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GRADO EN INGENIERÍA EN TECNOLOGÍAS INDUSTRIALES

TRABAJO FIN DE GRADO

COMPARISON OF SINGLE-LEVEL AND BI-LEVEL APPROACHES IN A SIMPLIFIED TARIFF DESIGN FOR REGULATED COST RECOVERY

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Madrid

Agosto de 2021

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Collaborating Entity: ICAI – Universidad Pontifica de Comillas.

ABSTRACT

The electricity system has been modeled in a simplified way from a bi-level and an equivalent single-level approach. The conclusion reached is that, by forcing the regulated cost recovery, those associated with tariffs are a constant in the minimization of consumer costs. Thus, the optimal results are identical whether decisions are made sequentially (bi-level) or simultaneously (single-level).

Keywords: Bi-level (closed-loop), Single-level (open-loop), KKT, Taylor's theorem, access-tariffs, regulated costs, DG investments.

1. Introduction

Under the expected decarbonization of the electrical system, where the generation of distributed energy for self-consumption will increase significantly, the revenues obtained from electrical access tariffs will decrease, risking the economic sustainability of network activities.

On account of the societies transformation process that increases the energy demand, carbon emissions are becoming a matter of concern as they can increase the globe's temperature several Celsius degrees. Therefore, under the pursue of reducing CO_2 emissions, investments in distributed generation (DG) resources have increased to promote sustainability. The main advantages of these technologies are that they reduce losses as they are located closer to consumer, they increase reliability as they are smaller and more numerous, so they reduce the use of high voltages. However, DG generation comes together with some drawbacks: they enlarge the complexity of the system balancing, requiring the availability of support technologies.

Moreover, the increase in DG investments will lead to a reduction in the energy consumption from the grid accordingly. Hence, there will be a clear mitigation on access-tariffs profits risking the economic sustainability of centralized generation (CG).

For these reasons, a mathematical bi-level optimization model has been created under a simplified design of the access-tariffs in order to recover regulated costs. In addition, an equivalent single-level problem was modeled with the aim of obtaining the major qualitative as well as quantitative advantages and disadvantages of both approaches. Input parameters for the case studies correspond to estimations of the Spanish electric market.

2. State of the art

The objective of this thesis is to assess how different the results can be when the problem is modeled through the bi-level programming compared to the single-level approach. The qualitative and quantitative outcomes of both models are going to be considered. For this reason, an analysis of similar studies where electrical tariffs are either set as variables or forecasted as inputs has been conducted.

When modeling liberalized electricity markets, different market behaviors should be considered. Therefore, under the approach of maximizing consumers' welfare, (Wogrin, 2013) models both bi-level and single-level approaches so as to compare outcomes. The thesis concludes that bi-level optimization describes the market better as sequential decisions allow generation companies to alter the market outcomes by adjusting the capacities to the market needs. This enables changes in prices and, therefore, focus on maximizing profits. The single-level formulation is conditioned by the strategic behavior and can lead to over-investments compared to the sequential decisions.

Moreover, (Cervilla et al., 2015) described the long-term evolution of access-tariffs through a bi-level problem where regulated costs recovery was required. Outcomes, in this case, reveal that whenever energy tariffs are reduced, and power rates increase is the optimal procedure to recover costs while minimizing them. Thanks to the sequentiality of the models, regulators (upper-level) are able to control consumers decisions (lower-level) by focusing on DG investments that alter access tariffs. (Martínez Velázquez et al., 2019) followed the same strategy but focusing on minimizing the default of regulated earning. The paper also analyzes various approaches for solving bi-level optimization problems in the electricity sector. Results state that applying KKT conditions to the Lagrangian of the lower-level gives accurate outcomes in a reduced computing time. Consequently, it has been the main reference as well as the starting point of this thesis.

Finally, bi-level approach in (Doménech Martínez et al., 2020) represents operation and investments decisions for generation companies (GENCO's) and consumers considering centralized and behind-the-meter DG generation over a multi-year time horizon. It is expected that consumers will empower and decrease their purchases from the grid due to the installation of behind-the-meter generation, so there is a necessity to assess the impact of network access tariffs.

3. Description of the models

The two models have been formulated seeking for the economic sustainability of the power system. The bi-level approach minimizes the default of regulated costs in the upper level, while minimizing the generation and investment costs in the second level. Moreover, the single-level's objective function is the sum of both levels in the bi-level approach. This means it minimizes the default of regulated earnings and consumers costs such as energy and power costs from access-tariffs, the electric costs from the grid, and investment costs.

The upper-level of the bi-level approach consists of the economic balance of the industry while being subject to the already mentioned second-level objective function. The sum of power costs and energy costs associated to access-tariffs together with the default and excess of regulated earnings should be enough to recover regulated costs. On the other hand, the lower-level considers the following constraints: the energy balance separated by agents, the update of the installed power, the power generated should be lower than or equal to the installed, and the power contracted should be greater than or equal to the power demanded from the grid.

As a consequence of the complexity of the bi-level model, it has been transformed into a single-level approach by applying the Karush-Kuhn-Tucker (KKT) conditions to the Lagrangian of the lower-level. In addition, to increase the simplicity of the model, the non-linearities that appear were linearized based on the big-M method and the principle of strong duality.

Regarding the equivalent single-level approach, the previously described objective function is subject to the same constraints of the bi-level optimization but taken into account at the same level. Since some non-linearities appear as well, the first-degree Taylor's approximation was applied to reduce its complexity.

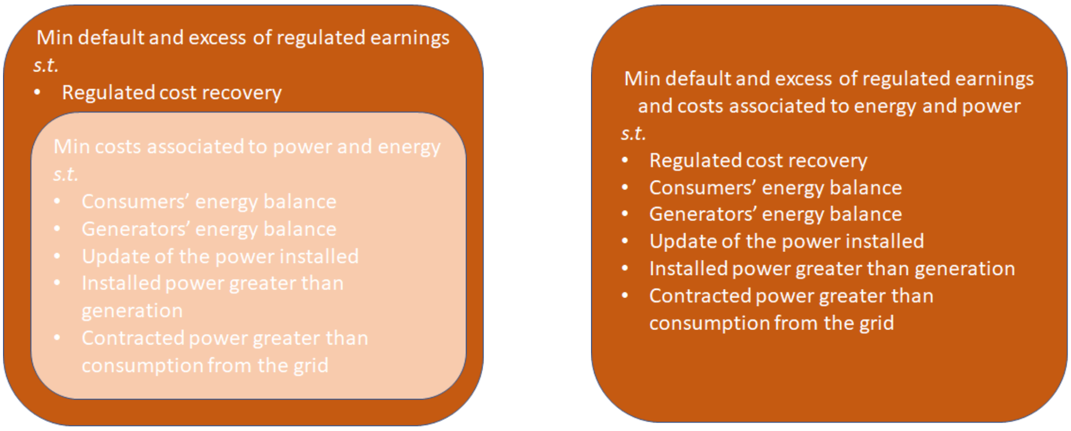
a) Bi-level
b) Single-level

Illustration 1: Bi-level and Single-level optimization models. Source: Own *elaboration.*

4. Results

The input data for the case studies has been estimated for the Spanish electrical system. Both models succeed in representing the market generically. First, regulated costs are always recovered satisfying the regulators objective. Moreover, whenever investment costs decrease, investments in renewable technologies increase and, in order to meet demand, consumption from the grid decreases. Furthermore, since regulated costs need to be recovered, access-tariffs rates turn out to be higher. Regarding the demand, if consumers' needs increase, both investments and grid consumption will grow, and access-tariffs will respond accordingly to retrieve costs.

Because of the simplicity of the single-level model, with a centralized consumer cost minimization, the cost per tariff is a constant in the objective function and equals the regulated costs targets. Consequently, no impact on the market energy price and on the tariffs is obtained. Moreover, in case all the terms of the objective function weigh the same, since access tariffs are insensitive, all regulated costs are associated to the default of earnings, and optimal outcomes from the single and the bilevel models are the same. This would mean that under the assumed hypotheses, it should not matter whether decisions are made sequentially or simultaneously.

Conclusions

Regarding the modeling, it can be concluded that, although the bi-level approach allows representing the sequentiality and hierarchy in the decision making, it is hard to solve. Not only is it necessary to reduce it to one level using the KKT first-order conditions, but it should also be linearized in order to be able to optimize it in a reduced computing time. Apart from this, whenever a new restriction is added to the model or even updated, the KKT conditions must be calculated again as well as the strong duality equivalence, which is a tedious limitation. Indeed, these drawbacks are meaningless since, from the assumptions made, it should not matter whether decisions are made sequentially or simultaneously since the optimal decisions are the same as if the problem was formulated under a single-level approach at first.

Regarding the resolution methodology, the nonlinear terms in the bilevel model have been linearized by using the strong duality equivalence without approximations, while the linearization of the single-level approach was done by the Taylor's approximation. This last linearization method requires a convergent iterative procedure that needs, in each iteration, an approximation of each nonlinear expression in the single-level approach. The convergence criterion was testing the maximum value of the absolute differences between the optimal decisions in the nonlinear expression and the corresponding intermediate parameters. It has been proved that the results end up getting closer and closer to the optimal values, proving the robustness of the model.

For future works, the abovementioned limitations of both models must be analyzed in more detail by including for example a profit maximization criterion for each agent or by adding more agents, more technologies like thermal generation, or even considering other dispatchable generation like storage of energy.

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COMPARACIÓN DE LOS ENFOQUES MONONIVEL Y BINIVEL EN EL DISEÑO SIMPLIFICADO DE TARIFAS DE ACCESO PARA LA RECUPERACIÓN DE COSTES REGULADOS

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RESUMEN DEL PROYECTO

Se ha modelado de manera simplificada el sistema eléctrico desde un enfoque binivel y otro mononivel equivalente. La conclusión a la que se ha llegado es que, al forzar la recuperación de costes, aquellos asociados a las tarifas son una constante en la minimización de costes del consumidor. Así, los resultados óptimos son idénticos tanto si las decisiones se toman secuencial (binivel) como simultáneamente (mononivel).

Palabras clave: Binivel, mononivel, KKT, teorema de Taylor, tarifas de acceso, costes regulados, inversiones en GD.

1. Introducción

Ante la esperada descarbonización del sistema eléctrico, donde la generación de energía distribuida para el autoconsumo aumentará significativamente, los ingresos obtenidos por las tarifas de acceso eléctrico disminuirán, poniendo en riesgo la sostenibilidad económica de las actividades de la red.

Debido al proceso de transformación de las sociedades que aumenta la demanda de energía, las emisiones de carbono se están convirtiendo en un asunto preocupante ya que pueden aumentar la temperatura del planeta varios grados centígrados. Por ello, con el objetivo de reducir las emisiones de CO2, las inversiones en recursos de generación distribuida (GD) han aumentado para promover la sostenibilidad del planeta. Las principales ventajas de estas tecnologías son que reducen las pérdidas al estar situadas más cerca de los consumidores, aumentan la fiabilidad al ser más pequeñas y numerosas, y, por tanto, reducen el uso de altas tensiones. Sin embargo, la GD viene acompañada de algunos inconvenientes. Principalmente aumentan la complejidad del equilibrio del sistema, lo que exige la disponibilidad de tecnologías de apoyo en la distribución y transmisión de la energía generada.

Además, el aumento de las inversiones en GD conllevará la correspondiente reducción del consumo de energía de la red. Por lo tanto, se producirá una clara mitigación de los beneficios de las tarifas de acceso, poniendo en riesgo la sostenibilidad económica de la generación centralizada (GC).

Por estas razones, se ha creado un modelo matemático de optimización binivel bajo un diseño simplificado de las tarifas de acceso para recuperar los costes regulados. Por otro lado, se ha modelado un problema mononivel equivalente con el objetivo de obtener las principales ventajas e inconvenientes de ambos enfoques tanto cualitativa como cuantitativamente. Por último, los parámetros de entrada para los casos de estudio corresponden a estimaciones del mercado eléctrico español.

2. Estado de la cuestión

El objetivo de este trabajo es evaluar cuán diferentes pueden ser los resultados cuando el problema se modela a través de la programación bi-nivel en comparación con el enfoque de un solo nivel. Se van a considerar tanto los resultados cualitativos como cuantitativos de ambos modelos. Para ello, se ha comenzado por realizar un análisis de estudios similares en los que las tarifas eléctricas se fijan como variables o se incluyen como entradas.

A la hora de modelar los mercados eléctricos libres, se podrían contemplar diferentes comportamientos del mercado. Por ello, bajo el enfoque de maximizar el bienestar de los consumidores, (Wogrin, 2013) modela tanto un problema bi-nivel como uno mono-nivel para comparar los resultados. La tesis concluye que la optimización en dos niveles describe mejor el mercado ya que las decisiones secuenciales permiten a las empresas de generación alterar los resultados del mercado ajustando las capacidades a las necesidades del mismo. Esto permite modificar los precios y, por tanto, centrarse en la maximización de los beneficios. La formulación de un solo nivel está condicionada por el comportamiento estratégico y puede conducir a un exceso de inversiones en comparación con las decisiones secuenciales.

Por otro lado, (Cervilla et al., 2015) describe la evolución a largo plazo de las tarifas de acceso a través de un problema de dos niveles en el que se requería la recuperación de los costes regulados. Los resultados, en este caso, revelan que siempre que se reduzcan las tarifas de energía y se aumenten las de potencia, se recuperan los costes mientras que se minimizan de manera óptima. Gracias a la secuencialidad de los modelos, los reguladores (nivel superior) son capaces de controlar las decisiones de los consumidores (nivel inferior) centrándose en las inversiones en GD que alteran las tarifas de acceso. (Martínez Velázquez et al., 2019) sigue la misma estrategia, no obstante, se centra en minimizar el defecto de ingresos regulados. El trabajo también analiza varios enfoques para resolver problemas de optimización bi-nivel en el sector eléctrico. Los resultados afirman que la aplicación de las condiciones KKT al Lagrangiano del nivel inferior proporciona resultados precisos en un tiempo de computación reducido. Por ello, ha sido la principal referencia, así como el punto de partida de este trabajo.

Por último, el problema bi-nivel de (Doménech Martínez et al., 2020) representa las decisiones de operación e inversión de las empresas de generación (GENCO's) y de los consumidores considerando la generación centralizada y distribuida detrás del contador en un horizonte temporal de varios años. Se espera que los consumidores potencien y disminuyan sus compras de la red debido a la instalación de generación detrás del contador, por lo que es necesario evaluar el impacto sobre las tarifas de acceso a la red.

3. Descripción de los modelos

Los dos modelos se han formulado buscando la sostenibilidad económica del sistema eléctrico. El enfoque de dos niveles minimiza el incumplimiento de los costes regulados en el nivel superior, mientras que minimiza los costes de generación e inversión en el segundo nivel. Además, la función objetivo del mono-nivel es la suma de ambos niveles en el enfoque bi-nivel. Esto significa que minimiza el defecto de los ingresos regulados y los costes de los consumidores, como los costes de energía y potencia de las tarifas de acceso, los costes eléctricos de la red y los costes de inversión.

El nivel superior del enfoque bi-nivel consiste en el equilibrio económico de la industria, estando sujeto a la función objetivo ya mencionada. La suma de los costes eléctricos y los costes energéticos asociados a las tarifas de acceso junto con el defecto y el exceso de ingresos regulados debe ser suficiente para recuperar los costes regulados. Por otro lado, el nivel inferior considera las siguientes restricciones: el balance energético separado por agentes, la actualización de la potencia instalada, la potencia generada debe ser menor que la instalada y la potencia contratada debe ser mayor que la contratada a la red.

Como consecuencia de la complejidad del modelo binivel, se ha transformado en un enfoque de un solo nivel aplicando las condiciones de Karush-Kuhn-Tucker (KKT) a la Lagrangiana del nivel inferior. Además, para aumentar la simplicidad del modelo, las no linealidades que aparecen se han linealizado basándose en el método big-M y en el principio de dualidad fuerte.

En cuanto al enfoque equivalente de un solo nivel, la función objetivo descrita anteriormente está sujeta a las mismas restricciones de la optimización de dos niveles, pero se tiene en cuenta en el mismo nivel. Como también aparecen algunas no linealidades, se aplicó la aproximación de Taylor de primer grado para reducir su complejidad.


a) Bi-nivel

b) Mono-nivel

Ilustración 1: Modelos de optimización mononivel y binivel. Fuente: propia.

4. Resultados

Los datos de entrada de los casos de estudio se han estimado para el sistema eléctrico español en 2021. Con esos datos, ambos modelos consiguen representar el mercado de forma genérica. En primer lugar, los costes regulados se recuperan siempre satisfaciendo el objetivo de los reguladores. Segundo, cuando los costes de inversión disminuyen, las inversiones en tecnologías renovables aumentan y, para satisfacer la demanda, el consumo de los consumidores de la red disminuye. Además, al tener que recuperar los costes regulados, el término variable de las tarifas de acceso resulta ser más alto. En cuanto a la demanda, en caso de que aumente, tanto las inversiones como el consumo de la red crecen, por lo que las tarifas de acceso responden en consecuencia para recuperar los costes.

Por otro lado, un resultado interesante para ambos modelos es que no importa el valor establecido para la tarifa de potencia, ya que la tarifa de energía óptima responderá para recuperar costes. Por tanto, el término fijo y el término variable tienen una correlación lineal negativa. Esto ocurre como consecuencia de la simplicidad del modelo, ya que sólo se considera un consumidor, no hay impacto en el precio de la energía en el mercado y no hay generación despachable. Al forzar la recuperación de costes, el coste por tarifa es siempre el mismo, es una constante en la minimización de costes del consumidor, por lo que es insensible a las tarifas.

Por último, al resolver el problema equivalente en un solo nivel, si todos los términos de la función objetivo pesan lo mismo, todos los costes regulados se asocian al defecto de ingresos. En consecuencia, los resultados obtenidos deberían descartarse. Por esta razón, cuando se penalizan los términos del nivel superior, los resultados óptimos que se obtienen de ambos modelos son los mismos, no sería relevante que la toma de decisiones fuera secuencial o simultánea. Sin embargo, esto sólo ocurriría en este caso ya que las variables de decisión del nivel superior son las tarifas de acceso en la formulación binivel que son insensibles.

5. Conclusiones

En cuanto al modelado, se puede concluir que el enfoque bi-nivel es difícil de resolver. No solo es necesario reducirlo a un solo nivel, sino que además hay que linealizarlo para poder optimizarlo en un tiempo reducido. Además, cada vez que se añade una nueva restricción al modelo o incluso se actualiza una, hay que volver a calcular las condiciones KKT y la equivalencia de dualidad fuerte. Esto provoca que el enfoque incluya varias limitaciones. La principal ventaja de este tipo de modelado es la secuencialidad de las decisiones. Sin embargo, debido a las simplificaciones, acaba siendo insensible a las variables del nivel superior. Por lo tanto, las decisiones óptimas son las mismas que si el problema se formulara bajo un enfoque de un solo nivel desde el principio.

Para concluir, se ha aplicado el Teorema de Taylor para linealizar el enfoque mono-nivel. Sin embargo, este método incluye cuatro nuevos parámetros en el problema que deben ser estimados en cada iteración. El procedimiento que se siguió para encontrar los resultados óptimos fue comparar el valor máximo de las diferencias absolutas entre la decisión optima y el parámetro con un valor pequeño en cada iteración. De este modo, los resultados acaban acercándose cada vez más al valor óptimo real, siempre y cuando la diferencia absoluta sea menor que el valor predeterminado. Por tanto, se demuestra la robustez del modelo, que consigue representar el sistema eléctrico de forma genérica.

Para futuros trabajos, habría que revisar las limitaciones de ambos modelos y reducir la simplicidad añadiendo más agentes, más tecnologías, generación térmica, o incluso considerar la generación despachable y el almacenamiento de energía.

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Chapter 1. INTRODUCTION

Under the expected decarbonization of the electrical system, where the generation of distributed energy for self-consumption will increase significantly, the revenues obtained from electrical access tariffs will decrease, risking the economic sustainability of network activities.

In today’s world, an economically and environmentally sustainable and high-quality supply of energy has become a must. Most citizens are unaware of the reliability and environmental constraints that come along with the electricity generation for their daily routines. Nowadays, energy is indispensable for most services such as heating, lighting, telecommunications, health care, or even for the use of home appliances. Therefore, the energy sector should be preserved by installing sufficient generation capacity with the aim of meeting society’s future electricity demand. At the same time, it is necessary to build a strong commitment to a sustainable and adequate use of today’s clean and efficient sources; such as renewable technologies.

Our planet is now suffering a dreadful crisis, and the consequences of climate change are becoming a dramatic cause of concern. This is due to the increasing carbon emissions, being 3,81 in 2000 and reaching 4,72 the global per-capita CO_2 emissions from fossil fuels and industry in 2019 (*Global Carbon Project*, 2020). Moreover, greenhouse emissions together with global warming will create a threat for future generations. The global average temperature could increase between 1,8 and 4 degrees in the following years depending on the extent to which carbon emissions are reduced. These are the main reasons why the decarbonization of the electrical system is one of the main goals for the 2020-2050 energy strategy of the EU. With the purpose of reducing the impact of this economic crisis while achieving climate neutrality, the Paris Agreement was adopted in 2015 by the Conference of Parties (COP) to the United Nations Framework Convention on Climate Change

(UNFCCC). The main objective of the convention is zero emissions no later than 2050 by holding global average temperature increase below 2ºC above preindustrial levels and targeting below 1,5ºC (Nations, n.d.). Consequently, investments in distributed generation (DG) are drastically increasing as these resources are key to reduce greenhouse gas emissions. When consumers self-generate energy, they are improving the operational capability of the grid reducing the peak of demand and improving the quality of the power (Sandhya & Chatterjee, 2021). Hence, with the introduction of greener approaches, the goal set in the Paris Agreement will be achieved.

Subsequently, there is a large number of factors that influence the incorporation of DG to our society that put the main focus on more sustainable and environmentally friendly strategies. Firstly, the main competitive edge of DG resources is that losses tend to be lower compared to the energy produced by centralized generation, since, very often, distributed generation resources (DER's) are installed close to where it is consumed. Nowadays, more and more consumers are already profiting from becoming prosumers by producing part of the energy they consume. While this will contribute to the decarbonization process, with distributed generation network charges are lower and socialization costs become higher, so more people are willing to self-generate their energy to further reduce their variable network charges (Kuang et al., 2011). Distributed generation may also increase reliability, as DG units are smaller but tend to be more numerous, as well as the decrement in the use of high voltages. As a consequence, to some extent distributed generation can improve system resiliency by, for example, creating isolated microgrids to help mitigate emergency conditions in case of extreme conditions (Sandhya & Chatterjee, 2021). However, RES variability increases the complexity of the system balancing, requiring support technologies available but with lower annual utilization.

This poses the challenges of the revenue reduction for these support centralized power plants (CG) with decreasing running hours. Many scientists claim that regulatory and legal changes will be required for a smart grid future based on renewable generation (Mehigan et al., 2018).

Therefore, the long-term sustainability of these technologies will be affected as there will be clear mitigation on access-tariffs profits as less people will consume energy from the grid.

Several researchers are still focusing on how to integrate both CG and DG technologies in order to optimize costs while achieving the goal of zero emissions. (Doménech Martínez et al., 2017) proposed a model for the long-term assessment of the electricity sector. The impact policymaker's decisions can have on investments and the operation of generation resources are considered in the thesis. In the theoretical mathematical model proposed, some of the modelling decisions are the quality of service and security of supply, the economic efficiency and sustainability, including the tariff structure design as well as the market design, and the environmental sustainability.

Having described the current situation that societies have to overcome, the long-term evolution of access tariffs together with the network costs recovery is the principal focus of this thesis. A bi-level programming model is proposed and compared to a single-level programming approach with the aim of reaching quantitative and qualitative conclusions on both approaches, their main advantages, drawbacks and differences. Investment and production of RES are the decisions in both models that, at the same time, consider a multiple time-horizon for the case study.

1.1 MOTIVATION

The economic and environmental implications that come together with distributed generation investments have been a matter of analysis and research for several years. With the aim of attaining the goals set in the Paris Agreement, investments in DG technologies are expected to grow exponentially due to its environmental benefits since this technology greatly reduces carbon emissions.

Moreover, nowadays and more and more often, residential consumers are becoming prosumers with the integration of DG for self-consumption and integrating their energy surplus to the grid. When consumers are able to generate their own energy with the possibility of storing it or even sell the excess, they are reducing their expenses on electricity. However, grid consumption diminishes as other sources of energy are going to be needed more frequently.

In addition, Spain has one of the highest indexes in energy consumption based on GDP, but it is similar to most of the countries that belong to the European Union. The electricity consumption per capita in Spain is 5,6 MWh/capita being 6,1 MWh/capita for the EU (IEA, 2021). For this reason, objectives of the Paris Agreement were set to all the countries belonging to Europe. Thanks to the good climatic conditions and the conscious population, investments in renewable energy are enlarging building a strong commitment to a clean consumption of energy.

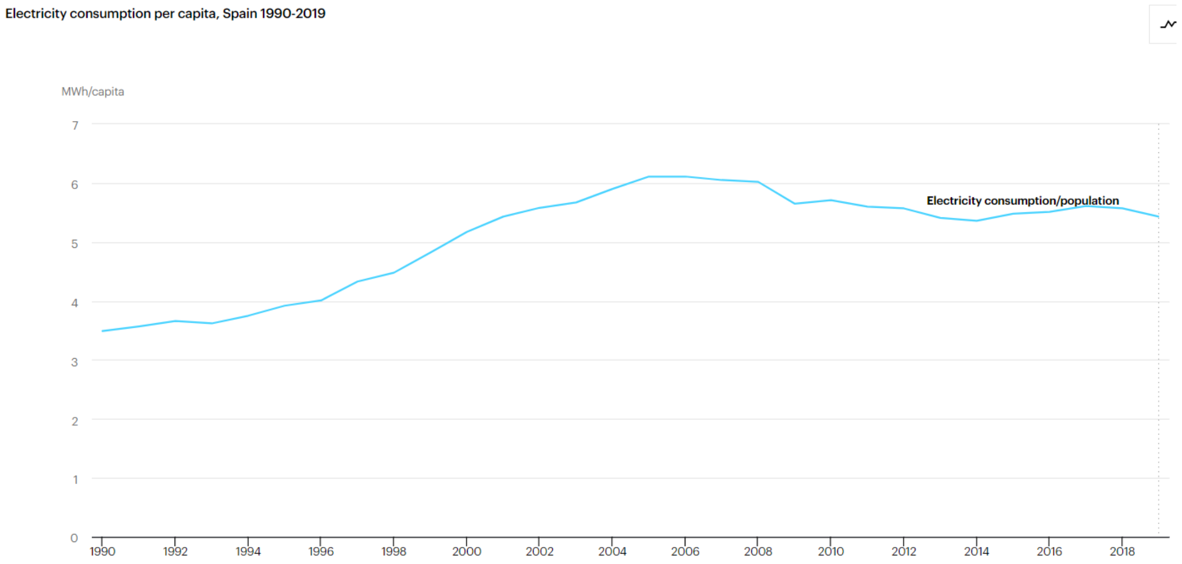

Figure 1: Electricity consumption per capita in Spain. Source: EIA.

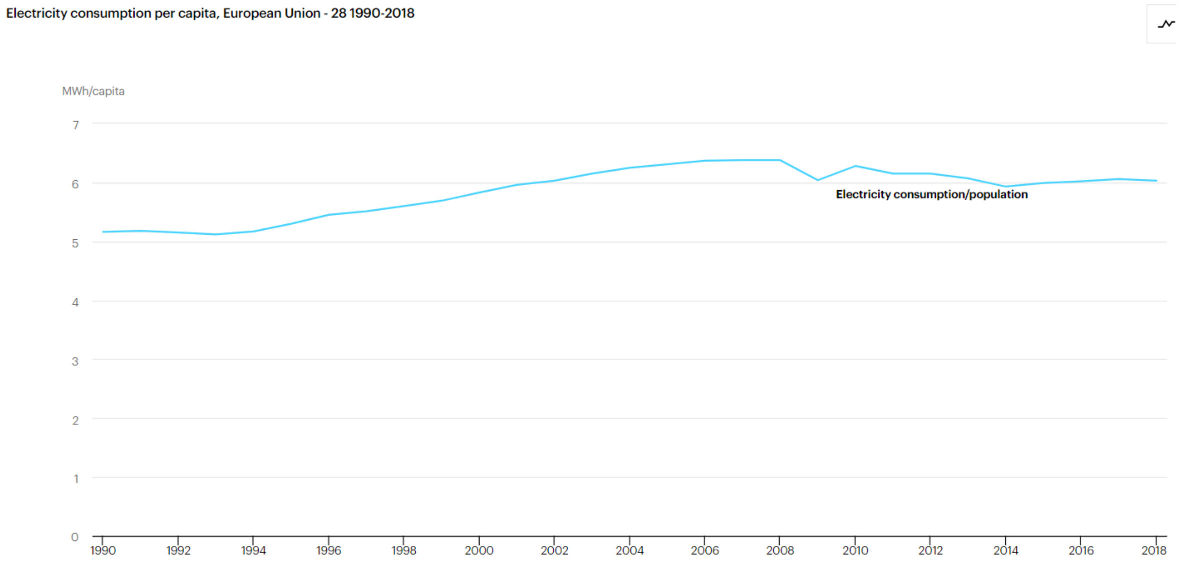

Figure 2: Electricity consumption per capita for the European Union. Source EIA.

