

3.1.3 Present Bias

This bias category represents the situations in which the economic agents have a high respect for the first payments of an investment because those are the expenses that have to be paid more promptly. Usually, the payments that take place years later from the present situation are not considered the most important ones because the agents identify them as a problem of their "future self". For example, the first payment of a car represents the biggest one and the agent classifies it as the most important one when considering whether to invest in that car or not. For that reason, the rest of the payments related to the car will be overseen and not considered as important as the first one. This happens with almost any investment because, in general, the first payment is always the most sizeable.

In order to model this irrational behaviour, this bias is going to be based on equation (11) and, finally, a variable discount factor will be used. The intention is to consider the first payment as the most important, but also making use of the discount factor as it is used on any other economic model. Besides, the formula will be modified from a maximization to a minimization because the costs of an investment are being taken into consideration and not the benefits. The final utility function that we are going to apply to the clients' minimization formula is the following:

$$\underset{x_y{}^i \in X^i}{\text{Min}}\ u_0 + \sum_{y=1}^{Y} \delta^y \cdot u_y = \underset{x_y{}^i \in X^i}{\min}\ -I_x{}^0 - \sum_{y=1}^{Y} \delta^y \cdot \widehat{c_x} \quad (20)$$

y: year of the investment

$I_x{}^0$: investment costs in the year 0, $I_x{}^0 > 0$

δ^y: discount factor, $0 < \delta^y < 1$

$\widehat{c_x}$: perceived future expenses during the lifetime of the investment (positive or negative)

In the sequel, the minimization will not be represented with the present bias effect as it would be too complex due to the high number of terms. However, this bias will be applied in the terms of the equation that take place in years different from the first one of the investments. Indeed, as a discount factor was already considered in [2], no modifications will be introduced. The general minimization formula will be described with the other two biases in equation (27) of next section 3.2.

3.2 Application of the Biases on the Model studied by the IIT

After considering and explaining the reasons behind the election of these three biases, the final integrated proposal will be shown at once in this section. In order to study the effect of all the parameters combined, an irrationality coefficient has been created:

The final clients' minimization formula will be as follows:

$$\min\left\{\begin{array}{c}\sum_{y}\Big(1-\big(AVERSION_y+SELF_y+REC_y\big)\cdot INAT_{TP_{c,y}}\Big)\cdot TP_{c,y}\cdot cp_{c,y}\\ +\sum_{t,y}\Big(1-\Big(aversion\big(p_{t,c,y}\big)+SELF_y+rec\big(p_{t,c,y}\big)\Big)\cdot INAT_{IC_{c,y}}\Big)\cdot IC_{t,c,y}\cdot p_{t,c,y}\\ +\sum_{h,y}\begin{pmatrix}(\lambda_{h,y}+TV_{c,y})\cdot dq_{c,h,y}\\ -(\lambda_{h,y}-TC_{c,y})\cdot eq_{c,h,y}\end{pmatrix}\end{array}\right\},\ \forall c \quad (21)$$

At this point the variables “aversion” and “rec” will be substituted by equations (15) and (16).

$$\min\left\{\begin{array}{c}\sum_{y}\Big(1-\big(AVERSION_y+SELF_y+REC_y\big)\cdot INAT_{TP_{c,y}}\Big)\cdot TP_{c,y}\cdot cp_{c,y}\\ +\sum_{t,y}\Big(1-\Big((ma+mr)\cdot p_{t,c,y}+(ba+br)+SELF_y\Big)\cdot INAT_{IC_{c,y}}\Big)\cdot IC_{t,c,y}\cdot p_{t,c,y}\\ +\sum_{h,y}\begin{pmatrix}(\lambda_{h,y}+TV_{c,y})\cdot dq_{c,h,y}\\ -(\lambda_{h,y}-TC_{c,y})\cdot eq_{c,h,y}\end{pmatrix}\end{array}\right\},\ \forall c \quad (22)$$

By developing the formula, some terms evolve to become the multiplication of two variables ($p_{t,c,y}\cdot cp_{c,y}$ or $p_{t,c,y}^2$)

$$\min\left\{\begin{array}{c}\sum_{y}\Big(1-\big(AVERSION_y+SELF_y+REC_y\big)\cdot INAT_{TP_{c,y}}\Big)\cdot TP_{c,y}\cdot cp_{c,y}\\ +\sum_{t,y}\Big[\Big(1-\Big((ba+br)+SELF_y\Big)\cdot INAT_{IC_{c,y}}\Big)\cdot IC_{t,c,y}\cdot p_{t,c,y}-(ma+mr)\cdot INAT_{IC_{c,y}}\cdot IC_{t,c,y}\cdot p_{t,c,y}^2\Big]\\ +\sum_{h,y}\begin{pmatrix}(\lambda_{h,y}+TV_{c,y})\cdot dq_{c,h,y}\\ -(\lambda_{h,y}-TC_{c,y})\cdot eq_{c,h,y}\end{pmatrix}\end{array}\right\},\ \forall c \quad (23)$$

