MÁSTER UNIVERSITARIO EN INGENIERÍA INDUSTRIAL

TRABAJO FIN DE MÁSTER

Quantitative evaluation of distribution network charges in a context of Digitalization, Decarbonization and Decentralization

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Madrid
Agosto de 2022

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EVALUACIÓN CUANTITATIVA DE LOS PEAJES DE RED DE DISTRIBUCIÓN EN UN CONTEXTO DE DIGITALIZACIÓN, DESCARBONIZACIÓN Y DESCENTRALIZACIÓN

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RESUMEN DEL PROYECTO

Las tarifas de red impactarán en las decisiones de los clientes en la transición energética. Este proyecto continuará con la evaluación de la metodología de cargos de red propuesta en el artículo "Revisando los peajes red eléctrica en un contexto de descarbonización, digitalización y descentralización", comparando tres estructuras tarifarias diferentes bajo el paradigma del 20% de consumidores de baja tensión instalando bombas de calor.

Palabras clave: peajes de red, bomba de calor, modelado matemático.

1. Introducción

Los sistemas eléctricos están enfrentando diversas transformaciones que están demandando una profunda revisión en los modelos de tarifas eléctricas. Antes de la liberalización del sector eléctrico, la asignación de costes del sistema correspondiente a cada empresa de servicios integrados verticalmente se hacía compartiendo estos costes entre diferentes clientes en función de su consumo de energía. La electricidad era generada por productores centralizados, transportada por flujos unidireccionales y consumida por los usuarios finales. Para tales configuraciones del sistema, las tarifas planas y volumétricas eran la forma de recuperar los costes regulados, ya que, a mayor consumo, mayor contribución a los costos del sistema y, por lo tanto, mayor cantidad a pagar [1]. Sin embargo, hoy en día, el consumo del usuario no es proporcional al uso que hace de las redes y el usuario es capaz de reaccionar a los precios de mercado y tarifas de red. Teniendo en cuenta estos cambios, parece indispensable un rediseño de la estructura tarifaria.

Este diseño debe tener en cuenta las principales tendencias en la transición del sector eléctrico: la habilitación de los consumidores para responder a los precios de la electricidad y las tarifas reguladas mediante el despliegue de medidores inteligentes y nuevas tecnologías de comunicación, convirtiéndose en participantes activos en el mercado de la electricidad reaccionando a los precios de mercado y cargos de red (Digitalización), el desarrollo de nuevas tecnologías, tales como, por ejemplo, cargas controladas termostáticamente, generación renovable distribuida, o almacenamiento de energía que cambia por completo el paradigma del esquema tradicional de generación-distribución-consumo (Descentralización) y la impetuosa necesidad de cumplir con los objetivos de reducción de emisiones de CO_2 en la Unión Europea que se materializan en la inversión de Sistemas de Energías Renovables (Descarbonización). Esta nueva metodología para asignar los costos de la red del sistema para hacer frente a estos cambios se propone en [2].

En esta tesis se presenta un caso de estudio basado en cargas térmicas para analizar si el diseño tarifario propuesto cumple con los objetivos de una tarifa eléctrica eficiente: recaudar el dinero invertido en el negocio y su costo de operación y mantenimiento, junto con los ingresos permitidos, y enviar las señales económicas adecuadas a los usuarios del sistema para asegurar la eficiencia económica y realizar las inversiones óptimas en el futuro. [3]

2. Metodología

Se comparan tres tarifas diferentes:

- Tarifa Volumétrica: Consiste en un cargo volumétrico fijo (€/kWh) para todas las horas. No se aplica granularidad temporal ni de ubicación. No obstante, se diferencian tres niveles de tensión (AT, MT y BT), por lo que la distribución de costes en cada nivel de tensión de la red se reparte entre los usuarios conectados al mismo nivel y los usuarios conectados a niveles inferiores.

- Tarifa de la CNMC (en vigor en España): los cobros volumétricos incentivan la instalación fotovoltaica y, por tanto, perjudica a quienes no pueden instalar paneles. Como solución, se introducen cargos por potencia contratada o demanda (€/kW) para imputar parte de los costes totales de la red, siendo el resto de los costes recuperados mediante cargos volumétricos. Este cargo por capacidad contratada se establece ex-ante y limita la potencia máxima que un usuario puede demandar. [2]. Por tanto, la española consta de dos cargos: Un cargo por capacidad contratada (€/kW-año), y un cargo volumétrico (€/kWh)

Respecto a la granularidad, la diferenciación temporal está presente por periodos: En esta tesis se ha simplificado la diferenciación temporal a tres periodos para todos los consumidores. Los cargos son mayores en las horas punta, para incentivar a los consumidores a contratar menos capacidad en esas horas, y trasladar su consumo a las horas punta y valle.

La granularidad espacial no está permitida en España. Sin embargo, ambas cargas son diferentes por niveles de voltaje. Al igual que en la tarifa volumétrica, los costos en cada nivel de tensión de la red se distribuyen entre los usuarios conectados al mismo nivel y los usuarios conectados a niveles inferiores.

- **Tarifa *Forward-Looking*** (la propuesta en [2]): Este diseño de tarifas sigue el razonamiento de que el principal desencadenante de futuras inversiones en la red es el uso máximo de cada elemento de la red, por lo que cuanto más congestionada esté una línea, antes se requerirán las inversiones. Por lo tanto, la Tarifa Forward-Looking consiste en dos cargos:

- **Un cargo por capacidad contratada (€/kW):** un cargo por capacidad en punta, aplicado por hora. El propósito de este cargo es hacer que los usuarios paguen en proporción a su contribución al flujo de energía cuando un elemento está potencialmente congestionado (es decir, cargado a más del 80% de su capacidad). De esta forma, la generación y la demanda se cobran por igual, pero en sentido contrario. La generación distribuida será recompensa si ayuda a que la red esté menos congestionada.

- **Un cargo residual fijo (€/cliente):** recupera el resto de los costes de red. De esta forma, las señales eficientes no se ven afectadas y los usuarios de la red no pueden evitar este pago modificando sus patrones de consumo.

En cuanto a la granularidad, en los cargos residuales fijos, los costes en cada nivel de tensión de la red se asignan entre los usuarios conectados al mismo nivel y los usuarios conectados a niveles inferiores y, la ubicación geográfica también se considera en los cargos por capacidad contratada, ya que se calculan elemento a elemento. Se considera granularidad temporal en el sentido de que el cargo por capacidad contratada es coincidente con el pico.

Estas tarifas se prueban bajo la circunstancia de que el 20% de los consumidores de baja tensión instalan bombas de calor. Para ello, se programaron tres modelos matemáticos en Matlab, se analizaron los resultados y se extrajeron conclusiones. El flujo de trabajo seguido se muestra en la Figura 1.

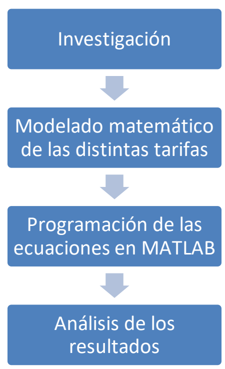

Figura 1. Flujo de trabajo seguido en la tesis

El algoritmo detrás de este análisis funciona de la siguiente manera:

Se establece un patrón de consumo para todos los usuarios de la red, y se dan todas las características de la red. Con esos datos se calcula el flujo de potencia, por lo que se conocen todos los flujos que circulan por cada ramal. Luego, se calcula la tarifa, es decir, los costos de la red se dividen entre los consumidores. Con esos precios establecidos, un consumidor instala una bomba de calor, por lo que su patrón de consumo varía teniendo en cuenta los precios de la electricidad y la temperatura interior del apartamento. Con ese nuevo patrón de consumo, se vuelve a calcular el flujo de energía. Si el nuevo caudal máximo por un ramal hace que el componente de la red esté a más del 80% de su capacidad, los costes de esa línea se incrementan. Con esos costes y los nuevos patrones de consumo, se calcula la nueva tarifa. El consumidor vuelve a encender su bomba de calor en un nuevo periodo regulatorio, por lo que se calcula el nuevo patrón de consumo, y se repiten los diferentes pasos.

3. Resultados

Tarifa Forward-Looking

Se calcula la tarifa de red inicial. Esta tarifa dispone de cargos más altos en las horas en que el consumo es máximo y cargos más bajos en las que el consumo es menor, para incentivar el consumo en aquellas horas en el que es menor. El usuario decide instalar una bomba de calor, y el patrón de consumo cambia.

Se incentiva al usuario a usar la bomba de calor en horas económicas, por lo que el consumo aumenta de 00:00h a 10:00h y no lo hace entre las 11:00h y 17:00h. Esto se debe al uso eficiente de la bomba de calor.

Desde las 00:00h hasta las 9:00h, el consumidor utiliza la bomba de calor únicamente para mantener la temperatura en 21ºC (la mínima posible aceptada). Por ello, se puede apreciar que aumenta su uso cuando el precio es el más bajo (25,66€) y que esta energía se utiliza para subir la temperatura de la casa hasta el máximo permitido (25ºC). De hecho, utiliza la bomba de calor justo antes de la subida de precio, por lo que el consumo es nulo en las horas más caras. Luego la temperatura desciende hasta alcanzar los 21ºC, momento en el que se vuelve a utilizar la bomba de calor para mantenerla constante. Así, se ha evitado consumir energía de la bomba de calor en periodos punta.

Con ese nuevo patrón de consumo, se vuelve a calcular el flujo de energía. Si el nuevo caudal máximo a través de un ramal hace que la utilización del componente de la red sea superior al 80% de su capacidad, los costos de esa línea se incrementan en una cantidad igual al costo de inversión anualizado considerando una vida útil de 20 años. Así, una vez finalizado el primer periodo regulatorio y considerando dicho consumo, y tras comprobar si son necesarios refuerzos en la red, se vuelve a calcular la tarifa de red.

La tarifa baja para este usuario en unas horas, que son las horas en las que antes no se utilizaba la bomba de calor, para incentivar el uso de la bomba de calor allí, y aumenta en las horas 10:00h y 20:00h, que eran las horas punta, para evitar el uso de la bomba de calor allí.

El flujo máximo de potencia tras el primer periodo no ha aumentado en ninguna línea por encima del umbral fijado (80% de la capacidad de la línea), por lo que no se necesitan refuerzos y los costes de la red no han variado. La tarifa propuesta actúa de la forma más eficiente posible: se incrementa el consumo de forma que el usuario que instala la bomba de calor no contribuye a aumentar el caudal máximo de potencia que circula por la red, y por tanto no aumentan los costes de red.

Entonces, se produce el segundo período regulatorio. El consumo aumenta en las horas en las que es más económico consumir, y disminuye en las horas contiguas, porque no se necesita la bomba de calor al estar la temperatura entre los límites, ya que el consumo ha aumentado en las horas 9 y 19.

Finalmente, con ese consumo se computa la tarifa de la red después del segundo periodo regulatorio. Se aumenta la tarifa en las horas 11, 12, 13 y 19, que son las puntas más altas, para desincentivar el consumo en esas horas, y se disminuye en la hora 10, para incentivar el uso de la bomba de calor en esa hora, ya que el siguiente tramo de horas serían las de mayor precio.

Los resultados de la Tarifa Forward-Looking en los distintos periodos se resumen en las Figuras 2 y 3. Mientras que la Figura 2 representa los cambios en el patrón de consumo del usuario que tiene instalada la bomba de calor, la Figura 3 representa la diferencia en el precio de la tarifa.

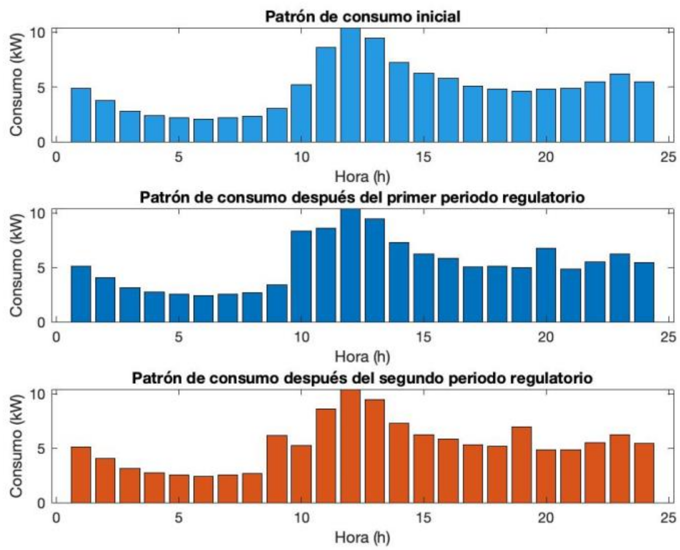

Figura 2. Cambios en el patrón de consumo bajo la tarifa Forward-Looking

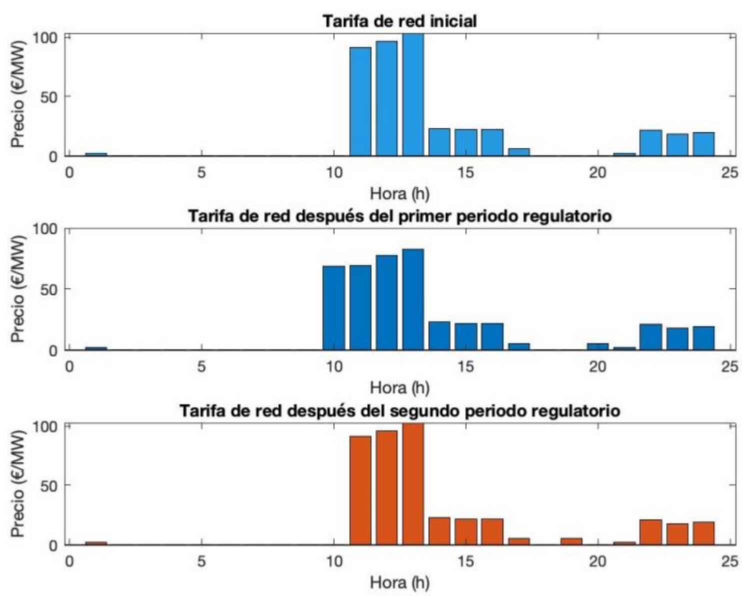

Figura 3. Cambios en la tarifa Forward-Looking

Tarifa Volumétrica

La diferencia entre el patrón de consumo inicial y el posterior al primer periodo regulatorio coincide con el consumo de la bomba de calor, que es plano. Como el precio es plano, el consumo de la bomba de calor es constante, y se utiliza para mantener la temperatura de la vivienda en el nivel mínimo permitido (21ºC).

Con ese nuevo patrón de consumo, se vuelve a calcular el flujo de energía. Si el nuevo caudal máximo por un ramal hace que el componente de la red esté a más del 80% de su capacidad, los costes de esa línea se incrementan porque se necesitarían nuevos refuerzos. Así, una vez finalizado el primer periodo regulatorio y considerando dicho consumo, y tras comprobar si son necesarios refuerzos en la red, se vuelve a calcular la tarifa de red.

La tarifa ha aumentado 6,63€/MW para este usuario en cada hora, lo que no tendría sentido en primera instancia, ya que el consumo ha aumentado. En teoría, si los costes se hubieran mantenido estables, el precio por MWh, debería haberse reducido. Sin embargo, como el flujo máximo de potencia después del primer período regulatorio cambió en varias líneas, los costos en esas líneas aumentan.

Se puede concluir entonces que la tarifa volumétrica no produce señales eficientes por lo que el consumo aumenta en horas valle. En este caso, el consumo del usuario aumenta en las horas punta de la red, y los refuerzos necesarios a lo largo de la red corren a cargo del consumidor que instala la bomba de calor (y también del resto de usuarios de esta línea).

Para el segundo periodo regulatorio, este hecho no altera el comportamiento del usuario, que aún continúa con el mismo consumo, pero soportando más costes.

Finalmente, cabe señalar que la capacidad de la línea en la que ha invertido el sistema es ahora un 20% mayor, lo que significa que la congestión de la rama está por debajo del umbral establecido. Por lo tanto, los costes de la red no aumentan en este período, por lo que no hay cambio en la tarifa.

En conclusión, los cambios de tarifa volumétrica no envían ninguna señal eficiente: no importa cuando el usuario consume electricidad ya que el precio no cambia.

Los resultados de la Tarifa Volumétrica en los diferentes periodos se resumen en las Figuras 4 y 5. Mientras que la Figura 4 representa los cambios en el patrón de consumo del usuario que tiene instalada la bomba de calor, la Figura 5 representa la diferencia en el precio de la tarifa.