In addition, the mentioned enlargement of DG will also result in a reduction of the revenues obtained from the grid's access tariffs risking the economic sustainability of network activities. Therefore, a bi-level and a single-level optimization model have been formulated in this thesis considering investments in renewable technologies such as wind and solar PV. Finally, the case study that is contemplated in this thesis will be focused on a simplified Spanish electrical system.

1.2 PROJECT'S OBJECTIVES

The main objectives of this project are described in this section. The aim of this thesis is to assess the main differences of a single-level and a bi-level formulation of the problem that determines the long-term evolution of tariffs that recovers regulated costs. This includes analyzing the different conclusions that will be reached with the two optimization models.

Looking forward to finding the main advantages and disadvantages of each formulation for the problem to be solved, the following partial objectives are addressed:

1. Mathematical formulation of a bi-level problem where the first level formulates the regulatory framework of the electrical system considering tariffs as decision variables, while the second level minimizes the investment and operation costs for consumers and generation companies subject to the first level inputs. This means that decisions are taken sequentially. The resolution algorithm is based on the KKT conditions with the aim of simplifying the model into a linear problem. The goal of this simplification is the implementation of the model in a GAMS prototype with a reduced computing time for scenarios simulation.
2. Mathematical linear formulation of the single-level model including the same approach and constraints as in the bi-level problem. The objective function of the first and the second level of the mentioned bi-level problem combined into a single optimization problem.
3. Study of the convergence of the single-level approach after linearizing its constraints and objective function.

4. Analysis of electrical tariffs together with the power contracted by the clients and their consumption from the grid under the purpose of recovering regulated costs.
5. Study of the application of the model developed in this thesis to the prediction of DG and CG investments.
6. Assessment of both quantitative and qualitative differences between the bi-level and the single-level programming models, exploring the advantages and disadvantages of each model with the aim of reaching reliable conclusions.

1.3 ALIGNMENT WITH THE SUSTAINABLE DEVELOPMENT GOALS

Apart from the six objectives that were mentioned previously, this thesis also focuses on attaining some of the Sustainable Development Goals (SDGs) that were Established by the United Nations. Most countries or regions are facing enormous challenges with these SDGs trying to confront climate change, natural disasters, or declining biodiversity. Even though this is a small project with few superior impacts, these objectives start with the individual responsibility of one another. Now, four of these SDGs will be reviewed including how this thesis aligns with these goals while estimating how to take action.

- GOAL 7: AFFORDABLE AND CLEAN ENERGY

Nowadays, the world is facing an energy transition from central generation to distributed generation. People are prepared for facing every major challenge and opportunity. For this reason, this thesis considers investments in renewable energies, looking for a reduction in CO_2 and GHG emissions plus energy efficiency.

- GOAL 9: INDUSTRY INNOVATION AND INFRASTRUCTURE

Innovation and investments in infrastructure are some of the main variables to be analyzed in this project regarding the electrical industry. They are considered to be crucial to obtain sustainable development. One of the best approaches to attain the decarbonization objectives for 2050 is investing in renewable technologies as well as smart grids and virtual power plants. This thesis focuses on the analysis of infrastructure investments in renewable technologies like solar PV and wind.

- GOAL 12: RESPONSIBLE PRODUCTION AND CONSUMPTION

This objective is probably the most relevant concerning this thesis. Responsible production and consumption are promoted with the aim of reducing greenhouse gas emissions while increasing resource efficiency. Consequently, by trying to recover network costs and modelling tariffs, an increase in the use of distributed energy resources is going to be encouraged with a long-term lessening in centralized resources.

- GOAL 13: CLIMATE ACTION

As mentioned above, following the objectives Established by the Paris Agreement, the decrease in CO_2 emissions continues to be our target. Climate change is a matter that affects us all, so the action is going to be taken by enlarging DG investments.

1.4 *METHODOLOGY AND PLANNING*

This section presents the planning and methodology that has been followed in order to achieve the objectives mentioned in the previous section. The formulation of the bi-level and single-level problems considered in this thesis has been developed with GAMS. Therefore, the tasks that should be completed are summarized and explained below.

	APRIL				MAY				JUNE				JULY				AUGUST			
	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Review of the state of art	■	■			■				■				■							
Formulation of BL approach		■	■	■	■	■														
Formulation of SL approach						■	■	■	■	■										
Program both models in GAMS						■	■	■	■	■										
Identify scenarios										■	■	■	■	■	■					
Validation and improvements										■	■	■	■	■	■					
Conclusions and report writing													■	■	■	■				
Presentation																	■	■	■	■

Table 1: Thesis' Timeline. Source: Own elaboration.

First, a review of the literature was done in order to sum up the theory behind our mathematical optimization model. A review of the state of the art was done during the first week of each month with the aim of finding more previous models in the literature. In April and May, the formulation of the bi-level approach was fulfilled. This task included the development of the model: the minimization of the defect of regulated incomes with the constraint of adjusting the tariff's long-term evolution in order to recover network costs in the first stage, and the cost minimization for both agents in the second stage. This optimization problem has been simplified using its KKT conditions and linearized afterward towards the approach of reducing its computing time when solving it.

In late May and June, the single-level problem was modelled under the objective of transforming it to a linear problem for a faster implementation in GAMS. The optimization model was developed prior to identifying the required parameters. While designing the problem, both the close-loop (bi-level) and open-loop (single-level) models were programmed in the system for conducting further analysis.

Finally, in late June and July, the identification of both the parameters and the case of study were done once the model has been programmed with GAMS. Afterward, the simulation scenarios were implemented in order to validate and improve the proposed model. This is the test period where all improvements were done before analyzing the results and extracting conclusions from the presented scenario. Finally, during July, the report of the thesis was written with the aim of presenting the project in August.

1.5 RESOURCES

Lastly, the resources used for doing the project are specified. The development and improvements of the model were done using GAMS, with a complete license provided by the Institute of Investigation and Technology (IIT). Whereas the analysis of the results of the algorithms, the edit of the thesis, and the production of presentations have been done using the office software (Word, Excel, PowerPoint…).

Chapter 2. STATE OF THE ART

The risk of economic sustainability of network activities due to the energy transition from centralized generation to distributed generation, and the relevant role of electrical access tariffs, are combined in this thesis in the pursuit of minimizing the default of regulated activities earnings. The objective of this thesis is to assess how different the results can be when the problem is modeled through the bi-level programming compared to the single-level approach. Both qualitative and quantitative outcomes of the two models are going to be considered.

Spain's electricity market liberalization allowed a transition from the vertical integration between generation and distribution, to a competitive market where each network remained as a natural monopoly. Customers reaped large benefits by maximizing their welfare. However, this liberalization increased the risk of environmental sustainability. A rise in carbon emissions was experienced in the country on account of the transformation process due to the increase in energy demand. This matter of concern is nowadays being solved with the introduction of new technologies to the market such as renewable technologies.

Game theory includes methods and tools to study the strategic interaction between two or more players. It is the most suitable method for analyzing industries in terms of economic matters. Therefore, in this thesis, investment and production decisions are developed by game theoretic approaches in the bi-level optimization model.

Historically, multilevel optimization problems, especially bi-level approaches, were closely related to the economic games of Stackelberg. In these games, there is an interaction between agents at different levels, modeling decisions that are taken sequentially. The leader chooses his optimal decision anticipating the follower's reaction. Consequently, these Stackelberg games are closely related to bi-level optimization modelling, where the upper-level would become the leader being the first to find values for its decisions, and the lower-level would be the follower, whose quantity decisions are taken depending on the leader's decisions taken as inputs. Some methodologies that could be followed to address these types of optimization problems are described in (Colson et al., 2007) and (Martínez Velázquez et al., 2019).

Both the single-level and bi-level approaches follow the Stackelberg games. However, the main difference between single-level and bi-level programming methods would be whether decisions are taken simultaneously (single-level) or sequentially (bi-level). Indeed, the single-level model is primarily based on cost minimization. Unlike other papers based on the same economic objective like (Nie et al., 2018), the single-level model that has been developed in this thesis also takes into account the tariffs determination at the same level.

In liberalized electricity markets, comparing different market behaviors could be useful for establishing the divergence between programming methods. Thus, in (Wogrin, 2013) a generation expansion planning problem is solved for liberalized electricity markets. The author succeeds in comparing a close loop, modeled with Stackelberg's equilibrium, with an open loop, formulated following Cournot's equilibrium. Both approaches are solved under the goal of maximizing consumer welfare in a multiyear time horizon but could reveal different outcomes. Results show that a liberalized market is better described following a bi-level approach. The main reason behind it is that sequential decisions allow generation companies to alter the market outcomes by adjusting the capacities to the market needs. This enables changes in prices and, therefore, focus on maximizing profits. The single-level formulation is conditioned by the strategic behavior and can lead to over-investments compared to the sequential decisions. Moreover, a comparison under various market situations is also described in (Ozdemir, 2013), which proposes equilibrium models for the generation expansion problems under perfect competition and Cournot's equilibrium.

Other references in the literature also formulate the problems based on maximizing investor's profits. (Botterud et al., 2005) proposes a single-level investment model in new power generation over a multiyear planning horizon, where demand is represented as a discrete Markov Chain. (Doménech Martínez et al., 2017) proposes a mathematical bi-level model that considers the interaction of policymakers' decisions with generation investments and operations, and customers' response in a liberalized power system. The lower level of the model minimizes end-users' energy expenses in distributed generation (DG), considering one bus is mainly used for distributed generation and another for centralized generation. (Baringo & Conejo, 2012) follows the same approach for the objective function of the lower level, while the upper level of the proposed model minimizes total consumer costs and use a MPEC (Mathematical Programming with Equilibrium Constraints) to identify the optimal wind projects to be developed and the required network reinforcements. Therefore, it only considers DG investments, more specifically, wind investments.

Plenty of literature focus on the minimization of consumer costs in the upper level like (Baringo & Conejo, 2012). In addition, (Martín-Martínez et al., 2017) proposes a model considering the interaction of both distributed generation and centralized generation through a single-level optimization model considering only the existence of residential consumers. The model ignores regulatory constraints but it considers the access-tariffs rates together with operation and maintenance costs (O&M) so as to minimize consumers costs. (Wang et al., 2018) proposes an optimization model of provincial-level power generation expansion considering biomass and nuclear power plants to analyze the benefits and disadvantages of both technologies to reduce costs and investments in fossil fuels. Finally, while minimizing costs, (Xie et al., 2020) illustrates a bi-level model where the first stage focuses on transmission and the second stage illustrates the distribution perspective for a coordinated distribution network.

With the goal of recovering regulated costs through energy and power access tariffs, and looking for the sustainability of the system and stability of the tariffs, (Cervilla et al., 2015) modelled a mathematical bi-level model to obtain the evolution of the access tariffs that provide the incomes needed to recover the regulated costs. The sequentiality of the model allows regulators (upper-level) to control consumers decisions (lower-level). This means that they can have an impact on the optimal DG investments as they are related to access tariffs. Moreover, including a multiyear time-horizon, the problem minimizes tariff costs in the upper-level, while minimizing consumer costs in the lower-level by taking into account DG investments and the costs of the energy from the grid. The optimal outcome states that a decrease in the energy tariffs together with an increase in the power ones would lead to the recovery of regulated costs while minimizing them.

The same strategy is followed in (Martínez Velázquez et al., 2019) with the sole divergence that the upper level minimizes the deficit in the recovering of the Regulated Activities' (RA) costs. This paper also analyzes the different methodologies used to solve bi-level problems considering regulator-consumer decisions in the electricity sector. It reveals that bi-level problems solved with their KKT conditions combined with the duality method reach the optimal solution in a smaller computing time.

The main reference for this thesis is (Doménech Martínez et al., 2020) which proposes a Nash equilibrium model that considers centralized and behind-the-meter distributed generation expansion. Over a multi-year time horizon, the author manages to maximize power generation company's (GENCO's) profits in the upper level, while minimizing consumer costs in the lower level. Therefore, it represents both the operation and investment decisions of both types of agents. It is expected that consumers will empower and decrease their purchases from the grid due to the installation of behind-the-meter generation, so there is a necessity to assess the impact of network access tariffs.

In addition, Electric energy storage (EES) systems represent a fundamental component of the smart grid for enhancing power system reliability, sustainability, and energy efficiency. (Parvania et al., 2014) propose an optimization model that compares hourly scheduling of centralized EES (CEES) and distributed EES (DEES) in transmission constrained system operations. Its objective is to minimize total production costs. Thus, it is useful for reducing hourly peak loads, operating costs, and the number of committed units, as well as eliminating the need for the utilization of expensive power system equipment.

To conclude this section, Cooperative Game Theory (CGT) secures DER investments, and reduces risks. For example, (Almansa Garrido et al., 2019) compares cooperative to non-cooperative models between households using distributed energy such as photovoltaic panels and batteries, concluding that coalition benefits depend on the access-tariffs structure. The proposed model contributes to the decarbonization of the system since it allows sales of excess energy thanks to the installed batteries.

Table 2 summarizes the resolution methods used for programming the abovementioned bi-level optimization problems. These approaches are the main reference of this thesis when reducing the complexity of both the proposed single-level and bi-level models.

Reference	**Type of problem**	**Resolution method**	**Relevant analysis/conclusions**
(Wogrin, 2013)	Generation Expansion	KKT + Duality + Analytical (diagonalization)	Model based on a maximization of the consumer's welfare while considering different consumer's behaviors.
(Doménech Martínez et al., 2020)	Generation Expansion	KKT	The model represents interactions between CG, DG, and market prices unlike literature.
(Martínez Velázquez et al., 2019)	Investment	KKT + Duality / Quadratic constraints/Linear stretch approximation	The Mixed Integer Quadratically Constrained model gives the most generic formulation of the problem.
(Doménech Martínez et al., 2017)	Investment	KKT	Theoretical mathematical formulation of policymaker's decisions considering both CG and DG.
(Baringo & Conejo, 2012)	Investment	KKT + Primal-Dual formulation	Wind power investments are conditioned by transmission reinforcements. So, they need to be jointly addressed.
(Ozdemir, 2013)	Generation Expansion	KKT	Analysis of different consumer's behaviors such as perfect competition or Cournot's competition, in equilibrium models.
(Xie et al., 2020)	Generation Expansion	KKT + Dual-Based method	Proposed model proves the economic benefits of the accommodation of renewable energies.
(Cervilla et al., 2015)	Investment	KKT + Binary variables	Optimal decision to stabilize electric tariffs consists of reducing the energy tariffs while incrementing the power ones.

Table 2: Resolution methods for bi-level problems from the literature. Source: Own elaboration.

As a consequence of the tariffs' deficit that appears due to a mismatch between the tariffs and the costs to be recovered, a great amount of research was done in order to eliminate deficit. In this thesis, under the same approach, both fixed and variable terms of the tariffs are considered endogenous variables. This means that its value should be determined by the value of other variables included in the model. In this case, its value depends on the decisions made for the energy and power contracted.

From the literature review, it is true that there are similar studies like *(Martínez Velázquez et al., 2019)* and *(Doménech Martínez et al., 2020)*, but they only focus on bi-level formulation. On the other hand, there is research where the objective is the comparison between bi-level and single-level approaches like *(Wogrin, 2013)*. However, it is a much more complex model of the electric sector where various types of consumer behaviors are considered.

For this reason, the state of the art has been done to analyze similar studies where electrical tariffs are either set as variables or forecasted as inputs. The modeling of the electric market is complicated, and many factors can alter the consumers cost minimization such as investments in renewable technologies. All in all, an extended evaluation of the different outcomes obtained from these papers have given rise to several questions for the case study. Is there a huge difference between simultaneous and sequential decisions in electric markets? As a result, this has been the main scope of this thesis.

Chapter 3. BI-LEVEL AND SINGLE-LEVEL FORMULATION

3.1 *JUSTIFICATION*

Under the upcoming increase in both centralized and distributed renewable generations (as a consequence of the decarbonization goal of the electrical industry), two models have been formulated seeking for the economic sustainability of the power system. In particular, the network cost recovery is the main focus of both models. Similarities and differences between the two approaches are going to be analyzed based on the execution of these models with the aim of obtaining potential conclusions for further recommendations. The bi-level approach minimizes the deficit of regulated costs recovery in the upper level, while minimizing the generation and investment costs in the second level taking into consideration both consumers and generation companies.

On the other hand, in the single-level approach tariffs, operation and investment decisions are taken simultaneously, so that its objective function is the sum of the upper-level and lower-level objective functions of the bi-level model. Therefore, this model minimizes the earnings deficit that come from electrical tariffs and, at the same time, the consumer’s and generator’s costs that result from their investments and operation energy strategies.

It should be noted that an hourly discrimination has been included in the model due to the variable energy demand and the variable generation of renewable technologies. Both models are described in this section for promoting economic and environmental sustainability, together with the algebraic simplifications for the linearization of both approaches.

3.2 MATHEMATICAL FORMULATION OF THE BI-LEVEL APPROACH

3.2.1 NOMENCLATURE

Both the single-level and bi-level approaches include the same variables in the modelling. The nomenclature used for the formulation of the objective functions and the constraints is presented below under the description of the sets, parameters, and variables involved in the generic description of the models that have been designed.

Parameters are presented in capital letters to differentiate them from sets and variables that are portrayed in lower case letters. Moreover, the Lagrange multipliers used as a consequence of the calculation and formulation of the Karush-Kuhn-Tucker (KKT) conditions for the lower level are going to be labeled under Greek letters.

Sets	**Meaning**
a	years (time-horizon)
t	technologies included in the model for electricity generation
h	hours
s	agents involved, both consumers and generators
$c(s)$	consumers
$g(s)$	generators

The set “s” considers both consumers and generators. This means that: $s = c\ U\ g$.

Upper-level parameters	**Meaning**
CR_a	Annual regulated costs of the electric system [€]

Lower-level parameters	**Meaning**
P_{ah}	Hourly marginal price of the electric energy [€/kWh]
CI_t^s	Investment cost at consumer's and supplier's level [€/kW]
D_{ah}^s	All the demand that comes from consumer's and the one that doesn't [kWh]
POT_t^s	Installed power in each technology at the beginning of the time-horizon at consumer's and supplier's level [kW]
PF_{tah}^s	Production factor for each technology [p.u.]

Upper-level variables	**Meaning**
tf_a	Fixed term (power) of the tariffs [€/kW]
tv_{ah}	Variable term (energy) of the tariffs [€/kWh]
d	Default of regulated earnings [€]
e	Excess of regulated earnings [€]

Lower-level variables	**Meaning**
cp_a^c	Contracted power from consumer's [kW]
dq_{ah}^c	Consumer's consumption from grid [kWh]
pt_{ta}^s	Total installed power at consumer's and supplier's level [kW]
p_{ta}^s	Annual installed power at consumer's and supplier's level [kW]
q_{tah}^s	Electric energy production at consumer's and supplier's level [kWh]

Lagrange Multipliers variables	**Meaning**
θ_{ah}	Dual variable of the generation balance. Total cost of the energy generated [€/kWh]
μ_{ah}	Dual variable of the consumer's balance. Total cost of the energy consumed from the grid (market price and variable term of the tariff) [€/kWh]
ρ_{ta}^s	Dual variable concerning the actualization of the installed power [€/kWh]
δ_{tah}^s	Dual variable concerning the upper bound of the generated power [€/kWh]

α_{tah}^{s}	Dual variable concerning the lower bound of the generated power [€/kWh]
δ_{ah}^{c}	Dual variable concerning the upper bound of the grid's consumption [€/kWh]
α_{ah}^{c}	Dual variable concerning the lower bound of the grid's consumption [€/kWh]
σ_{ta}^{s}	Dual variable concerning the lower bound of the new installed power [€/kWh]

As a consequence of the simplification of the bi-level optimization problem, the set of variables displayed above are going to be used in the resolution of the problem. With the aim of reducing the complexity of the mathematical optimization problem, the bi-level model is going to be transformed into an equivalent single-level approach. Therefore, the calculation of the Lagrangian function of the lower level is required with the aim of using the Karush-Kuhn-Tucker requirements for the modification of the model.

Moreover, since the calculation of the KKT requirements for the lower-level formulation come together with some nonlinearities in the complementarity of slack conditions, the application of the big-M method is used to simplify the resolution. This method basically consists of introducing binary variables multiplied by the parameter M, which is an extremely big number compared to the rest of the parameters. This allows the relaxation of the non-linear constraints as explained in (Cococcioni & Fiaschi, 2020). Hence, these binary variables are defined as follows.

Binary variables	**Meaning**
δM_{tah}^{s}	Binary variable for the complementarity condition of the of the constraint that defines the non-dispatchable production (10)
αM_{tah}^{s}	Binary variable for the complementarity condition of the constraint that sets the lower bound of energy production (10)
δM_{ah}^{c}	Binary variable for the complementarity condition of constraint that defines that the power contracted should be greater than the energy consumption from the grid (12)

αM_{ah}^{c}	Binary variable for the complementarity condition of the constraint that sets the lower bound of energy consumption from the grid (12)
σM_{ta}^{s}	Binary variable for the complementarity condition of the constraint that sets the lower bound of investments (11)

Once the description of the sets, parameters, and variables that are going to be used in the problem statement has been completed. The bi-level approach is going to be formulated.

3.2.2 PROBLEM FORMULATION

3.2.2.1 Upper-level

The upper level of the model consists of the economic balance of the electrical industry. Both variable and fixed costs from the electrical tariffs are considered. The variable costs are multiplied by the consumer's consumption from the electrical grid, which is a certain amount of energy, while the fixed costs are multiplied by the consumer's contracted power. The sum of both terms together with the default of earnings due to the electrical tariffs minus the excess., should be greater than the sum of the regulated costs. This constraint is represented under equation (1) where costs are being recovered throughout the predetermined time-horizon, it does not imply an annual recovery.

$$\sum_{a} tf_a \cdot cp_a^c + \sum_{a,h} tv_{ah} \cdot dq_{ah}^c + d - e \geq \sum_{a} CR_a \tag{1}$$

As a consequence of the cooperation between both levels of the problem, this constraint is non-linear since it includes the multiplication of two decision variables both in the first and second terms of the constraint. The annual fixed rates are multiplied by the annual power contracted by the clients, which are decisions variables of the upper- and lower-level accordingly. The second term corresponds to the multiplication of the hourly variable tariff rate and the clients' consumption from the grid, which are also decision variables of the problem. The sum of both terms together with the slack minus the excess should be enough to recover regulated costs, which are an input parameter.

As stated previously, the objective of the problem is to minimize the default and the excess of the regulated earnings with respect to the regulated costs so that the incomes from the tariffs approximate as much as possible the costs to be recovered. Therefore, the upper level optimization problem can be formulated as:

$$\min_{tf_a, tv_{ah}} \; d + e \tag{2}$$

Note that tariffs decisions and generation and operation decisions are not taken simultaneously, and there is an interaction between the different levels. The optimal decisions of the upper-level (PINF) are the starting point of the lower-level optimization.

$$(cp_a^c, dq_{ah}^c) \in arg\ PINF \tag{3}$$

As can be seen, both the consumer's contracted power (cp_a^c) and the consumer's consumption from the grid (dq_{ah}^c), which are decision variables of the lower-level, ought to be the optimal solution for the lower-level.

In addition, all decision variables of the upper-level should be greater than zero. Negative prices are not considered nor non-positive slack or excess:

$$d, e, tf_a, tv_{ah} \geq 0 \tag{4}$$

3.2.2.2 Lower-level

In the lower level of the model, both generation companies and consumers interact with each other minimizing their individual costs while satisfying the constraints such as the demand. In the simplified problem formulated, generation companies can invest in solar photovoltaic (solar PV) and wind.

Regarding consumers, their purpose is to minimize their energy costs given a non-flexible hourly demand. These costs depend on the grid access-tariffs from the upper-level (energy and contracted power tariffs), the investment costs on self-solar PV generation, and on the electric cost bought from the grid. For simplicity, the electricity price has been considered an external input, and variable operation costs null.

Therefore, the objective function for the lower-level is:

$$\min \sum_{a} tf_a \cdot cp_a^c + \sum_{a,h} (tv_a + P_{ah}) \cdot dq_{ah}^c + \sum_{s,t,a} CI_{ta}^s \cdot p_a^s \tag{5}$$

With regards to the constraints that should be satisfied by both agents, consumers and generation companies, the power balance is the main restriction that must be considered. It has been modeled in two separate constraints, one referring to the generation companies and the other to consumers:

- All the centralized energy produced by the generation companies must meet the customer's electricity demand from the grid as well as transmission and distribution losses.

$$\sum_{t} q_{tah}^g = dq_{ah}^c + D_{ah}^g \tag{6}$$

- Since, for simplicity, the model considers only one consumer, the whole electricity generation from DG resources together with the grid's electricity supply should satisfy the customer's demand. So the customer is not allowed to transmit his excess energy back to the grid. As a result of this assumption, the remaining power balance constraint is the following:

$$\sum_{t} q_{tah}^c + dq_{ah}^c = D_{ah}^c \tag{7}$$

Since the total installed power needs to be calculated year by year, a constraint has been created to bring up to date this variable. It consists of the summation of the total installed power from the previous year plus the respective yearly total new installed power.

$$pt_{ta}^{s} = pt_{t,a-1}^{s} \cdot I_{a>1} + POT_{t}^{s} \cdot I_{a=1} + p_{ta}^{s} \qquad (8)$$

The additional variable included in this constraint is a binary variable:

$$I_s(x) = \begin{cases} 1 \; if \; x \in s \\ 0 \; if \; x \notin s \end{cases} \qquad (9)$$

Moreover, the total installed power multiplied by the production factor ought to be greater than or equal to the energy produced by the respective agent, being both greater than zero.

$$0 \leq q_{tah}^{s} \leq pt_{ta}^{s} \cdot PF_{tah}^{s} \qquad (10)$$

Concerning the new power installed by each technology every year, it could be greater than or equal to zero.

$$0 \leq p_{ta}^{s} \qquad (11)$$

To conclude, the last restriction that should be included in the model is that the consumer's contracted power should be greater than the consumer's consumption from the grid that, at the same time, should be greater than or equal to zero.

$$0 \leq dq_{ah}^{c} \leq cp_{a}^{c} \qquad (12)$$

Once both levels have been modeled, the optimal decision is going to be taken sequentially. The leader decides his optimal solution anticipating the follower's reaction.

3.2.2.3 Simplification of the model

The original bilevel problem has been transformed into a single level problem by replacing the lower-level problem by its Karush-Kuhn-Tucker conditions (KKT), and the no linearities have also been linearized.

Even though GAMS would be able to find a feasible solution for the bi-level optimization problem, transforming the problem into a single-level model will ease the process since the CPLEX algorithm is more mature which means that the open-loop approach significantly reduces the computational time.