Now things will be simplified even more by making some assumptions. We assume that the power term tariff, *TP*, is something that is not going to have any inattention ($INAT\_TP_{c,y}=0$). Then:

$$Atp_{c,y}=\Big(1-\big(AVERSION_y+SELF_y+REC_y\big)\cdot INAT\_TP_{c,y}\Big)=1$$

Therefore:

$$\min\left\{\begin{array}{c}\sum_{y}TP_{c,y}\cdot cp_{c,y}\\ +\sum_{t,y}\big[Aic_{c,y}\cdot IC_{t,c,y}\cdot p_{t,c,y}-Bic_{c,y}\cdot IC_{t,c,y}\cdot p_{t,c,y}^2\big]\\ +\sum_{h,y}\begin{pmatrix}(\lambda_{h,y}+TV_{c,y})\cdot dq_{c,h,y}\\ -(\lambda_{h,y}-TC_{c,y})\cdot eq_{c,h,y}\end{pmatrix}\end{array}\right\},\ \forall c \quad (24)$$

where $Aic_{c,y}$ and $Bic_{c,y}$ are:

$$Aic_{c,y} = \left(1 - \left((ba + br) + SELF_y\right) \cdot INAT_{IC_{c,y}}\right) \tag{25}$$

$$Bic_{c,y} = (ma + mr) \cdot INAT_{IC_{c,y}} \tag{26}$$

Finally, taking into consideration (24) and (1), the next integrated cost minimization must be solved.

$$\min \left(\sum_c \left\{ \begin{array}{c} \sum_y TP_{c,y} \cdot cp_{c,y} \\ + \sum_{t,y} \left[Aic_{c,y} \cdot IC_{t,c,y} \cdot p_{t,c,y} - Bic_{c,y} \cdot IC_{t,c,y} \cdot p_{t,c,y}^2 \right] \\ + \sum_{h,y} \left[\begin{array}{c} TV_{c,y} \cdot dq_{c,h,y} + TC_{c,y} \cdot eq_{c,h,y} \\ + \theta_{c,h,y} \cdot 0.5 \cdot \left(eq_{c,h,y} - dq_{c,h,y}\right)^2 \end{array} \right] \end{array} \right\} \right) \tag{27}$$

This integration is a "mathematical trick" that consists of doing the Lagrangian of each of the separated minimization or maximization objective functions (clients and centralized agents respectively), do the derivative and equal it to 0 and to prove that these derivatives are the same as the corresponding lagrangian of (27). In case the reader wants a more thorough explanation of the "mathematical trick", it is explained in [2].

Unfortunately, there is one limitation derived from (27). There is a quadratic term that is preceded by a minus ($-Bic_{c,y} \cdot IC_{t,c,y} \cdot p_{t,c,y}^2$) which leads to a non-convex objective function. This problem can be solved by changing the sign of the quadratic term. As the term $Bic_{c,y}$ can be negative due to the sum of the slopes *ma* and *mr* (26), the sign of the whole term would be changed to positive.

Reciprocity, as commented previously, represents the situations where an agent invests in a product because of the necessity to copy the behaviour of the rest of the agents. This variable (reciprocity) has a positive correlation with the power instalments, ***p***, therefore the aversion variable needs to have a negative slope. This would represent a similarity aversion case. For example, in such a case (similarity aversion), if the agents perceive an increase in other agent's *p*, they will avoid making the same decisions as them and, in consequence, they will decrease their investment (negative correlation).

$$ma < 0 \tag{28}$$

$$mr > 0 \tag{29}$$

As a result of the constraints (29) and (30), the number of case studies is limited. For example, it is not possible to run a scenario in which the variables' slopes (*ma* and *mr*) are positive because, as explained, the solver would not be able to find an optimal solution. For this reason, only two study cases (original case and similarity aversion case) will be analysed on section 4.

4 RESULTS

In this section, the results obtained from the application of our proposal (section 4) to the model in [2] will be discussed. To acquire these results, a set of study cases will be created by running a number of simulations where the parameters proposed in section 4 are modified. This is done in order to depict varying degrees of irrational behaviour from the agents.