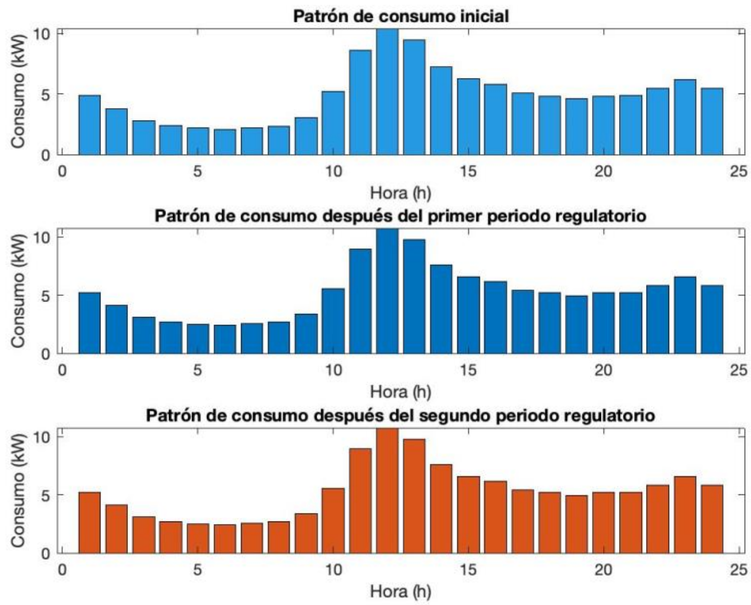

Figura 4. Cambios en el patrón de consumo bajo la tarifa volumétrica

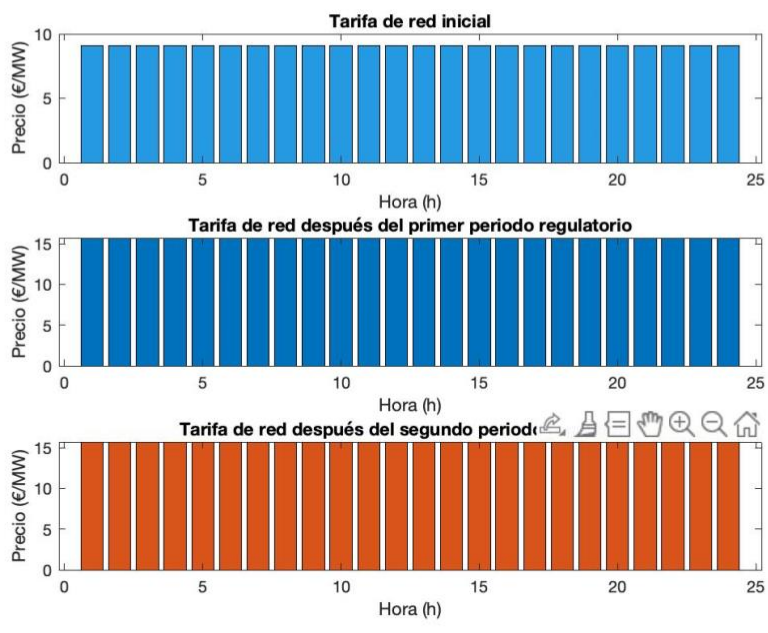

Figura 5. Cambios en la tarifa volumétrica

Tarifa española

Se calcula la tarifa inicial de la red, con cargos superiores en las horas en las que el consumo es máximo y cargos inferiores en las que el consumo es menor en función de bloques horarios, para incentivar el consumo en aquellas horas en las que el consumo es inferior, observando que las horas de 00:00h a 08:00h son incluso gratuitas, ya que son aquellas en las que el consumo es menor, que corresponden al periodo “3”.

El usuario decide instalar una bomba de calor, y el consumo cambia. La diferencia coincide con el consumo de la bomba de calor. Se incentiva al usuario a utilizar la bomba de calor en horario económico, por lo que el consumo aumenta de 00:00h a 08:00h (período gratuito) y no lo hace entre las 09:00h y las 13:00h. Esto se debe al uso eficiente de la bomba de calor. La temperatura dentro de la casa se mantiene en el mínimo (21ºC) mientras el precio es constante. Sin embargo, sube cuando se acciona la bomba de calor y eso corresponde a la hora 06:00h en la que el precio total está a punto de subir. Aumenta hasta el máximo (25ºC) para poder mantenerse dentro de los límites hasta que el precio vuelva a bajar.

Una vez finalizado el primer periodo regulatorio y considerando dicho consumo, se vuelve a computar la tarifa de red. La tarifa de red aumenta para este usuario en los periodos 1 y 2 a medida que aumenta el consumo.

En teoría, si los costos se hubieran mantenido estables, el precio por MWh, debería haberse reducido. Sin embargo, como el caudal máximo de potencia tras el primer periodo regulatorio ha cambiado en varias líneas, los costes en dichas líneas aumentan, y el consumidor 9 (el que tiene instalada la bomba de calor) corre con parte de esos costes.

Entonces, se produce el segundo período regulatorio. Con esa nueva tarifa de red, el usuario cambia ligeramente su patrón de consumo.

El consumo aumenta en la hora 08:00h, cuando las tarifas de red son gratuitas, y se reduce desde las 14:00h hasta las 18:00h, donde se encuentran las tarifas más altas, teniendo en cuenta además que la temperatura interior debe mantenerse entre 21ºC y 25ºC.

Finalmente, la capacidad de la línea en la que ha invertido el sistema es un 20% superior, por lo que la nueva capacidad está por debajo del umbral fijado, por lo que la tarifa que se vuelve a computar se mantiene igual que en el periodo anterior.

Todo este comportamiento demuestra que la tarifa española envía señales más eficientes que la tarifa volumétrica, pero no se pueden evitar algunos refuerzos, en el sentido de que se incentiva al consumidor a consumir en horarios más baratos, pero de todos modos tendría que asumir los mismos costes de los refuerzos.

Los resultados para la tarifa española en los diferentes periodos se resumen en las Figuras 6 y 7. Mientras que la Figura 6 representa los cambios en el patrón de consumo del usuario que tiene instalada la bomba de calor, la Figura 7 representa la diferencia en el precio de la tarifa.

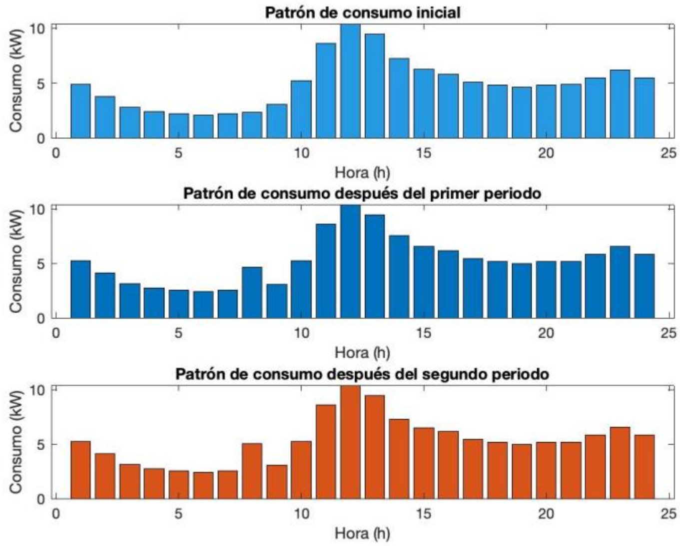

Figura 6. Cambios en el patrón de consumo bajo la tarifa española

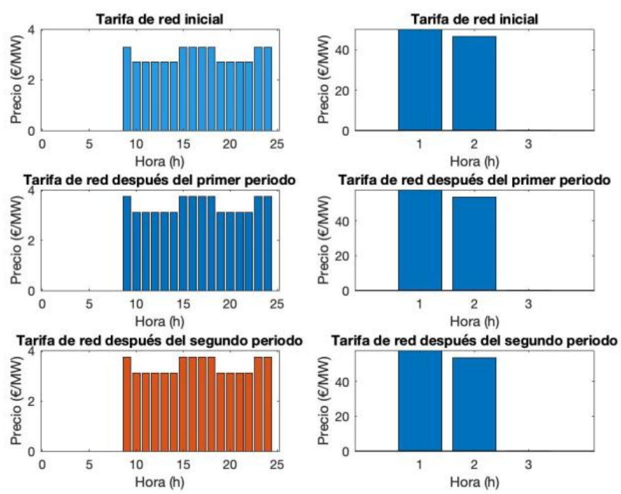

Figura 7. Cambios la tarifa española

4. Conclusiones

Por un lado, la tarifa propuesta actúa de la forma más eficiente posible: se incrementa el consumo de forma que el usuario que instala la bomba de calor no contribuye a aumentar el caudal máximo de potencia que circula por la red, y, por tanto, los costes de red no aumentan. Para el segundo periodo regulatorio, el consumo se modifica de forma eficiente, ya que se ha facilitado al usuario las señales necesarias para modificar sabiamente su patrón.

Sin embargo, por otro lado, ni la estructura tarifaria en España, ni la estructura tarifaria volumétrica funcionan así: al contrario, bajo estas estructuras tarifarias, se incentiva el uso de la bomba de calor en horas en las que el consumidor contribuiría a la congestión de una línea, aumentando por tanto los costes de refuerzo y mantenimiento de la línea y, en consecuencia, aumentando los costes para el usuario que tiene instalado este dispositivo, y para los demás del mismo nivel de tensión.

En conclusión, la tarifa propuesta destaca por encima de las otras estructuras tarifarias bajo este caso de estudio. Sin embargo, se debería ampliar la investigación con otros casos de estudios para probar este punto en otras circunstancias.

5. Referencias

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QUANTITATIVE EVALUATION OF DISTRIBUTION NETWORK CHARGES IN A CONTEXT OF DIGITALIZATION, DECARBONIZATION AND DECENTRALIZATION

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SUMMARY OF THE PROJECT

Network tariffs will impact the customer decisions in the energy transition. This project will continue with the evaluation of the network charges methodology proposed in the paper "Revisiting electricity network tariffs in a context of Decarbonization, Digitalization, and Decentralization", by comparing three different tariff structures under the paradigm of 20% of low voltage consumers installing heat pumps.

Key words: Tariff, Heat pump, mathematical modelling.

1. Introduction

Electricity systems are confronting several transformations that are demanding a profound revision in electricity tariff's models. Before the liberalization of the electricity sector, the allocation of bundled system costs corresponding to each vertically integrated utility was made sharing these costs among different customers based on their energy consumption. Electricity was generated by centralized producers, transported by unidirectional flows, and consumed by the end users. For such system configurations, flat and volumetric tariffs were the way to recover regulated costs as the higher the consumption, the higher the contribution to system costs and therefore, the greater the amount needed to be paid [1]. However, nowadays, the consumption of the user is not proportional to the use that he makes of the networks and the user is capable to react to the market prices and network charges. Bearing in mind these changes, a redesign of tariff's structure seems indispensable.

This design has to take into account the main trends in the transition of the power sector: the enablement of consumers to respond to electricity prices and regulated tariffs by the deployment of smart meters and new communication technologies, becoming active participants in the electricity market by reacting to the market prices and network charges (Digitalization), the development of new technologies, such as, but not limited to thermostatically controlled loads, distributed renewable generation, or energy storage that completely changes the paradigm of the traditional scheme of generation-distribution-consumption (Decentralization) and the impetuous need to comply with the CO_2 emission reduction targets in the European Union that are materialized in the investment of Renewable Energy Systems (Decarbonization). This new methodology to allocate the system network's costs to deal with these changes is proposed in [2].

In this thesis, a case study based on thermal loads is presented to analyze if the proposed tariff design accomplishes the objectives of an efficient electricity tariff: to collect the money invested in the business and its operating and maintenance cost, along with the allowed revenues and to send the appropriate economic signals to the system users to ensure economic efficiency and make the optimal investments in the future. [3]

2. Methodology

Three different tariffs are compared:

- **Volumetric Tariff:** This charge consists of a flat volumetric charge (€/kWh) for all hours. Neither temporal nor locational granularity are applied. However, three voltage levels are differentiated (HV, MV and LV), so the distribution of costs at each network voltage level is allocated among the users connected at the same level and the users connected at lower levels.

- **Spanish Tariff:** volumetric charges incentivize PV installation and, therefore, that is prejudicial to those that cannot do so. As a solution, contracted capacity, or demand charges (€/kW) are introduced to allocate part of the total network costs, being the rest of the costs recovered by volumetric charges. This contracted capacity charge is stablished ex-ante and limits the maximum power that a user can demand. [2]. Therefore, the Spanish Tariff consist of two charges: A contracted capacity charge (€/kW-year), and a volumetric charge (€/kWh)

  Regarding granularity, temporal differentiation is present by periods: In this thesis, the time differentiation has been simplified to three periods for all consumers. The charges are greater in peak periods, to encourage consumers to contract less capacity in those ones, and to move their consumption to shoulder and off-peak periods.

  Spatial granularity is not allowed in Spain. However, both charges are different by voltage levels. As in the volumetric tariff, costs at each network voltage level are allocated among the users connected at the same level and the users connected at lower levels.

- **Forward-Looking Tariff,** which is the one proposed in [2]. This tariff design follows the reasoning that the main trigger for future network investments is the maximum peak usage of each network element, so the more congested is a line, the sooner the investments will be required. Therefore, the Forward-Looking Tariff consist of two charges:
  - A contracted capacity charge (€/kW): a peak-coincident capacity charged applied on an hourly basis. The purpose of this charge is to make the users pay in proportion to their contribution to the power flow when an element is potentially congested (i.e., loaded to more than 80% of its capacity). This way, generation and demand are charged equally but in the opposite direction. So DERs will be rewarded if they help the network to be less congested.
  - A fixed residual charge (€/customer): recovers the remaining network costs. This way, the efficient signals are not impacted, and network users cannot avoid this payment by modifying their consumption patterns.

Regarding granularity, in the fixed residual charges, costs at each network voltage level are allocated among the users connected at the same level and the users connected at lower levels and, the geographical location is as well considered in the contracted capacity charges as it is calculated element-by-element. Temporal granularity is considered in the sense that the contracted capacity charge is peak coincident.

These tariffs are tested under the circumstance of 20% of low voltage consumers installing heat pumps. To do so, three mathematical models were programmed in Matlab, results were analyzed, and conclusions were extracted. The workflow followed is shown in Figure 1.

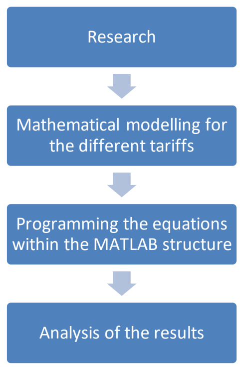

Figure 1. Workflow followed in the thesis

The algorithm behind this analysis works as follows:

A consumption pattern is set for all the users in the network, and all the characteristics of the network are given. With that data, the power flow is computed, so all the flows flowing through each branch are known. Then, the tariff is computed, that is, the costs of the network are divided among the consumers. With those prices settled, a consumer installs a heat pump, so its consumption pattern varies considering prices for electricity and the temperature inside the apartment. With that new consumption pattern, the power flow is again computed. If the new maximum flow through a branch makes the component of the network be at more than 80% of its capacity, the costs for that line are increased. With those costs and the new consumption patterns, the new tariff is computed. The consumer turns on again his heat pump in a new regulatory period, so the new consumption pattern is calculated, and the different steps are repeated.

3. Results

Forward-Looking Tariff
The initial network tariff is calculated. It has higher charges in hours where the consumption is maximum and lower charges where the consumption is lower, to incentive the consumption in those hours where it is lower. The user decides to install a heat pump, and the consumption pattern changes.

The user is incentivized to use the heat pump in cheap hours, so that is the reason why the consumption increases hours from 0 to 10 and there is a lack of increase between hours 11 and 17. This is due to the efficient use of the heat pump.

From 00:00h to 9:00h, the consumer uses the heat pump just to maintain the temperature in 21ºC (the minimum possible accepted). Then, it can be appreciated that he increases its use when the price is the lowest (25,66€) and that this energy is used to rise the temperature of the house until the maximum allowed (25ºC). In fact, it uses the heat pump just prior to the price rise, so that the consumption is zero in the most expensive hours. The temperature then decreases until it reaches 21ºC, when the heat pump is used again to maintain it constant. Thus, it has been avoided to consume energy from the heat pump in peak periods.
With that new consumption pattern, the power flow is again computed. If the new maximum flow through a branch makes the utilization of the component of the network be at more than 80% of its capacity, the costs for that line are increased an amount equal to the annualized investment cost considering a life expectancy of 20 years. So, once the first regulatory period has ended and considering that consumption, and after checking if reinforcements in the network are needed, the network tariff is again computed.