For the resolution of the problem, as stated previously, the KKT requirements have been applied to the convex optimization problem of the lower level: stationarity, complementary slackness, primal feasibility, and dual feasibility. An explanation on how to establish these conditions is given in (Giorgi et al., 2016). For the application of these conditions, the calculation of the Lagrangian function leads to the following function. (See ANNEX I – LAGRANGIAN FUNCTION AND KKT CONDITIONS

).

$$\begin{aligned}
L = \sum_{a} tf_a \cdot cp_a^c + \sum_{a,h} (tv_a + P_{ah}) \cdot dq_{ah}^c + \sum_{s,t,a} CI_{ta}^s \cdot p_a^s \\
+ \sum_{a,h} \theta_{ah} \cdot \Big(\sum_{t} q_{tah}^g - dq_{ah}^c - D_{ah}^g\Big) \\
+ \sum_{a,h} \mu_{ah} \cdot \Big(\sum_{t} q_{tah}^c + dq_{ah}^c - D_{ah}^c\Big) \\
+ \sum_{s,t,a} \rho_{ta}^s \cdot \big(pt_{ta}^s - pt_{ta-1}^s \cdot I_{a>1} - POT_t^s \cdot I_{a=1} - p_{ta}^s\big) \\
+ \sum_{s,t,a,h} \delta_{tah}^s \cdot \big(q_{tah}^s - PF_{tah}^s \cdot pt_{ta}^s\big) \\
+ \sum_{s,t,a,h} \alpha_{tah}^s \cdot \big(-q_{tah}^s\big) \\
+ \sum_{a,h} \delta_{ah}^c \cdot \big(dq_{ah}^c - cp_a^c\big) + \sum_{a,h} \alpha_{ah}^c \cdot \big(-dq_{ah}^c\big) + \sum_{s,t,a} \sigma_{ta}^s \cdot \big(-p_{ta}^s\big)
\end{aligned} \qquad (13)$$

The KKT conditions applied to the model are summarized in (Martínez Velázquez et al., 2019). As a result, the following constraints have been added to the model:

- The gradient of the Lagrangian function equal to zero:

$$tf_a - \sum_{h} \delta_{ah}^c = 0 \qquad (14)$$

$$tv_{ah} + P_{ah} - \theta_{ah} + \mu_{ah} + \delta_{ah}^c - \alpha_{ah}^c = 0 \qquad (15)$$

$$\rho_{ta}^s - \rho_{t,a+1}^s \cdot I_{a<A} - \sum_{h} \delta_{tah}^s \cdot PF_{tah}^s = 0 \qquad (16)$$

$$CI_{ta}^s - \rho_{ta}^s - \sigma_{ta}^s = 0 \qquad (17)$$

$$\theta_{ah} \cdot I_{s=g} + \mu_{ah} \cdot I_{s=c} + \delta^{s}_{tah} - \alpha^{s}_{tah} = 0 \quad (18)$$

- Complementary slackness conditions:

$$\delta^{s}_{tah} \cdot (q^{s}_{tah} - PF^{s}_{tah} \cdot pt^{s}_{ta}) = 0 \quad (19)$$

$$\alpha^{s}_{tah} \cdot (-q^{s}_{tah}) = 0 \quad (20)$$

$$\delta^{c}_{ah} \cdot (dq^{c}_{ah} - cp^{c}_{a}) = 0 \quad (21)$$

$$\alpha^{c}_{ah} \cdot (-dq^{c}_{ah}) = 0 \quad (22)$$

$$\sigma^{s}_{ta} \cdot (-p^{s}_{ta}) = 0 \quad (23)$$

- Primal feasibility corresponds to equations (6), (7), (8), (9), (10), (11), and (12).
- Dual feasibility. This means that the signs of the KKT multipliers should be opposite to the sign of the dual variables:

$$\delta^{s}_{tah}, \alpha^{s}_{tah}, \delta^{c}_{ah}, \alpha^{c}_{ah}, \sigma^{s}_{ta} \geq 0 \quad (24)$$

When these conditions are included in the modelling of the bi-level approach, decisions are still computed sequentially even though the problem is solved in one-stage. This means that the formulation of the problem is reduced to the objective function of the upper-level together with the constraints of the same level while taking into account the constraints of the lower level together with the KKT conditions.

3.2.2.4 Linearization

Further simplification is needed due the non-linearities to formulate a Mixed Integer Linear Programming (MILP) to apply CPLEX algorithms. The linearization of the complementarity of slacks conditions was held using the big-M method, while the linearization of the upper-level constraint was done using the theory of strong duality.

- Complementarity of slack conditions

The big-M method is going to be used to linearize the constraints which imply that the multiplication of two variables is equal to zero. This method has added one binary variable per constraint that requires linearization, while developing two different constraints that force one of the variables to be zero. The value of M should be high enough to relax the constraints.

$$\delta_{tah}^{s} \leq (1-\delta M_{tah}^{s}) \cdot M \tag{25}$$

$$PF_{tah}^{s} \cdot pt_{ta}^{s} - q_{tah}^{s} \leq \delta M_{tah}^{s} \cdot M \tag{26}$$

$$\alpha_{tah}^{s} \leq (1-\alpha M_{tah}^{s}) \cdot M \tag{27}$$

$$q_{tah}^{s} \leq \alpha M_{tah}^{s} \cdot M \tag{28}$$

$$\delta_{ah}^{c} \leq (1-\delta M_{ah}^{c}) \cdot M \tag{29}$$

$$cp_{a}^{c} - dq_{ah}^{c} \leq \delta M_{ah}^{c} \cdot M \tag{30}$$

$$\alpha_{ah}^{c} \leq (1-\alpha M_{ah}^{c}) \cdot M \tag{31}$$

$$dq_{ah}^{c} \leq \alpha M_{ah}^{c} \cdot M \tag{32}$$

$$\sigma_{ta}^{s} \leq (1-\sigma M_{ta}^{s}) \cdot M \tag{33}$$

$$p_{ta}^{s} \leq \sigma M_{ta}^{s} \cdot M \tag{34}$$

$$\delta M_{tah}^{s}, \alpha M_{tah}^{s}, \delta M_{ah}^{c}, \alpha M_{ah}^{c}, \sigma M_{ta}^{s} \in \{0,1\} \tag{35}$$

- Upper-level constraint

The linearization of the cost recovery constraint from the leader’s problem has been linearized assuming strong duality. This means, that the gap between the primal and dual optimal values is approximately zero at optimality, negligible. Therefore, the objective function of the primal and dual problems could be considered the same since they lead to equivalent results.

The primal objective function of the lower-level is described in equation (5). On the other hand, the dual objective function is the following.

$$-\sum_{a,h} D^{g}_{ah} \cdot \theta_{ah} - \sum_{a,h} D^{c}_{ah} \cdot \mu_{ah} - \sum_{s,t,a} POT^{s}_{t} \cdot \rho^{s}_{ta} \tag{ 36}$$

If the duality gap is equal to zero, both objective functions will be the same:

$$\begin{aligned} &\sum_{a} tf_a \cdot cp^{c}_{a} + \sum_{a,h} (tv_a + P_{ah}) \cdot dq^{c}_{ah} + \sum_{s,t,a} CI^{s}_{ta} \cdot p^{s}_{a} \\ &\qquad = -\sum_{a,h} D^{g}_{ah} \cdot \theta_{ah} - \sum_{a,h} D^{c}_{ah} \cdot \mu_{ah} - \sum_{s,t,a} POT^{s}_{t} \cdot \rho^{s}_{ta} \end{aligned} \tag{37}$$

Solving for the upper-level cost recovery constraint, a linear equivalent formulation has been found.

$$\begin{aligned} &\sum_{a} tf_a \cdot cp^{c}_{a} + \sum_{a,h} tv_a \cdot dq^{c}_{ah} \\ &\qquad = -\sum_{a,h} P_{ah} \cdot dq^{c}_{ah} - \sum_{s,t,a} CI^{s}_{ta} \cdot p^{s}_{a} - \sum_{a,h} D^{g}_{ah} \cdot \theta_{ah} \\ &\qquad - \sum_{a,h} D^{c}_{ah} \cdot \mu_{ah} - \sum_{s,t,a} POT^{s}_{t} \cdot \rho^{s}_{ta} \end{aligned} \tag{38}$$

Now that the multilevel formulation has been transformed into a simpler function, the upper-level constraint is formulated as the following linear function which includes both primal and dual decision variables.

$$-\sum_{a,h} P_{ah}\cdot dq^{c}_{ah} - \sum_{s,t,a} CI^{s}_{ta}\cdot p^{s}_{a} - \sum_{a,h} D^{g}_{ah}\cdot \theta_{ah} - \sum_{a,h} D^{c}_{ah}\cdot \mu_{ah} \qquad (39)$$

$$-\sum_{s,t,a} POT^{s}_{t}\cdot \rho^{s}_{ta} + d \geq \sum_{a} CR_{a}$$

3.2.2.5 MPLM

Once these changes have been applied, the model is ready to be coded in GAMS and solved with CPLEX algorithm using MILP programming as both the objective functions together with all the stated constraints are linear functions. This means that GAMS will not need to compute a multidimensional problem since it has been simplified into a Mathematical Problem with Lagrange Multipliers (MPLM). The abridgment of the model will result in a shortening of the computing time.

Hence, the complete closed loop model is summarized under equations (2), (3),(4), (6)-(12),(14)-(35), and (39).

3.3 MATHEMATICAL FORMULATION OF THE SINGLE-LEVEL APPROACH

The main difference between the single-level approach and the bi-level approach is how decisions are made. In the single-level approach, decisions are taken simultaneously while in the bi-level approach, they are taken sequentially. Therefore, in this case, the deficit of the regulatory costs, and the expansion and exploitation costs of the system are all minimized simultaneously. Note that the single-level approach is in fact a simplified approach to the more realistic bi-level decision problem, and that the assessment of their differences is the main objective of this thesis.

3.3.1 NOMENCLATURE

As mentioned previously, since both approaches follow the same objective, the nomenclature used is almost the same. Sets and variables are going to be presented in lower case letters while parameters are portrayed in capital letters. The sole divergence between sets, parameters, and variables between both models arise as a consequence of the linearization of the open-loop model. Hence, the new parameters, which have been included as the initial point for the Taylor function, are shown below.

Parameters	**Meaning**
TFT_a^0	Initial value of the fixed term (power) of the tariffs [€/kW]
TVT_{ah}^0	Initial value of the variable term (energy) of the tariffs [€/kWh]
$CPT_a^{0,c}$	Initial value of the power contractor by consumer’s [kW]
$DQT_{ah}^{0,c}$	Initial value of the consumer’s consumption from the grid [kWh]

These parameters appear due to the application of Taylor’s theorem to simplify the multidimensional formulated problem into a linear model. Indeed, its practice will be explained later in the paper.

Since there is no need to reformulate the problem with the KKT conditions, the binary variables as well as the Lagrange multipliers variables, are no longer taken into consideration.

3.3.2 PROBLEM FORMULATION

The objective function of the single-level problem is the sum of the objective functions of both the upper-level and the single-level, so that it minimizes the default and excess of regulated costs recovery, and the expansion and exploitation costs of the system:

$$\min d + e + \sum_{a} tf_a \cdot cp_a^c + \sum_{a,h} (tv_a + P_{ah}) \cdot dq_{ah}^c + \sum_{s,t,a} CI_{ta}^s \cdot p_a^s \quad (40)$$

Being subject to constraints (1),(4), (6), (7), (8), (9), (10), (11), and (12), where the objective function (40) and the economic balance constraint (1) are non-linear. The multidimensional formulation could make the optimal solution of the problem hard to find. For this reason, an equivalent linear problem has been formulated.

3.3.2.1 *Linearization*

The non-linearity found in the objective function is the same as the algebraic function that has been defined for the economic balance constraint. Neither of these functions embrace first-degree terms. Therefore, the problem is eligible to be simplified by applying the Taylor's theorem the optimization problem.

Hence, the linearization of the restriction has been calculated by applying derivatives in a point to calculate the hyperplane that crosses through that point. Then, solutions are going to be calculated iteratively with a new hyperplane in each iteration. This method could be seen as a dynamic system where a local solution for the optimization problem is found once the iterating process is over.

Indeed, pursuing the objective of simplifying the previously stated non-linear function, the linear approximation has been calculated following the same approach that has been previously explained. A deeper explanation of this method has been included in ANNEX II – TAYLOR'S THEOREM.

First, the Taylor linear approximation of the fixed term of the tariffs multiplied by the power contracted by the client $(tf_a \cdot cp_a^c)$ would result in the approximation $f_1(tv_{ah}, dq_{ah}^c)$:

$$\begin{aligned} f_1(tf_a, cp_a^c) = {} & \sum_a TFT_a^0 \cdot CPT_a^{0,c} \\ & + \sum_a \left[CPT_a^{0,c} \cdot (tf_a - TFT_a^0) + TFT_a^0 \cdot \left(cp_a^c - CPT_a^{0,c}\right)\right] \end{aligned} \tag{41}$$

Applying the same Taylor approximation to $tv_{ah} \cdot dq_{ah}^c$ would derive in $f_2(tv_{ah}, dq_{ah}^c)$:

$$\begin{aligned} f_2(tv_{ah}, dq_{ah}^c) = {} & \sum_a TVT_{ah}^0 \cdot DQT_{ah}^{0,c} \\ & + \sum_{a,h} \left[DQT_{ah}^{0,c} \cdot (tv_{ah} - TVT_{ah}^0) + TVT_{ah}^0 \right. \\ & \left. \cdot \left(dq_{ah}^c - DQT_{ah}^{0,c}\right)\right] \end{aligned} \tag{42}$$

The main disadvantage of this method is that the initial values of these four variables should be updated in every iteration when seeking the optimal decisions.

The upgraded objective function is presented in equation (43) while the linear approximation of the economic balance constraint has resulted in equation (44).

$$\begin{aligned} \min d + e + \sum_{a,h} P_{ah} \cdot dq_{ah}^c + \sum_{s,t,a} CI_{ta}^s \cdot p_a^s + f_1(tf_a, cp_a^c) \\ + f_2(tv_{ah}, dq_{ah}^c) \end{aligned} \tag{43}$$

$$f_1(tf_a, cp_a^c) + f_2(tv_{ah}, dq_{ah}^c) + d - e \geq \sum_a CR_a \tag{44}$$

Note that since $f_1(tf_a, cp_a^c)$ and $f_2(tv_a, dq_{ah}^c)$ are Taylor's approximations, the results from the single-level model are good estimations of the optimal outcomes.

3.3.2.2 Final optimization problem

Once the Taylor's approximation has been applied, the model is ready to be coded and run with GAMS using CPLEX MILP algorithm. The complete open-loop model is summarized under equations (43), (44),(4), (6), (7), (8), (9), (10), (11), and (12).

Chapter 4. RESULTS ANALYSIS

In this section, the case study that has been subject to analysis is going to be described. The input data together with the resources used to obtain the required information are presented below. Afterwards, a report of the results obtained from the examination of the bi-level and single-level approaches is going to be stated as well as a computational analysis. The computer is a Lenovo ideapad 710-13ISK with Intel (R) Core (TM) i5-6260U CPU and 8 GB RAM. The computer's operating system is 64-bit, x64-based processor. The models have been coded with GAMS version 34.3.0 released on February 25th, 2021.

For the elaboration of the base case, a time horizon of 5 years has been included. Each year is represented by one day of the year (24 hours), more precisely the 10th of June. Furthermore, several initial assumptions were taken into account when solving both models with the aim of obtaining more plausible outcomes.

- The fixed term of the access tariffs was set as a constant throughout the time horizon.
- The variable term of the access tariffs was set as constant at every hour of the time horizon.
- Multiannual execution with one load.
- Renewable technologies such as wind and solar PV.
- One consumer and one generator, no excess energy can be sold.
- Perfect competition as market behavior.
- Negligible distribution losses.
- Consumers are considered price-takers.

Consequently, the degrees of freedom have been reduced to ease the comparison between models as generation capacity expansion planning is complex in liberalized markets like the electric sector. Despite this, the outcomes obtained from both problems are valid since they generically simulate reality while stablishing the correct order of magnitude for each of the variables that have been considered.

4.1 INPUT DATA

Although the model is very simplified, the input data selected was inspired in the Spanish power system. Hence, a brief introduction of its technologies and the energy generated in 2020 are provided to give the reader a general picture.

Since both, the goal of the European Union as well as Spain, is the decarbonization of the electrical system and in the energy generation process, investments in renewable energies have been increased in the last years to reduce the use of fossil fuels by replacing them with renewable technologies.

Spain is taking advantage of the strong Iberian Winds together with the bright sun rays that bathe the Spanish surface. As a consequence of the economies of scale, investments in utility-scale DG are nowadays growing. Moreover, the Spanish government is encouraging its citizens to become prosumers, which enlarges the acquisition of renewable sources thanks to incentives. For this reason, the only renewable sources that have been taken into account in this paper are wind and solar photovoltaic (PV) generation.

This section presents the sources used to obtain information about the input data used in both models to generate different scenarios under the objective of simulating the electric market of Spain. As explained in the introduction, the main focus of this thesis is to analyze qualitatively the main differences between the open-loop and the closed-loop approaches. Therefore, there is no need to input the exact real values of the parameters included in the problem, but all the information that has been introduced is representative enough to obtain an overview of the current and future consumption and generation in Spain.

Power and energy terms of the access-tariffs (TFT_a^0, TVT_{ah}^0)

The total energy price that consumers pay for the energy consumed includes the cost of the electricity from the market, the access tariffs (power and energy terms) to recover the regulated costs, and the taxes (for simplicity not considered in this model).

First, the values that have been included as initial estimates of the single-level model are going to be described. The power fixed rates of the electrical tariffs avoid the fluctuations of the energy costs in the wholesale market. This parameter only takes into account the amount of power contracted by the client and it has been estimated from ESIOS (CNMV & Red Eléctrica Española, 2021). As a result, the fixed rate used in this paper is 37,20 €/kW and it is considered constant throughout the time horizon due to the variability of renewable generation. These sources do not manage to reduce the peak of consumption that represents the duck curve. Therefore, the fixed rate for one week of the year 2019 would be a reasonable approximation of this input parameter.

With regards to the variable rates, a specific week of the year has been chosen as representative: 10th – 16th June 2020. These rates have been obtained from ESIOS (CNMV & Red Eléctrica Española, 2021) as well. It consists of the hourly access tolls and charges (access tariffs) that are part of the regulated price for small consumers. This parameter used to be constant throughout the day in 2020. However, a restructure of the prices of energy has been put into action in 2021.

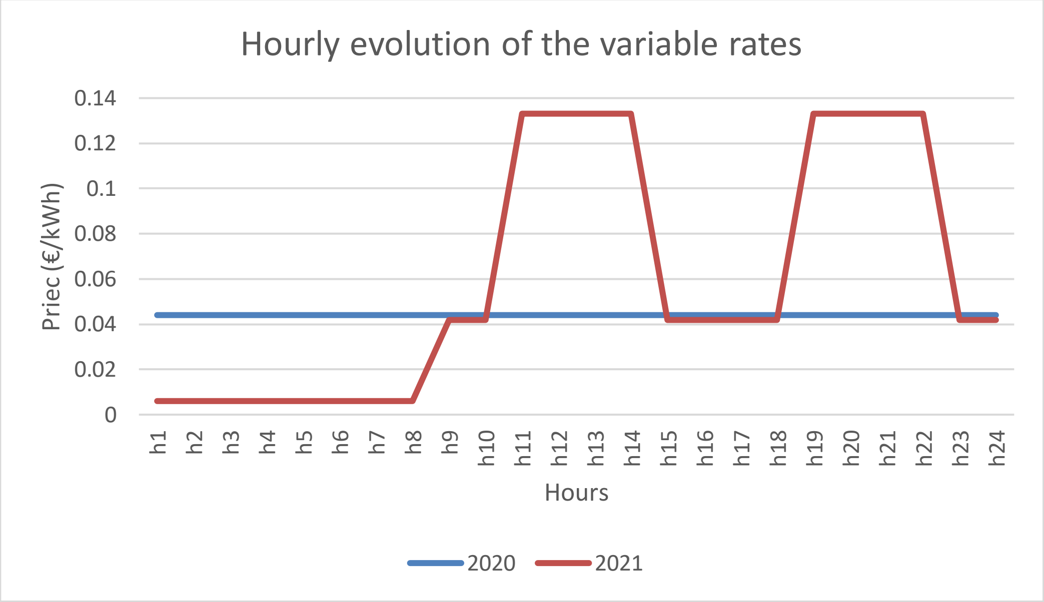

Figure 3: Hourly evolution of the variable rates. Source: Own elaboration.

The three-tiered electricity tariffs system is divided into peak hours, flat hours, and valley hours. The cheapest rate would be the valley rate, from midnight until 8 am, and during weekends and holidays being 0,006 €/kWh. This means that the variable term of the access tariffs, which only take into consideration the amount of energy consumed from the grid, is higher during the day. Indeed, these prices go up to 0,13312 €/kWh during peak hours (11.00-14.00 and 19.00-22.00) while being 0,04177 €/kWh during flat hours.

Furthermore, an increase in pricing of natural gas and CO_2 in the wholesale market is the main reason for the prices of access tariffs to grow. Consequently, prices have been rising since 2019 according to the data from (*MIBGAS - Mercado Ibérico Del Gas*, 2021). This means that an annual increase of 1% in the variable price of energy for the upcoming years would not be far from reality.

Power contracted by the client ($CPT_a^{0,c}$)

Moreover, the initial point that has been selected as input for the energy contracted at the beginning of the time horizon has also been modeled assuming an annual increase of 1%. The new standards of living are based on innovative solutions and technologies, which come together with a greater consumption of energy. Baring this in mind, a fair value for the estimation of this parameter in 2021 would be 122.4 MW as explained by the (CNMV, 2020).

Consumers' consumption from the grid ($DQT_{ah}^{0,c}$)

Regarding the consumers' consumption from the grid, it varies hourly as well as the variable rate of the access tariffs, so its representative value has been obtained from the 24th week of the year 2020. In addition, the energy consumed once the maximum power contracted has been reached, is expected to increase year by year. The main reason for this growth is that the population is continuously growing not only in Spain but also all over the globe. The expansion in developed countries' population together with their high standards of living makes an annual enlargement of 1% in the consumers' consumption from the grid a reasonable consideration. The initial values entered as input in the model have been obtained from ESIOS collaborating with (CNMV & Red Eléctrica Española, 2020).

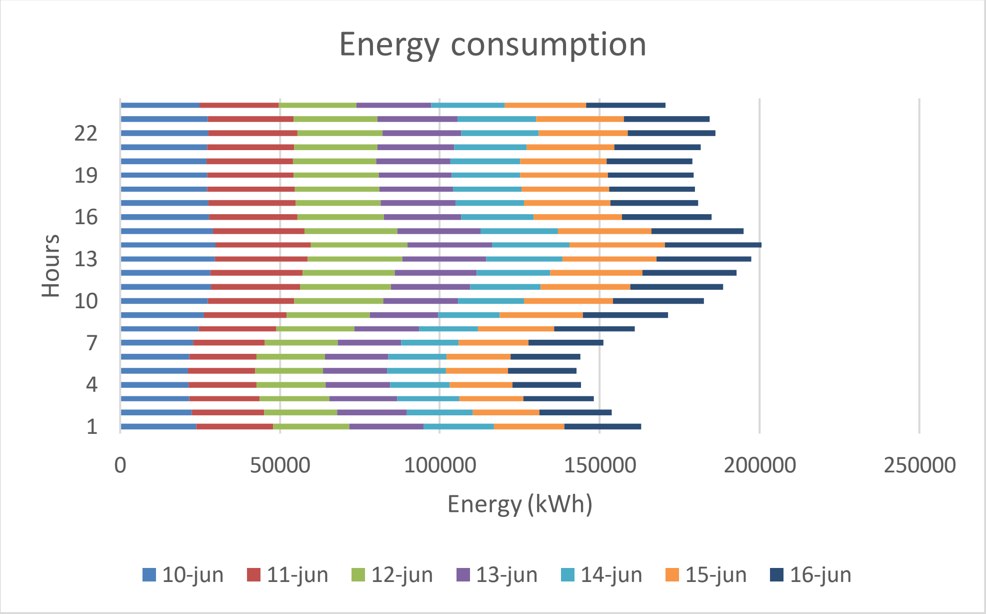

Figure 4: Energy consumption from the grid. Week 10th-16th June 2020. Source: Own elaboration.

Power installed at the beginning of the time-horizon (pt_{ta}^{s})

In addition, the generation power installed at the beginning of the time horizon can be estimated from the statistics posted in *"El Sistema Eléctrico Español 2020"* (Red Eléctrica Española, 2020). At the consumers level, the only installed power that is going to be considered is photovoltaic. On the other hand, at GENCO's level, both wind and solar photovoltaic energy are produced, being the wind generation much bigger than the PV. In the last few years, the electric system has succeeded in installing a greater amount of renewable power. At the end of 2020, the power installed by renewables accounted for 56% of the total installed power being 59,1GW. This could be the turning point for the energy transition with an increasingly renewable energy generation accounting for 27GW from wind power plants and 11GW of solar PV power plants. Moreover, Figure 5 summarizes the evolution of the electric power installed by source in the Iberian Península.

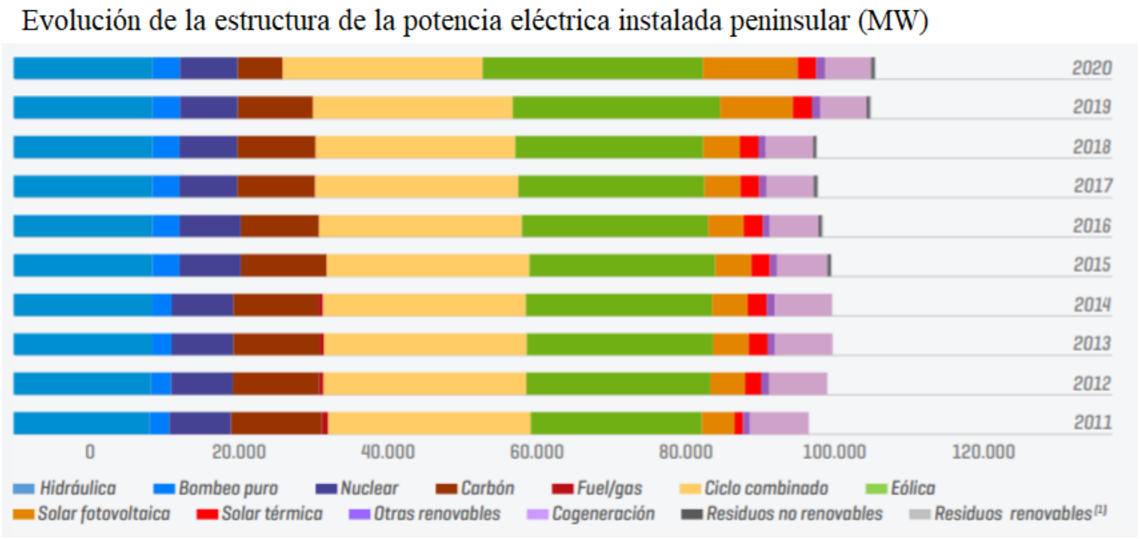

Figure 5: Electric power installed in the Iberian Península in 2020. Source: CNMC and REE.

Demand (D^{s}_{ah})

Regarding the consumers' demand, real data from the 24th week of the year 2021 has been obtained from REE. Therefore, at consumers' level, the amount of power that has been entered as input is the real demand for that week. As for the generators' level, the value that represents the power generation is the expected demand. Figure 6 represents the evolution of the net demand. As it could be seen, generation companies (GENCO's) have smoothly estimated consumers' behavior as they use the previous day's data for their predictions.

Moreover, the electric market has been modeled with one consumer and one generator. This means that the overall Spanish consumption and generation corresponds to the only consumer included in both approaches.

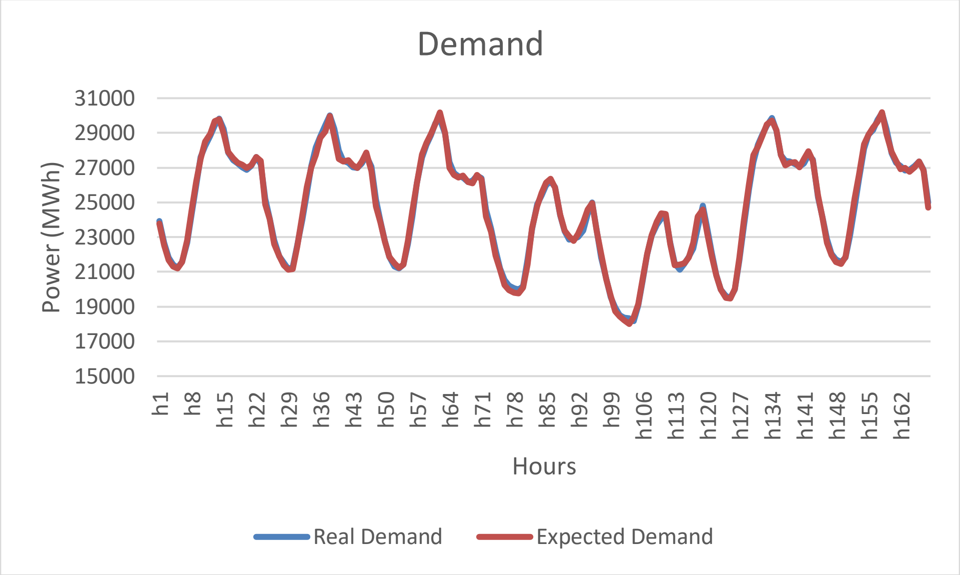

Figure 6: Demand from 10th until the 16th of June 2021. Source: Own elaboration.