Firstly, the base case will be run. In this scenario no irrationality biases are considered representing a scenario where the agents are rational, objective when deciding whether to invest in DG or not.

Secondly, only the effect of inattention will be studied in order to understand the effect that different knowledges of the product have on the potential investments and demand of energy to the network. This effect will be studied by keeping the other social coefficients constant throughout three different cases. The variation of the inattention within each scenario is a 2% information discount rate as said on section 4.1.2.

An additional three cases will be constructed varying self-interest instead with the purpose of analysing the effect that different degrees of selfishness can have on the installed power and demand of energy of the network. Table 2 contains the values of these coefficients that will be used for these cases.

All of these cases will be evaluated for a 15 year period scenario (2018-2032) with the purpose to recreate a real life investment on DG technologies.

	Rational Inattention	**Self-Interest**	**Aversion**	**Reciprocity**	**Discount Rate**
Base Case	0	0	0	0	0.03
Low Inattention High Selfishness	Decreases 0.12 →0.07	Decreases 0.1 →0.05	$-0.003 \cdot p_{t,c,y} - 0.2$	$0.002 \cdot p_{t,c,y} - 0.111$	0.03
Medium Inattention High Selfishness	Decreases 0.4 →0.23	Decreases 0.1 →0.05	$-0.003 \cdot p_{t,c,y} - 0.2$	$0.002 \cdot p_{t,c,y} - 0.111$	0.03
High Inattention High Selfishness	Decreases 0.7 →0.42	Decreases 0.1 →0.05	$-0.003 \cdot p_{t,c,y} - 0.2$	$0.002 \cdot p_{t,c,y} - 0.111$	0.03

Medium Inattention Medium Selfishness	Decreases 0.4 →0.23	Decreases 0.38 →0.23	$-0.003 \cdot p_{t,c,y} - 0.2$	$0.002 \cdot p_{t,c,y} - 0.111$	0.03
Medium Inattention Low Selfishness	Decreases 0.4 →0.23	Decreases 0.5 →0.66	$-0.003 \cdot p_{t,c,y} - 0.2$	$0.002 \cdot p_{t,c,y} - 0.111$	0.03

Table 2. Comparison of the irrationality terms values per scenario.

As a reminder, a brief explanation of the irrationality terms will be made:

- Rational Inattention: considers the lack of attention of the agent with respect to the study of the product as an investment, due to the dearth of time for taking the decision, no knowledge of the product, shortage of resources, etc.

- Aversion: or aversion to follow the trend dictated by the rest of society.

- Reciprocity: this variable represents how much an agent considers the needs of a society or of the neighbours of a community as opposed to their own needs.

- Self-Interest: this parameter represents the behaviour of an economic agent in relation to the behaviour of the rest of economic agents.

Aversion and Reciprocity depend on installed power ***p***, as was discussed in section 4. The dependency function for Reciprocity is calculated by applying the methodology from section 4 with the intercept value obtained from Table 1. As Similarity Aversion is not considered in Table 1, its intercept value was assumed to be -0.2, since it is of opposite sign and similar magnitude to Behindness Aversion from Table 1. The same methodology from section 4 was applied in order to determine the slope of the dependency.

The results obtained will be compared and analysed in order to assess the sensitivity of the parameters that have been added to formula (27). These results were obtained by iterating the following variables that are present on formula (27): energy production, energy installation, energy demand and energy injection into the grid.

The output variables that will be analysed in each study case are the following:

- The costs to the system.
- The energy installed per DG technology (batteries -CARG- and solar) by distributed agents.
- The demanded energy to the system.

- The correlation (R^2) between the total DG power installed per scenario and the total demanded energy per scenario.
- The power installed per technology (batteries -CARG-, wind, combined cycle -CC-, solar and, finally, turbine generation -TG-) by distributed and centralized agents.

The economic agents that are present in these scenarios are the clients and the GENCOs. This last one will only be considered for the analysis of the last output variable. The clients are the following:

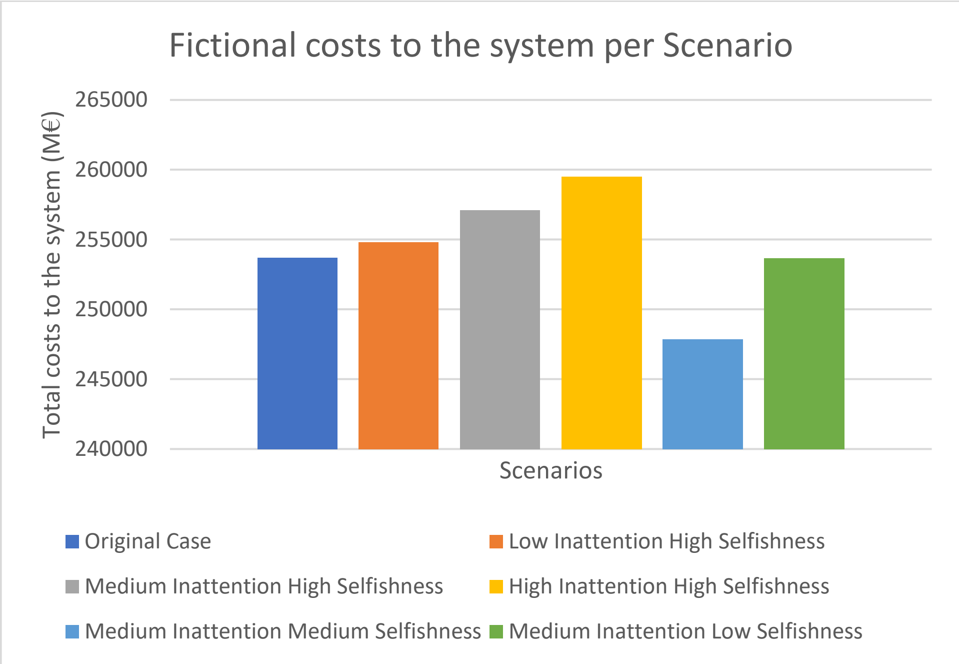
clients	sectors
C01	metalurgia
C02	quimica
C03	industrialimentacion
C04	maderapapel
C05	mineria
C06	comercioservicios
C07	resiunifami
C08	resibloque
C09	resiunifamiclima
C10	resibloqueclima
C11	restauracion
C12	comeralimentacion

Table 3. List of sector of clients by their code names.

4.1 Fictional costs to the system analysis

	Base Case	Low Inattention High Selfishness	Medium Inattention High Selfishness	High Inattention High Selfishness	Medium Inattention Medium Selfishness	Medium Inattention Low Selfishness
Costs	253702.64	254800.86	257097.26	259513.38	247885.29	253657.96

Table 4. Data comparison of the costs to the system per scenario (M€).



Graph 1. Fictional costs to the system per scenario over the 15-year investment period.

Table 4 and Graph 1 contain the costs to the system values calculated by the model for all cases mentioned. The costs to the system represent the money value invested in the system along the investment timeframe considered. As commented on the objectives described in section 2, this project models the irrational behaviour of the agents when investing in DG technologies. In particular, as the original case scenario does not consider those irrationality terms, it can be assumed that these are the real, objective, costs when no biases affect the product perception. The rest of scenarios will depict fictional perceived costs for the consumer.

As would be expected, higher inattention values imply less knowledge of the product resulting in a higher perception of the investment cost which, in turn, increases the total costs that took place in the system. On the other hand, the variation of the self-interest parameter is not directly related with the output variation of the total fictional costs.

4.2 DG installed by clients analysis

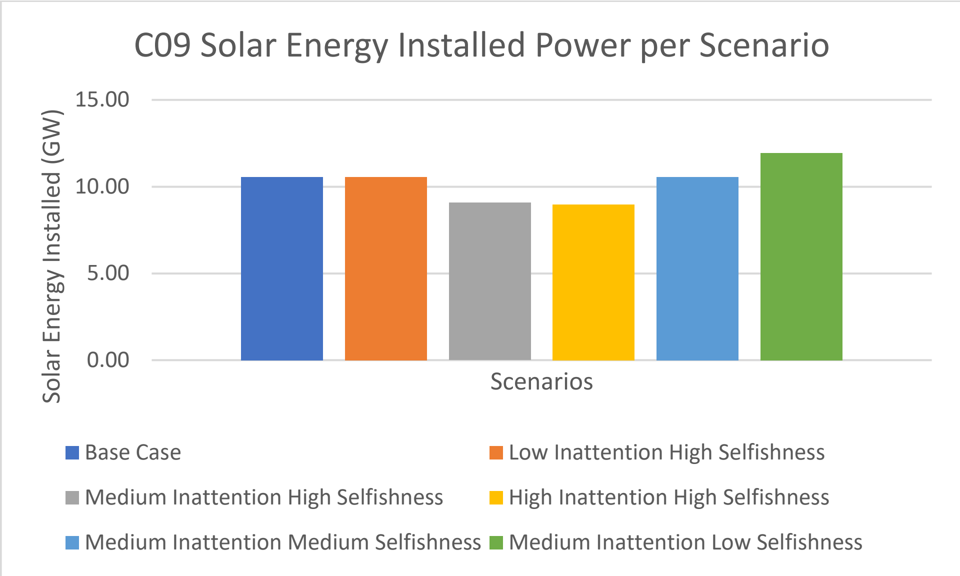
	Base Case	Low Inattention High Selfishness	Medium Inattention High Selfishness	High Inattention High Selfishness	Medium Inattention Medium Selfishness	Medium Inattention Low Selfishness
C01	4.99	4.99	4.91	4.55	4.99	6.02
C02	1.76	1.76	1.76	1.60	1.76	2.12
C03	3.96	3.96	3.96	3.62	3.96	4.22
C04	2.54	2.54	2.54	2.32	2.54	2.70
C05	2.13	2.13	2.13	1.95	2.13	2.27