The tariff decreases for this user in some hours, which are the hours in which the heat pump was not used before, to incentivize the use of the heat pump there, and increases in hours 10 and 20, which were the peak hours, to avoid the use of the heat pump there.

The maximum power flow after the first period has not increased in any line above the threshold set (80% of the capacity of the line), so reinforcements are not needed, meaning that the network costs have not changed. The proposed tariff acts in the most efficient way possible: the consumption is increased in a way that the user that installs the heat pump does not contribute to increasing the maximum power flow running through the network, and therefore the network costs do not increase.

Then, the second regulatory period occurs. Consumption increases in hours where is cheaper to consume, and decreases in adjacent hours, because the heat pump is not needed as the temperature is between the limits, as consumption has increased in hours 9 and 19.

Finally, with that consumption, the network tariff after the second regulatory period is computed, The tariff is increased in hours 11, 12, 13 and 19, which are the highest peaks, so as to disincentivize the consumption in those hours, and decreased in hour 10, to incentivize the use of the heat pump in that hour, because the next set of hours would be the highest-priced ones.

The results for the Forward-Looking Tariff in the different periods are summarized in Figures 2 and 3. While Figure 2 represents the changes in the consumption pattern of the user that has the heat pump installed, Figure 3 represents the difference in the price of the tariff.

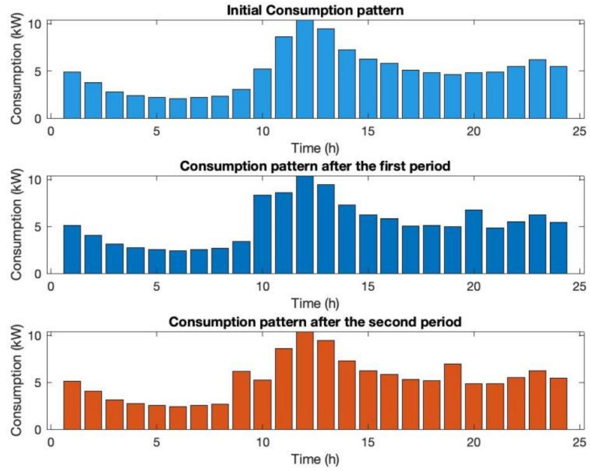

Figure 2. Variation of the consumption pattern of the user that has a heat pump installed in the Forward-Looking Tariff scenario.

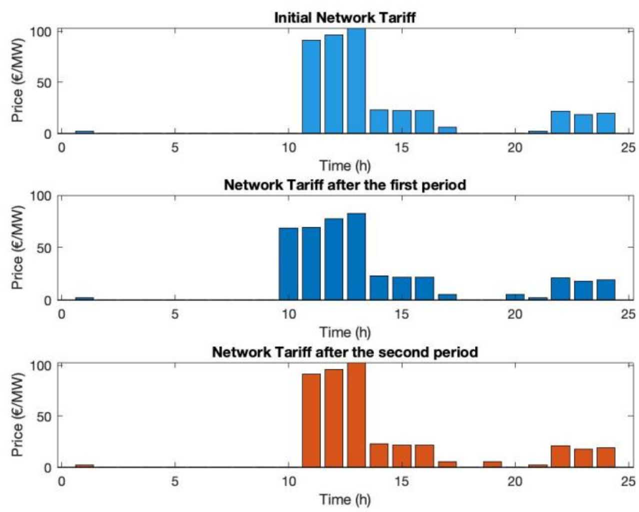

Figure 3. Variation Network Tariff of the user that has a heat pump installed in the Forward-Looking Tariff scenario.

Volumetric Tariff

The difference between the initial consumption pattern and the one after the first regulatory period coincides with the consumption of the heat pump, which is flat. As the price is flat, the consumption of the heat pump is constant, and it is used to maintain the temperature of the house at the minimum level allowed (21ºC).

With that new consumption pattern, the power flow is again computed. If the new maximum flow through a branch makes the component of the network at more than 80% of its capacity, the costs for that line are increased because new reinforcements would be needed. So, once the first regulatory period has ended and considering that consumption, and after checking if reinforcements in the network are needed, the network tariff is again computed.

The tariff has increased by 6.63€/MW for this user in every single hour, which would not make sense as first, as the consumption has increased. In theory, if the costs would have remained stable, the price per MWh, must have been reduced. However, as the maximum power flow after the first regulatory period changed in several lines, the costs in those lines increase.

It can then be concluded that the volumetric tariff does not produce efficient signals so that the consumption increases in off-peak hours. In this case, the consumption of the user increases during network peak hours, and reinforcements needed along the network are borne by consumer 9 (and also by the rest that use this line).

For the second regulatory period, this fact does not alter the behavior of the user, still continues with the same consumption, but bearing more costs.

Finally, it should be noted that the capacity of the line in which the system has invested is now 20% higher, meaning that the congestion of the branch is below the threshold set. Therefore, the costs of the network do not increase in this period, so there is no change in the tariff.

All in all, the Volumetric tariff changes do not send any efficient signal at all: it does not matter when the user consumes electricity as the price does not change.

The results for the Volumetric Tariff in the different periods are summarized in Figures 4 and 5. While Figure 4 represents the changes in the consumption pattern of the user that has the heat pump installed, Figure 5 represents the difference in the price of the tariff.

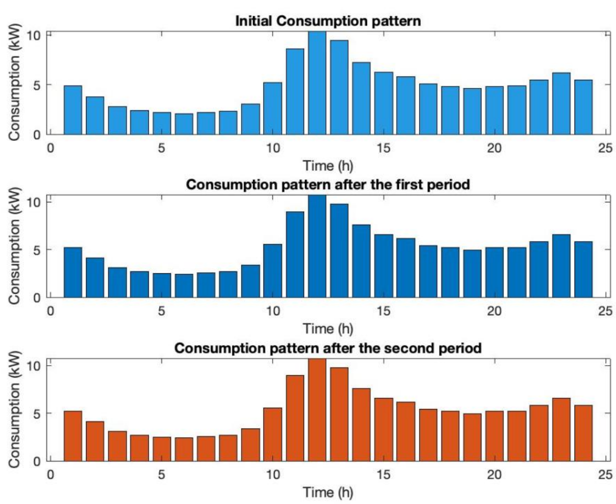

Figure 4. Variation of the consumption pattern of the user that has a heat pump installed in the Volumetric Tariff scenario.

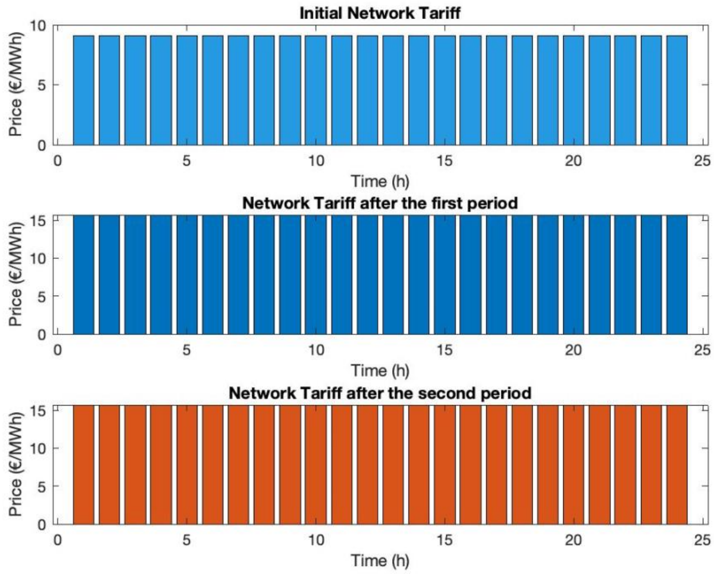

Figure 5. Variation Network Tariff of the user that has a heat pump installed in the Volumetric Tariff scenario.

Spanish tariff

The initial network tariff is calculated, with higher charges in hours where the consumption is maximum and lower charges where the consumption is lower depending on time blocks, so as to incentive the consumption in those hours where the consumption is lower, noting that hours from 0 to 8 are even free, as they are the ones in which the consumption is lower, which corresponds to period "3".

The user decides to install a heat pump, and the consumption changes. The difference coincides with the consumption of the heat pump. The user is incentivized to use the heat pump in cheap hours, so that is the reason why the consumption increases hours from 0 to 8 (free period) and there is a lack of increase between hours 9 and 13. This is due to the efficient use of the heat pump. The temperature inside the house is maintained at the minimum (21ºC) while the price is constant. However, it rises when the heat pump is actioned and that corresponds to hour 6 when the total price is about to rise. It increases up to the maximum (25ºC) so as to be able to remain within the limits until the price lowers again.

Once the first regulatory period has ended and considering that consumption, the network tariff is again computed. The network tariff increases for this user in periods 1 and 2 as the consumption has increased.

In theory, if the costs would have remained stable, the price per MWh, must have been reduced. However, as the maximum power flow after the first regulatory period has changed in several lines, the costs in those lines increased, and consumer 9 (the one that has the heat pump installed) bear part of those costs.

Then, the second regulatory period occurs. With that new network tariff, the user changes slightly its consumption pattern.

The consumption increases in hour 8, when network charges are free, and it is reduced from 14:00h to 18:00h, where the higher charges are encountered, taking also into consideration that the indoors temperature has to be maintained between 21ºC and 25ºC.

Finally, the capacity of the line in which the system has invested is 20% higher, meaning that the capacity is below the threshold set, so the tariff that is again computed, remains the same than in the previous period.

All this behavior proves that the Spanish tariff sends more efficient signals than the volumetric tariff, but some reinforcements cannot be avoided, in the sense that the consumer is incentivized to consume in cheaper hours, but he would have to bear the same costs of the reinforcements either way.

The results for the Spanish tariff in the different periods are summarized in Figures 6 and 7. While Figure 6 represents the changes in the consumption pattern of the user that has the heat pump installed, Figure 7 represents the difference in the price of the tariff.

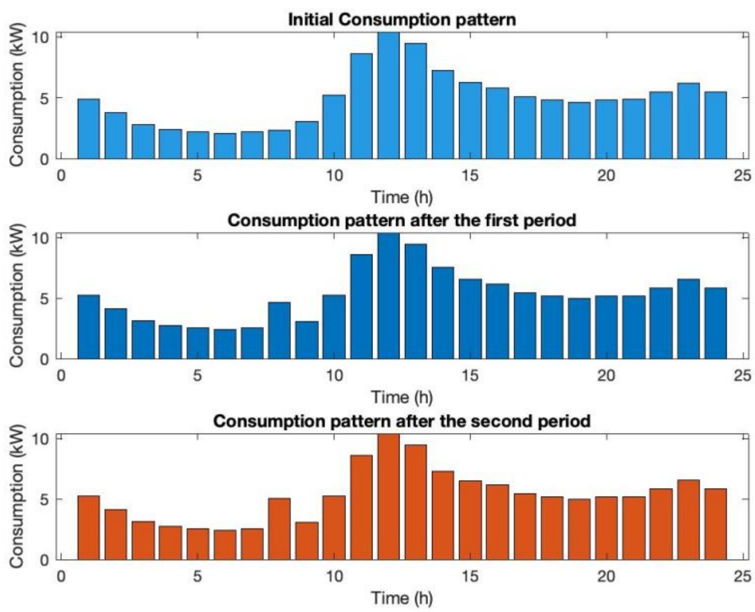

Figure 6. Variation of the consumption pattern of the user that has a heat pump installed in the Spanish Tariff scenario.

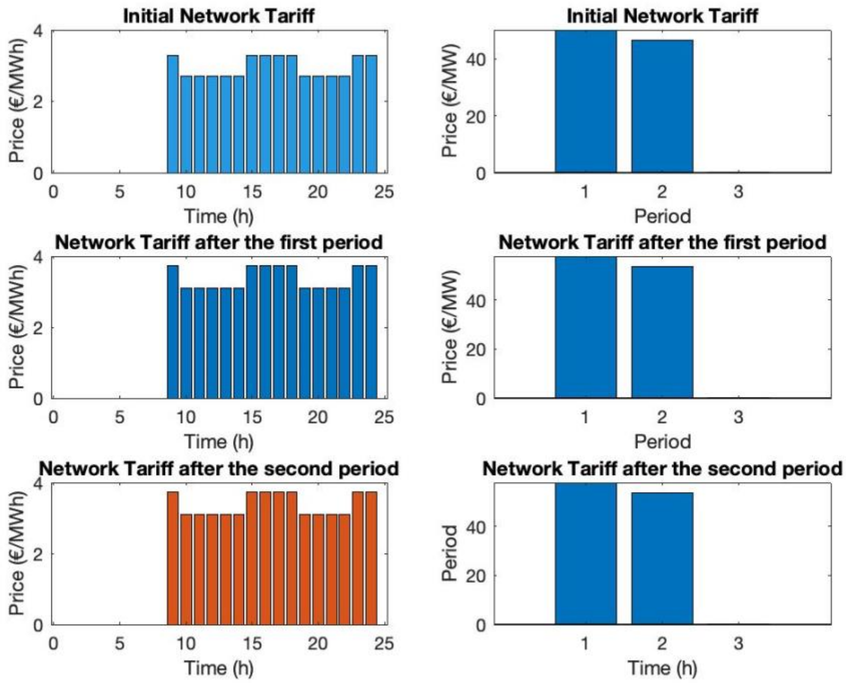

Figure 7. Variation Network Tariff of the user that has a heat pump installed in the SpanishTariff scenario.

4. Conclusions

On the one hand, the proposed tariff acts in the most efficient way possible: the consumption is increased in a way that the user that installs the heat pump does not contribute to increase the maximum power flow running through the network, and therefore the network costs do not increase. For the second regulatory period, the consumption is modified efficiently, as the user has been provided with the necessary signals to modify his pattern wisely. However, on the other hand, neither the Spanish tariff structure, nor the volumetric tariff structure work this way: on the contrary, under these tariff structures, the use of the heat pump is incentivized in hours when the consumer would contribute to the congestion of a line, therefore increasing the reinforcement and maintenance costs of the line and, as a consequence, increasing the costs for the user that has installed this device, and for the others at the same voltage level.

In conclusion, the proposed tariff outperforms other tariff structures in the presented case study. However, more research has to be done to prove this point under other circumstances.

5. References

[1] Schittekatte, T.; Meeus, L. *Limits of Traditional Distribution Network Tar*iff *Design and Options to Move Beyond*; Robert Schuman Centre for Advanced Studies Policy Briefs; Florence School of Regulation: Florence, Italy, 2018; ISBN 978-92-9084-613-0.

[2] Morell Dameto, N.; Chaves-Ávila, J.P.; Gómez San Román, T. Revisiting Electricity Network Tariffs in a Context of Decarbonization, Digitalization, and Decentralization. Energies 2020, 13, 3111. https://doi.org/10.3390/en13123111

[3] Miguel Peña D.; Morell Dameto, N.; Chaves-Ávila, J.P.; Evaluation of Distribution network charges designs in the context of Decarbonization, Digitalization, and Decentralization. January 2021.

Introduction

Electricity systems are confronting several transformations that are demanding a profound revision in electricity tariff's models.

Before the liberalization of the electricity sector, the allocation of bundled system costs corresponding to each vertically integrated utility was made sharing these costs among different customers based on their energy consumption. Electricity was generated by centralized producers, transported by unidirectional flows, and consumed by the end users. For such system configurations, flat and volumetric tariffs were the way to recover regulated costs as the higher the consumption, the higher the contribution to system costs and therefore, the greater the amount needed to be paid [1]. However, nowadays, the consumption of the user is not proportional to the use that he makes of the networks and the user is capable to react to the market prices. Bearing in mind these changes, a redesign of tariff's structure seems indispensable.