Marginal prices of energy (P_{ah})

Additionally, marginal costs are the only operating costs considered in this thesis as RES operating costs are null. The operating cost of energy in the model is set in the wholesale market by matching the offers of the generation companies with the suppliers and direct consumers. Hence, the marginal price of electricity has been taken from the Spanish daily market data. The same week as mentioned previously has been chosen as representative for this parameter in 2021. However, since prices have been set high this year due to the global pandemic recovery, no increase nor decrease has been considered as input for the following years. These prices do not follow a specific pattern, but they are still lower from midnight until 8 am as shown in Figure 8.

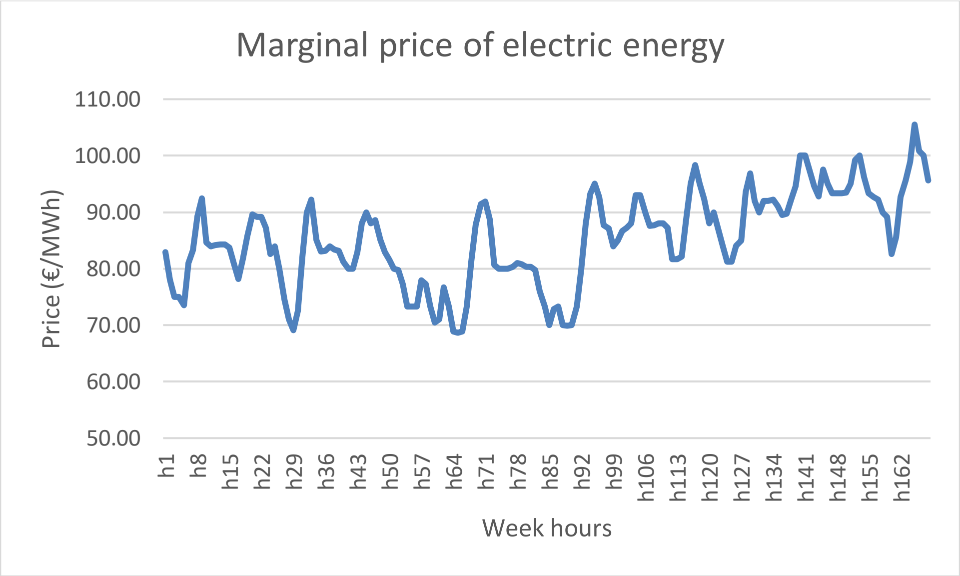

Figure 7: Marginal price of energy from 10th until the 16th of June 2021. Source: Own elaboration.

Regulated costs (CR_a)

Moreover, regulated costs cover the capacity payments, interruptibility services, equipment lease, energy losses, and remuneration to the system and market operator. Such amount accounts for 16.864 M€ in 2020, being 40,8% network costs and 59,2% access costs (CNMV, 2020). These costs have been decreasing since 2017, which means that 16.700 M€ is a good estimation of the regulated costs concerning the modeling.

Investment costs (CI^{s}_{ta})

Moreover, another parameter that should be input in the open- and closed-loop approaches are investment costs in renewable resources. These input data have been estimated from the analysis made in NREL (National Renewable Energy Laboratory, 2018) and EIA (U.S. Energy Information Administration, 2019). Hence, with the aim of reducing the complexity of the model while including data as realistically as possible, the values used to represent the investment costs are the investments in capital expenditures (CapEx) made once a new generation facility is installed. This is a reasonable assumption since fixed and variable operating costs (OpEx) for renewable energies are negligible compared to the initial investments.

Investment costs for future years have been calculated through linear interpolation between the data from NREL and EIA for years 2016, 2030, and 2050. At the generators' level only solar PV and onshore wind generation have been considered. On the other hand, solar PV investments are the only ones that have been incorporated at consumers' level as it is already the cheapest form of electricity generation in many market segments. On account of that, costs for a residential generation have been set up to 1.000.000 €/kW for wind technologies so that the customer would rather install solar PV for distributed generation. Then, solar PV input investment costs are 2.784 €/kW for consumers and 1.329 €/kW for generators.

Moreover, the resources used to find these data expressed the values in [$/kW], so a conversion factor was used to do the currency conversion from US dollars to euros. A fair factor for 2020 would be 0,89 EUR/USD. Nevertheless, this factor is continuously changing so it should be revised for future work. In this case, the solar PV investment costs that have been input are 2.784 €/kW for consumers and 1.329 €/kW for generators. Whereas the estimation of these costs for wind generation account for 1.461 €/kW in 2021.

Production factor (PF_{tah}^{s})

Finally, the last parameter that has been included in the model and has not yet been described is the production factor of the renewable technologies, wind and solar PV. During the day, the amount of energy generated is not the same, especially the energy generated by solar is null at night. For this reason, the production factor should be taken into account when comparing the total installed power with the production by technology. This factor is simply calculated by dividing the real generation by the installed generation power. Moreover, this factor is going to be considered the same no matter the type of agent, as the energy produced by these sources should be more or less the same regardless of whether you are focused on consumption or generation.

The source of information used to obtain the data about the production factor is ESIOS. What is more, is that it depends on the type of technology being considered. Wind turbines generate a greater amount of energy all over the day than solar PV. Therefore, Figure 9 represents how different they are.

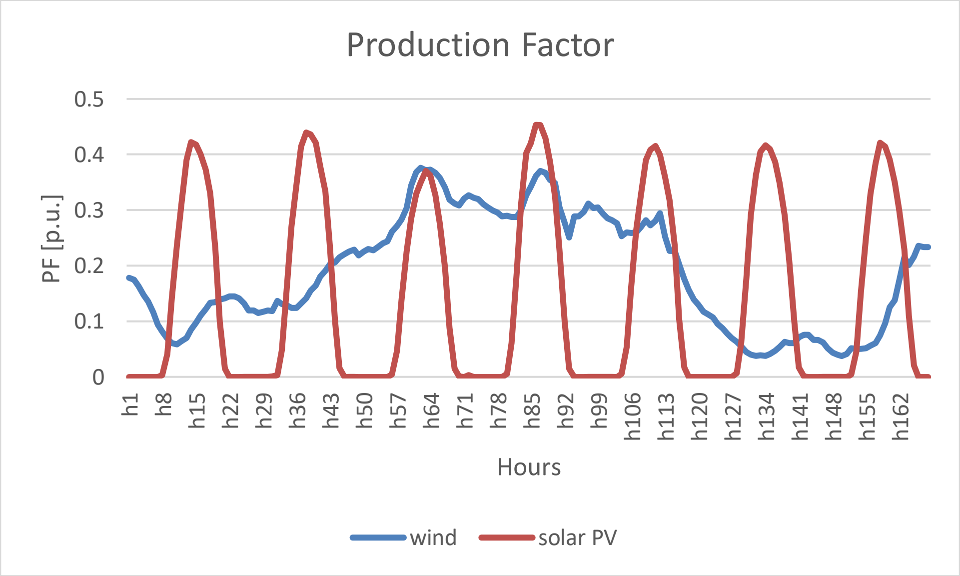

Figure 8: Production Factor for renewable resources from 10th until the 16th of June 2021. Source: Own elaboration.

4.2 *CASE STUDIES*

In this section, the case studies that have been used to contrast the single-level and the bi-level problems are described. In each case study, an analysis of the recovery of network costs together with a comparison between the optimal values assigned by the two approaches to the decision variables has been done.

4.2.1 ANALYSIS OF THE BI-LEVEL RESULTS

The optimal outcomes of the bilevel model are presented in Table 3.

	Annual tf [M€/GW]	Hourly tv [M€/GWh]	Annual cp [GW]	Annual dq [GWh]	cost recovery [M€]	regulated costs [M€]
2021	0	0,07351	7,34993	622,40855	16700	16700

Table 3: 2021 recovery of regulated costs (Bi-level approach). Source: Own elaboration.

The most important result is that regulators are able to recover network costs, which could be translated into a null and void default and excess of regulated earnings $(d + e)$.

Once the cost recovery has been proved, various sensitivity analysis have been conducted to prove the effectiveness of the model when representing reality. First, when modifying the fixed rate of the access tariffs, investment decisions should be adjusted accordingly. However, as a consequence of the simplicity of the model, this does not occur. The main reason behind it is that the regulators constraint to cover costs includes the same terms $\sum_a tf_a \cdot cp_a^c + \sum_{a,h} tv_{ah} \cdot dq_{ah}^c$ in the lower-level objective function which makes this term constant in the lower level when fully satisfying the regulated costs. Therefore, as shown in Table 4, a change in the access-tariff terms does not affect the rest of the decision variables of the model.

	tf [€/kW]	tv [€/kWh]	cp [GW]	dq [GW]	p.wind [GW]	p.pv [GW]	cost recovery [M€]
base case	0,00000	0,07351	7,34993	622,40855	357,29959	22,77296	16700,00000
case 1	0,20000	0,07348	7,34993	622,40855	357,29959	22,77296	16700,00000
case 2	0,50000	0,07344	7,34993	622,40855	357,29959	22,77296	16700,00000
case 3	0,70000	0,07342	7,34993	622,40855	357,29959	22,77296	16700,00000
case 4	1,00000	0,07338	7,34993	622,40855	357,29959	22,77296	16700,00000

Table 4: Sensitivity analysis of the access-tariffs 2021 (Bi-level approach). Source: Own elaboration.

Moreover, since the abovementioned term needs to be adjusted to regulated costs, the variable term and the fixed rates of the tariffs have a negative linear correlation, as Figure 9 shows, meaning that the consumer faces always the same tariffs as a whole, which leads to numerous optimal solutions. This is due to the lack of dependance between access-tariffs and the demand.

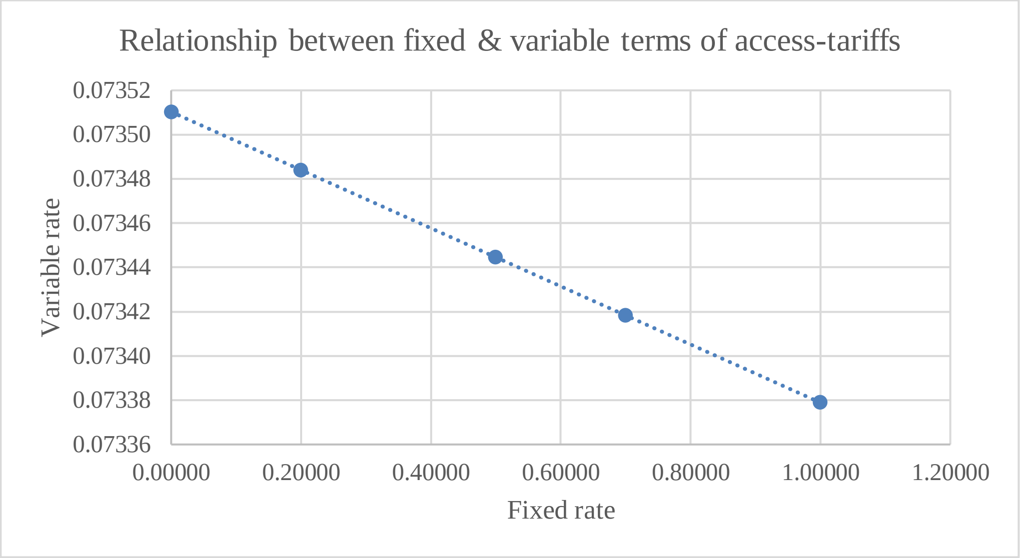

Figure 9: Correlation between fixed and variable access-tariff rates in 2021 (Bi-level approach). Source: Own elaboration.

With the aim of proving that the model responds to an increase or decrease in demand, two cases have been modeled by dividing demand by 10 or multiplying it by the same amount. Results of these cases are summarized in Figure 5, where case 1 refers to the reduction in demand and case 2 to the enlargement. These outcomes reveal that there is a linear dependence between demand and the clients' consumption from the grid. When demand decreases, consumption follows the same trend, causing the energy term to increase in the same proportion to recover costs. Consequently, the power contracted by the client and investments diminish as costs are still minimized, so there is no need for over-generation. These conclusions could also have been deduced by looking at the model constraints. Therefore, it is verified that the problem responds as expected.

	tf [€/kW]	tv [€/kWh]	cp [GW]	dq [GW]	p.wind [GW]	p.pv [GW]
base case	0,00000	0,07351	7,34993	622,40855	357,29959	22,77296
case 1	0,00000	0,73516	0,73490	62,23760	11,10672	0,00000
case 2	0,00000	0,00735	73,50030	6224,11805	330,72564	330,72564

Table 5: Sensitivity analysis with demand (bi-level approach). Source: Own elaboration.

Regarding the installation of new power from renewable technologies, it should increase in case investment costs are lower than usual according to the model. Indeed, overall investments increase if investment costs are low (case 1). However, taking a deeper look into what it is happening, wind power investments decrease in a smaller rate than the enlargement of solar PV investments. The main reason behind this is that investment costs on solar energy are expected to decrease at a higher rate than those corresponding to wind generation. More precisely, investment costs on solar energy for consumers fall faster than those for generation companies since the Spanish government is encouraging their citizens to become prosumers. These outcomes are presented afterwards, where case 1 represents a decrease and case 2 an increase in costs.

In addition, according to the logic of the optimization problem, whenever investments increase, consumption from the grid should diminish so as not to generate an excess of energy as it would not be cost effective. This would be translated into a reduction in the power contracted by the client and the clients’ consumption from the grid as shown in Table 6. Nevertheless, costs should always be recovered so the rates of the access-tariffs respond accordingly.

Finally, an increase in investment costs should lead to a decrease in investments on renewable technologies and, consequently, an increase in the consumption from the grid so as to meet demand. However, since the optimal value of consumers’ consumption from the grid already attained its upper bound in the base case, the model fails in representing these variations as demand has already been met.

	tf [€/kW]	tv [€/kWh]	cp [GW]	dq [GW]	p.wind [GW]	p.pv [GW]
base case	0,00000	0,07351	7,34993	622,40855	357,29959	22,77296
case 1	0,00000	0,14712	6,79537	310,98693	353,65628	167,56629
case 2	0,00000	0,07351	7,34993	622,40855	357,29959	22,77296

Table 6: Sensitivity analysis with investment costs (bi-level approach). Source: Own elaboration.

To conclude the analysis of the bi-level approach, a sensitivity analysis was conducted by modifying the marginal price of energy as depicted in Table 7. Since marginal prices of energy are an input to the model, consumers should consume small quantities of energy in order to notice the difference between lower prices and higher prices. Moreover, consumers' consumption from the grid already attained its upper bound in the base case. For this reason, the difference between outcomes is negligible regardless of a price increase or decrease as input demand corresponds to the sum of all the consumers represented under one single client in this thesis. That is why the marginal price of energy does not affect the decision making.

	tf [€/kW]	tv [€/kWh]	cp [GW]	dq [GW]	p.wind [GW]	p.pv [GW]
base case	0,00000	0,07351	7,34993	622,40855	357,29959	22,77296
case 1	0,00000	0,07351	7,34993	622,40855	357,29959	22,77296
case 2	0,00000	0,07351	7,34993	622,40855	357,29959	22,77296

Table 7: Sensitivity analysis with the marginal price of energy (bi-level approach). Source: Own elaboration.

All in all, due to the simplifications that have been made to the model and its linear formulation, the closed-loop approach includes various limitations that should be taken into consideration in future works. The price of energy should always depend on consumption, there is more than one consumer or generation company in the market, dispatchable energy should be considered and investments could be done in other renewable technologies while storing excess energy.

4.2.2 ANALYSIS OF THE SINGLE-LEVEL RESULTS

Regarding the open loop model, it presents the investment-operation market in a single stage. After running the model in GAMS without any penalization, several drawbacks appear. The main inconvenient of taking decisions simultaneously has to do with the objective function. The terms that belong to the upper-level of the bi-level approach and the terms that correspond to the single-level approach weigh the same. As a consequence, the model gives null values to the variable and fixed tariff rates while recovering the regulated costs with the slack, the default of regulated earnings. This could be the optimal solution, but it does not represent the electric market since consumers would be able to consume as much energy as they desire at no cost. To avoid this issue, more weigh is given to the terms that belong to first level of the closed loop formulation as shown in the following equation.

$$\min P \cdot (d + e) + \sum_{a,h} P_{ah} \cdot dq_{ah}^{c} + \sum_{s,t,a} CI_{ta}^{s} \cdot p_{a}^{s} + f_1(tf_a, cp_a^c) + f_2(tv_{ah}, dq_{ah}^{c}) \tag{45}$$

Now, the objective function of single-level model is multicriteria because it integrates the bi-level functions into an open-loop approach. In addition, the penalization has been included in the model as P=1000. Consequently, the default of regulated earnings becomes null, attaining the main objective of regulators. Hence, the power contracted by the client achieves fair values as consumers' consumption is no longer unlimited. Concerning the client's consumption from the grid, it is constrained by the energy balance, so it always attains similar values. Moreover, investments in new renewable technologies are only done by generation companies in the first two years of the time-horizon contemplated in this case study. Installing the greatest amount of power in the first year: 357,3 GW of wind power and 22,8 GW of solar PV power to meet demand. A more detailed version of the results can be found in ANNEX VI – RESULTS OF THE SINGLE-LEVEL APPROACH.

Regarding the recovery of network costs, the single-level approach recovers 100% of the costs throughout the five-year time-horizon without exceeding the total amount of regulated costs (83.500 M€). This proves that in case the electric sector follows this approach, they will succeed in retrieving the network costs in the long-term as there would be no default of regulated earnings.

In this case, while checking whether costs are being recovered, a sensitivity analysis on the access-tariff rates has been done like in the bi-level approach. Under the objective of proving that earnings from access-tariffs recover regulated costs when they are minimized, results reveal that neither of the rest of the decision variables are affected when modifying these rates. The reason behind it is the same as in the bi-level approach: the sum of the terms corresponding to the energy and power earnings attain the value of the left-hand-side of the regulators constraint when costs are being minimized. Hence, the sum yields a constant value based on the linear relationship between variable and fixed access-tariff rates shown in Figure 9. A more detailed version of these results is given in Table 8 while checking the cost recovery.

	tf [€/kW]	tv [€/kWh]	cp [GW]	dq [GW]	p.wind [GW]	p.pv [GW]	cost recovery [M€]
base case	0,0	0,072055	37,492044	3174,909141	357,310741	22,776538	83500
case 1	0,2	0,072048	37,492044	3174,909141	357,310741	22,776538	83500
case 2	0,5	0,072039	37,492044	3174,909141	357,310741	22,776538	83500
case 3	0,7	0,072032	37,492044	3174,909141	357,310741	22,776538	83500
case 4	1,0	0,072022	37,492044	3174,909141	357,310741	22,776538	83500

Table 8: Sensitivity analysis of the access-tariffs throughout the time-horizon (Single-level approach).
Source: Own elaboration.

With regards to the rest of the sensitivity analysis that have been performed, the cases that have been considered are exactly the same as in the bi-level approach under the objective of comparing the outcomes of both optimization models. Nevertheless, results are very close, so they are going to be briefly compared.

First, an increase as well as a decrease in demand was input to the model. A decrease in demand results in a reduction of both investments and consumption from the grid according to the energy balance. As a consequence of the diminishment in consumption, energy rates of the access-tariffs have been increased so as to recover regulated costs. As presented in Table 9, in the opposite case, decision variables respond the other way around similarly to the closed-loop approach.

	tf [€/kW]	tv [€/kWh]	cp [GW]	dq [GW]	p.wind [GW]	p.pv [GW]
base case	0,000000	0,073510	7,349933	622,408552	357,299587	22,772964
case 1	0,000000	0,735141	0,734896	62,237602	11,106720	0,000000
case 2	0,000000	0,007351	73,500302	6224,118052	3816,274874	3816,274874

Table 9: Sensitivity analysis with demand (single-level approach). Source: Own elaboration.

Whenever investment costs change, decision variables also respond accordingly in the open-loop approach. If costs are lower (case 1), overall investments increase and consumption from the grid decreases to not over-generate energy. As consumption decreases, with the aim of succeeding in recovering costs, the variable term of the access-tariffs increases. In case costs were higher (case 2), decision variables would respond the other way round as revealed in Table 10.

	tf [€/kW]	tv [€/kWh]	cp [GW]	dq [GW]	p.wind [GW]	p.pv [GW]
base case	0,000000	0,073510	7,349933	622,408552	357,299587	22,772964
case 1	0,000000	0,129693	6,798086	352,782995	354,561473	82,848915
case 2	0,000000	0,073510	7,349933	622,408552	357,299587	22,772964

Table 10: Sensitivity analysis with investment costs (single-level approach). Source: Own elaboration.

Furthermore, regarding the marginal price of energy, no alteration causes significant changes in the optimal results as demonstrated in Table 11. The same conclusion was obtained from the bi-level approach which means there is no need for further explanations.

	tf [€/kW]	tv [€/kWh]	cp [GW]	dq [GW]	p.wind [GW]	p.pv [GW]
base case	0,000000	0,073510	7,349933	622,408552	357,299587	22,772964
case 1	0,000000	0,073510	7,349933	622,408552	357,299587	22,772964
case 2	0,000000	0,073510	7,349933	622,408552	357,299587	22,772964

Table 11: Sensitivity analysis with the marginal price of energy (single-level approach). Source: Own elaboration.

To sum up, it can be concluded that the outcomes from the open-loop formulation are not valid if the objective function is not weighted appropriately. Once the terms that correspond to the upper-level have been penalized, results model the electric market generically. However, due to all the simplifications that come together with one-stage linear modelling, more research should be done.

4.2.3 COMPARISON BETWEEN APPROACHES

As discussed above the main difference between the bi-level and single-level approaches is how decisions are made. In the closed loop, decisions are taken sequentially which makes the model look more realistic. On the other hand, the open loop takes decisions simultaneously which should lead to over-investments. However, it does not happen in these cases as upper-level decision variables of the bi-level approach are insensitive.

As stated previously, both models respond in the same way to changes in demand, investment costs, tariffs and energy prices. This means that with the same input data, optimal results should be the same for all the decision variables. Table 12 and Table 13 describe the total investments together with the total contracted power by the client and the total consumer’s consumption from the grid.

	tf (M€/GW)	tv (M€/GWh)	total cp (GW)	total dq (GWh)
Single-level	0,00000	0,07351	7,34993	622,40855
Bi-level	0,00000	0,07351	7,34993	622,40855

Table 12: Comparison of costs (2021). Source: Own elaboration.

	total investments (GW)	
	wind	solar PV
Single-level	357,2996	22,7730
Bi-level	357,2996	22,7730

Table 13: Comparison of the investments in renewable technologies (2021). Source: Own elaboration.

Obtaining the same optimal outcomes means that it is not relevant whether decisions are made simultaneously or sequentially. As mentioned, this is due to the fact that the problem is so simplified (one consumer, no impact on the market energy price, and no dispatchable generation) that leads to a constant cost per tariff in the consumer cost minimization.

4.3 COMPUTATIONAL ANALYSIS

4.3.1 CONVERGENCE OF THE SINGLE-LEVEL MODEL

In this part of the thesis, the convergence of the algebraic model programmed for the open-loop approach is going to be analyzed. As previously explained, the single-level formulation of the problem contains two terms that are non-linear. Therefore, the approach that was followed to simplify it was the first-degree Taylor's approximation, which introduced four new parameters to the model. These parameters need to be updated after every iteration in order to obtain the optimal value of the corresponding decision variables. The upgrade performed in each iteration is carried out by assigning the optimal value of the variables to the initial value of the equivalent Taylor's parameter in the previous iteration, until convergence.

Under the purpose of establishing the end of the iterating process, a consistent method was selected. It basically consists of calculating the absolute difference between the optimal value of the decision variables and the given initial value in each iteration. Afterwards, the maximum value of these differences was calculated for each variable and compared to a specific threshold, depending on the measurement units.

In this case, fixed rates of the access-tariffs and the corresponding variable rates are both measured in €/kWh. Hence, the maximum value for the absolute difference for both variables should have the same order of magnitude. The chosen value has been set to 0,0001 so as to have accurate results. In the case of the power contracted by the client and the client's consumption from the grid, they are presented in GW and GWh accordingly. This means that the tolerance should also be among the same order of magnitude. For the sake of simplicity, the tolerance value has been set identical also to 0,0001. Even so, different values could have been set as maximum difference for the disparate variables.

Regarding the case study considered in this thesis, the main purpose is to check the robustness of the resolution methodology, in other words, prove that the optimal solution obtained is always identical for different starting conditions. To this end, a sensitivity analysis has been conducted, multiplying the initial values for the Taylor's parameters by different numbers. This leads to various initial points with different orders of magnitude. Having said this, six factors have been used: 0.5,1,1.5,5,10, and 100. The results obtained for the convergence of each case are summarized in ANNEX IV – CONVERGENCE RESULTS FOR THE SINGLE-LEVEL APPROACH. Moreover, the convergence results obtained for the first year, 2021, are going to be presented in different graphs for each value under the purpose of proving the merging of the iterating process.

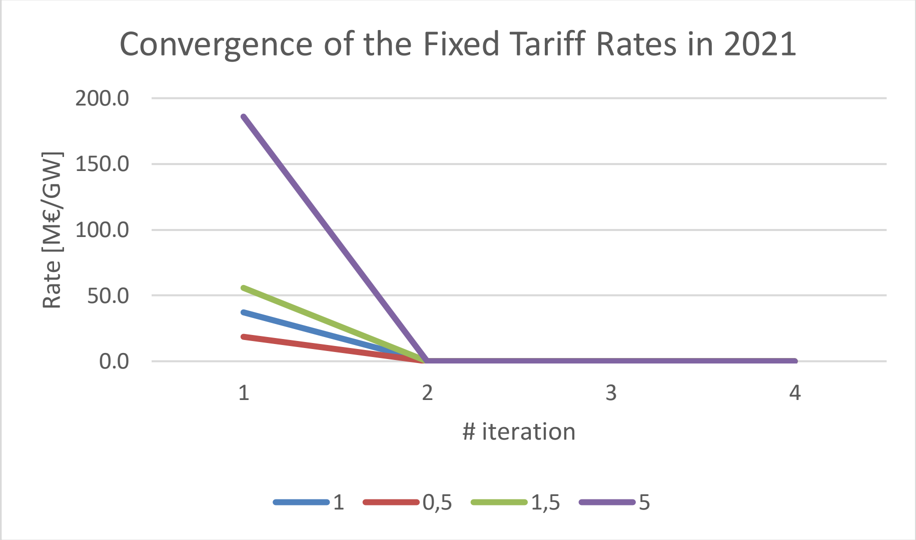

Figure 10: Convergence of the fixed term of the access tariffs in 2021.

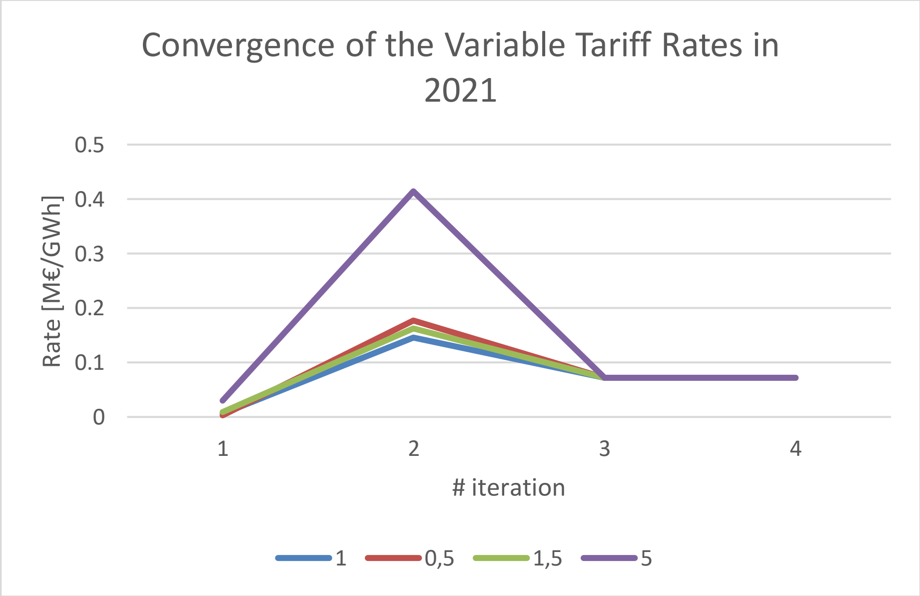

Figure 11: Convergence of the variable term of the access tariffs in the first hour of 2021.