C06	23.80	23.80	23.78	23.78	23.80	23.80
C07	5.36	5.36	5.18	5.01	5.36	5.43
C08	2.68	2.68	2.59	2.59	2.68	2.77
C09	10.56	10.56	9.07	8.98	10.56	11.95
C10	5.69	5.16	5.00	4.58	5.16	6.30
C11	0.00	0.00	0.00	0.00	0.00	1.62
C12	2.78	2.78	2.70	2.51	2.78	2.79
Total	66.25	65.72	63.61	61.49	65.72	72.00

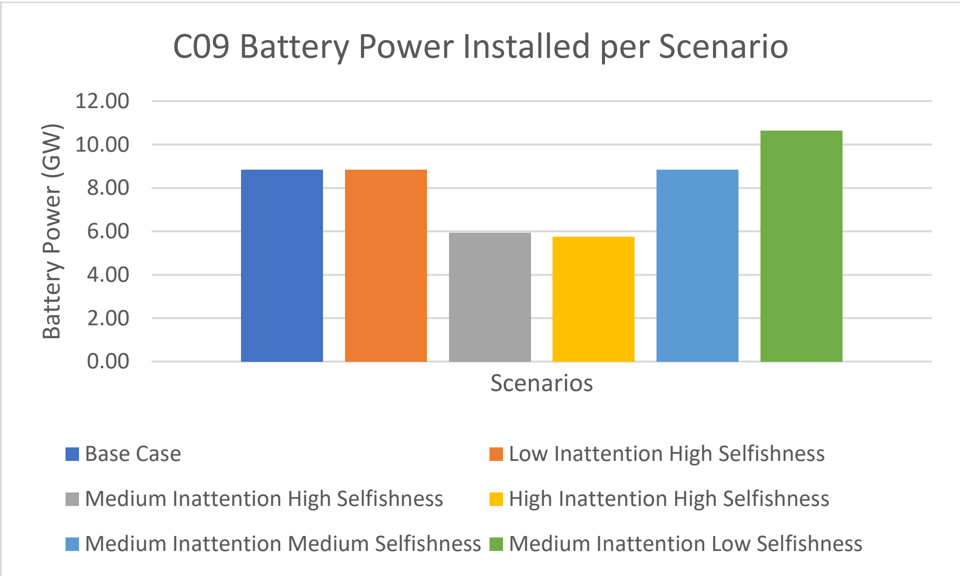
Table 5. Data comparison of solar energy installed per client and scenario (GW).

	Base Case	**Low Inattention High Selfishness**	**Medium Inattention High Selfishness**	**High Inattention High Selfishness**	**Medium Inattention Medium Selfishness**	**Medium Inattention Low Selfishness**
C01	1.99	1.99	1.87	1.33	1.99	2.82
C02	0.70	0.70	0.70	0.47	0.70	0.99
C03	1.18	1.18	1.18	1.14	1.18	1.21
C04	0.76	0.76	0.76	0.73	0.76	0.77
C05	0.64	0.64	0.64	0.62	0.64	0.65
C06	7.52	7.52	7.52	7.52	7.52	7.52
C07	3.52	3.52	3.16	3.16	3.52	3.65
C08	1.76	1.76	1.58	1.58	1.76	1.83
C09	8.83	8.83	5.92	5.75	8.83	10.64
C10	4.61	3.87	3.02	2.87	3.87	5.29
C11	4.87	4.87	4.87	4.87	4.87	5.22
C12	1.04	1.04	1.02	0.97	1.04	1.04
Total	37.40	36.66	32.22	31.00	36.66	41.64

Table 6. Data comparison of battery power installed per client and scenario (GW).



Graph 2. Solar energy installed (GW) per scenario by client 9 (C09) over the 15-year investment period.



Graph 3. Battery Capacity installed (GW) per scenario by client 9 (C09) over the 15-year investment period.