This design has to take into account the main trends in the transition of the power sector: the enablement of consumers to respond to electricity prices and regulated tariffs by the deployment of smart meters and new communication technologies, becoming active participants in the electricity market by reacting to the market prices (Digitalization), the development of new technologies, such as, but not limited to thermostatically controlled loads, distributed renewable generation, or energy storage that completely changes the paradigm of the traditional scheme of generation-distribution-consumption (Decentralization) and the impetuous need to comply with the CO_2 emission reduction targets in the European Union that are materialized in the investment of Renewable Energy Systems (Decarbonization). This new methodology to allocate the system network's costs to deal with these changes is proposed in [2]

In this thesis, a case study based on thermal loads is presented to analyze if the proposed tariff design accomplishes with the objectives of an efficient electricity tariff: to collect the money invested in the business and its operating and maintenance cost, along with the allowed revenues and to send the appropriate economic signals to the system users to ensure economic efficiency and make the optimal investments in the future. [3]

State of the art

Along the years, research has been carried out trying to reach an efficient network tariff that achieves a fair and equitable share of the costs and charges allocated to customers, while complying with tariff principles at the same time, such as [4] where a new tariff design methodology based on cost causality was presented. Moreover, in the light of the new paradigm of the 3D's[1], other papers, like [5] or [6] have focused on discussing the principles of electricity network charging considering the challenges of increasing amounts of distributed generation, electric vehicles, and energy storage. Particularly, [7] studies whether the UK system favors certain types of network user who do not bear either the efficient or fair share of the total distribution system costs.

In this context, [2] proposes a new tariff structure considering principles such as, but not limited to, economic efficiency, equity, and transparency, and takes into account the decentralization, decarbonization and digitalization movement that is occurring. The effectiveness of this proposal was analyzed in the same paper, where the effect of one LV consumer installing PV panels for self-generation was studied, and results provided evidence of the benefits of applying the proposed methodology in comparison to other current practical tariff design. In [3], this methodology was again revisited but this time, the target was a consumer installing batteries or charging his Electric Vehicle (from now on, EV). In both studies, the results evidenced the benefits of applying the proposed methodology in comparison to other current practical tariff designs (a volumetric traditional tariff and the CNMC[2] Spanish tariff), concluding that the Forward-Looking Tariff incentivizes efficient operational decisions potentially made by responsive customers.

[1] Decarbonization, Decentralization and Digitalization

[2] Comisión Nacional de los Mercados y la Competencia

Motivation and Roadmap

The aim of this thesis is to contribute to the design of an electricity network tariff that will principally provide the user with the efficient signals to behave according to the needs of the system. Particularly, the effect of introducing heat pumps in the electric network will be studied, as this thesis is written in a context of increasing penetration of these devices in our country.

According to IDAE [8] data reflect a clear upward trend for this technology, which exceeds 4 million plants installed, when in 2014 the number of these was lower than 2 million. Moreover, recently, the Council of Ministers endorsed the MITECO[3] proposal to strengthen the incentive programs for renewable thermal systems and to enhance the penetration of the heat pump, by expanding the range of heat pumps and equipment that can be installed to be subject to incentives proposed by the government. [9] Furthermore, globally, almost 180 million heat pumps were used for heating in 2020, as the global stock increased nearly 10% per year over the past 5 years. This growth is evident across all primary heating markets – North America, Europe and Northern Asia and, in the Net Zero Emissions by 2050 Scenario, the installed heat pump stock should reach 600 million by 2030. Heat pumps could supply more than 90% of global space and water heating at a lower CO_2 emissions level than condensing gas boiler technology [10], so studying the effect under different tariff's scenarios is worthwhile, given that they will play a major role in the future of decarbonization.

Also, it will help Nicolás Morell Dameto with his PhD research developments on the topic. The Forward-Looking Tariff design made in [2] is tested quantitatively in this document in the case of a consumer installing thermal loads (in particular, heat pumps). To do so, three mathematical models (one for each tariff studied) are programmed.

This document is structured as follows: a first section in which the three tariffs that are going to be studied are presented, a second part where the methodology followed to develop the

[3] Ministry for the Ecological Transition and the Demographic Challenge

different models is explained, a third chapter where each case study is explained and results are analyzed, and the last section where conclusions are remarked. Finally, as this thesis has been developed using Matlab Software, the transposition of the mathematical formulation to the code can be found in several Annexes at the end of this document.

Project alignment with Sustainable Development Goals (SDGs)

Disclaimer: All the information in this section related to SDGs was gathered from [11] and all the reports made by the United Nations that are found subsequently in their official website.

The main goal of this thesis is to assess if the proposed tariff design accomplishes its two main objectives: to collect the money invested in the network business and its operating and maintenance cost, along with the allowed revenues and to send the appropriate economic signals to the system users to ensure economic efficiency and make the optimal investments in the future. Should these objectives be tackled, efficient investments would maximize social welfare and reduce system costs, that will be reflected on the tariffs. This contributes not only to the public well-being but also to the Sustainable Development Goals (SDGs) dated for 2030.

The Sustainable Development Goals are a collection of 17 global goals designed to achieve a better and more sustainable future for all. They address the global challenges we face, including those related to poverty, inequality, climate change, environmental degradation, peace, and justice. They are the main global consensus agenda for the integral progress of our societies. The main SDG that this project complies with is **SDG7: Affordable and clean energy**, although it can be aligned with others. Specially, SDG7.1 pursues to ensure universal access to affordable, reliable, and modern energy services. This is accomplished just by the fact of trying to create a new electricity tariff that pursues the cost-efficient usage of the network as well as an equitable share of the costs for network users, guaranteeing that energy is more affordable for the users. SDG7.2 pursues to double the global rate of improvement in energy efficiency and SDG7.B seeks to expand infrastructure and upgrade technology for supplying modern and sustainable energy services for all. These two objectives are related to this thesis since the creation of an Forward-Looking Tariff ensures that the investments in networks and in renewable energy sources are the ones that maximize social welfare.

1. Tariff design

Broadly speaking, the electricity bill is the monthly cost that the user has to pay for the electricity that he consumes. However, he does not pay just for “electricity” itself, defining electricity as the form of energy resulting from the energy withdraw from the grid, but for all the system costs that are incurred for the user to have that electricity delivered home. These are:

- The price of the electrical energy, that includes the costs of generation and auxiliary services necessary for the operation of the system.
- The regulated costs to pay transportation and distribution networks.
- Other regulated costs derived from public policies, such as the historical support for renewables, the annuity of the deficit, or the compensations for the extra-peninsular systems.
- The costs of commercialization.
- Taxes, such as electricity tax and VAT.

Thus, electricity tariffs recover the regulated part of those costs. Hence, tariff design consists of developing a tariff structure that efficiently allocates regulated costs to consumers. However, while the energy costs are allocated through the wholesale markets, among others, and the costs of commercialization are decided by each electricity retail company, the methodology to allocate regulated costs is summarized in three steps: first, to identify the costs that are object of the study, then, to decide how they are going to be allocated and finally, to determine if locational and/or temporal granularity is needed.

Especially, the costs that concern us in this paper are the regulated ones to pay for transportation and distribution networks. Network costs mainly include investment (CAPEX), and operation and maintenance (OPEX) of networks assets. Also, energy losses and quality of service costs are included in OPEX. The drivers of these costs (i.e., the magnitudes related to network users that contribute to increasing the amount of costs) can be the peak consumption of the user, the energy consumed or injected in the network by the user or the new connection of a network user [2]. Therefore, cost allocation can be done by three different types of charges:

- Energy-based charges (€/MWh)
- Capacity-based charges (€/kW)
- Fixed charges per customer (€/customer)

Regarding granularity, this is defined as the scale or level of detail in which charges are computed. In this case, granularity can be temporal or spatial. On the one hand, deciding about temporal granularity implies choosing if charges are going to have temporal differentiation, that is, if they are going to be depending on time or static. On the other hand, to decide about locational granularity means to select if the charges applied are going to have locational differentiation, that is, if they are going to depend on where the user is located. An ideal tariff would have a high temporal and locational granularity. However, this solution is difficult to apply, complex to understand by regular customers, and could be inequitable since rural users could end up paying higher fees because of their dispersion [2].

The different tariffs studied are three: Volumetric Tariff, CNMC Spanish Tariff and the Forward-Looking Tariff, which is the one proposed in [2].

1.1 Volumetric Tariff

This charge consists of a flat volumetric charge (€/kWh) for all hours. This was used traditionally, when it was assumed that low-income customers will consume less than high-income ones. Therefore, it made sense to charge the costs proportionally to the consumption. However, decentralization and decarbonization have allowed users (mainly high-income ones) to install DERs, so they consume less energy (as they generate energy for themselves), and with this tariff, end-up paying less costs. Therefore, to compensate the DER owner's avoided payments, the rest of the users that do not have DERs installed, pay more. As a result, this incentivizes further PV installation. Authors refer to this problem as the death spiral (direct feedback between volumetric tariffs and DER deployment). [2,12-14].

Regarding granularity, neither temporal nor locational granularity are applied. However, three voltage levels are differentiated (HV, MV and LV), so the distribution of costs at each network voltage level is allocated among the users connected at the same level and the users connected at lower levels.

1.2 Spanish CNMC Tariff

In the previous model it has been seen that volumetric charges incentivize PV installation and, therefore, that is prejudicial to those that cannot do so. As a solution, contracted capacity, or demand charges (€/kW) are introduced to allocate part of the total network costs, being the rest of the costs recovered by volumetric charges. This contracted capacity charge is stablished ex-ante and limits the maximum power that a user can demand. [2]

Therefore, the Spanish CNMC Tariff consist of two charges:

- A contracted capacity charge (€/kW-year)
- A volumetric charge (€/kWh)

Regarding granularity, temporal differentiation is present by periods: CNMC low-voltage tariffs divide each day into three time-blocks (peak, shoulder and off-peak); while CNMC medium- and high- voltage tariffs present six different time blocks. In this thesis, the time differentiation has been simplified to three periods for all consumers. Hours belonging to each period are: P1: h10 to h14 and h19 to h22; P2: h9, h15 to h18 and h23 to h24; and P3: h1 to h8. The charges are greater in peak periods, to encourage consumers to contract less capacity in those ones, and to move their consumption to shoulder and off-peak periods.

Spatial granularity is not allowed in Spain. However, both charges are different by voltage levels. As in the volumetric tariff, costs at each network voltage level are allocated among the users connected at the same level and the users connected at lower levels.

Two considerations are taken into account for the design of this model, but, if wished, one can extend the information on the calculation process by reading [2]:

- The capacity charge is responsible for recovering the high-voltage (HV) network costs and 75% of the medium-voltage (MV) and low-voltage (LV) costs, while the energy charge is collecting 25% of MV and 25% of LV costs.
- The costs from a voltage level are allocated to the different periods according to the proportion of peak hours found at each period, knowing that the peak hours are considered to be the eight hours of highest consumption.

1.3 Forward-Looking Tariff

This tariff design follows the reasoning that the main trigger for future network investments is the maximum peak usage of each network element, so the more congested is a line, the sooner the investments will be required.

Therefore, the Forward-Looking Tariff consist of two charges [2]:

- A contracted capacity charge (€/kW): a peak-coincident capacity charged applied on an hourly basis. The purpose of this charge is to make the users pay in proportion to their contribution to the power flow when an element is potentially congested (i.e., loaded to more than 60% of its capacity). This way, generation and demand are charged equally but in the opposite direction. So DERs will be rewarded if they help the network to be less congested.
- A fixed residual charge (€/customer): recovers the remaining network costs. This way, the efficient signals are not impacted, and network users cannot avoid this payment by modifying their consumption patterns.

Regarding granularity, in the fixed residual charges, costs at each network voltage level are allocated among the users connected at the same level and the users connected at lower levels and, the geographical location is as well considered in the contracted capacity charges as it is calculated element-by-element. Temporal granularity is considered in the sense that the contracted capacity charge is peak coincident.

Besides, it considers the remuneration for the end-users' energy injection into the network.

2. Methodology

In this section, the mathematical models for the optimization of the use of the heat pump under the three different tariffs will be explained. These are applied into a network model, which will be described, and consist of the testing of these tariffs when a user installs and uses a heat pump to regulate the temperature of an indoor space.

2.1 Network Model

The network model consists of three voltage levels (HV, MV, LV), with transformers connecting them. In the HV and in the MV part, there is a generator and two loads on each of them, whereas in the LV part, there are five loads and two generators. Consumer 9 (node 18) will have the heat pump installed. Note that if one out of 5 consumers have a heat pump installed, in reality would mean that 20% of consumers have a heat pump installed. A drawing of the model can be seen in Figure 1. However, it must be noted that generators in nodes 20 and 11 have been turned off to simplify the study. The load curves are known for each consumer.

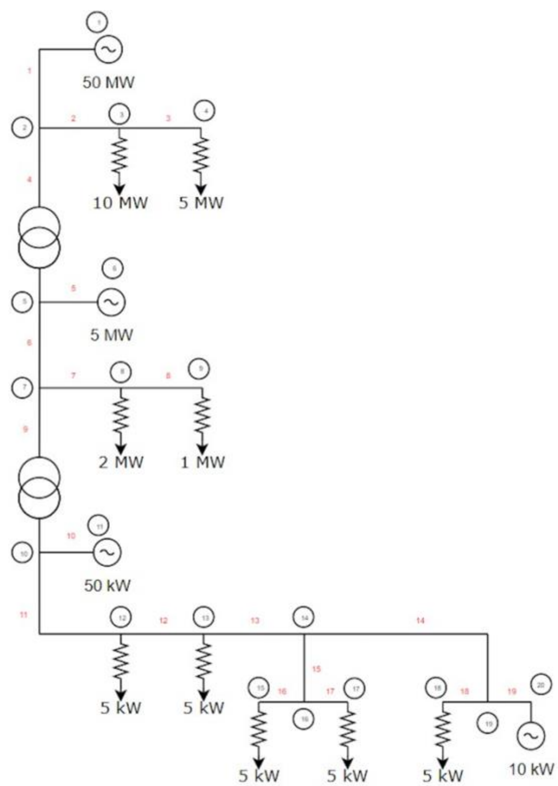

Figure 1. Network model [2]

The annual maintenance costs and the annualized investment costs are also known for each network element. They are shown in Table 1.

Table 1. Annualized costs for each network element

Annualized costs (Net present value)	Investment cost (€/km)	Maintenance cost (€/km)
LINE	900	30
SUBSTATION	17500	5000
TRANSFORMER	12000	500

The initial data for each branch is found in Table 2, in which zones 1, 2 and 3 represent high voltage (HV), medium voltage (MV) and low voltage (LV) zones, respectively. Note that the data for the maximum capacity is rounded.

Table 2. Initial branch data

Nº of branch	Length (km)	Substations	Transformers	Max. Capacity (MW)	Zone	Maint. cost (€)	Inv. cost (€)
1	2	0	0	21	1	60	104.90
2	1	0	0	22	1	30	52.45
3	1	0	0	10	1	30	52.45
4	12	1	0	4	2	5360	1649.27
5	6	0	0	6	2	180	314.70
6	6	0	0	5	2	180	314.70
7	6	0	0	5	2	180	314.70
8	6	0	0	2	2	180	314.70
9	7	0	1	0.05	3	710	1066.49
10	3	0	0	0.08	3	90	157.35
11	10	0	0	0.05	3	300	524.50
12	4	0	0	0.04	3	120	209.80
13	4	0	0	0.03	3	120	209.80
14	15	0	0	0.013	3	450	786.76
15	1	0	0	0.02	3	30	52.45
16	1	0	0	0.013	3	30	52.45
17	1	0	0	0.013	3	30	52.45
18	1	0	0	0.013	3	30	52.45
19	1	0	0	0.08	3	30	52.45

2.2 Heat Pump modelling

Disclaimer: All the information in this section related to heat pump's functioning was gathered from [15]. To understand the equations of the three models, this section explains what a heat pump is, how it works from a thermodynamical point of view, how is its efficiency measured and why it can be considered a device that uses renewable energy.

A heat pump is commonly known as a device used to climatize a house taking advantage of the outside temperature and the thermodynamic properties of the house itself. The technology behind it is called a reverse thermodynamic cycle. It is known as inverse because it operates in the opposite way to how a power cycle does. Thus, while in a power cycle heat is taken from a hot source, some of it is converted into work and the rest is transferred to a cold source, in a reverse cycle heat is taken from a cold source, work is consumed, and the rest is supplied to a hot spot. Therefore, the reverse cycle takes heat from a low temperature source (cooling it) and transfers heat to a high temperature source (heating it). The functionality of the cycle can be to absorb heat from one source or transfer heat to another. Both processes (absorption and release of heat) occur simultaneously, taking advantage of one or the other. Depending on which of the two effects is considered useful, either it is a refrigerating machine or a heat pump.

However, in Spain, it is worth noting that at a commercial level, it is common to call a heat pump a reversible equipment applied to climatizing, that is, an installation that produces heat in winter and cold in summer.