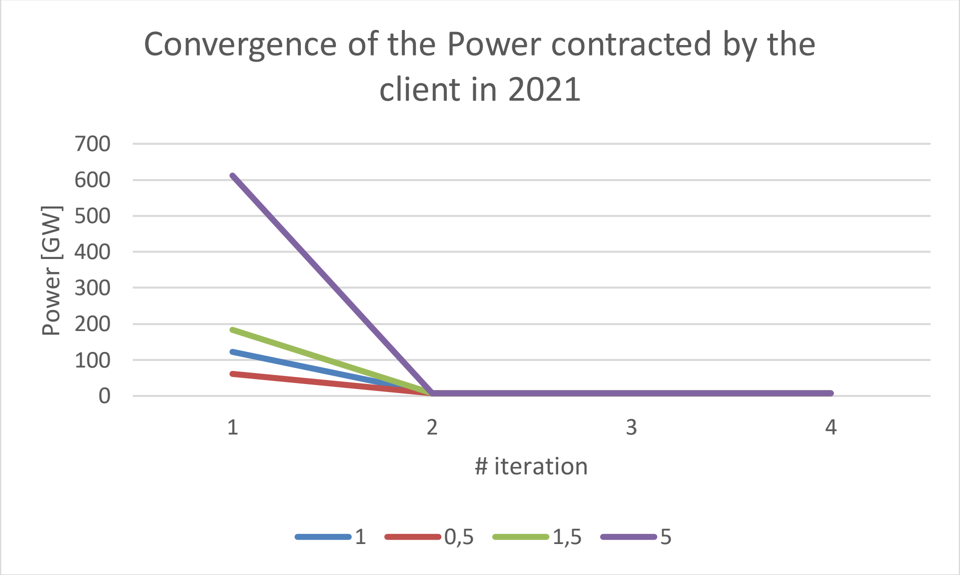

Figure 12: Convergence of the power contracted by the client in 2021.

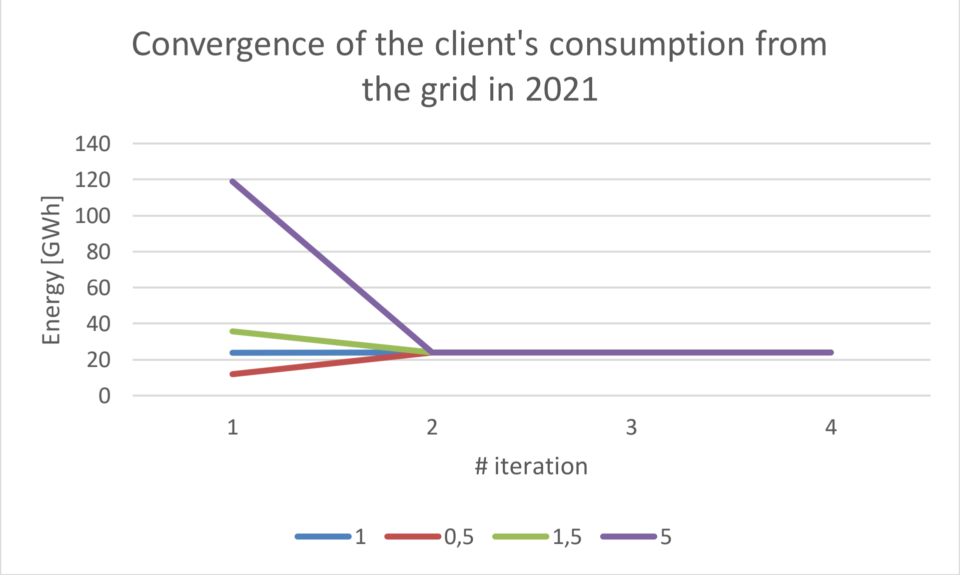

Figure 13: Convergence of the client's consumption from the grid in the first hour of 2021.

Both the graph corresponding to the fixed term of the tariffs and the one related to the contracted power by the client have the same shape since the assigned initial values were over-estimated. This is the main reason of this coincidence. However, in case the input values were modified, the graph's contour would not necessarily be the same.

In addition, the last Taylor's parameter to converge is the variable term of the access tariffs as shown in the graphs. In the second iteration, costs are recovered but their value is not minimal. Then, the solution is not optimal, so the iterating process continues until the difference between the optimal value and the assigned initial value is lesser than the stablished number.

It should also be noted that the iterative process ends after the fourth iteration due to the simplicity of the model. If the Taylor's approximation was applied to another problem with a greater number of constraints or a more complex objective function, the number of iterations performed before finding the optimal solution would have been greater.

To conclude, it can be inferred from these graphs that the formulation for the iteration of the single-level is robust as it converges no matter the assigned value to the Taylor's parameters. The greatest divergence between the assigned initial value and the optimal value of each iteration appears always between the first and second one. But it is indeed in the last iteration where the results in all cases coincide since the approximations end up getting closer and closer to the real optimal value sought.

Chapter 5. CONCLUSIONS

In this part of the thesis, an analysis is going to be made on whether the goals set at the beginning of this thesis have been attained. These objectives have to do with the modeling of the open- and closed-loop problems, the convergence of the single-level approach, and, finally, the results analysis including a comparison between the two models that have been designed.

5.1 *CONCLUSIONS ON THE MODELING*

First, the bi-level approach has been modeled taking into account the work carried out by (Martínez Velázquez et al., 2019). The closed loop problem has been improved by adding several constraints and parameters to obtain more realistic results, such as the production factor parameter for renewable technologies.

Throughout the description of this approach, the bilevel problem was simplified into an open-loop formulation. By calculating the derivative of the Lagrangian function of the lower-level, the KKT conditions can be applied so as to transform the model into a one-stage mathematical problem. The main inconvenient of this method is that whenever a new constraint is added, the derivate of the Lagrangian function should be calculated again with all the corresponding simplifications. Therefore, it can be concluded that this approach is complicated, and modeling requires a great deal of time. A bi-level problem could have been input to GAMS. However, its computing time is higher than the one needed for a single-level problem, and local convergence might arise.

Once the KKT simplification has been modeled, several non-linearities appear. Therefore, by using the M-method together with the condition of the strong duality, a linear approximation of the problem has been successfully obtained. It is true that the big-M method is very common for solving non-linearities, which means that its application does not make the model more complicated. However, the linearization using the strong duality principle is different for every optimization problem. This means that whenever a new constraint is added or even the objective function changes, the application of the strong duality principle should be redone. As a whole, bi-level problems are considered hard to solve due to all the inconvenients that can appear throughout the modeling and their own non-convexities.

Regarding the formulation of the designed equivalent single-level approach, it consists of adding the objective functions of the two-stages of the closed loop problem into a unique objective function. Moreover, all constraints must be taken into account at the same level. This results in a non-linear model that has been simplified by applying the first-degree Taylor's approximation. This likeness approach introduces four new variables into the problem that represent the initial values of the access-tariff rates, the contracted power and the consumption from the grid. An iterative fix-point algorithm has been applied to obtain the closest outcome to the optimal solution.

To sum up, both models represent the regulatory and economic framework of the electric market. However, it seems that the closed-loop problem has a much more complex formulation. For this reason, the advantages and disadvantages of both formulations have been analyzed.

5.2 CONCLUSIONS ON THE RESOLUTION METHODOLOGY OF THE SINGLE-LEVEL PROBLEM

Since both the objective function and the economic balance constraint in the single-level model include several non-linear terms, the Taylor's theorem was applied under the objective of obtaining an approximation of the model. Since the non-linear functions were derivable, the first-degree Taylor's approximation around a point has been applied.

Consequently, new parameters were introduced to the model as the initial values of such approximations, and in particular for the fixed and variable terms of the access tariffs, the power contracted by the client, and the client's consumption from the grid.

The maximum of the absolute difference between the assigned initial value and the optimal value of each iteration was compared to a coherent tolerance to stop the iterating process. The approximations end up getting closer to the optimal value sought. Moreover, since the iterating process finishes in the fourth iteration, it can be concluded that the model has a rapid convergence as a consequence of its simplicity.

Finally, it has been proved that the model is robust to the initial values of the Taylor's approximations.

5.1 CONCLUSIONS ON THE RESULTS

The closed-loop and open-loop formulation of the electric market consider the same regulatory, economic, and energy constraints. The upper-level models the regulatory framework, and then, the lower-level describes the energy balance for consumers and generators, which means that decisions are taken sequentially. On the single level, because of the simultaneity of the decisions, everything has been taken into account at the same time, which should lead to over-investments. This would be the main difference between both approaches.

At first, it seemed like the bi-level was closer to reality as investment decisions were supposed to be separated from the operational. However, both models succeed in recovering network costs (once the cost recovering in the single-level approach has been guaranteed with the penalization of the default and excess of the regulated earnings) and the results obtained have the same order of magnitude independently of the problem formulation.

Outcomes reveal that there is no difference between making decisions simultaneously or sequentially. This is mainly due to the fact that a constant value for the access-tariffs cost is obtained in the objective functions, as a result of the simplifications assumed, which led to optimal decisions that do not depend on the tariff rates (the main decisions of the upper-level in the closed-loop approach).

Since it is very important that the open-loop model provides reliable results, in this thesis, once the difference between the regulated costs and their targets has been penalized, the optimal outcomes have been proved to be realistic enough compared to a much more complex model such as the bi-level problem. This means that the single-level model has succeeded in representing the electrical market in simple terms.

Moreover, by fixing the power term of these tariffs to different values, a linear negative correlation between the fixed and variable rates has been obtained, leading to multiple optimal solutions (identical in terms of access-tariffs cost), as well as the same investments in renewable technologies when satisfying the electricity demand.

On the other hand, both models end up representing the electric market in a similar and simplified way. Whenever demand is increased, investments in renewable technologies increase as well as the consumers' consumption from the grid to meet the energy balance. Consequently, access-tariffs are adjusted to recover regulated costs.

In addition, when investment costs decrease due to economies of scale, consumers and generators tend to install new sources of power which enables them to generate a greater amount of energy. As a result, consumer's consumption from the grid is prone to suffer a diminishment complicating the cost recovery, and regulators are forced to enlarge access tariff rates.

Both models include some limitations when representing the reality. Due to all the limitations that appear in the single-level approach (penalization adjustment, Taylor approximation, etc), it should be rejected for future modeling of the electric sector. As for the bi-level formulation, it does not require further approximations nor artificial penalizations of the model compared to the open-loop approach, but it should still be subject to future improvements.

5.2 RECOMENDATIONS FOR FUTURE STUDIES

Future studies should focus on the bilevel representation of the electric market, as the sequentiality of decisions has been proven as a more plausible solution. Therefore, a greater focus should be put on the economic and technical aspects of this market to create more accurate forecasts.

Since the degrees of freedom were reduced when evaluating the outcomes of both models, a new approach could be to include more than one consumer and generation company to improve the comparison between the open-loop and closed-loop models. If the electric market is separated in this way, different types of market could be modeled such as oligopoly and perfect competition, so outcomes would be more reliable.

In this thesis, the only two renewable resources that have been considered are wind and solar PV. Nevertheless, it could be interesting to include other renewable technologies to increase the amount of energy generated like hydro generation, or bioenergy. Indeed, thermal energy has not been incorporated to the model. Therefore, this source of generation could be added to the problem in future studies.

Moreover, energy storage could also be included in the model. The production of renewable energy is not the same every day, there are multiple factors that alter the daily production. For this reason, energy should be stored in batteries for self-consumption or in larger-scale projects that take advantage of potential energy to drive sustainability and effectiveness.

In addition, one of the objectives of this thesis was to analyze the recovery of network costs throughout a specific time-horizon. In the case studies, only five years were contemplated which makes the long-term capacity expansion planning simpler. Hence, by increasing the number of years for future forecasts, the complexity of the problem for generation companies and regulators increases significantly.

Marginal prices could have been modeled quadratically or even made dependent of the clients' consumption. By focusing on another approach and relating the consumption to the tariff rates, the model would lead to more realistic outcomes were costs from access-tariffs are not constant for consumers. Furthermore, investment costs should also include fuel costs together with fixed and variable operating and maintenance costs. These costs will also increase the reliability of the model as capital expenditures were the only investment costs considered in this thesis.

To conclude, throughout this thesis, it has been revealed that the linear approximation of the open-loop problem was not accurate enough to model the electric market. It is true that this approach is less realistic than a bilevel problem where operating and investment decisions are taken sequentially. However, it could be interesting to linearize the closed-loop model under different methods and compare their main outcomes.

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ANNEX I – LAGRANGIAN FUNCTION AND KKT CONDITIONS

The generic mathematical formulation of the Lagrangian function is presented below, where $L(x,y)$ is the Lagrangian function, $f(x,y)$ is the objective function of the problem stated, $g_i(x,y)$ are the constraints and μ_i are the Lagrange multipliers that are known to have opposite signs to the dual variables of the lower level.

$$\nabla L(x,y) = \nabla f(x,y) - \mu_i \cdot \nabla g_i(x,y)$$

However, this formulation of the Lagrangian function is only used when implementing the method of the Lagrange multipliers, which is only valid when the optimization problem includes equality constraints. In case the model includes inequalities, the KKT conditions should be used for finding the optimal solution. Thus, the formulation of the Lagrangian function is summarized below, where $f(x,y)$ is the objective function of the problem stated, $g_i(x,y)$ are the equality constraints, μ_i are the Lagrange multipliers, $h_i(x,y)$ are the inequality constraints λ_i are the KKT multipliers.

$$\nabla L(x,y) = \nabla f(x,y) - \mu_i \cdot \nabla g_i(x,y) - \lambda_i \cdot \nabla h_i(x,y)$$

Once this function has been defined, with the aim of calculating the optimal solution of an optimization problem, new constraints should be included. These upcoming restrictions appear as a consequence of the KKT conditions: stationarity, complementary slackness, primal feasibility, and dual feasibility.

The stationarity condition states that the gradient of the Lagrangian function should be equal to zero. This condition adds as many constraints as variables included in the function. Moreover, the complementarity of slackness means that if a dual variable is greater than zero, the primal constraint must be an equality. And if the primal constraint is slack, greater than zero, then the dual variable should be tight, equal to zero as explained in (Vishwanathan, n.d.). Finally, the last constraints that are included in the model are the signs of the Lagrange multipliers, whose sign should be opposite to the one of the dual variables.

ANNEX II – TAYLOR'S THEOREM

The theory behind the application of Taylor's theorem for finding the first-degree Taylor polynomial is that the opposite direction of the gradient vector in a point is the direction where the function decreases the most rapidly. Therefore, if the function is continuous and derivable, the best approximation of the function will be its first derivative around a point. This means that there is a higher probability of finding the optimal solution when iterating in that direction. Having said this, the general procedure for calculating the first-degree Taylor's polynomial for a multidimensional problem would be:

$$f(x,y) \cong L(x,y) \tag{46}$$

$$L(x,y,z) = f(a,b) + f_x(a,b) \cdot (x-a) + f_y(a,b) \cdot (y-b)$$

An example of the application of this theorem is given in (Fernández Bes et al., 2014).

ANNEX III – GAMS CODE

The GAMS code which models both the bi-level and single-level optimization problems is presented below.

```
$ontext
         BILEVEL AND SINGLELEVEL APPROACH
         ALEJANDRA ARANGUREN ALONSO
         24/08/21
$offtext

option optcr = 0;
option reslim = 1000000;

SETS
a        "years"    /2020*2024/
t        "technologies"     /WIND,PV/
s        "agents (consumer or generator)" /c1, g1/
h        "hours" /h1*h24/
c(s)     "consumer"      /c1/
g(s)     "generator"       /g1/
iter     "iteration"  /1*200/
;

*dynamic set to solve infeasibilities
SET aa(a) / 2020,2021,2022,2023,2024/;
*aa(a)=NO;
*aa(a)$(ORD(a) le 2)=YES;

$INCLUDE inc_parametros.in

PARAMETER
epsi1     /0.0001/
epsi2     /0.0001/
epsi3     /0.0001/
epsi4     /0.0001/
;

POSITIVE VARIABLES
tf_a(a)             "fixed term (power) of the tariffs"
tv_ah(a,h)          "variable term (energy) of the tariffs"
d                   "default of the regulated income"
e

cp_ca(c,a)          "client's contracted power"
dq_cah(c,a,h)       "client's consumption from the grid"
```

```
pt_sta(s,t,a)       "total power installed at consumer's or generator's level"
p_sta(s,t,a)        "new power installed at consumer's or generator's level"
q_stah(s,t,a,h)     "production at consumer's or generator's level"

del_stah(s,t,a,h)   "Lagrange multipliers"
alf_stah(s,t,a,h)
del_cah(c,a,h)
alf_cah(c,a,h)
sig_sta(s,t,a)
;

BINARY VARIABLES
delM_stah(s,t,a,h)  "binary variables for the linearization using the big-M
method"
alfM_stah(s,t,a,h)
delM_cah(c,a,h)
alfM_cah(c,a,h)
sigM_sta(s,t,a)
;

VARIABLE
BLOF             "objective function value (bi-level problem)"
SLOF             "objective function value (single-level problem)"

th_ah(a,h)          "Lagrange multipliers"
mu_ah(a,h)
ro_sta(s,t,a)
;

*$ONTEXT
*upper bounds for big-M method - to reduce computing time
pt_sta.up(s,t,aa)=100*CPT_ca(s,aa);
q_stah.up(s,t,aa,h)=5*D_sah(s,aa,h);
cp_ca.up(c,aa)=SUM(h,D_sah(c,aa,h));
dq_cah.up(c,aa,h)=SUM(t,pt_sta.up(c,t,aa))/100;
p_sta.up(s,t,aa)=pt_sta.up(s,t,aa)/10;
*$OFFTEXT

*ESCALADO DE PARÁMETROS de kW a GW / kWh a GWh y de € a M€
*los precios no se escalan ya que se multiplicarían y dividirían por el mismo
número (€/MWh a k€/GWh)
CR_a(aa)=CR_a(aa)/1000000;
D_sah(s,aa,h)=D_sah(s,aa,h)/1000000;
POT_st(s,t)=POT_st(s,t)/1000000;
CPT_ca(c,aa)=CPT_ca(c,aa)/1000000;
DQT_cah(c,aa,h)=DQT_cah(c,aa,h)/1000000;

*the chosen value corresponds to one week
tf_a.fx(aa)=TFT_a(aa)*1/7;
```

```
*tv_ah.fx(aa,h)=0.1;

*to check the single-level convergence (sensitivity)
TFT_a(aa)=TFT_a(aa)*100;
TVT_ah(aa,h)=TVT_ah(aa,h)*100;
CPT_ca(c,aa)=CPT_ca(c,aa)*100;
DQT_cah(c,aa,h)=DQT_cah(c,aa,h)*100;


EQUATIONS
BFO                         "upper-level objective function (bi-level)"
SFO                         "sum of the upper and lower level objective functions
(single-level)"
RE                          "upper level restriction (cover regulated costs)"
TRE                         "economic balance constraint (cover regulated costs
in the single-level)"
TARIFF(aa,h)
TARIFFS(aa,h)
FIJO (aa)

dL_dcp_ca                   "derivative of the lagrangian of the lower level
(cp_ca = 0)"
dL_ddq_cah(c,a,h)           "derivative of the lagrangian of the lower level
(dq_ca = 0)"
dL_dpt_sta(s,t,a)           "derivative of the lagrangian of the lower level
(pt_sta = 0)"
dL_dp_sta(s,t,a)            "derivative of the lagrangian of the lower level
(p_sta = 0)"
dL_ddq_stah(s,t,a,h)         "derivative of the lagrangian of the lower level
(q_sta = 0)"

re_balg_ah(a,h)             "lower level restriction (power balance - generator)"
re_balc_ah(a,h)             "lower level restriction (power balance - consumer)"
re_act_pt_sta(s,t,a)        "lower level restriction (update of the power
installed)"
re_limq_stah(s,t,a,h)       "lower level restriction (production limit)"
re_limdq_cah(c,a,h)         "lower level restriction (grid's consumption limit)"

M1_delM_stah(s,t,a,h)       "linearization complementarity condition 1-delM_sta"
MdelM_stah(s,t,a,h)         "linearization complementarity condition delM_sta"
M1_alfM_stah(s,t,a,h)       "linearization complementarity condition 1-alfM_sta"
MalfM_stah(s,t,a,h)         "linearization complementarity condition alfM_sta"
M1_delM_cah(c,a,h)          "linearization complementarity condition 1-delM_ca"
MdelM_cah(c,a,h)            "linearization complementarity condition delM_ca"
M1_alfM_cah(c,a,h)          "linearization complementarity condition 1-alfM_ca"
MalfM_cah(c,a,h)            "linearization complementarity condition alfM_ca"
M1_sigM_sta(s,t,a)          "linearization complementarity condition 1-sigM_sta"
MsigM_sta(s,t,a)            "linearization complementarity condition sigM_sta"
```

```
;


BFO      ..      BLOF =E= d+e;
SFO      ..      SLOF =E= SUM([s,t,aa], CI_sta(s,t,aa)*p_sta(s,t,aa))+SUM([aa,h],
365/1*P_ah(aa,h)*dq_cah('c1',aa,h))+1000*(d+e)+SUM(aa,TFT_a(aa)*CPT_ca('c1',aa))
                 +SUM(aa,CPT_ca('c1',aa)*(tf_a(aa)-
TFT_a(aa))+TFT_a(aa)*(4.06*cp_ca('c1',aa)-4.06*CPT_ca('c1',aa)))
                 +SUM([aa,h],365/1*TVT_ah(aa,h)*DQT_cah('c1',aa,h))
                 +SUM([aa,h],365/1*DQT_cah('c1',aa,h)*(tv_ah(aa,h)-
TVT_ah(aa,h))+TVT_ah(aa,h)*(dq_cah('c1',aa,h)-DQT_cah('c1',aa,h)));
RE       ..      - SUM([aa,h], 365/1*D_sah('g1',aa,h)*th_ah(aa,h)) - SUM([aa,h],
365/1*D_sah('c1',aa,h)*mu_ah(aa,h))
                 - SUM([s,t], POT_st(s,t)*ro_sta(s,t,'2020')) - SUM([aa,h],
365/1*P_ah(aa,h)*dq_cah('c1',aa,h))
                 - SUM([s,t,aa], CI_sta(s,t,aa)*p_sta(s,t,aa)) + d - e =G=
SUM(aa, CR_a(aa));
TRE      ..      d-e+SUM(aa,TFT_a(aa)*CPT_ca('c1',aa))
                 +SUM(aa,CPT_ca('c1',aa)*(tf_a(aa)-
TFT_a(aa))+TFT_a(aa)*(4.06*cp_ca('c1',aa)-4.06*CPT_ca('c1',aa)))
                 +SUM([aa,h],365/1*TVT_ah(aa,h)*DQT_cah('c1',aa,h))
                 +SUM([aa,h],365/1*DQT_cah('c1',aa,h)*(tv_ah(aa,h)-
TVT_ah(aa,h))+TVT_ah(aa,h)*(dq_cah('c1',aa,h)-DQT_cah('c1',aa,h)))=G= SUM(aa,
CR_a(aa));
TARIFF(aa,h)$(ord(h) ne card(h))    ..      tv_ah(aa,h) =E= tv_ah(aa,h+1);
TARIFFS(aa,h)$(ord(aa) ne card(aa))   ..    tv_ah(aa,h) =E= tv_ah(aa+1,h);
FIJO(aa)$(ord(aa) ne card (aa))     ..      tf_a(aa) =E= tf_a(aa+1);

dL_dcp_ca(c,aa)            ..      tf_a(aa) - SUM(h, 365/1*del_cah(c,aa,h)) =E= 0;
dL_ddq_cah(c,aa,h)         ..      tv_ah(aa,h) + P_ah(aa,h) - th_ah(aa,h) +
mu_ah(aa,h) + del_cah(c,aa,h) - alf_cah(c,aa,h) =E= 0;
dL_dpt_sta(s,t,aa)         ..      ro_sta(s,t,aa) -
ro_sta(s,t,aa+1)$(ord(aa)<card(aa)) -
SUM(h,365/1*del_stah(s,t,aa,h)*PF_stah(s,t,aa,h)) =E= 0;
dL_dp_sta(s,t,aa)          ..      CI_sta(s,t,aa) - ro_sta(s,t,aa) -
sig_sta(s,t,aa) =E= 0;
dL_ddq_stah(s,t,aa,h)      ..      th_ah(aa,h)$g(s) + mu_ah(aa,h)$c(s) +
del_stah(s,t,aa,h) - alf_stah(s,t,aa,h) =E= 0;

re_balg_ah(aa,h)           ..      SUM(t, q_stah('g1',t,aa,h)) =E=
dq_cah('c1',aa,h) + D_sah('g1',aa,h);
re_balc_ah(aa,h)           ..      SUM(t, q_stah('c1',t,aa,h)) + dq_cah('c1',aa,h)
=E= D_sah('c1',aa,h);
re_act_pt_sta(s,t,aa)      ..      pt_sta(s,t,aa) =E= pt_sta(s,t,aa-1)$(ord(aa)>1)
+ POT_st(s,t)$(ord(aa)=1) + p_sta(s,t,aa);
re_limq_stah(s,t,aa,h)     ..      q_stah(s,t,aa,h) =L=
pt_sta(s,t,aa)*PF_stah(s,t,aa,h);
re_limdq_cah(c,aa,h)       ..      dq_cah(c,aa,h) =L= 4.06*cp_ca(c,aa);
```

```
M1_delM_stah(s,t,aa,h)     ..      del_stah(s,t,aa,h) =L= (1-
delM_stah(s,t,aa,h))*(pt_sta.up(s,t,aa)-q_stah.lo(s,t,aa,h));
MdelM_stah(s,t,aa,h)       ..      PF_stah(s,t,aa,h)*pt_sta(s,t,aa) -
q_stah(s,t,aa,h) =L= delM_stah(s,t,aa,h)*(pt_sta.up(s,t,aa)-q_stah.lo(s,t,aa,h));
M1_alfM_stah(s,t,aa,h)     ..      alf_stah(s,t,aa,h) =L= (1-
alfM_stah(s,t,aa,h))*q_stah.up(s,t,aa,h);
MalfM_stah(s,t,aa,h)       ..      q_stah(s,t,aa,h) =L=
alfM_stah(s,t,aa,h)*q_stah.up(s,t,aa,h);
M1_delM_cah(c,aa,h)        ..      del_cah(c,aa,h) =L= (1-
delM_cah(c,aa,h))*(4.06*cp_ca.up(c,aa)-dq_cah.lo(c,aa,h));
MdelM_cah(c,aa,h)          ..      4.06*cp_ca(c,aa) - dq_cah(c,aa,h) =L=
delM_cah(c,aa,h)*(4.06*cp_ca.up(c,aa)-dq_cah.lo(c,aa,h));
M1_alfM_cah(c,aa,h)        ..      alf_cah(c,aa,h) =L= (1-
alfM_cah(c,aa,h))*dq_cah.up(c,aa,h);
MalfM_cah(c,aa,h)          ..      dq_cah(c,aa,h) =L=
alfM_cah(c,aa,h)*dq_cah.up(c,aa,h);
M1_sigM_sta(s,t,aa)        ..      sig_sta(s,t,aa) =L= (1-
sigM_sta(s,t,aa))*p_sta.up(s,t,aa);
MsigM_sta(s,t,aa)          ..      p_sta(s,t,aa) =L=
sigM_sta(s,t,aa)*p_sta.up(s,t,aa);

MODEL BILEVEL
/BFO,RE,TARIFF,TARIFFS,FIJO,dL_dcp_ca,dL_ddq_cah,dL_dpt_sta,dL_dp_sta,dL_ddq_stah
,re_balg_ah,re_balc_ah,re_act_pt_sta,re_limq_stah,re_limdq_cah,M1_delM_stah,MdelM
_stah,M1_alfM_stah,MalfM_stah,M1_delM_cah,MdelM_cah,M1_alfM_cah,MalfM_cah,M1_sigM
_sta,MsigM_sta/;
MODEL SINGLELEVEL
/SFO,TRE,TARIFF,TARIFFS,FIJO,re_balg_ah,re_balc_ah,re_act_pt_sta,re_limq_stah,re_
limdq_cah/;

PARAMETER
STOP             "controls when the iteration process ends"
FLAG_BILEVEL     "controls which model is going to be solved"

TFT_aI(a,iter)             "stores fixed tariffs (initial value in each
iteration)"
TVT_ahI(a,h,iter)          "stores variable tariffs (initial value in each
iteration)"
CPT_caI(c,a,iter)          "stores client's contracted power (initial value in
each iteration)"
DQT_cahI(c,a,h,iter)       "stores client's consumption from the grid (initial
value in each iteration)"

DIFTFT_aI(a,iter)            "difference between current and previous iterations
(fixed tariffs)"
DIFTVT_ahI(a,h,iter)         "difference between current and previous iterations
(variable tariffs)"
DIFCPT_caI(c,a,iter)         "difference between current and previous iterations
(client's contracted power)"
```

```
DIFDQT_cahI(c,a,h,iter)      "difference between current and previous iterations
(client's consumption from the grid)"

MAXTFT_aI(iter)          "max value of the difference between current and previous
iterations (fixed tariffs)"
MAXTVT_ahI(iter)         "max value of the difference between current and previous
iterations (variable tariffs)"
MAXCPT_caI(iter)         "max value of the difference between current and previous
iterations (client's contracted power)"
MAXDQT_cahI(iter)        "max value of the difference between current and previous
iterations (client's consumption from the grid)"

* to store the optimal values of the bilevel problem
TFBL_A(a)
TVBL_AH(a,h)
DBL
CPBL_CA(c,a)
DQBL_CAH(c,a,h)
PTBL_STA(s,t,a)
PBL_STA(s,t,a)
QBL_STAH(s,t,a,h)
THBL_AH(a,h)
MUBL_AH(a,h)
ROBL_STA(s,t,a)
DELBL_STAH(s,t,a,h)
ALFBL_STAH(s,t,a,h)
DELBL_CAH(c,a,h)
ALFBL_CAH(c,a,h)
SIGBL_STA(s,t,a)

* to store optimal values of the single-level problem
TFSL_A(a)
TVSL_AH(a,h)
DSL
CPSL_CA(c,a)
DQSL_CAH(c,a,h)
PTSL_STA(s,t,a)
PSL_STA(s,t,a)
QSL_STAH(s,t,a,h)
;

*to always start the iterating process of the single-level approach
STOP=0;
*to decide which model is going to be solved
FLAG_BILEVEL=0;

alias(iter,iter1)

*$ONTEXT
```

```
IF (FLAG_BILEVEL=1,

  SOLVE BILEVEL USING MIP MINIMIZING BLOF;

* optimal values of the BL variables stored in parameters
  TFBL_A(aa)=tf_a.l(aa);
  TVBL_AH(aa,h)=tv_ah.l(aa,h);
  DBL=d.l;
  CPBL_CA(c,aa)=cp_ca.l(c,aa);
  DQBL_CAH(c,aa,h)=dq_cah.l(c,aa,h);
  PTBL_STA(s,t,aa)=pt_sta.l(s,t,aa);
  PBL_STA(s,t,aa)=p_sta.l(s,t,aa);
  QBL_STAH(s,t,aa,h)=q_stah.l(s,t,aa,h);
  THBL_AH(aa,h)=th_ah.l(aa,h);
  MUBL_AH(aa,h)=mu_ah.l(aa,h);
  ROBL_STA(s,t,aa)=ro_sta.l(s,t,aa);
  DELBL_STAH(s,t,aa,h)=del_stah.l(s,t,aa,h);
  ALFBL_STAH(s,t,aa,h)=alf_stah.l(s,t,aa,h);
  DELBL_CAH(c,aa,h)=del_cah.l(c,aa,h);
  ALFBL_CAH(c,aa,h)=alf_cah.l(c,aa,h);
  SIGBL_STA(s,t,aa)=sig_sta.l(s,t,aa);

ELSE

* parameters that store the initial values of the parameters for the iteration
  TFT_aI(aa,iter)$(ORD(iter) eq 1)=TFT_a(aa);
  TVT_ahI(aa,h,iter)$(ORD(iter) eq 1)=TVT_ah(aa,h);
  CPT_caI(c,aa,iter)$(ORD(iter) eq 1)=CPT_ca(c,aa);
  DQT_cahI(c,aa,h,iter)$(ORD(iter) eq 1)=DQT_cah(c,aa,h);

  LOOP(iter$((ORD(iter) le 200) and (STOP eq 0)),

*   parameters that store initial values of the iteration
    TFT_a(aa)=TFT_aI(aa,iter);
    TVT_ah(aa,h)=TVT_ahI(aa,h,iter);
    CPT_ca(c,aa)=CPT_caI(c,aa,iter);
    DQT_cah(c,aa,h)=DQT_cahI(c,aa,h,iter);

    SOLVE SINGLELEVEL USING MIP MINIMIZING SLOF;

*   optimal values of variables stored as initial values for the following
iteration
    TFT_aI(aa,iter+1)=tf_a.l(aa);
    TVT_ahI(aa,h,iter+1)=tv_ah.l(aa,h);
    CPT_caI(c,aa,iter+1)=cp_ca.l(c,aa);
    DQT_cahI(c,aa,h,iter+1)=dq_cah.l(c,aa,h);

*   absolute value of the difference between current initial values and optimal
values
```

```
    DIFTFT_aI(aa,iter)=ABS(TFT_aI(aa,iter+1)-TFT_aI(aa,iter));
    DIFTVT_ahI(aa,h,iter)=ABS(TVT_ahI(aa,h,iter+1)-TVT_ahI(aa,h,iter));
    DIFCPT_caI(c,aa,iter)=ABS(CPT_caI(c,aa,iter+1)-CPT_caI(c,aa,iter));
    DIFDQT_cahI(c,aa,h,iter)=ABS(DQT_cahI(c,aa,h,iter+1)-DQT_cahI(c,aa,h,iter));
*   maximum value of the previous differences
    MAXTFT_aI(iter)$(ORD(iter) gt 0)=SMAX(aa,DIFTFT_aI(aa,iter));
    MAXTVT_ahI(iter)$(ORD(iter) gt 0)=SMAX((aa,h),DIFTVT_ahI(aa,h,iter));
    MAXCPT_caI(iter)$(ORD(iter) gt 0)=SMAX((c,aa),DIFCPT_caI(c,aa,iter));
    MAXDQT_cahI(iter)$(ORD(iter) gt 0)=SMAX((c,aa,h),DIFDQT_cahI(c,aa,h,iter));

    IF(((MAXTFT_aI(iter) lt epsi1) AND (MAXTVT_ahI(iter) lt epsi2) AND
(MAXCPT_caI(iter) lt epsi3) AND (MAXDQT_cahI(iter) lt epsi4)),
          STOP=1;
*         optimal values of the SL variables stored in parameters
          TFSL_A(aa)=tf_a.l(aa);
          TVSL_AH(aa,h)=tv_ah.l(aa,h);
          DSL=d.l;
          CPSL_CA(c,aa)=cp_ca.l(c,aa);
          DQSL_CAH(c,aa,h)=dq_cah.l(c,aa,h);
          PTSL_STA(s,t,aa)=pt_sta.l(s,t,aa);
          PSL_STA(s,t,aa)=p_sta.l(s,t,aa);
          QSL_STAH(s,t,aa,h)=q_stah.l(s,t,aa,h);
    );
 );
);


*DESESCALADO DE PARÁMETROS (unidades finales kW,kWh,€ - los precios no se
convierten)
CR_a(aa)=CR_a(aa)*1000000;
D_sah(s,aa,h)=D_sah(s,aa,h)*1000000;
POT_st(s,t)=POT_st(s,t)*1000000;
CPT_ca(c,aa)=CPT_ca(c,aa)*1000000;
DQT_cah(c,aa,h)=DQT_cah(c,aa,h)*1000000;
*DESESCALADO DE VARIABLES
*SL
DSL=DSL*1000000;
CPSL_CA(c,aa)=CPSL_CA(c,aa)*1000000;
DQSL_CAH(c,aa,h)=DQSL_CAH(c,aa,h)*1000000;
PTSL_STA(s,t,aa)=PTSL_STA(s,t,aa)*1000000;
PSL_STA(s,t,aa)=PSL_STA(s,t,aa)*1000000;
QSL_STAH(s,t,aa,h)=QSL_STAH(s,t,aa,h)*1000000;
*BL
DBL=DBL*1000000;
CPBL_CA(c,aa)=CPBL_CA(c,aa)*1000000;
DQBL_CAH(c,aa,h)=DQBL_CAH(c,aa,h)*1000000;
PTBL_STA(s,t,aa)=PTBL_STA(s,t,aa)*1000000;
PBL_STA(s,t,aa)=PBL_STA(s,t,aa)*1000000;
QBL_STAH(s,t,aa,h)=QBL_STAH(s,t,aa,h)*1000000;
```

```
execute_unload "..\salidas\Salidas_MIP_lin_CASO_A.gdx"

DISPLAY TFT_aI;
DISPLAY TVT_ahI;
DISPLAY CPT_caI;
DISPLAY DQT_cahI;
DISPLAY STOP;
```