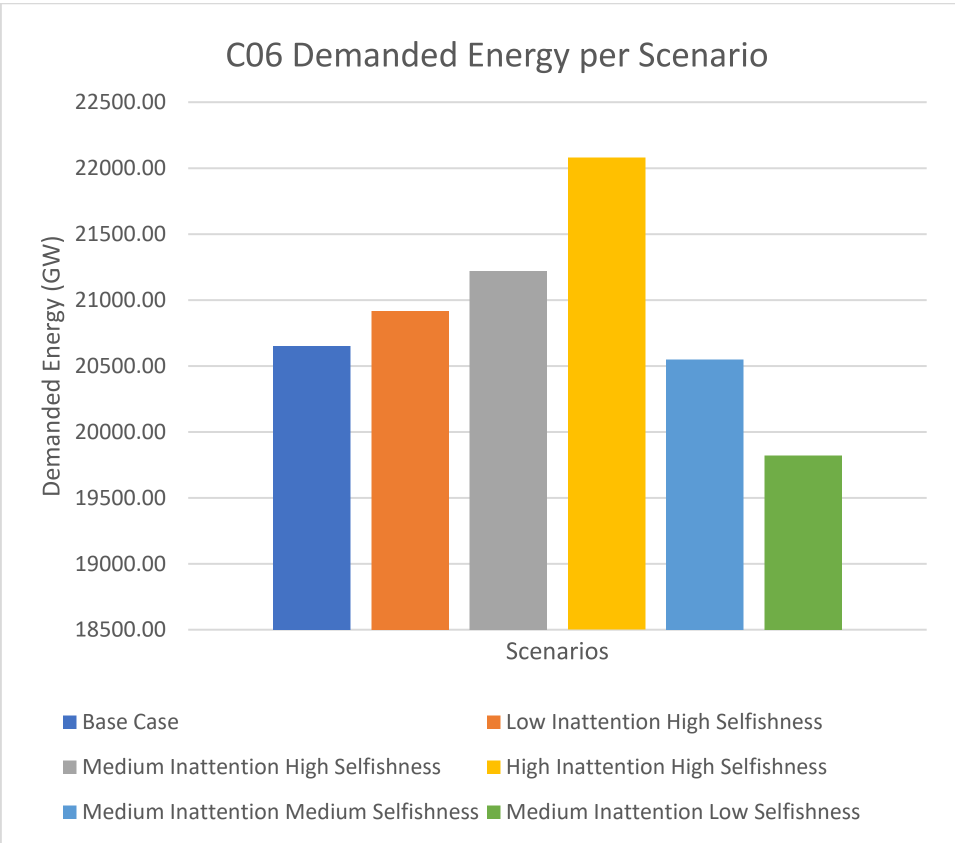
Tables 5 and 6 contain the DG installed power (for batteries and solar energy) values calculated by the model for all cases mentioned. To better show the impact of the social coefficients on the clients behaviour the focus will be targeted to the behaviour of client 9 (C09). Their installation decisions are displayed in Graph 2 and 3.

As would be expected, higher inattention values imply less knowledge of the product resulting in a higher perception of the cost which in turn discourages investing. On the other hand, as the self-interest parameter decreases, which signifies more altruistic behaviour, the investments by clients in solar and batteries technologies increase.

4.3 Demanded energy to the market by client analysis

	Base Case	Low Inattention High Selfishness	Medium Inattention High Selfishness	High Inattention High Selfishness	Medium Inattention Medium Selfishness	Medium Inattention Low Selfishness
C01	8233.81	8239.43	8275.07	8365.79	8239.66	8070.12
C02	2901.06	2903.08	2914.71	2950.29	2903.10	2831.00
C03	2755.51	2797.59	2881.66	2997.27	2699.77	2512.96
C04	1760.35	1786.21	1842.54	1919.82	1723.19	1609.94
C05	1478.16	1499.39	1547.67	1613.83	1445.53	1354.08
C06	20652.04	20917.82	21220.28	22078.45	20550.75	19821.11
C07	4673.41	4730.56	4829.29	4962.42	4667.07	4420.96
C08	2162.78	2177.43	2241.35	2347.66	2168.62	2060.50
C09	8321.44	8396.98	8635.39	8866.51	8326.51	7729.35
C10	3332.61	3439.18	3508.81	3709.85	3336.03	3125.33
C11	2046.16	2042.80	2035.78	2026.62	2050.34	1993.63
C12	2217.12	2240.61	2316.07	2366.42	2217.43	2101.45
Total	60534.49	61171.15	62248.68	64205.00	60328.04	57630.50

Table 7. Data comparison of demanded energy per client and scenario (GW).