In principle, any thermodynamic power cycle becomes a refrigeration cycle by running it in the opposite direction. However, the Rankine method has such advantages that historically it has been the most widely used. Figure 2 shows the schematic of a basic inverse Rankine cycle.

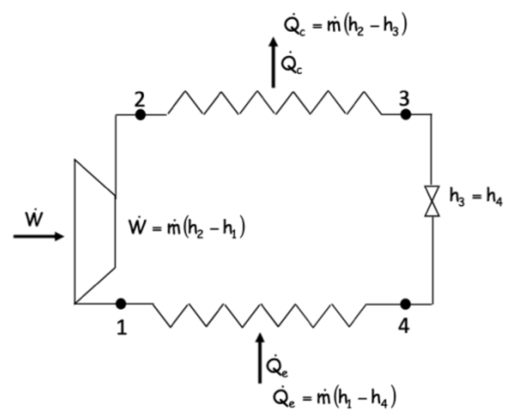

Figure 2. Schematic diagram of a reverse Rankine cycle [5].

It consists of the following processes:

- Process 1-2. The pressure of the steam is increased.in the compressor
- Process 2-3. The heat is transferred to the hot spot in the condenser (heat exchanger where the vapor leaving the compressor is condensed, coming out as a liquid without losing pressure).
- Process 3-4. Expansion of the liquid in a valve, which lowers its pressure.
- Process 4-1. The heat is absorbed in the cold source (system to be cooled) in a heat exchanger called an evaporator. In it, the wet steam coming out of the valve evaporates to saturated steam without losing pressure.

The global energy balance is $W+Q_e=Q_c$, where W is the absorbed power, Q_e is the cooling capacity and Q_c is the heating capacity. Also, the efficiency is defined as a Coefficient of Performance $(COP)=Q_c/W$, and must be greater than 1.

A reverse cycle working in heating mode always takes low-temperature thermal energy from the environment (ground, air or water) so that, together with the work consumed by the compressor, the pump delivers it to the demand converted into high temperature heat. This operation could be interpreted as using renewable energy (which the evaporator takes from the environment) to produce heat, but noting carefully that the heat pump uses electrical energy to drive a compressor, and the origin of this energy is not always a renewable source.

To produce this electrical energy, let us say that the generation system takes 1 unit of primary energy, losing 0.6 units of it in generation and transport of electricity. The 0.4 units of electrical energy supplied to the compressor motor is converted into 0.34 units of mechanical work on its crankshaft. This mechanical work is combined with 0.84 units captured from the environment through the evaporator, thus supplying the heat pump with 1.18 units of energy (electrical and low-temperature thermal), which the heat pump converts into 1.18 high temperature thermal power units. In this example, the pump delivers 1.18 units of final energy on demand from 1 unit of primary energy.

As seen in the example, the installation of heat pumps makes users save energy taking advantage of outside temperature, as they employ less work to obtain more heat. If users were to save money in their energy bill, they would be reactive to energy prices and network tariffs, by climatizing their house in off-peak periods, maintaining the indoor temperature taking advantage of thermal inertia of walls in peak periods.

To optimize the use of the heat pump three mathematical models are proposed, one for each tariff.

2.3 Mathematical model for the operation of a Heat Pump under the Forward-Looking Tariff

In this part of the chapter, the mathematical model for the operation of a Heat Pump under the Forward-Looking Tariff is explained. Firstly, the terms used in the formulas are defined and then, the equations itself are detailed. Finally, the values for the parameters are given.

2.3.1 Nomenclature

Sets

t = hour (h)

Parameters

$ENERGYCOST_t$ = Total cost of energy consumed each hour (€/kWh).

$CAPACITYCOST_t$ = Total cost of network capacity charges each hour (€/kW).

POWERHP = Installed capacity of heat pump (kW)

COP = Coefficient of Performance of the heat pump (-)

HPLOSS = Losses of the heat pump (-)

R_1 = Heat transfer coefficient (indoor) (Cº/kW)

R_2= Heat transfer coefficient (outdoors) (Cº/kW)

C = thermal building wall equivalent capacitor (kWh/Cº)

TOUT = Temperature outside (Cº)

Positive variables

$EnergyBought_t$ = Energy consumed by the customer from the grid to meet all the demand for each hour (kWh)

$CapacityBought_t$ = Capacity bought by the customer for each hour (kW)

$clientConsumption_t$ = Energy consumed by the customer from the grid to meet all the demand except the climatization of the house for each hour (kWh)

$tempHP_t$ = Electricity consumed by heat pump for each hour (kWh)

$tInd_t$ = hourly temperature Indoor (ºC)

2.3.2 Equations

Objective function

$$\min_{x}[(ENERGYCOST_t \cdot EnergyBought_t + CAPACITYCOST_t \cdot CapacityBought_t)]$$

The objective function of this model is to minimize daily the cost the consumer pays for their bill (as the sum of the costs paid each hour). The proposed tariff in [2] has a capacity charge differentiated hourly. Therefore, the end-user would be charged for the peak capacity consumed each hour. So, the objective function minimizes the hourly price that the consumer is paying. By solving this objective function, the optimal behavior that the client would carry out when installing the heat pump. In such a way this serves us for the tariff design.

Besides, it is also known that the energy bought each hour cannot exceed the hourly contracted capacity, therefore:

$$CapacityBought_t \geq EnergyBought_t$$

Then, because the capacity bought will try to be higher or equal to the energy bought and there are no more restrictions in this respect, as capacity bought is trying to be minimized, this constraint can be deleted and the objective function results:

$$\min_{x}[(ENERGYCOST_t + CAPACITYCOST_t) \cdot EnergyBought_t]$$

Constraints

First, the nominal power of the Heat Pump must be greater or equal than the power (kW) that it is consuming every hour.

$$POWERHP \geq tempHP_t$$

Secondly, the energy bought is the sum of the electricity used to power and use the heat pump plus the normal client consumption of electricity for other uses, such as, but not limited to, lighting.

$$EnergyBought_t = tempHP_t + clientConsumption_t$$

In third place, the temperature of the indoor space has to be maintained within limits. These bounds have been stablished between 21ºC and 25ºC, which is a reasonable comfortable margin of temperatures for a house, according to [6].

$$21 \leq tInd_t \leq 25$$

Finally, the fourth equation models the change in temperature of an indoor space depending on several thermodynamical parameters that vary depending on the transmission capacity of the walls and size of the place that has to be climatized, the losses and efficiency of the heat pump and the temperature outside the place.

$$tInd_t = tInd_{t-1} - \frac{1}{C \cdot R_2} \cdot (tInd_{t-1} - TOUT) + R_1(tempHP_t \cdot \frac{COP(1 - HPLOSS)}{0.8}) + (\frac{R_1 + R_2}{C \cdot R_2} - R_1)(tempHP_{t-1} \cdot \frac{COP(1 - HPLOSS)}{0.8})$$

It is extracted from [7], and the physical explanation is also extracted from it. The reasoning that is behind this equation is that the daily temperature behavior can be modeled using an equivalent electric circuit as the one shown in Figure 3, where the capacitor (C) represents the thermal energy stored by the wall in a house, and resistances (R_1 and R_2) model the existing thermal conduction through the wall and the convection between the air and the wall.

Outdoor temperature is considered as a voltage source, as temperature changes are considered negligible in an hour, and heating input Q is symbolized as a current source. Finally, indoor temperature T_{ind} is the voltage level at the output of the current source. The evolution over time of the indoor temperature T_{ind} is obtained solving this circuit, applying a discretization method.

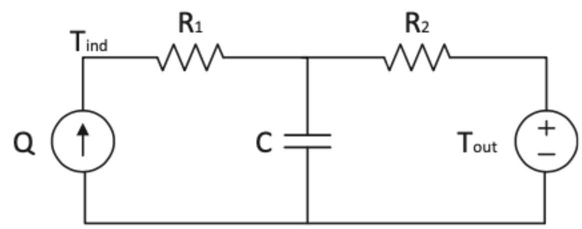

Figure 3. Equivalent electric circuit used to model the indoor temperature of a place [7]

2.3.3 Values of the Parameters

Energy parameters: $ENERGYCOST_t$ and $CAPACITYCOST_t$

The cost of the energy is the sum of the wholesale energy price plus the network charges. The network charges will vary with the model and the iterations, but the energy price is fixed. A flat energy price has been used, although in reality it changes hourly, but it shows better how the model reacts to network charges without the interference of energy prices. The capacity costs are also known in the first iteration, as they depend on previously decided investment needs, but will change depending on the evolution of the iterations.

Heat Pump Parameters: POWERHP, COP and HPLOSS

The capacity of the heat pump is supposed to be 5 kW, a standard size for a heat pump, according to [16]. Regarding COP, publications as [17] and [18] estimate that 2.5 would be a reasonable COP for a heat pump, and [19] confirms so. Lastly, the thermal losses of the heat pump have been estimated to be 15% of the total energy, as [19] does.

T_{OUT}

The temperature outdoors is supposed to be fixed and established in 2ºC, an average winter temperature in Spain.

Thermodynamic Parameters: R_1, R_2 and C

The thermodynamic parameters were established empirically, by running a trial-and-error model until a natural behavior was observed. This test was run in excel, and it consisted in modelling the fourth equation and continuously change the values of the parameters R_1, R_2 and C to see how the indoor temperature would react and if it would do so sensibly. To facilitate the understanding of the process, the terms of the equation will be, from now on, referred to as:

- First term: $-\frac{1}{C \cdot R_2} \cdot (tInd_{t-1} - TOUT) + R_1$
- Second term: $R_1(tempHP_t \cdot \frac{COP(1-HPLOSS)}{0.8})$
- Third term: $(\frac{R_1+R_2}{C \cdot R_2} - R_1)(tempHP_{t-1} \cdot \frac{COP(1-HPLOSS)}{0.8})$

To run the test, we first gave a value for the parameters we knew, and we decided the initial value for a temperature indoor: let us say 15ºC. The first values that were set are shown in Table 1. There would be as many rows as hours in a day, but in Table 3 just one row is shown.

Table 3. Initial values for the parameters to test the Thermodynamic equation

h	tInd	C	R2	R1	TOUT	tempHPt	COP	HPLOSS	tempHP (t-1)
0	15				2	0	2.5	0.15	0

The behavior that is expected from the evolution of the indoor temperature is:

- If tempHP, which is the consumption (in kWh) of the heat pump in one hour is actioned (that is, if it is greater than 0 kWh), the temperature in that instant has to rise.
- It cannot be expected that if the heat pump consumes 1 kWh the temperature rises in a disproportionate way, for example, increasing 5ºC. The second term of the equation models this rise. This value must be such that the temperature cannot rise more than 3ºC. Setting R_1=0.5 Cº/kW made that term be 1.3281 and the maximum rise 2.5ºC, as it can be seen in Figure 4.
- Once the temperature has risen, it has to be maintained, or at least has to decrease (if no more energy is consumed by the heat pump) at a slow pace, for instance, no more than 1ºC per hour. If, for example, from one hour to another, the temperature changes 1.5ºC, or goes back to the original temperature, that would mean that the insulation of the house would be poor, as the temperature is just maintained if the heat pump consumes energy. Therefore, the value of the third term, which corresponds to the ramp that decreases, has to be negative (as it has to decrease) and lower than the second term in absolute value (as the decrease must be lower than the increase), so that temperature is maintained and does not change more than 1.5ºC per hour. Having already set R_1 to 0.5 Cº/kW, we then set R2 to 20Cº/kW and C to 2.73 kWh/Cº, so the value of the term was 0.1668, which is lower than 1.3281 (the value of the second term), and the resulting biggest decrease in temperature was 1.1ºC/h.
- The total consumption of the house along the day has to be similar to a typical consumption of a house. That means, that the value for "tempHPt" (the consumption of the heat pump) should be close to the following data: a consumption of 4.8kWh a day, or 140kWh a month, which is typical in winter for an average household.

From this study, some conclusions were extracted:

- C is thermal inertia: the greater it is, the more likely is the indoor temperature to stay stable under a change in external conditions.
- The summation has three terms: If the third term is close to 0, and the heat pump consumption is constant, the second and the third term will be eliminated so, even though the consumption is high, the temperature will remain constant or will decrease slowly.
- For the same reason, if the constant $(R_1+R_2)/(C \cdot R_2)$ is reasonable but the parameter C (or R_2) is not as desired, so it is increased by X units, R_2 (or C) would have to be decreased X units, so the denominator remains unchanged.
- R_1 is the inverse of the thermal resistance that exist between the indoor zone and the walls, whereas R_2 is the inverse of the resistance that exists between walls and the exterior. The units are Cº/kW, so, the higher the value, the faster the temperature changes with 1 kW of power. It makes sense that the exterior resistance is lower (R_2 higher) because it considers the radiation and the wind effect (convection), so the exchange is easier. If there was no wind, the resistance would be higher (the temperature exchange would be more difficult).

Given all these specifications, the values for the resistances result in R_1=0.5 Cº/kW, R_2=20Cº/kW and C=2.73 kWh/Cº. An example of the resulting indoor temperature in a 24-hours example, given that there is a consumption of 2.4 kWh in hours 4 and 11 is depicted in Figure 4.

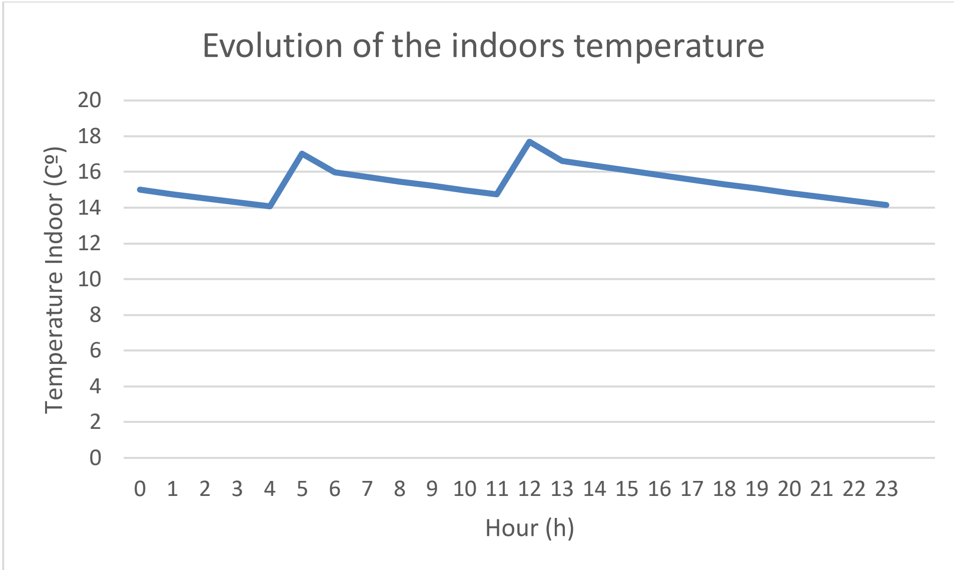

Figure 4. Example of the behavior of the indoors temperature of the model with time

A summary of the equations is found next:

$$\min_x [(ENERGYCOST_t + CAPACITYCOST_t) \cdot EnergyBought_t]$$

Subject to:

$$POWERHP \geq tempHP_t$$

$$EnergyBought_t = tempHP_t + clientConsumption_t$$

$$21 \leq tInd_t \leq 25$$

$$tInd_t = tInd_{t-1} - \frac{1}{C \cdot R_2} \cdot (tInd_{t-1} - TOUT) + R_1(tempHP_t \cdot \frac{COP(1 - HPLOSS)}{0.8}) + (\frac{R_1 + R_2}{C \cdot R_2} - R_1)(tempHP_{t-1} \cdot \frac{COP(1 - HPLOSS)}{0.8})$$

2.4 Mathematical model for the operation of a Heat Pump under the Volumetric Tariff

In this part of the chapter, the mathematical model for the operation of a Heat Pump under the Volumetric Tariff is explained. Firstly, the terms used in the formulas are defined and then, the equations itself are detailed. Afterwards, the values for the parameters are given and finally, the behavior of the model is tested, and results are analyzed.

2.4.1 Nomenclature

The nomenclature in the model for the Volumetric Tariff remains unchanged with respect to it in the Forward-Looking Tariff model. [See Section 2.3.1]

2.4.2 Equations

The mathematical model for the Volumetric Tariff is almost the same as the one for the Forward-Looking Tariff. The difference between these two models is that the Volumetric Tariff consists of a flat volumetric charge (€/kWh) for all hours. Therefore, as there is no capacity charge, the variables related to the capacity bought are not considered.