ANNEX IV – CONVERGENCE RESULTS FOR THE SINGLE-LEVEL APPROACH

In this section, results from the single-level convergence of the iteration held as a consequence of the linear approximation following the Taylor's theorem approach are presented. Regarding the variable rates of the access tariffs, only one year is shown as one of the constraints that have been included in the model establishes that these rates have to be the same every year.

First, the results obtained from the base case without multiplying by any factor the initial value of the Taylor's parameters are depicted. The units in which results are displayed are the following:

- Fixed tariff rates [M€/GW]
- Variable tariff rates [M€/GWh]
- Power contracted by the client [GW]
- Consumption from the grid [GWh]

CONVERGENCE FIXED TARIFF RATES				
a / #iteration	1	2	3	4
2021	37,20000	0,00000	0,00000	0,00000
2022	37,20000	0,00000	0,00000	0,00000
2023	37,20000	0,00000	0,00000	0,00000
2024	37,20000	0,00000	0,00000	0,00000
2025	37,20000	0,00000	0,00000	0,00000

Table 14: Convergence of the fixed term of the access tariffs. Source: Own elaboration.

CONVERGENCE VARIABLE TARIFF RATES				
hours / #iteration	1	2	3	4

1	0,00600	0,14855	0,07205	0,07205
2	0,00600	0,14855	0,07205	0,07205
3	0,00600	0,14855	0,07205	0,07205
4	0,00600	0,14855	0,07205	0,07205
5	0,00600	0,14855	0,07205	0,07205
6	0,00600	0,14855	0,07205	0,07205
7	0,00600	0,14855	0,07205	0,07205
8	0,00600	0,14855	0,07205	0,07205
9	0,04177	0,14855	0,07205	0,07205
10	0,04177	0,14855	0,07205	0,07205
11	0,13312	0,14855	0,07205	0,07205
12	0,13312	0,14855	0,07205	0,07205
13	0,13312	0,14855	0,07205	0,07205
14	0,13312	0,14855	0,07205	0,07205
15	0,04177	0,14855	0,07205	0,07205
16	0,04177	0,14855	0,07205	0,07205
17	0,04177	0,14855	0,07205	0,07205
18	0,04177	0,14855	0,07205	0,07205
19	0,13312	0,14855	0,07205	0,07205
20	0,13312	0,14855	0,07205	0,07205
21	0,13312	0,14855	0,07205	0,07205
22	0,13312	0,14855	0,07205	0,07205
23	0,04177	0,14855	0,07205	0,07205
24	0,04177	0,14855	0,07205	0,07205

Table 15: Convergence of the variable term of the access tariffs. Source: Own elaboration.

CONVERGENCE CONTRACTED POWER BY CLIENTS				
year / #iteration	1	2	3	4
2021	122,35900	7,35004	7,35004	7,35004
2022	123,58259	7,42354	7,42354	7,42354
2023	124,81842	7,49778	7,49778	7,49778
2024	126,06660	7,57275	7,57275	7,57275
2025	127,32727	7,64848	7,64848	7,64848

Table 16: Convergence of the power contracted by the clients. Source: Own elaboration.

CONVERGENCE OF THE CLIENT'S CONSUMPTION FROM THE GRID					
year	hour / #iteration	1	2	3	4

2021	1	23,78040	23,93233	23,93233	23,93233
	2	22,51440	22,68283	22,68283	22,68283
	3	21,69320	21,83950	21,83950	21,83950
	4	21,32360	21,43300	21,43300	21,43300
	5	21,18920	21,23283	21,23283	21,23283
	6	21,57350	21,55967	21,55967	21,55967
	7	22,80890	22,66683	22,66683	22,66683
	8	24,56200	24,34617	24,34617	24,34617
	9	26,18340	25,97217	25,97217	25,97217
	10	27,50950	27,59833	27,59833	27,59833
	11	28,51320	28,23500	28,23500	28,23500
	12	28,29180	28,82100	28,82100	28,82100
	13	29,66280	29,40867	29,40867	29,40867
	14	29,77050	29,84117	29,84117	29,84117
	15	28,98790	29,22567	29,22567	29,22567
	16	27,89590	27,87950	27,87950	27,87950
	17	27,55560	27,44450	27,44450	27,44450
	18	27,27560	27,25650	27,25650	27,25650
	19	27,16520	27,01900	27,01900	27,01900
	20	26,97690	26,87167	26,87167	26,87167
	21	27,12480	27,09517	27,09517	27,09517
	22	27,62480	27,61100	27,61100	27,61100
	23	27,40520	27,21033	27,21033	27,21033
	24	24,87130	25,22933	25,22933	25,22933
2022	1	24,01820	24,17166	24,17166	24,17166
	2	22,73954	22,90966	22,90966	22,90966
	3	21,91013	22,05790	22,05790	22,05790
	4	21,53684	21,64733	21,64733	21,64733
	5	21,40109	21,44516	21,44516	21,44516
	6	21,78924	21,77526	21,77526	21,77526
	7	23,03699	22,89350	22,89350	22,89350
	8	24,80762	24,58963	24,58963	24,58963
	9	26,44523	26,23189	26,23189	26,23189
	10	27,78460	27,87432	27,87432	27,87432
	11	28,79833	28,51735	28,51735	28,51735

	12	28,57472	29,10921	29,10921	29,10921
	13	29,95943	29,70275	29,70275	29,70275
	14	30,06821	30,13958	30,13958	30,13958
	15	29,27778	29,51792	29,51792	29,51792
	16	28,17486	28,15829	28,15830	28,15830
	17	27,83116	27,71894	27,71895	27,71895
	18	27,54836	27,52906	27,52907	27,52907
	19	27,43685	27,28919	27,28919	27,28919
	20	27,24667	27,14038	27,14038	27,14038
	21	27,39605	27,36612	27,36612	27,36612
	22	27,90105	27,88711	27,88711	27,88711
	23	27,67925	27,48244	27,48244	27,48244
	24	25,12001	25,48163	25,48163	25,48163
2023	1	24,25839	24,41337	24,41337	24,41337
	2	22,96694	23,13876	23,13876	23,13876
	3	22,12923	22,27847	22,27847	22,27847
	4	21,75220	21,86380	21,86380	21,86380
	5	21,61510	21,65961	21,65961	21,65961
	6	22,00713	21,99302	21,99302	21,99302
	7	23,26736	23,12244	23,12244	23,12244
	8	25,05570	24,83552	24,83552	24,83552
	9	26,70969	26,49421	26,49421	26,49421
	10	28,06244	28,15306	28,15306	28,15306
	11	29,08632	28,80252	28,80252	28,80252
	12	28,86047	29,40030	29,40030	29,40030
	13	30,25902	29,99978	29,99978	29,99978
	14	30,36889	30,44097	30,44097	30,44097
	15	29,57056	29,81310	29,81310	29,81310
	16	28,45661	28,43988	28,43988	28,43988
	17	28,10947	27,99613	27,99613	27,99613
	18	27,82384	27,80436	27,80436	27,80436
	19	27,71122	27,56208	27,56208	27,56208
	20	27,51914	27,41179	27,41179	27,41179
	21	27,67001	27,63978	27,63978	27,63978
	22	28,18006	28,16598	28,16598	28,16598

	23	27,95604	27,75726	27,75726	27,75726
	24	25,37121	25,73644	25,73644	25,73644
2024	1	24,50097	24,65751	24,65751	24,65751
	2	23,19661	23,37015	23,37015	23,37015
	3	22,35053	22,50126	22,50126	22,50126
	4	21,96973	22,08244	22,08244	22,08244
	5	21,83125	21,87621	21,87621	21,87621
	6	22,22720	22,21295	22,21295	22,21295
	7	23,50003	23,35366	23,35366	23,35366
	8	25,30625	25,08388	25,08388	25,08388
	9	26,97678	26,75915	26,75915	26,75915
	10	28,34307	28,43459	28,43459	28,43459
	11	29,37718	29,09055	29,09055	29,09055
	12	29,14907	29,69430	29,69431	29,69431
	13	30,56161	30,29978	30,29978	30,29978
	14	30,67258	30,74538	30,74538	30,74538
	15	29,86626	30,11123	30,11123	30,11123
	16	28,74117	28,72428	28,72428	28,72428
	17	28,39056	28,27610	28,27610	28,27610
	18	28,10208	28,08240	28,08240	28,08240
	19	27,98833	27,83770	27,83770	27,83770
	20	27,79433	27,68590	27,68591	27,68591
	21	27,94671	27,91618	27,91618	27,91618
	22	28,46186	28,44764	28,44764	28,44764
	23	28,23560	28,03483	28,03483	28,03483
	24	25,62493	25,99381	25,99381	25,99381
2025	1	24,74598	24,90408	24,90408	24,90408
	2	23,42857	23,60385	23,60385	23,60385
	3	22,57403	22,72627	22,72627	22,72627
	4	22,18942	22,30327	22,30327	22,30327
	5	22,04957	22,09497	22,09497	22,09497
	6	22,44947	22,43508	22,43508	22,43508
	7	23,73503	23,58720	23,58720	23,58720
	8	25,55932	25,33472	25,33472	25,33472
	9	27,24655	27,02674	27,02674	27,02674

	10	28,62650	28,71894	28,71894	28,71894
	11	29,67095	29,38145	29,38145	29,38145
	12	29,44056	29,99125	29,99125	29,99125
	13	30,86723	30,60278	30,60278	30,60278
	14	30,97930	31,05284	31,05284	31,05284
	15	30,16492	30,41235	30,41235	30,41235
	16	29,02859	29,01152	29,01152	29,01152
	17	28,67447	28,55886	28,55886	28,55886
	18	28,38310	28,36322	28,36322	28,36322
	19	28,26822	28,11608	28,11608	28,11608
	20	28,07227	27,96276	27,96276	27,96276
	21	28,22618	28,19534	28,19534	28,19534
	22	28,74648	28,73212	28,73212	28,73212
	23	28,51796	28,31518	28,31518	28,31518
	24	25,88117	26,25375	26,25375	26,25375

Table 17: Convergence of the client's consumption from the grid. Source: Own elaboration.

Then, the Taylor's parameters have been multiplied by different factors with the aim of conducting a sensitivity analysis:

- 0.5

CONVERGENCE FIXED TARIFF RATES				
a/#iteration	1	2	3	4
2021	18,60000	0,00000	0,00000	0,00000
2022	18,60000	0,00000	0,00000	0,00000
2023	18,60000	0,00000	0,00000	0,00000
2024	18,60000	0,00000	0,00000	0,00000
2025	18,60000	0,00000	0,00000	0,00000

Table 18: Convergence of the fixed term of the access tariffs (Factor 0.5). Source: Own elaboration.

CONVERGENCE VARIABLE TARIFF RATES				
hours / #iteration	1	2	3	4
1	0,0030	0,1770	0,0721	0,0721
2	0,0030	0,1770	0,0721	0,0721
3	0,0030	0,1770	0,0721	0,0721

4	0,0030	0,1770	0,0721	0,0721
5	0,0030	0,1770	0,0721	0,0721
6	0,0030	0,1770	0,0721	0,0721
7	0,0030	0,1770	0,0721	0,0721
8	0,0030	0,1770	0,0721	0,0721
9	0,0209	0,1770	0,0721	0,0721
10	0,0209	0,1770	0,0721	0,0721
11	0,0666	0,1770	0,0721	0,0721
12	0,0666	0,1770	0,0721	0,0721
13	0,0666	0,1770	0,0721	0,0721
14	0,0666	0,1770	0,0721	0,0721
15	0,0209	0,1770	0,0721	0,0721
16	0,0209	0,1770	0,0721	0,0721
17	0,0209	0,1770	0,0721	0,0721
18	0,0209	0,1770	0,0721	0,0721
19	0,0666	0,1770	0,0721	0,0721
20	0,0666	0,1770	0,0721	0,0721
21	0,0666	0,1770	0,0721	0,0721
22	0,0666	0,1770	0,0721	0,0721
23	0,0209	0,1770	0,0721	0,0721
24	0,0209	0,1770	0,0721	0,0721

Table 19: Convergence of the variable term of the access tariffs (Factor 0.5). Source: Own elaboration.

CONVERGENCE CONTRACTED POWER BY CLIENTS				
year / #iteration	1	2	3	4
2021	61,17950	7,35004	7,35004	7,35004
2022	61,79130	7,42354	7,42354	7,42354
2023	62,40921	7,49778	7,49778	7,49778
2024	63,03330	7,57275	7,57275	7,57275
2025	63,66363	7,64848	7,64848	7,64848

Table 20: Convergence of the power contracted by the clients (Factor 0.5). Source: Own elaboration.

CONVERGENCE OF THE CLIENT'S CONSUMPTION FROM THE GRID					
year	hour / #iteration	1	2	3	4
2021	1	11,89020	23,93233	23,93233	23,93233
	2	11,25720	22,68283	22,68283	22,68283
	3	10,84660	21,83950	21,83950	21,83950

	4	10,66180	21,43300	21,43300	21,43300
	5	10,59460	21,23283	21,23283	21,23283
	6	10,78675	21,55967	21,55967	21,55967
	7	11,40445	22,66683	22,66683	22,66683
	8	12,28100	24,34617	24,34617	24,34617
	9	13,09170	25,97217	25,97217	25,97217
	10	13,75475	27,59833	27,59833	27,59833
	11	14,25660	28,23500	28,23500	28,23500
	12	14,14590	28,82100	28,82100	28,82100
	13	14,83140	29,40867	29,40867	29,40867
	14	14,88525	29,84117	29,84117	29,84117
	15	14,49395	29,22567	29,22567	29,22567
	16	13,94795	27,87950	27,87950	27,87950
	17	13,77780	27,44450	27,44450	27,44450
	18	13,63780	27,25650	27,25650	27,25650
	19	13,58260	27,01900	27,01900	27,01900
	20	13,48845	26,87167	26,87167	26,87167
	21	13,56240	27,09517	27,09517	27,09517
	22	13,81240	27,61100	27,61100	27,61100
	23	13,70260	27,21033	27,21033	27,21033
	24	12,43565	25,22933	25,22933	25,22933
2022	1	12,00910	24,17166	24,17166	24,17166
	2	11,36977	22,90966	22,90966	22,90966
	3	10,95507	22,05790	22,05790	22,05790
	4	10,76842	21,64733	21,64733	21,64733
	5	10,70055	21,44516	21,44516	21,44516
	6	10,89462	21,77526	21,77526	21,77526
	7	11,51849	22,89350	22,89350	22,89350
	8	12,40381	24,58963	24,58963	24,58963
	9	13,22262	26,23189	26,23189	26,23189
	10	13,89230	27,87432	27,87432	27,87432
	11	14,39917	28,51735	28,51735	28,51735
	12	14,28736	29,10921	29,10921	29,10921
	13	14,97971	29,70275	29,70275	29,70275
	14	15,03410	30,13958	30,13958	30,13958

	15	14,63889	29,51792	29,51792	29,51792
	16	14,08743	28,15829	28,15829	28,15829
	17	13,91558	27,71894	27,71894	27,71894
	18	13,77418	27,52906	27,52906	27,52906
	19	13,71843	27,28919	27,28919	27,28919
	20	13,62333	27,14038	27,14038	27,14038
	21	13,69802	27,36612	27,36612	27,36612
	22	13,95052	27,88711	27,88711	27,88711
	23	13,83963	27,48244	27,48244	27,48244
	24	12,56001	25,48163	25,48163	25,48163
2023	1	12,12919	24,41337	24,41337	24,41337
	2	11,48347	23,13876	23,13876	23,13876
	3	11,06462	22,27847	22,27847	22,27847
	4	10,87610	21,86380	21,86380	21,86380
	5	10,80755	21,65961	21,65961	21,65961
	6	11,00356	21,99302	21,99302	21,99302
	7	11,63368	23,12244	23,12244	23,12244
	8	12,52785	24,83552	24,83552	24,83552
	9	13,35484	26,49421	26,49421	26,49421
	10	14,03122	28,15306	28,15306	28,15306
	11	14,54316	28,80252	28,80252	28,80252
	12	14,43023	29,40030	29,40030	29,40030
	13	15,12951	29,99978	29,99978	29,99978
	14	15,18444	30,44097	30,44097	30,44097
	15	14,78528	29,81310	29,81310	29,81310
	16	14,22830	28,43988	28,43988	28,43988
	17	14,05473	27,99613	27,99613	27,99613
	18	13,91192	27,80436	27,80436	27,80436
	19	13,85561	27,56208	27,56208	27,56208
	20	13,75957	27,41179	27,41179	27,41179
	21	13,83500	27,63978	27,63978	27,63978
	22	14,09003	28,16598	28,16598	28,16598
	23	13,97802	27,75726	27,75726	27,75726
	24	12,68561	25,73644	25,73644	25,73644
2024	1	12,25048	24,65751	24,65751	24,65751

	2	11,59830	23,37015	23,37015	23,37015
	3	11,17526	22,50126	22,50126	22,50126
	4	10,98486	22,08244	22,08244	22,08244
	5	10,91563	21,87621	21,87621	21,87621
	6	11,11360	22,21295	22,21295	22,21295
	7	11,75002	23,35366	23,35366	23,35366
	8	12,65313	25,08388	25,08388	25,08388
	9	13,48839	26,75915	26,75915	26,75915
	10	14,17153	28,43459	28,43459	28,43459
	11	14,68859	29,09055	29,09055	29,09055
	12	14,57453	29,69430	29,69430	29,69430
	13	15,28081	30,29978	30,29978	30,29978
	14	15,33629	30,74538	30,74538	30,74538
	15	14,93313	30,11123	30,11123	30,11123
	16	14,37059	28,72428	28,72428	28,72428
	17	14,19528	28,27610	28,27610	28,27610
	18	14,05104	28,08240	28,08240	28,08240
	19	13,99417	27,83770	27,83770	27,83770
	20	13,89716	27,68590	27,68590	27,68590
	21	13,97335	27,91618	27,91618	27,91618
	22	14,23093	28,44764	28,44764	28,44764
	23	14,11780	28,03483	28,03483	28,03483
	24	12,81246	25,99381	25,99381	25,99381
2025	1	12,372990	24,904082	24,904082	24,904082
	2	11,714287	23,603847	23,603847	23,603847
	3	11,287015	22,726271	22,726271	22,726271
	4	11,094712	22,303266	22,303266	22,303266
	5	11,024783	22,094972	22,094972	22,094972
	6	11,224735	22,435076	22,435076	22,435076
	7	11,867516	23,587198	23,587198	23,587198
	8	12,779658	25,334719	25,334719	25,334719
	9	13,623276	27,026741	27,026741	27,026741
	10	14,313248	28,718936	28,718936	28,718936
	11	14,835475	29,381454	29,381454	29,381454
	12	14,720280	29,991248	29,991248	29,991248

		13	15,433614	30,602776	30,602776	30,602776
		14	15,489651	31,052837	31,052837	31,052837
		15	15,082462	30,412345	30,412345	30,412345
		16	14,514293	29,011519	29,011519	29,011519
		17	14,337234	28,558856	28,558856	28,558856
		18	14,191549	28,363223	28,363223	28,363223
		19	14,134108	28,116080	28,116080	28,116080
		20	14,036135	27,962764	27,962764	27,962764
		21	14,113088	28,195339	28,195339	28,195339
		22	14,373239	28,732117	28,732117	28,732117
		23	14,258981	28,315182	28,315182	28,315182
		24	12,940587	26,253745	26,253745	26,253745

Table 21: Convergence of the client's consumption from the grid (Factor 0.5). Source: Own elaboration.