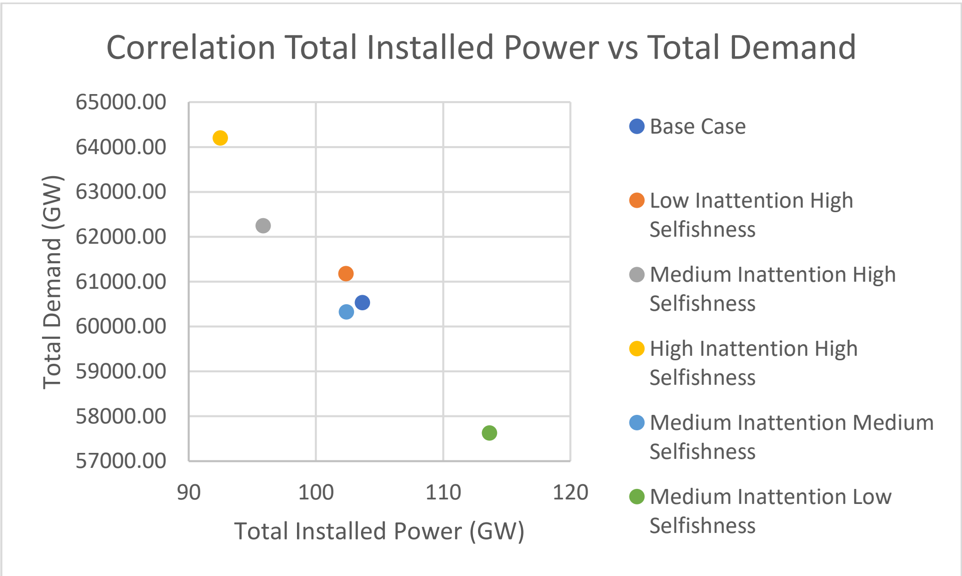


Graph 4. Demanded energy (GW) per scenario by client 6 (C06) over the 15-year investment period.

Table 7 contains the demanded energy values calculated by the model for all cases mentioned. To better show the impact of the social coefficients on the clients behaviour we will focus on the behaviour of client 6 (C06 - services). Their energy demand decisions are displayed in Graph 4.

As has been commented, higher inattention values imply less knowledge of the product resulting in a higher perception of the cost which in turn discourages investing. As a result of lower investments, the clients need to demand more energy to the network, therefore, the higher the inattention, the higher the demand. On the other hand, as the self-interest parameter decreases (less altruistic), the investments increase and, in consequence, the necessity to demand energy to the network is lower.

4.4 Demanded energy to installed power correlation analysis



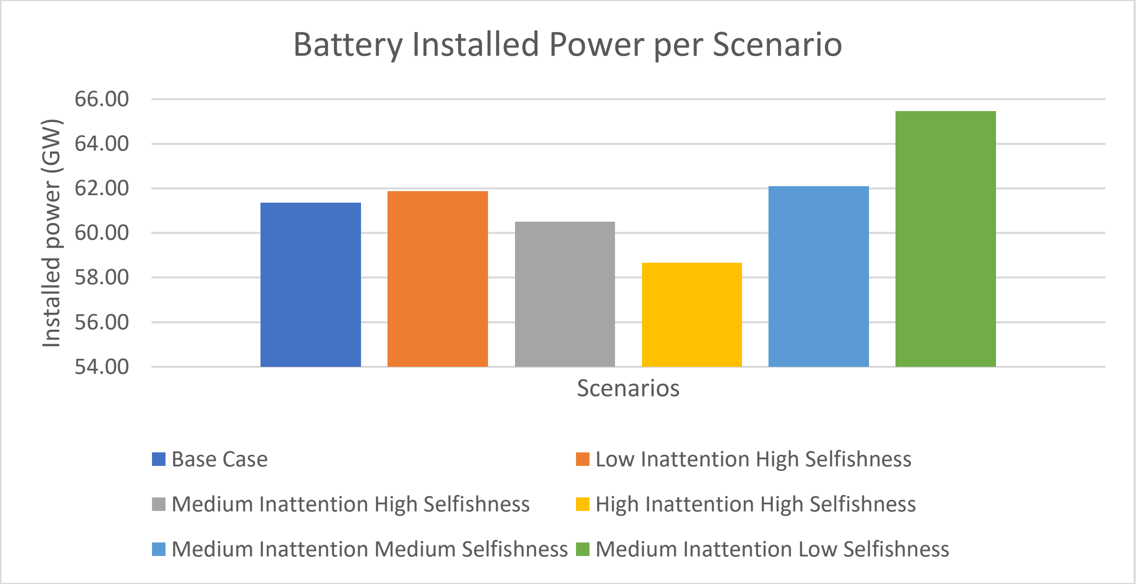
Graph 5. Correlation between Total Demanded Energy (GW) per scenario vs. Total Installed Power (client investors) per scenario.