Thus, a summary of the equations is found next:

$$\min_{x}[(ENERGYCOST_t) \cdot EnergyBought_t]$$

Subject to:

$$POWERHP \geq tempHP_t$$

$$EnergyBought_t = tempHP_t + clientConsumption_t$$

$$21 \leq tInd_t \leq 25$$

$$\begin{aligned} tInd_t = tInd_{t-1} - \frac{1}{C \cdot R_2} \cdot (tInd_{t-1} - TOUT) + R_1(tempHP_t \cdot \frac{COP(1 - HPLOSS)}{0.8}) \\ + (\frac{R_1 + R_2}{C \cdot R_2} - R_1)(tempHP_{t-1} \cdot \frac{COP(1 - HPLOSS)}{0.8}) \end{aligned}$$

2.4.3 Parameters

The parameters of this model with respect to the Forward-Looking Tariff model remain unchanged [See Section 2.3.3], except for the energy cost, which is the sum of the energy price and the network charges, and these last, as it has been seen, vary depending on each tariff design.

2.5 Mathematical model for the operation of a Heat Pump under the CNMC Tariff

In this part of the chapter, the mathematical model for the operation of a Heat Pump under the CNMC's Tariff is explained. Firstly, the terms used in the formulas are defined and then, the equations itself are detailed. Afterwards, the values for the parameters are given and finally, the behavior of the model is tested, and results are analyzed. Particularly, the mathematical model for the CNMC Tariff brings several differences with respect to the rest of the models.

2.5.1 Nomenclature

This time, the hours of the day are grouped into three time periods, and the contracted capacity charge is applied to the maximum consumption in each of these periods. The rest of the nomenclature remains unchanged with respect to the Heat Pump operation model under the Forward-Looking Tariff.

Sets

t = hour (h)

P = period ∈ $(1,2,3)$

Parameters

$ENERGYCOST_t$ = Total cost of energy consumed each hour (€/kWh).

$CAPACITYCOST_P$ = Total cost of capacity charges (€/kW), which will remain unchanged inside a period.

POWERHP = Installed capacity of heat pump (kW)

COP = Coefficient of Performance of the heat pump (-)

HPLOSS = Losses of the heat pump (-)

R_1 = Heat transfer coefficient (indoor) (Cº/kW)

R_2= Heat transfer coefficient (outdoors) (Cº/kW)

C = thermal building wall equivalent capacitor (kWh/Cº)

TOUT = Temperature outside (Cº)

Positive variables

$EnergyBought_t$ = Energy consumed by the customer from the grid to meet all the demand for each hour (kWh)

$CapacityBought_p$ = Capacity bought by the customer for each period (kW)

$clientConsumption_t$ = Energy consumed by the customer from the grid to meet all the demand except the climatization of the house for each hour (kWh)

$tempHP_t$ = Electricity consumed to heat the house for each hour (kWh)

$tInd_t$ = hourly temperature Indoor (ºC)

2.5.2 Equations

Objective function

$$\min_x [(ENERGYCOST_t \cdot EnergyBought_t + CAPACITYCOST_P \cdot CapacityBought_P)]$$

The objective function seeks to minimize the total user's payment. The user will be paying each hour for two charges: a volumetric charge applied to the energy bought, and a capacity charge that is applied to the capacity bought in each period. The later will remain constant inside each period, whereas the former will change each hour.

Constraints

All the constraints are the same than the ones that can be found in the Forward-Looking Tariff model [See Section 2.3.2]. However, two more constraints are added.

First, the capacity purchased in each period has to be greater or equal than the energy purchased in each of the hours of the period.

$$CapacityBought_P \geq EnergyBought_{t\ \epsilon\ Period}$$

Second, the CNMC's tariff establishes that the contracted capacity during time block 3 has to be higher than contracted capacity in time block 2, and this higher than contracted capacity in time block 1. Therefore, these two constraints are also included:

$$Capacity\ Bought_{Period\,3} \geq Capacity\ Bought_{Period\,2}$$
$$Capacity\ Bought_{Period\,2} \geq Capacity\ Bought_{Period\,1}$$

Thus, a summary of the equations is found next:

$$\min_{x}[(ENERGYCOST_t \cdot EnergyBought_t + CAPACITYCOST_P \cdot CapacityBought_P)]$$

Subject to:

$$POWERHP \geq tempHP_t$$

$$EnergyBought_t = tempHP_t + clientConsumption_t$$

$$21 \leq tInd_t \leq 25$$
$$tInd_t = tInd_{t-1} - \frac{1}{C \cdot R_2} \cdot (tInd_{t-1} - TOUT) + R_1(tempHP_t \cdot \frac{COP(1-HPLOSS)}{0.8}) + (\frac{R_1 + R_2}{C \cdot R_2} - R_1)(tempHP_{t-1} \cdot \frac{COP(1-HPLOSS)}{0.8})$$

$$CapacityBought_P \geq EnergyBought_{t\ \epsilon\ Period}$$

$$Capacity\ \mathrm{Bought}_{Period\ 3} \geq Capacity\ \mathrm{Bought}_{Period\ 2}$$
$$Capacity\ \mathrm{Bought}_{Period\ 2} \geq Capacity\ \mathrm{Bought}_{Period\ 1}$$

2.5.3 Parameters

The parameters of this model with respect to the Forward-Looking Tariff's model remain unchanged [See Section 2.3.3], except for the energy cost, which is the sum of the energy price and the network charges, and these last, as it has been seen, vary depending on each tariff design. Also, the capacity cost varies depending on each tariff design, so will change from Forward Looking tariff to CNMC tariff.

3. Results of heat pump functioning under different tariffs

The methodology to apply in the case studies is the one used in [3]. The purpose of the studies is to test the efficiency of the Forward-Looking Tariff and to compare it to the other tariffs described previously along the document. To do so, several steps are required as described below.

First, the initial prices and consumption patterns for all users are stablished. Then, the user (in this case, the one connected to node 9, which at the end represents 20% of the low voltage consumers) has a heat pump installed, so his consumption pattern in particular and the electricity network charges in general change with respect to the original state. Both (the change in the consumption pattern of the user and the increase in costs due to the reinforcements in the network to satisfy the new demand) would imply a modification of the charges for the second regulatory period. Finally, the model runs again to compare the difference in charges and consumption patterns modified by the behavior of the end-user that has the heat pump installed and the changes in the future tariff.

Therefore, depending on the tariff applied, the load profile of the user change. Hence, the analysis evaluates whether the tariffs are sending efficient economic signals for the user to behave efficiently.

The algorithm that is behind this analysis works as follows:

- **STEP 1:** A consumption pattern is set for all of the users in the network, and also all the characteristics of the network (Look at Table 2).
- **STEP 2:** With that data, the power flow is computed, so all of the flows flowing through each branch are known.
- **STEP 3:** Then, the tariff is computed, that is, the costs of the network are divided among the consumers of the network.
- **STEP 4:** With those prices settled, a consumer (in this case, consumer 9) installs a heat pump, so its consumption pattern varies considering prices for electricity and the temperature inside the apartment.
- **STEP 5:** With that new consumption pattern, the power flow is again computed.

- **STEP 6:** If the new maximum flow through a branch makes the component of the network be at more than 80% of its capacity, the costs for that line are increased.
- **STEP 7:** With those costs and the new consumption patterns, the new tariff is computed.
- **STEP 8**: The consumer turns on again his heat pump in a new regulatory period, so the new consumption pattern is calculated
- Then, **steps 5, 6 and 7** are repeated.

3.1 Forward-Looking Tariff

The initial consumption pattern of the consumer who has the heat pump installed is the one presented in Figure 5 (One has to remind that this consumption pattern was extracted from real data of a network user). Of course, it coincides exactly with the power flow through branch 18, which is shown in Figure 6.

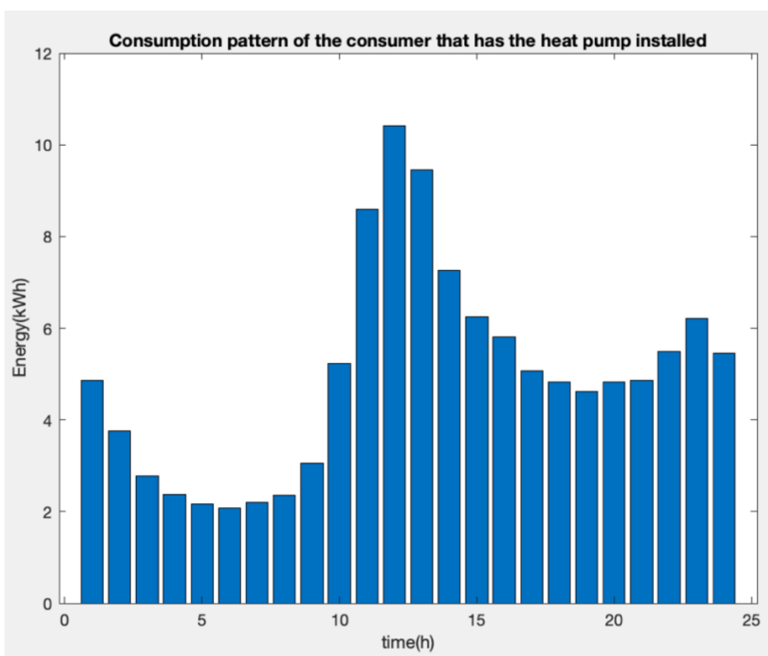

Figure 5. Consumption pattern of the consumer that has the heat pump installed

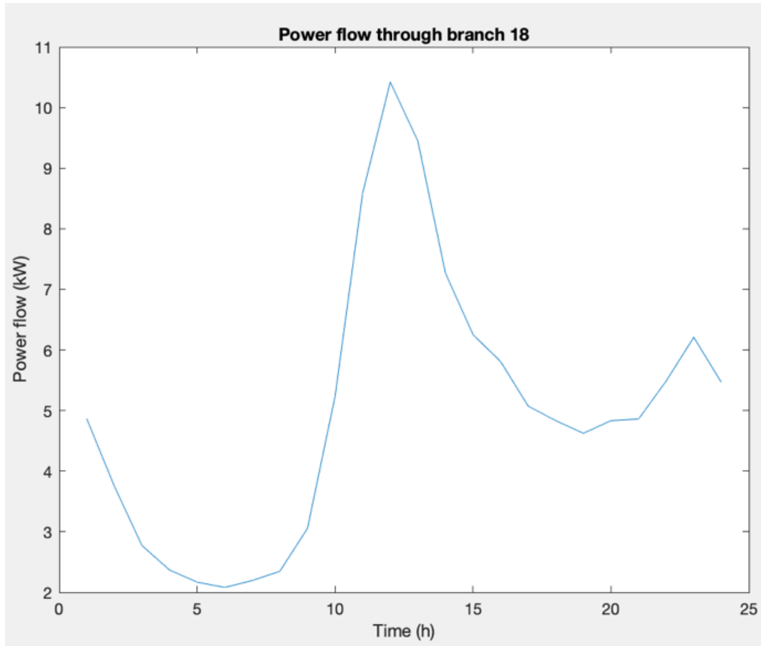

Figure 6. Initial power flow through branch 18

Considering that consumption pattern, the initial network tariff is shown in Figure 7, with higher charges in hours where the consumption is maximum and lower charges where the consumption is lower, to incentive the consumption in those hours where the consumption is lower.

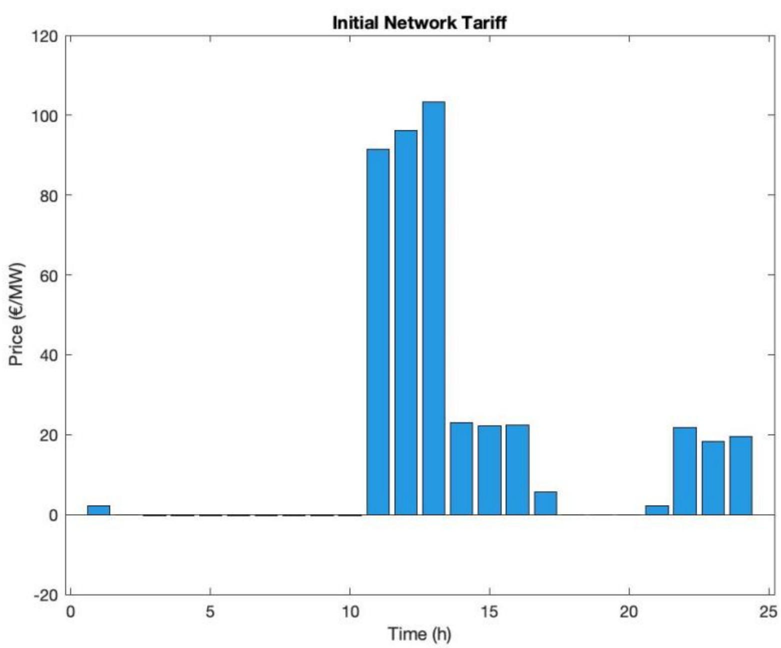

Figure 7. Initial Forward-Looking network tariff

The data of the branches is shown in Table 4. This includes:

- The capacity of the branches, which was set in purpose to set the congestion degree to 79%.
- The percentage of total capacity, which is 79% for all the lines
- The initial maximum power flow through the branches, obtained from computing the power flow with the initial data.
- The initial maintenance and investment cost, which was extracted from [3].

Table 4. Capacity and costs of each branch

Nº of branch	Capacity of the line (MW)	Initial maint. cost (€)	Inv. cost (€)	Initial max power flow (MW)	Percentage of total capacity (%)
1	20.359	60	104.9	16.08	79%
2	21.943	30	52.5	17.34	79%
3	9.521	30	52.5	7.52	79%
4	3.615	5360	1649.3	2.86	79%
5	6.327	180	314.7	5.00	79%
6	4.844	180	314.7	3.83	79%
7	4.803	180	314.7	3.79	79%
8	2.074	180	314.7	1.64	79%
9	0.050	710	1066.5	0.04	79%
10	0.080	90	157.4	0.00	0%
11	0.050	300	524.5	0.04	79%
12	0.036	120	209.8	0.03	79%
13	0.029	120	209.8	0.02	79%
14	0.013	450	786.8	0.01	79%
15	0.021	30	52.5	0.02	79%
16	0.013	30	52.5	0.01	79%
17	0.013	30	52.5	0.01	79%
18	0.013	30	52.5	0.01	79%
19	0.080	30	52.5	0.00	0%

The user decides to install a heat pump, and the new consumption pattern is shown in Figure 8.

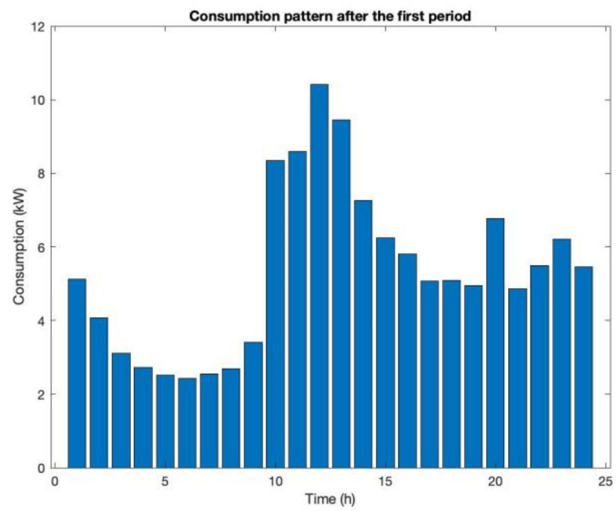

Figure 8. Consumption pattern of the user that installs the heat pump after the first regulatory period under the Forward-Looking Tariff structure.

The difference regarding the initial profile, depicted in Figure 9, coincides with the consumption of the heat pump.