- 1.5

CONVERGENCE FIXED TARIFF RATES				
a/#iteration	1	2	3	4
2021	55,80000	0,00000	0,00000	0,00000
2022	55,80000	0,00000	0,00000	0,00000
2023	55,80000	0,00000	0,00000	0,00000
2024	55,80000	0,00000	0,00000	0,00000
2025	55,80000	0,00000	0,00000	0,00000

Table 22: Convergence of the fixed term of the access tariffs (Factor 1.5). Source: Own elaboration.

CONVERGENCE VARIABLE TARIFF RATES				
hours / #iteration	1	2	3	4
1	0,0090	0,1624	0,0721	0,0721
2	0,0090	0,1624	0,0721	0,0721
3	0,0090	0,1624	0,0721	0,0721
4	0,0090	0,1624	0,0721	0,0721
5	0,0090	0,1624	0,0721	0,0721
6	0,0090	0,1624	0,0721	0,0721
7	0,0090	0,1624	0,0721	0,0721
8	0,0090	0,1624	0,0721	0,0721
9	0,0627	0,1624	0,0721	0,0721

10	0,0627	0,1624	0,0721	0,0721
11	0,1997	0,1624	0,0721	0,0721
12	0,1997	0,1624	0,0721	0,0721
13	0,1997	0,1624	0,0721	0,0721
14	0,1997	0,1624	0,0721	0,0721
15	0,0627	0,1624	0,0721	0,0721
16	0,0627	0,1624	0,0721	0,0721
17	0,0627	0,1624	0,0721	0,0721
18	0,0627	0,1624	0,0721	0,0721
19	0,1997	0,1624	0,0721	0,0721
20	0,1997	0,1624	0,0721	0,0721
21	0,1997	0,1624	0,0721	0,0721
22	0,1997	0,1624	0,0721	0,0721
23	0,0627	0,1624	0,0721	0,0721
24	0,0627	0,1624	0,0721	0,0721

Table 23: Convergence of the variable term of the access tariffs (Factor 1.5). Source: Own elaboration.

CONVERGENCE CONTRACTED POWER BY CLIENTS				
year / #iteration	1	2	3	4
2021	183,53850	7,35004	7,35004	7,35004
2022	185,37389	7,42354	7,42354	7,42354
2023	187,22762	7,49778	7,49778	7,49778
2024	189,09990	7,57275	7,57275	7,57275
2025	190,99090	7,64848	7,64848	7,64848

Table 24: Convergence of the power contracted by the clients (Factor 1.5). Source: Own elaboration.

CONVERGENCE OF THE CLIENT'S CONSUMPTION FROM THE GRID					
year	hour / #iteration	1	2	3	4
2021	1	35,67060	23,93233	23,93233	23,93233
	2	33,77160	22,68283	22,68283	22,68283
	3	32,53980	21,83950	21,83950	21,83950
	4	31,98540	21,43300	21,43300	21,43300
	5	31,78380	21,23283	21,23283	21,23283
	6	32,36025	21,55967	21,55967	21,55967
	7	34,21335	22,66683	22,66683	22,66683
	8	36,84300	24,34617	24,34617	24,34617
	9	39,27510	25,97217	25,97217	25,97217

	10	41,26425	27,59833	27,59833	27,59833
	11	42,76980	28,23500	28,23500	28,23500
	12	42,43770	28,82100	28,82100	28,82100
	13	44,49420	29,40867	29,40867	29,40867
	14	44,65575	29,84117	29,84117	29,84117
	15	43,48185	29,22567	29,22567	29,22567
	16	41,84385	27,87950	27,87950	27,87950
	17	41,33340	27,44450	27,44450	27,44450
	18	40,91340	27,25650	27,25650	27,25650
	19	40,74780	27,01900	27,01900	27,01900
	20	40,46535	26,87167	26,87167	26,87167
	21	40,68720	27,09517	27,09517	27,09517
	22	41,43720	27,61100	27,61100	27,61100
	23	41,10780	27,21033	27,21033	27,21033
	24	37,30695	25,22933	25,22933	25,22933
2022	1	36,02731	24,17166	24,17166	24,17166
	2	34,10932	22,90966	22,90966	22,90966
	3	32,86520	22,05790	22,05790	22,05790
	4	32,30525	21,64733	21,64733	21,64733
	5	32,10164	21,44516	21,44516	21,44516
	6	32,68385	21,77526	21,77526	21,77526
	7	34,55548	22,89350	22,89350	22,89350
	8	37,21143	24,58963	24,58963	24,58963
	9	39,66785	26,23189	26,23189	26,23189
	10	41,67689	27,87432	27,87432	27,87432
	11	43,19750	28,51735	28,51735	28,51735
	12	42,86208	29,10921	29,10921	29,10921
	13	44,93914	29,70275	29,70275	29,70275
	14	45,10231	30,13958	30,13958	30,13958
	15	43,91667	29,51792	29,51792	29,51792
	16	42,26229	28,15829	28,15829	28,15829
	17	41,74673	27,71894	27,71894	27,71894
	18	41,32253	27,52906	27,52906	27,52906
	19	41,15528	27,28919	27,28919	27,28919
	20	40,87000	27,14038	27,14038	27,14038

	21	41,09407	27,36612	27,36612	27,36612
	22	41,85157	27,88711	27,88711	27,88711
	23	41,51888	27,48244	27,48244	27,48244
	24	37,68002	25,48163	25,48163	25,48163
2023	1	36,38758	24,41337	24,41337	24,41337
	2	34,45041	23,13876	23,13876	23,13876
	3	33,19385	22,27847	22,27847	22,27847
	4	32,62831	21,86380	21,86380	21,86380
	5	32,42265	21,65961	21,65961	21,65961
	6	33,01069	21,99302	21,99302	21,99302
	7	34,90104	23,12244	23,12244	23,12244
	8	37,58354	24,83552	24,83552	24,83552
	9	40,06453	26,49421	26,49421	26,49421
	10	42,09366	28,15306	28,15306	28,15306
	11	43,62947	28,80252	28,80252	28,80252
	12	43,29070	29,40030	29,40030	29,40030
	13	45,38853	29,99978	29,99978	29,99978
	14	45,55333	30,44097	30,44097	30,44097
	15	44,35584	29,81310	29,81310	29,81310
	16	42,68491	28,43988	28,43988	28,43988
	17	42,16420	27,99613	27,99613	27,99613
	18	41,73576	27,80436	27,80436	27,80436
	19	41,56683	27,56208	27,56208	27,56208
	20	41,27870	27,41179	27,41179	27,41179
	21	41,50501	27,63978	27,63978	27,63978
	22	42,27009	28,16598	28,16598	28,16598
	23	41,93407	27,75726	27,75726	27,75726
	24	38,05682	25,73644	25,73644	25,73644
2024	1	36,75145	24,65751	24,65751	24,65751
	2	34,79491	23,37015	23,37015	23,37015
	3	33,52579	22,50126	22,50126	22,50126
	4	32,95459	22,08244	22,08244	22,08244
	5	32,74688	21,87621	21,87621	21,87621
	6	33,34080	22,21295	22,21295	22,21295
	7	35,25005	23,35366	23,35366	23,35366

	8	37,95938	25,08388	25,08388	25,08388
	9	40,46517	26,75915	26,75915	26,75915
	10	42,51460	28,43459	28,43459	28,43459
	11	44,06577	29,09055	29,09055	29,09055
	12	43,72360	29,69430	29,69430	29,69430
	13	45,84242	30,29978	30,29978	30,29978
	14	46,00886	30,74538	30,74538	30,74538
	15	44,79939	30,11123	30,11123	30,11123
	16	43,11176	28,72428	28,72428	28,72428
	17	42,58584	28,27610	28,27610	28,27610
	18	42,15312	28,08240	28,08240	28,08240
	19	41,98250	27,83770	27,83770	27,83770
	20	41,69149	27,68590	27,68590	27,68590
	21	41,92006	27,91618	27,91618	27,91618
	22	42,69279	28,44764	28,44764	28,44764
	23	42,35341	28,03483	28,03483	28,03483
	24	38,43739	25,99381	25,99381	25,99381
2025	1	37,11897	24,90408	24,90408	24,90408
	2	35,14286	23,60385	23,60385	23,60385
	3	33,86105	22,72627	22,72627	22,72627
	4	33,28414	22,30327	22,30327	22,30327
	5	33,07435	22,09497	22,09497	22,09497
	6	33,67421	22,43508	22,43508	22,43508
	7	35,60255	23,58720	23,58720	23,58720
	8	38,33897	25,33472	25,33472	25,33472
	9	40,86983	27,02674	27,02674	27,02674
	10	42,93974	28,71894	28,71894	28,71894
	11	44,50643	29,38145	29,38145	29,38145
	12	44,16084	29,99125	29,99125	29,99125
	13	46,30084	30,60278	30,60278	30,60278
	14	46,46895	31,05284	31,05284	31,05284
	15	45,24739	30,41235	30,41235	30,41235
	16	43,54288	29,01152	29,01152	29,01152
	17	43,01170	28,55886	28,55886	28,55886
	18	42,57465	28,36322	28,36322	28,36322

	19	42,40232	28,11608	28,11608	28,11608
	20	42,10841	27,96276	27,96276	27,96276
	21	42,33926	28,19534	28,19534	28,19534
	22	43,11972	28,73212	28,73212	28,73212
	23	42,77694	28,31518	28,31518	28,31518
	24	38,82176	26,25375	26,25375	26,25375

Table 25: Convergence of the client's consumption from the grid (Factor 1.5). Source: Own elaboration.

- 5

CONVERGENCE FIXED TARIFF RATES				
a/#iteration	1	2	3	4
2021	186,00000	0,00000	0,00000	0,00000
2022	186,00000	0,00000	0,00000	0,00000
2023	186,00000	0,00000	0,00000	0,00000
2024	186,00000	0,00000	0,00000	0,00000
2025	186,00000	0,00000	0,00000	0,00000

Table 26: Convergence of the fixed term of the access tariffs (Factor 5). Source: Own elaboration.

CONVERGENCE VARIABLE TARIFF RATES				
hours / #iteration	1	2	3	4
1	0,0300	0,4142	0,0721	0,0721
2	0,0300	0,4142	0,0721	0,0721
3	0,0300	0,4142	0,0721	0,0721
4	0,0300	0,4142	0,0721	0,0721
5	0,0300	0,4142	0,0721	0,0721
6	0,0300	0,4142	0,0721	0,0721
7	0,0300	0,4142	0,0721	0,0721
8	0,0300	0,4142	0,0721	0,0721
9	0,2089	0,4142	0,0721	0,0721
10	0,2089	0,4142	0,0721	0,0721
11	0,6656	0,4142	0,0721	0,0721
12	0,6656	0,4142	0,0721	0,0721
13	0,6656	0,4142	0,0721	0,0721
14	0,6656	0,4142	0,0721	0,0721
15	0,2089	0,4142	0,0721	0,0721

16	0,2089	0,4142	0,0721	0,0721
17	0,2089	0,4142	0,0721	0,0721
18	0,2089	0,4142	0,0721	0,0721
19	0,6656	0,4142	0,0721	0,0721
20	0,6656	0,4142	0,0721	0,0721
21	0,6656	0,4142	0,0721	0,0721
22	0,6656	0,4142	0,0721	0,0721
23	0,2089	0,4142	0,0721	0,0721
24	0,2089	0,4142	0,0721	0,0721

Table 27: Convergence of the variable term of the access tariffs (Factor 5). Source: Own elaboration.

CONVERGENCE CONTRACTED POWER BY CLIENTS				
year / #iteration	1	2	3	4
2021	611,79500	7,35004	7,35004	7,35004
2022	617,91295	7,42354	7,42354	7,42354
2023	624,09208	7,49778	7,49778	7,49778
2024	630,33300	7,57275	7,57275	7,57275
2025	636,63633	7,64848	7,64848	7,64848

Table 28: Convergence of the power contracted by the clients (Factor 5). Source: Own elaboration.

CONVERGENCE OF THE CLIENT'S CONSUMPTION FROM THE GRID					
year	hour / #iteration	1	2	3	4
2021	1	118,90200	23,93233	23,93233	23,93233
	2	112,57200	22,68283	22,68283	22,68283
	3	108,46600	21,83950	21,83950	21,83950
	4	106,61800	21,43300	21,43300	21,43300
	5	105,94600	21,23283	21,23283	21,23283
	6	107,86750	21,55967	21,55967	21,55967
	7	114,04450	22,66683	22,66683	22,66683
	8	122,81000	24,34617	24,34617	24,34617
	9	130,91700	25,97217	25,97217	25,97217
	10	137,54750	27,59833	27,59833	27,59833
	11	142,56600	28,23500	28,23500	28,23500
	12	141,45900	28,82100	28,82100	28,82100
	13	148,31400	29,40867	29,40867	29,40867
	14	148,85250	29,84117	29,84117	29,84117

	15	144,93950	29,22567	29,22567	29,22567
	16	139,47950	27,87950	27,87950	27,87950
	17	137,77800	27,44450	27,44450	27,44450
	18	136,37800	27,25650	27,25650	27,25650
	19	135,82600	27,01900	27,01900	27,01900
	20	134,88450	26,87167	26,87167	26,87167
	21	135,62400	27,09517	27,09517	27,09517
	22	138,12400	27,61100	27,61100	27,61100
	23	137,02600	27,21033	27,21033	27,21033
	24	124,35650	25,22933	25,22933	25,22933
2022	1	120,09102	24,17166	24,17166	24,17166
	2	113,69772	22,90966	22,90966	22,90966
	3	109,55066	22,05790	22,05790	22,05790
	4	107,68418	21,64733	21,64733	21,64733
	5	107,00546	21,44516	21,44516	21,44516
	6	108,94618	21,77526	21,77526	21,77526
	7	115,18495	22,89350	22,89350	22,89350
	8	124,03810	24,58963	24,58963	24,58963
	9	132,22617	26,23189	26,23189	26,23189
	10	138,92298	27,87432	27,87432	27,87432
	11	143,99166	28,51735	28,51735	28,51735
	12	142,87359	29,10921	29,10921	29,10921
	13	149,79714	29,70275	29,70275	29,70275
	14	150,34103	30,13958	30,13958	30,13958
	15	146,38890	29,51792	29,51792	29,51792
	16	140,87430	28,15829	28,15829	28,15829
	17	139,15578	27,71894	27,71894	27,71894
	18	137,74178	27,52906	27,52906	27,52906
	19	137,18426	27,28919	27,28919	27,28919
	20	136,23335	27,14038	27,14038	27,14038
	21	136,98024	27,36612	27,36612	27,36612
	22	139,50524	27,88711	27,88711	27,88711
	23	138,39626	27,48244	27,48244	27,48244
	24	125,60007	25,48163	25,48163	25,48163
2023	1	121,29193	24,41337	24,41337	24,41337

	2	114,83470	23,13876	23,13876	23,13876
	3	110,64617	22,27847	22,27847	22,27847
	4	108,76102	21,86380	21,86380	21,86380
	5	108,07551	21,65961	21,65961	21,65961
	6	110,03564	21,99302	21,99302	21,99302
	7	116,33679	23,12244	23,12244	23,12244
	8	125,27848	24,83552	24,83552	24,83552
	9	133,54843	26,49421	26,49421	26,49421
	10	140,31220	28,15306	28,15306	28,15306
	11	145,43158	28,80252	28,80252	28,80252
	12	144,30233	29,40030	29,40030	29,40030
	13	151,29511	29,99978	29,99978	29,99978
	14	151,84444	30,44097	30,44097	30,44097
	15	147,85278	29,81310	29,81310	29,81310
	16	142,28304	28,43988	28,43988	28,43988
	17	140,54734	27,99613	27,99613	27,99613
	18	139,11920	27,80436	27,80436	27,80436
	19	138,55610	27,56208	27,56208	27,56208
	20	137,59568	27,41179	27,41179	27,41179
	21	138,35004	27,63978	27,63978	27,63978
	22	140,90029	28,16598	28,16598	28,16598
	23	139,78022	27,75726	27,75726	27,75726
	24	126,85607	25,73644	25,73644	25,73644
2024	1	122,50485	24,65751	24,65751	24,65751
	2	115,98304	23,37015	23,37015	23,37015
	3	111,75263	22,50126	22,50126	22,50126
	4	109,84863	22,08244	22,08244	22,08244
	5	109,15627	21,87621	21,87621	21,87621
	6	111,13599	22,21295	22,21295	22,21295
	7	117,50016	23,35366	23,35366	23,35366
	8	126,53127	25,08388	25,08388	25,08388
	9	134,88392	26,75915	26,75915	26,75915
	10	141,71533	28,43459	28,43459	28,43459
	11	146,88589	29,09055	29,09055	29,09055
	12	145,74535	29,69430	29,69430	29,69430

	13	152,80806	30,29978	30,29978	30,29978
	14	153,36288	30,74538	30,74538	30,74538
	15	149,33131	30,11123	30,11123	30,11123
	16	143,70587	28,72428	28,72428	28,72428
	17	141,95281	28,27610	28,27610	28,27610
	18	140,51039	28,08240	28,08240	28,08240
	19	139,94166	27,83770	27,83770	27,83770
	20	138,97164	27,68590	27,68590	27,68590
	21	139,73354	27,91618	27,91618	27,91618
	22	142,30930	28,44764	28,44764	28,44764
	23	141,17802	28,03483	28,03483	28,03483
	24	128,12463	25,99381	25,99381	25,99381
2025	1	123,72990	24,90408	24,90408	24,90408
	2	117,14287	23,60385	23,60385	23,60385
	3	112,87015	22,72627	22,72627	22,72627
	4	110,94712	22,30327	22,30327	22,30327
	5	110,24783	22,09497	22,09497	22,09497
	6	112,24735	22,43508	22,43508	22,43508
	7	118,67516	23,58720	23,58720	23,58720
	8	127,79658	25,33472	25,33472	25,33472
	9	136,23276	27,02674	27,02674	27,02674
	10	143,13248	28,71894	28,71894	28,71894
	11	148,35475	29,38145	29,38145	29,38145
	12	147,20280	29,99125	29,99125	29,99125
	13	154,33614	30,60278	30,60278	30,60278
	14	154,89651	31,05284	31,05284	31,05284
	15	150,82462	30,41235	30,41235	30,41235
	16	145,14293	29,01152	29,01152	29,01152
	17	143,37234	28,55886	28,55886	28,55886
	18	141,91549	28,36322	28,36322	28,36322
	19	141,34108	28,11608	28,11608	28,11608
	20	140,36135	27,96276	27,96276	27,96276
	21	141,13088	28,19534	28,19534	28,19534
	22	143,73239	28,73212	28,73212	28,73212
	23	142,58981	28,31518	28,31518	28,31518

	24	129,40587	26,25375	26,25375	26,25375

Table 29: Convergence of the client's consumption from the grid (Factor 5). Source: Own elaboration.

- 10

CONVERGENCE FIXED TARIFF RATES				
a/#iteration	1	2	3	4
2021	372,00000	0,00000	0,00000	0,00000
2022	372,00000	0,00000	0,00000	0,00000
2023	372,00000	0,00000	0,00000	0,00000
2024	372,00000	0,00000	0,00000	0,00000
2025	372,00000	0,00000	0,00000	0,00000

Table 30: Convergence of the fixed term of the access tariffs (Factor 10). Source: Own elaboration.

CONVERGENCE VARIABLE TARIFF RATES				
hours / #iteration	1	2	3	4
1	0,06000	0,81473	0,07205	0,07205
2	0,06000	0,81473	0,07205	0,07205
3	0,06000	0,81473	0,07205	0,07205
4	0,06000	0,81473	0,07205	0,07205
5	0,06000	0,81473	0,07205	0,07205
6	0,06000	0,81473	0,07205	0,07205
7	0,06000	0,81473	0,07205	0,07205
8	0,06000	0,81473	0,07205	0,07205
9	0,41770	0,81473	0,07205	0,07205
10	0,41770	0,81473	0,07205	0,07205
11	1,33120	0,81473	0,07205	0,07205
12	1,33120	0,81473	0,07205	0,07205
13	1,33120	0,81473	0,07205	0,07205
14	1,33120	0,81473	0,07205	0,07205
15	0,41770	0,81473	0,07205	0,07205
16	0,41770	0,81473	0,07205	0,07205
17	0,41770	0,81473	0,07205	0,07205
18	0,41770	0,81473	0,07205	0,07205
19	1,33120	0,81473	0,07205	0,07205
20	1,33120	0,81473	0,07205	0,07205
21	1,33120	0,81473	0,07205	0,07205

22	1,33120	0,81473	0,07205	0,07205
23	0,41770	0,81473	0,07205	0,07205
24	0,41770	0,81473	0,07205	0,07205

Table 31: Convergence of the variable term of the access tariffs (Factor 10). Source: Own elaboration.

CONVERGENCE CONTRACTED POWER BY CLIENTS				
year / #iteration	1	2	3	4
2021	1223,59000	7,35004	7,35004	7,35004
2022	1235,82590	7,42354	7,42354	7,42354
2023	1248,18416	7,49778	7,49778	7,49778
2024	1260,66600	7,57275	7,57275	7,57275
2025	1273,27266	7,64848	7,64848	7,64848

Table 32: Convergence of the power contracted by the clients (Factor 10). Source: Own elaboration.

CONVERGENCE OF THE CLIENT'S CONSUMPTION FROM THE GRID					
year	hour / #iteration	1	2	3	4
2021	1	237,80400	23,93233	23,93233	23,93233
	2	225,14400	22,68283	22,68283	22,68283
	3	216,93200	21,83950	21,83950	21,83950
	4	213,23600	21,43300	21,43300	21,43300
	5	211,89200	21,23283	21,23283	21,23283
	6	215,73500	21,55967	21,55967	21,55967
	7	228,08900	22,66683	22,66683	22,66683
	8	245,62000	24,34617	24,34617	24,34617
	9	261,83400	25,97217	25,97217	25,97217
	10	275,09500	27,59833	27,59833	27,59833
	11	285,13200	28,23500	28,23500	28,23500
	12	282,91800	28,82100	28,82100	28,82100
	13	296,62800	29,40867	29,40867	29,40867
	14	297,70500	29,84117	29,84117	29,84117
	15	289,87900	29,22567	29,22567	29,22567
	16	278,95900	27,87950	27,87950	27,87950
	17	275,55600	27,44450	27,44450	27,44450
	18	272,75600	27,25650	27,25650	27,25650
	19	271,65200	27,01900	27,01900	27,01900
	20	269,76900	26,87167	26,87167	26,87167

	21	271,24800	27,09517	27,09517	27,09517
	22	276,24800	27,61100	27,61100	27,61100
	23	274,05200	27,21033	27,21033	27,21033
	24	248,71300	25,22933	25,22933	25,22933
2022	1	240,18204	24,17166	24,17166	24,17166
	2	227,39544	22,90966	22,90966	22,90966
	3	219,10132	22,05790	22,05790	22,05790
	4	215,36836	21,64733	21,64733	21,64733
	5	214,01092	21,44516	21,44516	21,44516
	6	217,89235	21,77526	21,77526	21,77526
	7	230,36989	22,89350	22,89350	22,89350
	8	248,07620	24,58963	24,58963	24,58963
	9	264,45234	26,23189	26,23189	26,23189
	10	277,84595	27,87432	27,87432	27,87432
	11	287,98332	28,51735	28,51735	28,51735
	12	285,74718	29,10921	29,10921	29,10921
	13	299,59428	29,70275	29,70275	29,70275
	14	300,68205	30,13958	30,13958	30,13958
	15	292,77779	29,51792	29,51792	29,51792
	16	281,74859	28,15829	28,15829	28,15829
	17	278,31156	27,71894	27,71894	27,71894
	18	275,48356	27,52906	27,52906	27,52906
	19	274,36852	27,28919	27,28919	27,28919
	20	272,46669	27,14038	27,14038	27,14038
	21	273,96048	27,36612	27,36612	27,36612
	22	279,01048	27,88711	27,88711	27,88711
	23	276,79252	27,48244	27,48244	27,48244
	24	251,20013	25,48163	25,48163	25,48163
2023	1	242,58386	24,41337	24,41337	24,41337
	2	229,66939	23,13876	23,13876	23,13876
	3	221,29233	22,27847	22,27847	22,27847
	4	217,52204	21,86380	21,86380	21,86380
	5	216,15103	21,65961	21,65961	21,65961
	6	220,07127	21,99302	21,99302	21,99302
	7	232,67359	23,12244	23,12244	23,12244

	8	250,55696	24,83552	24,83552	24,83552
	9	267,09686	26,49421	26,49421	26,49421
	10	280,62441	28,15306	28,15306	28,15306
	11	290,86315	28,80252	28,80252	28,80252
	12	288,60465	29,40030	29,40030	29,40030
	13	302,59022	29,99978	29,99978	29,99978
	14	303,68887	30,44097	30,44097	30,44097
	15	295,70557	29,81310	29,81310	29,81310
	16	284,56608	28,43988	28,43988	28,43988
	17	281,09468	27,99613	27,99613	27,99613
	18	278,23840	27,80436	27,80436	27,80436
	19	277,11221	27,56208	27,56208	27,56208
	20	275,19136	27,41179	27,41179	27,41179
	21	276,70008	27,63978	27,63978	27,63978
	22	281,80058	28,16598	28,16598	28,16598
	23	279,56045	27,75726	27,75726	27,75726
	24	253,71213	25,73644	25,73644	25,73644
2024	1	245,00970	24,65751	24,65751	24,65751
	2	231,96609	23,37015	23,37015	23,37015
	3	223,50526	22,50126	22,50126	22,50126
	4	219,69726	22,08244	22,08244	22,08244
	5	218,31254	21,87621	21,87621	21,87621
	6	222,27199	22,21295	22,21295	22,21295
	7	235,00032	23,35366	23,35366	23,35366
	8	253,06253	25,08388	25,08388	25,08388
	9	269,76783	26,75915	26,75915	26,75915
	10	283,43065	28,43459	28,43459	28,43459
	11	293,77178	29,09055	29,09055	29,09055
	12	291,49070	29,69430	29,69430	29,69430
	13	305,61613	30,29978	30,29978	30,29978
	14	306,72576	30,74538	30,74538	30,74538
	15	298,66262	30,11123	30,11123	30,11123
	16	287,41174	28,72428	28,72428	28,72428
	17	283,90562	28,27610	28,27610	28,27610
	18	281,02078	28,08240	28,08240	28,08240

	19	279,88333	27,83770	27,83770	27,83770
	20	277,94327	27,68590	27,68590	27,68590
	21	279,46709	27,91618	27,91618	27,91618
	22	284,61859	28,44764	28,44764	28,44764
	23	282,35605	28,03483	28,03483	28,03483
	24	256,24925	25,99381	25,99381	25,99381
2025	1	247,45980	24,90408	24,90408	24,90408
	2	234,28575	23,60385	23,60385	23,60385
	3	225,74031	22,72627	22,72627	22,72627
	4	221,89424	22,30327	22,30327	22,30327
	5	220,49566	22,09497	22,09497	22,09497
	6	224,49471	22,43508	22,43508	22,43508
	7	237,35033	23,58720	23,58720	23,58720
	8	255,59316	25,33472	25,33472	25,33472
	9	272,46551	27,02674	27,02674	27,02674
	10	286,26496	28,71894	28,71894	28,71894
	11	296,70950	29,38145	29,38145	29,38145
	12	294,40561	29,99125	29,99125	29,99125
	13	308,67229	30,60278	30,60278	30,60278
	14	309,79302	31,05284	31,05284	31,05284
	15	301,64925	30,41235	30,41235	30,41235
	16	290,28585	29,01152	29,01152	29,01152
	17	286,74468	28,55886	28,55886	28,55886
	18	283,83099	28,36322	28,36322	28,36322
	19	282,68216	28,11608	28,11608	28,11608
	20	280,72270	27,96276	27,96276	27,96276
	21	282,26176	28,19534	28,19534	28,19534
	22	287,46478	28,73212	28,73212	28,73212
	23	285,17961	28,31518	28,31518	28,31518
	24	258,81175	26,25375	26,25375	26,25375

Table 33: Convergence of the client's consumption from the grid (Factor 10). Source: Own elaboration.