As could be perceived in the last two sections (5.2 and 5.3), there is a relation between the demanded energy and the installed power. The higher the increase in installed power per scenario is, the higher the decrease in demanded energy to the market as seen in Graph 5. This relation is strong as the parameter R^2 (0.9604) determines.

4.5 DG installed by clients and GENCOs per technology analysis

	Base Case	Low Inattention High Selfishness	Medium Inattention High Selfishness	High Inattention High Selfishness	Medium Inattention Medium Selfishness	Medium Inattention Low Selfishness
CARG	61.33	61.86	60.50	58.65	62.10	65.46
CC	0.00	0.00	0.00	0.00	0.00	0.00
eolica	342.30	342.30	342.30	342.30	342.30	342.30
solar	100.59	100.59	100.59	131.37	100.59	100.59
TG	0.00	0.00	0.00	0.00	0.00	0.00
Total	565.55	566.61	563.89	590.96	567.09	573.80

Table 8. Data comparison of installed power per technology and scenario (GW).



Graph 6. Batteries installed power (GW) by agents and GENCOs per scenario.

Table 8 contain the DG installed values calculated by the model for all scenarios mentioned. To better show the impact of the social coefficients on the DG installed power by consumers and GENCOs, we will focus on the variation of the irrationality terms for the batteries. Their installation decisions are displayed in Graph 6.

The higher inattention values, the lower the knowledge of the product, the higher the perception of the costs and, supposedly, the lower the investments in technologies. However, in this particular case, the variation of the perception of the cost does not have a clear reflection on the installed power. On the other hand, as the self-interest parameter decreases, which signifies less altruistic behaviour, the perception of the cost goes down increasing investments.

5 CONCLUSIONS

In this project, CEVESA has been modified in order to better model the behaviour of economic agents and be able to recreate more precisely the investments in DG technologies. This has been done by applying the bounded rationality biases found in [17].

After obtaining the results on section 5, a general conclusion can be reached in a Similarity Aversion scenario concerning:

1. The sensitivity of the rational inattention and the selfishness parameters.
2. The correlation between irrationality terms.
3. The correlation between the instalments and the demand energy variables.

- Rational Inattention: the higher the inattention on the product, the higher the perception of the costs and, consequently, the lower the instalments of DG technologies. This results in a higher demand of energy to the market in order to compensate the lack of energy that DG technologies would provide to consumers.

$$\uparrow Inattention = \uparrow Perceived\ Costs = \downarrow Investments\ = \uparrow Demand$$

- Self-Interest: the lower the selfishness of the client, the higher the investment in DG technologies. This consequently results in a decrease of the demanded energy from the market by the client because the energy is already being auto generated.

$$\downarrow SelfInterest = \uparrow Investments\ = \downarrow Demand$$

- Correlation between irrationality terms: based on the results obtained in section 5, it can be concluded that the irrationality terms are modelled in a similar way and have a similar effect on the perceived costs, even though the concept behind each one of those is different. In general, these terms are modelled by adding a coefficient that makes the real costs become fictional (or perceived) costs.

- Correlation between installed power and demanded energy: as seen in Graph 5, the demanded energy to the network is strongly correlated to the installed power. The higher the instalments, the lower the necessity of the clients to demand energy from the network. This correlation is reflected on the R^2 parameter (0.9604).

The methodology used in this project is an acceptable approach to the modelling of economic agents' behaviour. However, there are several complications:

- The **algorithm used** in order to optimize (27) is not adapted to process the presence of a negative quadratic term and, as a consequence, the set of study cases is limited.

- **Not all the biases were considered**. This results in an analysis of the behaviour of the clients that is not completely precise. In the future, the missing biases approaches should be studied.

- The **irrational behaviour of the GENCOs** was not considered and this results in a less precise behaviour analysis. In future developments, the GENCOs irrational behaviour should be considered. For example, the inattention of the GENCOs. This parameter is assumed to be lower than the one of a common consumer, but the value have not been able to be determined. The inattention of the GENCOs requires a more complex and thorough study.

- The **assumptions made**. With the purpose of being able to compile and find an optimal solution, some assumptions were made (equations (29) and (30)). In future developments, these assumptions would have to be revised so that a more complete model that depicts better the agents behaviour can be addressed.

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