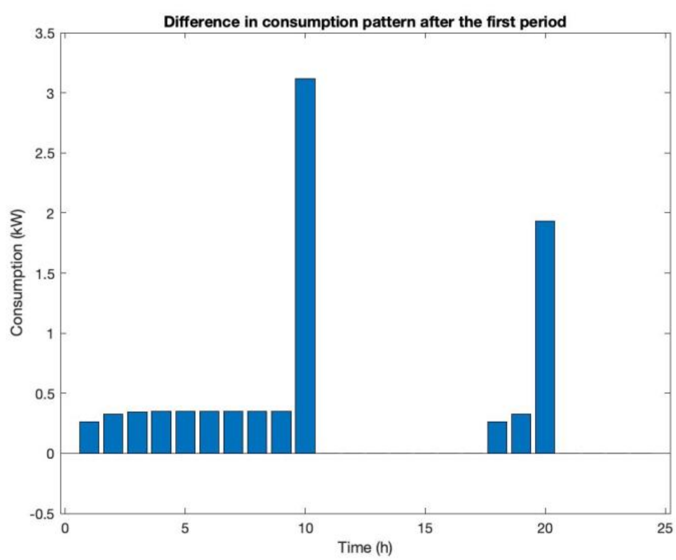

Figure 9. Difference between the consumption pattern after the first regulatory period

The user is incentivized to use the heat pump in cheap hours, so that is the reason why the consumption increases hours from 0 to 10 and there is a lack of increase between hours 11 and 17. This is due to the efficient use of the heat pump, as it is plotted in Figure 10 and 11.

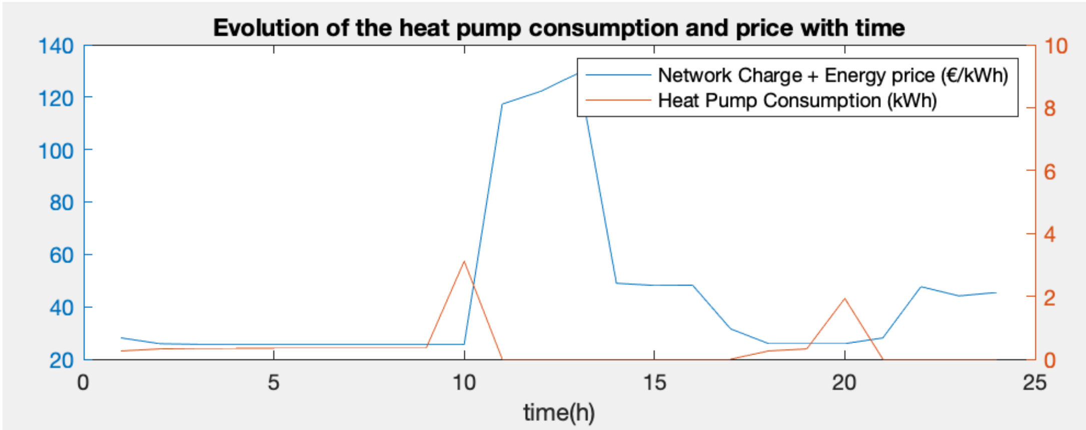

Figure 10. Behavior of the consumption in time with respect to price when the Forward-Looking Tariff is applied

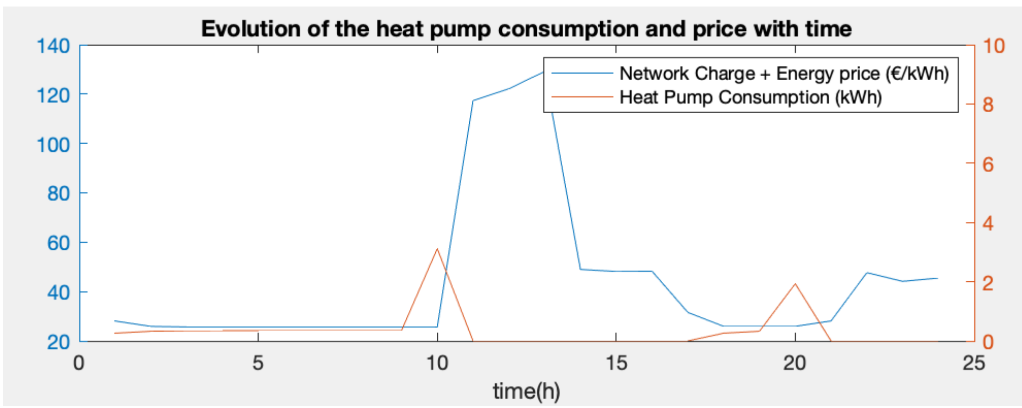

Figure 11. Behavior of the indoor temperature with respect to price when the Forward-Looking Tariff is applied

From 00:00h to 9:00h, the consumer uses the heat pump just to maintain the temperature in 21ºC (the minimum possible accepted). Then, it can be appreciated that he increases its use when the price is the lowest (25,66€) and that this energy is used to rise the temperature of the house until the maximum allowed (25ºC). In fact, it uses the heat pump just prior to the price rise, so that the consumption is zero in the most expensive hours. The temperature then decreases until it reaches 21ºC, when the heat pump is used again to maintain it constant. Thus, it has been avoided to consume energy from the heat pump in peak periods.

With that new consumption pattern, the power flow is again computed. If the new maximum flow through a branch makes the utilization of the component of the network be at more than 80% of its capacity, the costs for that line are increased an amount equal to the annualized investment cost considering a life expectancy of 20 years. So, once the first regulatory period has ended and considering that consumption, and after checking if reinforcements in the network are needed, the network tariff is again computed, shown in Figure 12.

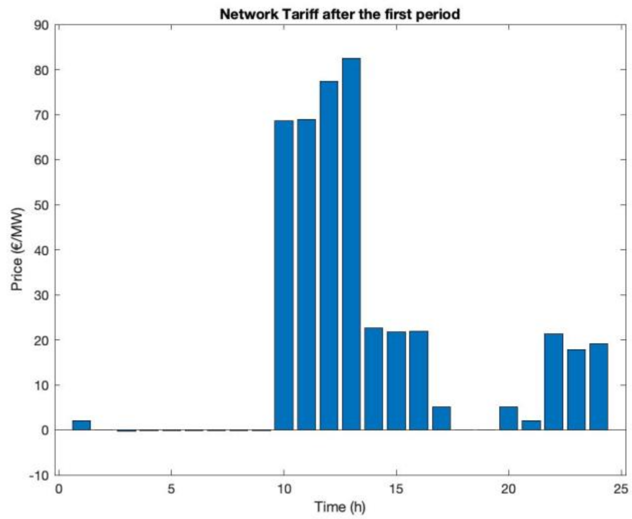

Figure 12. Network Tariff in the case of the Forward-Looking tariff structure after the first regulatory period.

The tariff decreases for this user in some hours, such as, but not limited to, hours 11,12 and 13 (which are the hours in which the heat pump was not used before, to incentivize the use of the heat pump there) and increases in hours 10 and 20 (which were the peak hours, to avoid the use of the heat pump there) as it is shown in Figure 13.

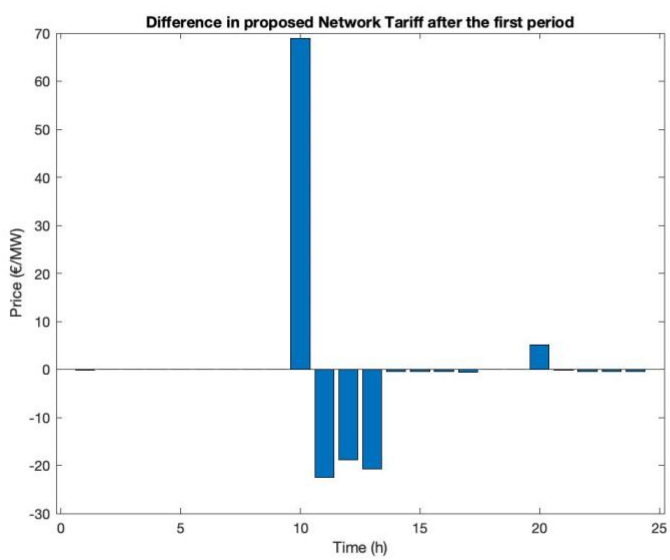

Figure 13. Difference in proposed Network Tariff after the first period

The maximum power flow after the first period has not increased in any line above the threshold set (80% of the capacity of the line), as observed in Table 5, so reinforcements are not needed, meaning that the network costs have not changed. The proposed tariff acts in the most efficient way possible: the consumption is increased in a way that the user that installs the heat pump does not contribute to increase the maximum power flow running through the network, and therefore the network costs do not increase. The fixed term (€/consumer) does not change either, as it can be appreciated in Table 6.

Table 5. Branch data after the first regulatory period under the Forward-Looking Tariff structure

Nº of branch	Capacity of the line (MW)	Max power flow after first period (MW)	Percentage of total capacity (%)	Initial Maint. cost (€)	Maint. Cost after first period
1	20.36	16.08	79%	60	60
2	21.94	17.34	79%	30	30
3	9.52	7.52	79%	30	30
4	3.62	2.86	79%	5360	5360
5	6.33	5.00	79%	180	180
6	4.84	3.83	79%	180	180
7	4.80	3.79	79%	180	180
8	2.07	1.64	79%	180	180
9	0.05	0.04	79%	710	710
10	0.08	0.00	0%	90	90
11	0.05	0.04	79%	300	300
12	0.04	0.03	79%	120	120
13	0.03	0.02	79%	120	120
14	0.01	0.01	79%	450	450
15	0.02	0.02	79%	30	30
16	0.01	0.01	79%	30	30
17	0.01	0.01	79%	30	30
18	0.01	0.01	79%	30	30
19	0.08	0.00	0%	30	30

Table 6. Fixed terms in each period when applying the Forward-Looking Tariff Structure

Initial fixed term (€/customer)	Fixed term after the first regulatory period (€/customer)	Fixed term after the second regulatory period (€/customer)
0.219	0.219	0.219

Then, the second regulatory period occurs. With that tariff, the consumption of the user is the one found in Figure 14, and the difference between this second regulatory period and the first one is shown in Figure 15. Consumption increases in hours where is cheaper to consume (hours 9 and 19), and decreases in adjacent hours, because the heat pump is not needed as the temperature is between the limits (hours 10 and 20), as consumption has increased in hours 9 and 19.

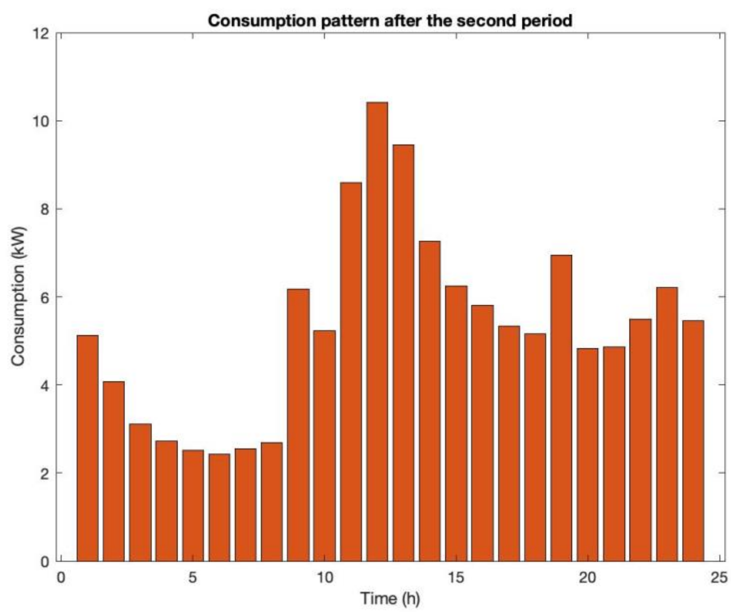

Figure 14. Consumption pattern after the second period under the Forward-Looking Tariff Structure

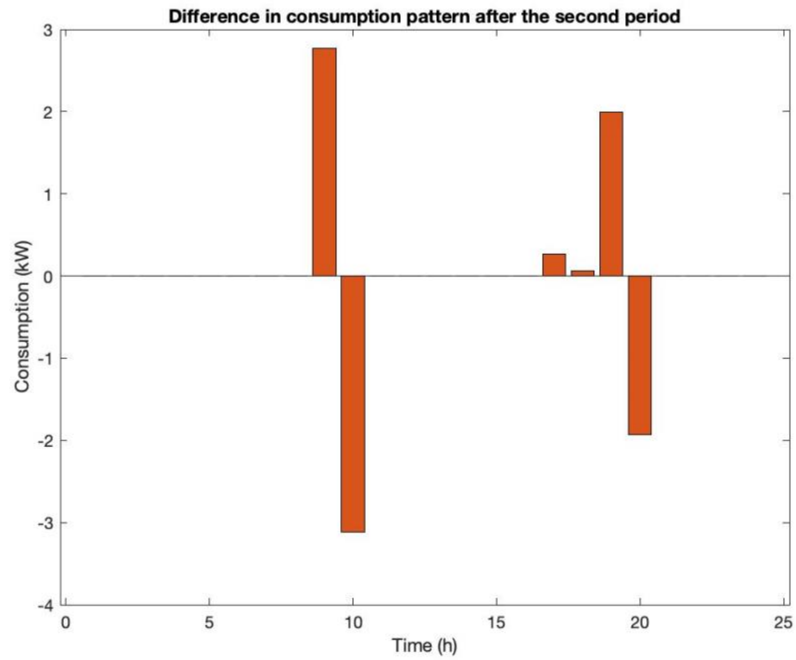

Figure 15. Difference between the consumption pattern in the first and the second period

Finally, with that consumption, the network tariff after the second regulatory period is computed, as it is shown in Figure 16, and the difference between period 2 and period 1 is shown in Figure 17. The tariff is increased in hours 11, 12, 13 and 19, which are the highest peaks, so as to disincentivize the consumption in those hours, and decreased in hour 10, to incentivize the use of the heat pump in that hour, because the next set of hours would be the highest-priced ones. The fixed term (€/consumer) does not change.

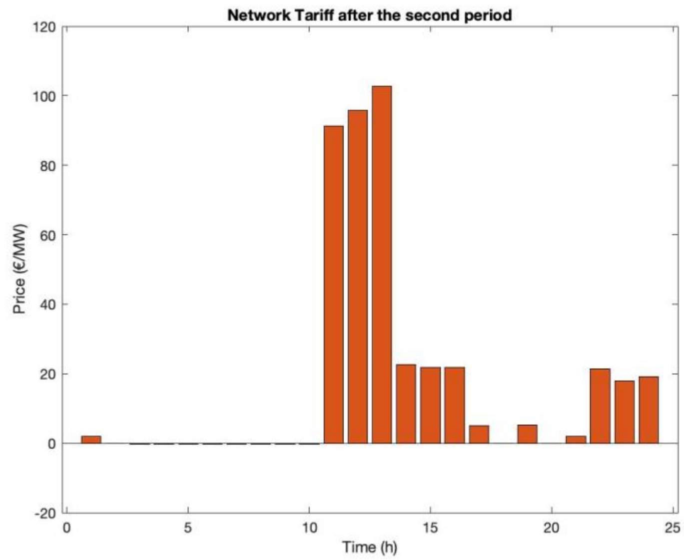

Figure 16. Network tariff after the second period under the Forward-Looking Tariff Structure

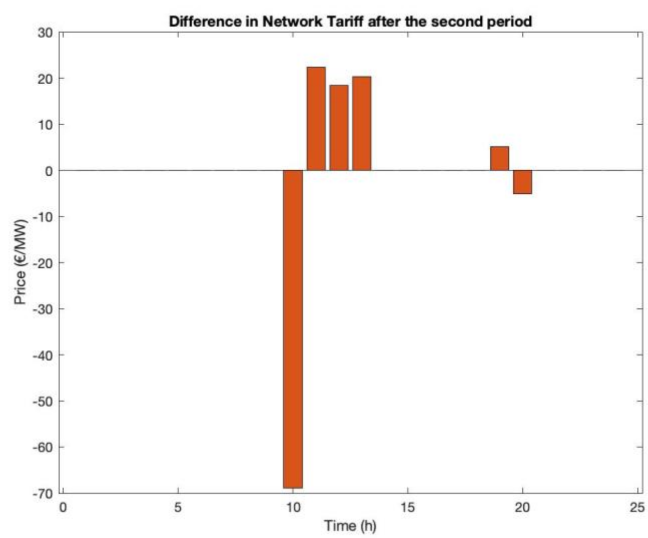

Figure 17. Difference between the Network Tariff after the second regulatory period under the Forward-Looking Tariff Structure

The results for the Forward-Looking Tariff in the different periods are summarized in Figures 18 and 19. While Figure 18 represents the changes in the consumption pattern of the user that has the heat pump installed, Figure 19 represent the difference in the price of the tariff.