- 100

CONVERGENCE FIXED TARIFF RATES

a/#iteration	1	2	3	4
2021	3720,00000	0,00000	0,00000	0,00000
2022	3720,00000	0,00000	0,00000	0,00000
2023	3720,00000	0,00000	0,00000	0,00000
2024	3720,00000	0,00000	0,00000	0,00000
2025	3720,00000	0,00000	0,00000	0,00000

Table 34: Convergence of the fixed term of the access tariffs (Factor 100). Source: Own elaboration.

CONVERGENCE VARIABLE TARIFF RATES				
hours / #iteration	1	2	3	4
1	0,60000	8,14738	0,07205	0,07205
2	0,60000	8,14738	0,07205	0,07205
3	0,60000	8,14738	0,07205	0,07205
4	0,60000	8,14738	0,07205	0,07205
5	0,60000	8,14738	0,07205	0,07205
6	0,60000	8,14738	0,07205	0,07205
7	0,60000	8,14738	0,07205	0,07205
8	0,60000	8,14738	0,07205	0,07205
9	4,17700	8,14738	0,07205	0,07205
10	4,17700	8,14738	0,07205	0,07205
11	13,31200	8,14738	0,07205	0,07205
12	13,31200	8,14738	0,07205	0,07205
13	13,31200	8,14738	0,07205	0,07205
14	13,31200	8,14738	0,07205	0,07205
15	4,17700	8,14738	0,07205	0,07205
16	4,17700	8,14738	0,07205	0,07205
17	4,17700	8,14738	0,07205	0,07205
18	4,17700	8,14738	0,07205	0,07205
19	13,31200	8,14738	0,07205	0,07205
20	13,31200	8,14738	0,07205	0,07205
21	13,31200	8,14738	0,07205	0,07205
22	13,31200	8,14738	0,07205	0,07205
23	4,17700	8,14738	0,07205	0,07205
24	4,17700	8,14738	0,07205	0,07205

Table 35: Convergence of the variable term of the access tariffs (Factor 100). Source: Own elaboration.

CONVERGENCE CONTRACTED POWER BY CLIENTS

year / #iteration	1	2	3	4
2021	12235,90000	7,35004	7,35004	7,35004
2022	12358,25900	7,42354	7,42354	7,42354
2023	12481,84159	7,49778	7,49778	7,49778
2024	12606,66001	7,57275	7,57275	7,57275
2025	12732,72661	7,64848	7,64848	7,64848

Table 36: Convergence of the power contracted by the clients (Factor 100). Source: Own elaboration.

CONVERGENCE OF THE CLIENT'S CONSUMPTION FROM THE GRID					
year	hour / #iteration	1	2	3	4
2021	1	2378,04000	23,93233	23,93233	23,93233
	2	2251,44000	22,68283	22,68283	22,68283
	3	2169,32000	21,83950	21,83950	21,83950
	4	2132,36000	21,43300	21,43300	21,43300
	5	2118,92000	21,23283	21,23283	21,23283
	6	2157,35000	21,55967	21,55967	21,55967
	7	2280,89000	22,66683	22,66683	22,66683
	8	2456,20000	24,34617	24,34617	24,34617
	9	2618,34000	25,97217	25,97217	25,97217
	10	2750,95000	27,59833	27,59833	27,59833
	11	2851,32000	28,23500	28,23500	28,23500
	12	2829,18000	28,82100	28,82100	28,82100
	13	2966,28000	29,40867	29,40867	29,40867
	14	2977,05000	29,84117	29,84117	29,84117
	15	2898,79000	29,22567	29,22567	29,22567
	16	2789,59000	27,87950	27,87950	27,87950
	17	2755,56000	27,44450	27,44450	27,44450
	18	2727,56000	27,25650	27,25650	27,25650
	19	2716,52000	27,01900	27,01900	27,01900
	20	2697,69000	26,87167	26,87167	26,87167
	21	2712,48000	27,09517	27,09517	27,09517
	22	2762,48000	27,61100	27,61100	27,61100
	23	2740,52000	27,21033	27,21033	27,21033
	24	2487,13000	25,22933	25,22933	25,22933
2022	1	2401,82040	24,17166	24,17166	24,17166

	2	2273,95440	22,90966	22,90966	22,90966
	3	2191,01320	22,05790	22,05790	22,05790
	4	2153,68360	21,64733	21,64733	21,64733
	5	2140,10920	21,44516	21,44516	21,44516
	6	2178,92350	21,77526	21,77526	21,77526
	7	2303,69890	22,89350	22,89350	22,89350
	8	2480,76200	24,58963	24,58963	24,58963
	9	2644,52340	26,23189	26,23189	26,23189
	10	2778,45950	27,87432	27,87432	27,87432
	11	2879,83320	28,51735	28,51735	28,51735
	12	2857,47180	29,10921	29,10921	29,10921
	13	2995,94280	29,70275	29,70275	29,70275
	14	3006,82050	30,13958	30,13958	30,13958
	15	2927,77790	29,51792	29,51792	29,51792
	16	2817,48590	28,15829	28,15830	28,15830
	17	2783,11560	27,71894	27,71895	27,71895
	18	2754,83560	27,52906	27,52907	27,52907
	19	2743,68520	27,28919	27,28919	27,28919
	20	2724,66690	27,14038	27,14038	27,14038
	21	2739,60480	27,36612	27,36612	27,36612
	22	2790,10480	27,88711	27,88711	27,88711
	23	2767,92520	27,48244	27,48244	27,48244
	24	2512,00130	25,48163	25,48163	25,48163
2023	1	2425,83860	24,41337	24,41337	24,41337
	2	2296,69394	23,13876	23,13876	23,13876
	3	2212,92333	22,27847	22,27847	22,27847
	4	2175,22044	21,86380	21,86380	21,86380
	5	2161,51029	21,65961	21,65961	21,65961
	6	2200,71274	21,99302	21,99302	21,99302
	7	2326,73589	23,12244	23,12244	23,12244
	8	2505,56962	24,83552	24,83552	24,83552
	9	2670,96863	26,49421	26,49421	26,49421
	10	2806,24410	28,15306	28,15306	28,15306
	11	2908,63153	28,80252	28,80252	28,80252
	12	2886,04652	29,40030	29,40030	29,40030

	13	3025,90223	29,99978	29,99978	29,99978
	14	3036,88871	30,44097	30,44097	30,44097
	15	2957,05568	29,81310	29,81310	29,81310
	16	2845,66076	28,43988	28,43988	28,43988
	17	2810,94676	27,99613	27,99613	27,99613
	18	2782,38396	27,80436	27,80436	27,80436
	19	2771,12205	27,56208	27,56208	27,56208
	20	2751,91357	27,41179	27,41179	27,41179
	21	2767,00085	27,63978	27,63978	27,63978
	22	2818,00585	28,16598	28,16598	28,16598
	23	2795,60445	27,75726	27,75726	27,75726
	24	2537,12131	25,73644	25,73644	25,73644
2024	1	2450,09699	24,65751	24,65751	24,65751
	2	2319,66088	23,37015	23,37015	23,37015
	3	2235,05257	22,50126	22,50126	22,50126
	4	2196,97264	22,08244	22,08244	22,08244
	5	2183,12539	21,87621	21,87621	21,87621
	6	2222,71986	22,21295	22,21295	22,21295
	7	2350,00325	23,35366	23,35366	23,35366
	8	2530,62532	25,08388	25,08388	25,08388
	9	2697,67832	26,75915	26,75915	26,75915
	10	2834,30654	28,43459	28,43459	28,43459
	11	2937,71785	29,09055	29,09055	29,09055
	12	2914,90698	29,69430	29,69431	29,69431
	13	3056,16125	30,29978	30,29978	30,29978
	14	3067,25759	30,74538	30,74538	30,74538
	15	2986,62624	30,11123	30,11123	30,11123
	16	2874,11737	28,72428	28,72428	28,72428
	17	2839,05622	28,27610	28,27610	28,27610
	18	2810,20780	28,08240	28,08240	28,08240
	19	2798,83327	27,83770	27,83770	27,83770
	20	2779,43270	27,68590	27,68591	27,68591
	21	2794,67086	27,91618	27,91618	27,91618
	22	2846,18591	28,44764	28,44764	28,44764
	23	2823,56050	28,03483	28,03483	28,03483

	24	2562,49253	25,99381	25,99381	25,99381
2025	1	2474,59796	24,90408	24,90408	24,90408
	2	2342,85749	23,60385	23,60385	23,60385
	3	2257,40309	22,72627	22,72627	22,72627
	4	2218,94237	22,30327	22,30327	22,30327
	5	2204,95665	22,09497	22,09497	22,09497
	6	2244,94706	22,43508	22,43508	22,43508
	7	2373,50328	23,58720	23,58720	23,58720
	8	2555,93157	25,33472	25,33472	25,33472
	9	2724,65510	27,02674	27,02674	27,02674
	10	2862,64960	28,71894	28,71894	28,71894
	11	2967,09503	29,38145	29,38145	29,38145
	12	2944,05605	29,99125	29,99125	29,99125
	13	3086,72286	30,60278	30,60278	30,60278
	14	3097,93017	31,05284	31,05284	31,05284
	15	3016,49250	30,41235	30,41235	30,41235
	16	2902,85854	29,01152	29,01152	29,01152
	17	2867,44679	28,55886	28,55886	28,55886
	18	2838,30987	28,36322	28,36322	28,36322
	19	2826,82161	28,11608	28,11608	28,11608
	20	2807,22703	27,96276	27,96276	27,96276
	21	2822,61757	28,19534	28,19534	28,19534
	22	2874,64777	28,73212	28,73212	28,73212
	23	2851,79610	28,31518	28,31518	28,31518
	24	2588,11745	26,25375	26,25375	26,25375

Table 37: Convergence of the client's consumption from the grid (Factor 100). Source: Own elaboration.

ANNEX V – RESULTS OF THE BI-LEVEL APPROACH

In this section, the optimal values of the decision variables for both the upper- and lower-level of the closed-loop model are presented. In this case, since the computing time is higher than for the single-level approach, results are only going to be shown for the first two years of the optimization.

SLACK AND EXCESS	
d	e
0	0

Table 38: Slack and excess of regulated earnings [M€] from the bi-level problem. Source: Own elaboration.

FIXED TARIFF RATES	
2021	2022
0,00000	0,00000

Table 39: Fixed term of the access tariffs [M€/GW] from the bi-level problem. Source: Own elaboration.

VARIABLE TARIFF RATES		
hour / year	2021	2022
1	0,07316	0,07316
2	0,07316	0,07316
3	0,07316	0,07316
4	0,07316	0,07316
5	0,07316	0,07316
6	0,07316	0,07316
7	0,07316	0,07316
8	0,07316	0,07316
9	0,07316	0,07316
10	0,07316	0,07316
11	0,07316	0,07316
12	0,07316	0,07316

13	0,07316	0,07316
14	0,07316	0,07316
15	0,07316	0,07316
16	0,07316	0,07316
17	0,07316	0,07316
18	0,07316	0,07316
19	0,07316	0,07316
20	0,07316	0,07316
21	0,07316	0,07316
22	0,07316	0,07316
23	0,07316	0,07316
24	0,07316	0,07316

Table 40:Variable term of the access tariffs [M€/GWh] from the bi-level problem. Source: Own elaboration.

POWER CONTRACTED BY THE CLIENT	
2021	2022
7,3499	7,4234

Table 41: Power contracted by the client [GW] from the bi-level problem. Source: Own elaboration.

CLIENT'S CONSUMPTION FROM THE GRID		
hour / year	2021	2022
1	23,9323	24,1717
2	22,6828	22,9097
3	21,8395	22,0579
4	21,4330	21,6473
5	21,2328	21,4452
6	21,5597	21,7753
7	22,6668	22,8935
8	24,3462	24,5896
9	25,9721	26,2318
10	27,5982	27,8742
11	28,2347	28,5171
12	28,8207	29,1089
13	29,4083	29,7023
14	29,8407	30,1391
15	29,2252	29,5175

16	27,8791	28,1579
17	27,4441	27,7186
18	27,2562	27,5287
19	27,0188	27,2890
20	26,8716	27,1403
21	27,0952	27,3661
22	27,6110	27,8871
23	27,2103	27,4824
24	25,2293	25,4816

Table 42: Client's consumption from the grid [GWh] from the bi-level problem. Source: Own elaboration.

NEW POWER INSTALLED				
year/technology	CONSUMER		GENERATOR	
	PV	WIND	PV	WIND
2021	0,0000	0,0000	22,7765	357,3107
2022	0,0000	0,0000	0,0000	0,0000

Table 43: Investments in renewable resources [GW] from the bi-level problem. Source: Own elaboration.

TOTAL INSTALLED POWER				
year/technology	CONSUMER		GENERATOR	
	PV	WIND	PV	WIND
2021	0,0010	0,0000	34,2195	384,3417
2022	0,0010	0,0000	34,2195	384,3417

Table 44: Total installed power from renewable resources [GW] from the bi-level problem. Source: Own elaboration.

PRODUCTION OF ENERGY					
year	hour/technology	CONSUMER		GENERATOR	
		PV	WIND	PV	WIND
2021	1	0,0000	0,0000	0,0000	47,7123
	2	0,0000	0,0000	0,0000	45,1968
	3	0,0000	0,0000	0,0000	43,5325
	4	0,0000	0,0000	0,0000	42,7570
	5	0,0000	0,0000	0,0000	42,4218
	6	0,0000	0,0000	0,0000	43,1337

	7	0,0000	0,0000	0,0435	45,4324
	8	0,0000	0,0000	0,0000	48,9082
	9	0,0000	0,0000	1,6504	50,5047
	10	0,0002	0,0000	5,6360	49,4722
	11	0,0003	0,0000	9,2431	47,5046
	12	0,0003	0,0000	11,9040	45,8387
	13	0,0004	0,0000	8,4534	50,6178
	14	0,0004	0,0000	15,0426	44,5692
	15	0,0004	0,0000	0,0000	58,2132
	16	0,0004	0,0000	0,0000	55,7751
	17	0,0004	0,0000	0,0000	55,0001
	18	0,0003	0,0000	0,0000	54,5322
	19	0,0002	0,0000	0,0000	54,1838
	20	0,0001	0,0000	0,0000	53,8486
	21	0,0000	0,0000	0,0000	54,2202
	22	0,0000	0,0000	0,0000	55,2360
	23	0,0000	0,0000	0,0000	54,6153
	24	0,0000	0,0000	0,0000	50,1003
2022	1	0,0000	0,0000	0,0000	48,1895
	2	0,0000	0,0000	0,0000	45,6488
	3	0,0000	0,0000	0,0000	43,9678
	4	0,0000	0,0000	0,0000	43,1846
	5	0,0000	0,0000	0,0000	42,8461
	6	0,0000	0,0000	0,0000	43,5650
	7	0,0000	0,0000	0,0438	45,8868
	8	0,0000	0,0000	0,0000	49,3972
	9	0,0000	0,0000	1,6668	51,0098
	10	0,0002	0,0000	5,6921	49,9672
	11	0,0003	0,0000	9,3378	47,9774
	12	0,0004	0,0000	12,0230	46,2970
	13	0,0004	0,0000	14,3349	45,3271
	14	0,0004	0,0000	15,1931	45,0147
	15	0,0004	0,0000	0,0000	58,7954
	16	0,0004	0,0000	0,0000	56,3328
	17	0,0004	0,0000	0,0000	55,5501

	18	0,0003	0,0000	0,0000	55,0775
	19	0,0002	0,0000	0,0000	54,7256
	20	0,0001	0,0000	0,0000	54,3871
	21	0,0000	0,0000	0,0000	54,7624
	22	0,0000	0,0000	0,0000	55,7884
	23	0,0000	0,0000	0,0000	55,1615
	24	0,0000	0,0000	0,0000	50,6013

Table 45: Energy production from renewable resources [GWh] from the bi-level problem. Source: Own elaboration.

ANNEX VI – RESULTS OF THE SINGLE-LEVEL APPROACH

In this section, the optimal values obtained for the decision variables after the optimization process are portrayed.

SLACK AND EXCESS	
d	e
0	0

Table 46: Slack and excess of regulated earnings [M€] from the single-level problem. Source: Own elaboration.

FIXED TARIFF RATES				
2021	2022	2023	2024	2025
0	0	0	0	0

Table 47: Fixed term of the access tariffs [M€/GW] from the single-level problem. Source: Own elaboration.

VARIABLE TARIFF RATES					
hour / year	2021	2022	2023	2024	2025
1	0,07205	0,07205	0,07205	0,07205	0,07205
2	0,07205	0,07205	0,07205	0,07205	0,07205
3	0,07205	0,07205	0,07205	0,07205	0,07205
4	0,07205	0,07205	0,07205	0,07205	0,07205
5	0,07205	0,07205	0,07205	0,07205	0,07205
6	0,07205	0,07205	0,07205	0,07205	0,07205
7	0,07205	0,07205	0,07205	0,07205	0,07205
8	0,07205	0,07205	0,07205	0,07205	0,07205
9	0,07205	0,07205	0,07205	0,07205	0,07205
10	0,07205	0,07205	0,07205	0,07205	0,07205
11	0,07205	0,07205	0,07205	0,07205	0,07205
12	0,07205	0,07205	0,07205	0,07205	0,07205
13	0,07205	0,07205	0,07205	0,07205	0,07205
14	0,07205	0,07205	0,07205	0,07205	0,07205

15	0,07205	0,07205	0,07205	0,07205	0,07205
16	0,07205	0,07205	0,07205	0,07205	0,07205
17	0,07205	0,07205	0,07205	0,07205	0,07205
18	0,07205	0,07205	0,07205	0,07205	0,07205
19	0,07205	0,07205	0,07205	0,07205	0,07205
20	0,07205	0,07205	0,07205	0,07205	0,07205
21	0,07205	0,07205	0,07205	0,07205	0,07205
22	0,07205	0,07205	0,07205	0,07205	0,07205
23	0,07205	0,07205	0,07205	0,07205	0,07205
24	0,07205	0,07205	0,07205	0,07205	0,07205

Table 48: Variable term of the access tariffs [M€/GW] from the single-level problem. Source: Own elaboration.

POWER CONTRACTED BY THE CLIENT				
2021	2022	2023	2024	2025
7,3500	7,4235	7,4978	7,5728	7,6485

Table 49: Power contracted by the client [GW] from the single-level problem. Source: Own elaboration.

CLIENT'S CONSUMPTION FROM THE GRID					
hour / year	2021	2022	2023	2024	2025
1	23,9323	24,1717	24,4134	24,6575	24,9041
2	22,6828	22,9097	23,1388	23,3701	23,6038
3	21,8395	22,0579	22,2785	22,5013	22,7263
4	21,4330	21,6473	21,8638	22,0824	22,3033
5	21,2328	21,4452	21,6596	21,8762	22,0950
6	21,5597	21,7753	21,9930	22,2129	22,4351
7	22,6668	22,8935	23,1224	23,3537	23,5872
8	24,3462	24,5896	24,8355	25,0839	25,3347
9	25,9722	26,2319	26,4942	26,7591	27,0267
10	27,5983	27,8743	28,1531	28,4346	28,7189
11	28,2350	28,5174	28,8025	29,0905	29,3815
12	28,8210	29,1092	29,4003	29,6943	29,9912
13	29,4087	29,7028	29,9998	30,2998	30,6028
14	29,8412	30,1396	30,4410	30,7454	31,0528
15	29,2257	29,5179	29,8131	30,1112	30,4123
16	27,8795	28,1583	28,4399	28,7243	29,0115
17	27,4445	27,7189	27,9961	28,2761	28,5589

18	27,2565	27,5291	27,8044	28,0824	28,3632
19	27,0190	27,2892	27,5621	27,8377	28,1161
20	26,8717	27,1404	27,4118	27,6859	27,9628
21	27,0952	27,3661	27,6398	27,9162	28,1953
22	27,6110	27,8871	28,1660	28,4476	28,7321
23	27,2103	27,4824	27,7573	28,0348	28,3152
24	25,2293	25,4816	25,7364	25,9938	26,2537

Table 50: Client's consumption from the grid [GWh] from the single-level problem. Source: Own elaboration.

NEW POWER INSTALLED				
year/technology	CONSUMER		GENERATOR	
	PV	WIND	PV	WIND
2021	0,0000	0,0000	22,7740	357,2996
2022	0,0000	0,0000	0,0036	0,0112
2023	0,0000	0,0000	0,0000	0,0000
2024	0,0000	0,0000	0,0000	0,0000
2025	0,0000	0,0000	0,0000	0,0000

Table 51: Investments in renewable resources [GW] from the single-level problem. Source: Own elaboration.

TOTAL INSTALLED POWER				
year/technology	CONSUMER		GENERATOR	
	PV	WIND	PV	WIND
2021	0,0000	0,0000	34,2170	384,3306
2022	0,0000	0,0000	34,2205	384,3417
2023	0,0000	0,0000	34,2205	384,3417
2024	0,0000	0,0000	34,2205	384,3417
2025	0,0000	0,0000	34,2205	384,3417

Table 52: Total installed power from renewable resources [GW] from the single-level problem. Source: Own elaboration.

PRODUCTION OF ENERGY					
year	hour/technology	CONSUMER		GENERATOR	
		PV	WIND	PV	WIND
2021	1	0,0000	0,0000	0,0000	47,7123
	2	0,0000	0,0000	0,0000	45,1968
	3	0,0000	0,0000	0,0000	43,5325

	4	0,0000	0,0000	0,0000	42,7570
	5	0,0000	0,0000	0,0000	42,4218
	6	0,0000	0,0000	0,0000	43,1337
	7	0,0000	0,0000	0,0000	45,4758
	8	0,0000	0,0000	0,0000	48,9082
	9	0,0000	0,0000	1,6503	50,5049
	10	0,0000	0,0000	5,5028	49,6055
	11	0,0000	0,0000	9,2447	47,5033
	12	0,0000	0,0000	9,8862	47,8568
	13	0,0000	0,0000	8,4553	50,6163
	14	0,0000	0,0000	5,3677	54,2444
	15	0,0000	0,0000	0,0000	58,2137
	16	0,0000	0,0000	0,0000	55,7755
	17	0,0000	0,0000	0,0000	55,0005
	18	0,0000	0,0000	0,0000	54,5325
	19	0,0000	0,0000	0,0000	54,1840
	20	0,0000	0,0000	0,0000	53,8487
	21	0,0000	0,0000	0,0000	54,2202
	22	0,0000	0,0000	0,0000	55,2360
	23	0,0000	0,0000	0,0000	54,6153
	24	0,0000	0,0000	0,0000	50,1003
2022	1	0,0000	0,0000	0,0000	48,1895
	2	0,0000	0,0000	0,0000	45,6488
	3	0,0000	0,0000	0,0000	43,9678
	4	0,0000	0,0000	0,0000	43,1846
	5	0,0000	0,0000	0,0000	42,8461
	6	0,0000	0,0000	0,0000	43,5650
	7	0,0000	0,0000	0,0000	45,9306
	8	0,0000	0,0000	0,0000	49,3972
	9	0,0000	0,0000	1,6669	51,0098
	10	0,0000	0,0000	5,5566	50,1028
	11	0,0000	0,0000	9,3381	47,9774
	12	0,0000	0,0000	9,9856	48,3348
	13	0,0000	0,0000	8,5372	51,1251
	14	0,0000	0,0000	5,4204	54,7879

	15	0,0000	0,0000	0,0000	58,7958
	16	0,0000	0,0000	0,0000	56,3333
	17	0,0000	0,0000	0,0000	55,5505
	18	0,0000	0,0000	0,0000	55,0778
	19	0,0000	0,0000	0,0000	54,7258
	20	0,0000	0,0000	0,0000	54,3872
	21	0,0000	0,0000	0,0000	54,7624
	22	0,0000	0,0000	0,0000	55,7884
	23	0,0000	0,0000	0,0000	55,1615
	24	0,0000	0,0000	0,0000	50,6013
2023	1	0,0000	0,0000	0,0000	48,6714
	2	0,0000	0,0000	0,0000	46,1053
	3	0,0000	0,0000	0,0000	44,4075
	4	0,0000	0,0000	0,0000	43,6164
	5	0,0000	0,0000	0,0000	43,2745
	6	0,0000	0,0000	0,0000	44,0007
	7	0,0000	0,0000	0,0000	46,3899
	8	0,0000	0,0000	0,0000	49,8912
	9	0,0000	0,0000	1,6825	51,5210
	10	0,0000	0,0000	5,6097	50,6063
	11	0,0000	0,0000	9,4315	48,4571
	12	0,0000	0,0000	12,1435	46,7601
	13	0,0000	0,0000	8,6227	51,6363
	14	0,0000	0,0000	5,4767	55,3337
	15	0,0000	0,0000	0,0000	59,3838
	16	0,0000	0,0000	0,0000	56,8966
	17	0,0000	0,0000	0,0000	56,1060
	18	0,0000	0,0000	0,0000	55,6286
	19	0,0000	0,0000	0,0000	55,2731
	20	0,0000	0,0000	0,0000	54,9310
	21	0,0000	0,0000	0,0000	55,3100
	22	0,0000	0,0000	0,0000	56,3462
	23	0,0000	0,0000	0,0000	55,7131
	24	0,0000	0,0000	0,0000	51,1074
2024	1	0,0000	0,0000	0,0000	49,1581

	2	0,0000	0,0000	0,0000	46,5663
	3	0,0000	0,0000	0,0000	44,8516
	4	0,0000	0,0000	0,0000	44,0526
	5	0,0000	0,0000	0,0000	43,7073
	6	0,0000	0,0000	0,0000	44,4407
	7	0,0000	0,0000	0,0000	46,8538
	8	0,0000	0,0000	0,0000	50,3901
	9	0,0000	0,0000	1,7004	52,0351
	10	0,0000	0,0000	5,6646	51,1136
	11	0,0000	0,0000	9,5254	48,9421
	12	0,0000	0,0000	12,2650	47,2277
	13	0,0000	0,0000	8,7064	52,1552
	14	0,0000	0,0000	5,5313	55,8871
	15	0,0000	0,0000	0,0000	59,9776
	16	0,0000	0,0000	0,0000	57,4656
	17	0,0000	0,0000	0,0000	56,6671
	18	0,0000	0,0000	0,0000	56,1849
	19	0,0000	0,0000	0,0000	55,8258
	20	0,0000	0,0000	0,0000	55,4803
	21	0,0000	0,0000	0,0000	55,8631
	22	0,0000	0,0000	0,0000	56,9097
	23	0,0000	0,0000	0,0000	56,2702
	24	0,0000	0,0000	0,0000	51,6184
2025	1	0,0000	0,0000	0,0000	49,6496
	2	0,0000	0,0000	0,0000	47,0320
	3	0,0000	0,0000	0,0000	45,3001
	4	0,0000	0,0000	0,0000	44,4931
	5	0,0000	0,0000	0,0000	44,1443
	6	0,0000	0,0000	0,0000	44,8851
	7	0,0000	0,0000	0,0000	47,3223
	8	0,0000	0,0000	0,0000	50,8940
	9	0,0000	0,0000	1,7175	52,5553
	10	0,0000	0,0000	5,7212	51,6248
	11	0,0000	0,0000	9,6182	49,4340
	12	0,0000	0,0000	10,2884	49,7992

	13	0,0000	0,0000	8,7962	52,6740
	14	0,0000	0,0000	5,5844	56,4483
	15	0,0000	0,0000	0,0000	60,5774
	16	0,0000	0,0000	0,0000	58,0402
	17	0,0000	0,0000	0,0000	57,2337
	18	0,0000	0,0000	0,0000	56,7467
	19	0,0000	0,0000	0,0000	56,3841
	20	0,0000	0,0000	0,0000	56,0351
	21	0,0000	0,0000	0,0000	56,4217
	22	0,0000	0,0000	0,0000	57,4788
	23	0,0000	0,0000	0,0000	56,8329
	24	0,0000	0,0000	0,0000	52,1346

Table 53: Energy production from renewable resources [GWh] from the single-level problem. Source: Own elaboration.