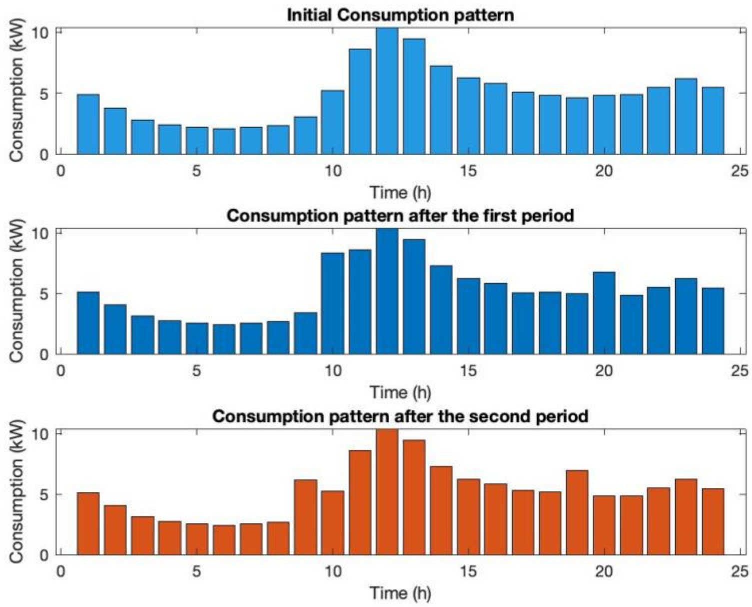

Figure 18. Variation of the consumption pattern of the user that has a heat pump installed in the Forward-Looking Tariff scenario.

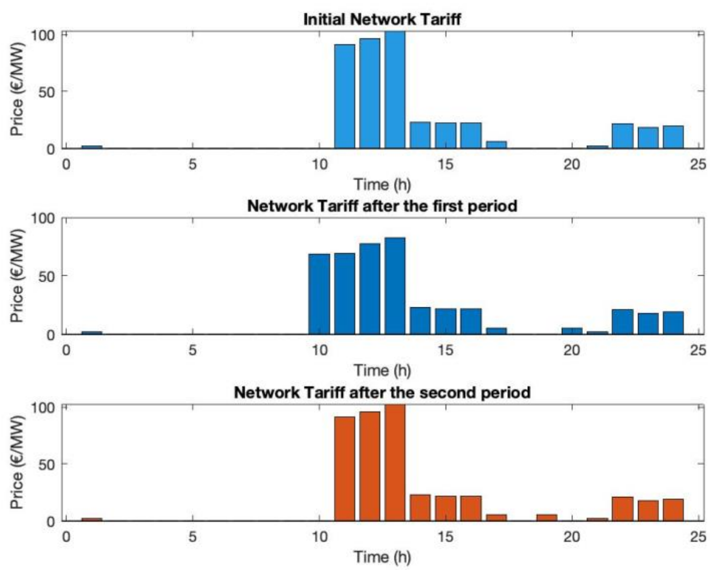

Figure 19. Variation Network Tariff of the user that has a heat pump installed in the Forward-Looking Tariff scenario.

3.2 Volumetric Tariff

The initial consumption pattern of the consumer that will be having the heat pump installed is the one found in Figure 5 (One has to remind that this consumption pattern was set as a predefined one of a common user). Of course, it coincides exactly with the power flow through branch 18, which is shown in Figure 6.

Considering that consumption pattern, the initial network tariff is shown in Figure 20, with the same charges independently of the consumption pattern of the user.

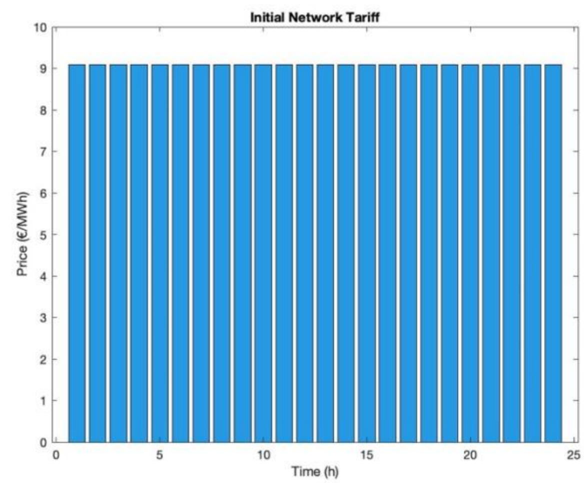

Figure 20. Initial Volumetric Network Tariff

The capacity of the branches, the investment and maintenance costs and the maximum power flow through the different branches are shown in Table 4.

The user decides to install a heat pump, and the new consumption pattern is shown in Figure 21.

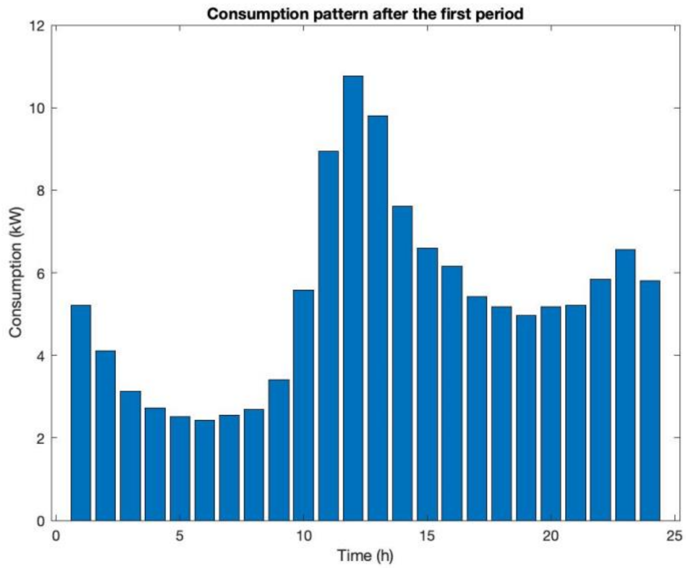

Figure 21. Consumption pattern after the first period under the Volumetric Tariff

The difference, depicted in this Figure 22, coincides with the consumption of the heat pump, which is flat. As the price is flat, the consumption of the heat pump is constant, and it is used to maintain the temperature of the house in the minimum level allowed (21ºC). This can be seen in Figure 23.

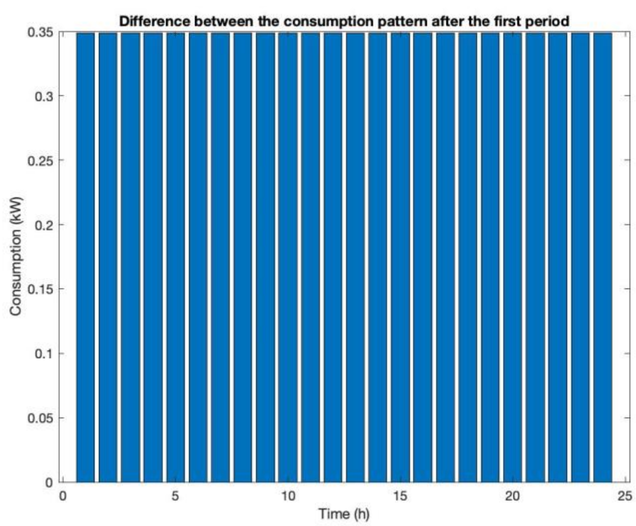

Figure 22. Difference between the consumption pattern after the first period under the Volumetric Tariff.

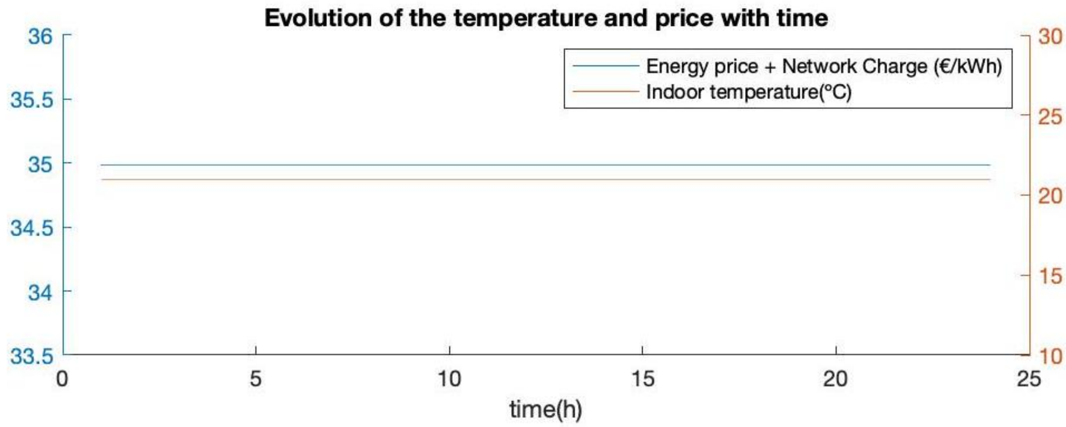

Figure 23. Behavior of the consumption in time with respect to price when the Volumetric Tariff is applied if wholesale market prices are flat

With that new consumption pattern, the power flow is again computed. If the new maximum flow through a branch makes the component of the network be at more than 80% of its capacity, the costs for that line are increased because new reinforcements would be needed. So, once the first regulatory period has ended and considering that consumption, and after checking if reinforcements in the network are needed, the network tariff is again computed, as shown in Figure 24.

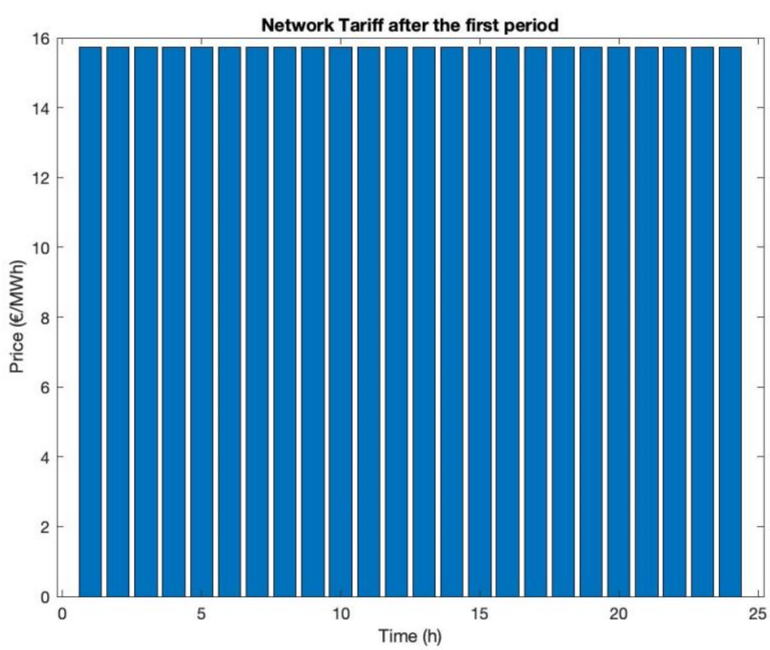

Figure 24. Network tariff after the first regulatory period under the volumetric tariff structure.

The tariff has increased by 6.63€/MWh for this user in every single hour, which would not make sense as first, as the consumption has increased. In theory, if the costs would have remained stable, the price per MWh, must have been reduced. However, as the maximum power flow after the first regulatory period changed in several lines (as it is shown in Table 7), the costs in those lines increase.

Table 7. Change in the maximum power flow running through the different branches after the first regulatory period.

Nº of branch	Capacity of the line (MW)	Max power flow after first period (MW)	Percentage of total capacity (%)	Initial Maint. cost (€)	Maint. Cost after first period
1	20.36	16.08	79.0%	60	60
2	21.94	17.34	79.0%	30	30
3	9.52	7.52	79.0%	30	30
4	3.62	2.86	79.0%	5360	5360
5	6.33	5.00	79.0%	180	180
6	4.84	3.83	79.0%	180	180
7	4.80	3.79	79.0%	180	180
8	2.07	1.64	79.0%	180	180
9	0.05	0.04	79.7%	710	710
10	0.08	0.00	0.0%	90	90
11	0.05	0.04	79.7%	300	300
12	0.04	0.03	80.0%	120	120
13	0.03	0.02	80.2%	120	420
14	0.01	0.01	81.6%	450	1575
15	0.02	0.02	79.0%	30	30
16	0.01	0.01	79.0%	30	30
17	0.01	0.01	79.0%	30	30
18	0.01	0.01	81.6%	30	105
19	0.08	0.00	0.0%	30	30

It can then be concluded that the volumetric tariff does not produce efficient signals so that the consumption increases in off-peak hours. In this case, the consumption of the user increases during network peak hours, and reinforcements needed along the network are borne by consumer 9 (and also by the rest that use this line).

For the second regulatory period, this fact does not alter the behavior of the user, still continues with the same consumption, but bearing more costs.

Finally, it should be noted that the capacity of the line in which the system has invested is now 20% higher, meaning that the congestion of the branch is below the threshold set, as seen in Table 8. Therefore, the costs of the network do not increase in this period, so there is no change in the tariff.

Table 8. Change in the capacity of several lines under the Volumetric Tariff Structure.

Nº of branch	Initial Capacity of the line (MW)	Percentage of total capacity after the first regulatory period (%)	New capacity of the line (MW)	Percentage of total capacity after the second regulatory period (%)
1	20.359	79.00%	20.359	79.00%
2	21.943	79.00%	21.943	79.00%
3	9.521	79.00%	9.521	79.00%
4	3.615	79.00%	3.615	78.99%
5	6.326	79.00%	6.327	79.00%
6	4.844	79.00%	4.844	79.01%
7	4.803	79.00%	4.803	79.00%
8	2.073	79.00%	2.074	79.00%
9	0.050	79.70%	0.050	79.70%
10	0.080	0.00%	0.080	0.00%
11	0.050	79.70%	0.050	79.70%
12	0.036	80.00%	0.036	79.96%
13	0.029	80.20%	0.035	66.83%
14	0.013	81.60%	0.016	68.03%
15	0.021	79.00%	0.021	79.00%
16	0.013	79.00%	0.013	79.00%
17	0.013	79.00%	0.013	79.00%
18	0.013	81.60%	0.016	68.03%
19	0.080	0.00%	0.080	0.00%

All in all, the Volumetric tariff changes do not send any efficient signal at all: it does not matter when the user consumes electricity as the price does not change.

The results for the Volumetric Tariff in the different periods are summarized in Figures 25 and 26. While Figure 25 represents the changes in the consumption pattern of the user that has the heat pump installed, Figure 26 represent the difference in the price of the tariff.

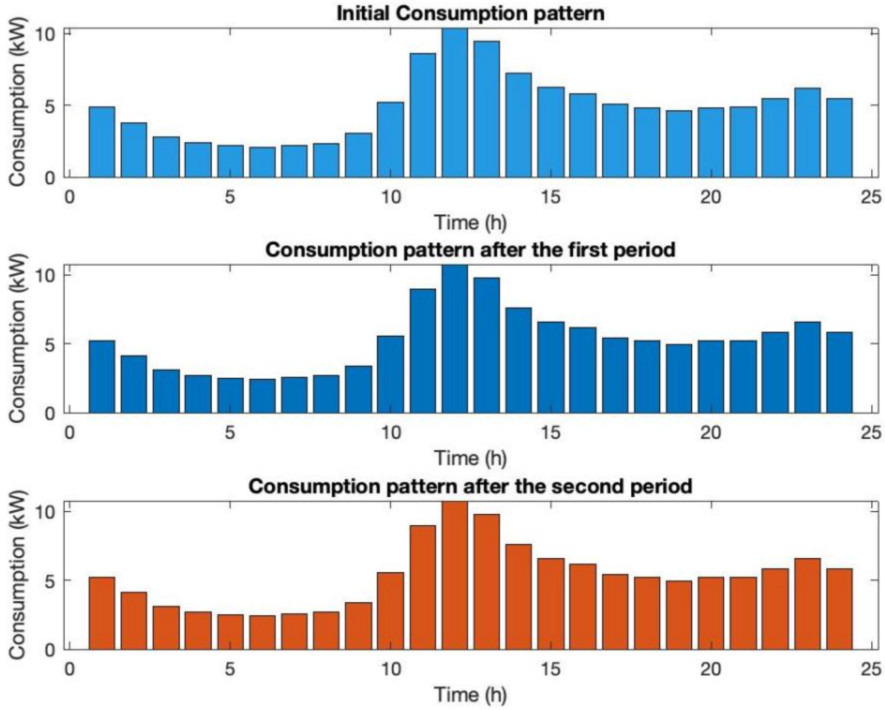

Figure 25. Variation of the consumption pattern of the user that has a heat pump installed in the Volumetric Tariff scenario.

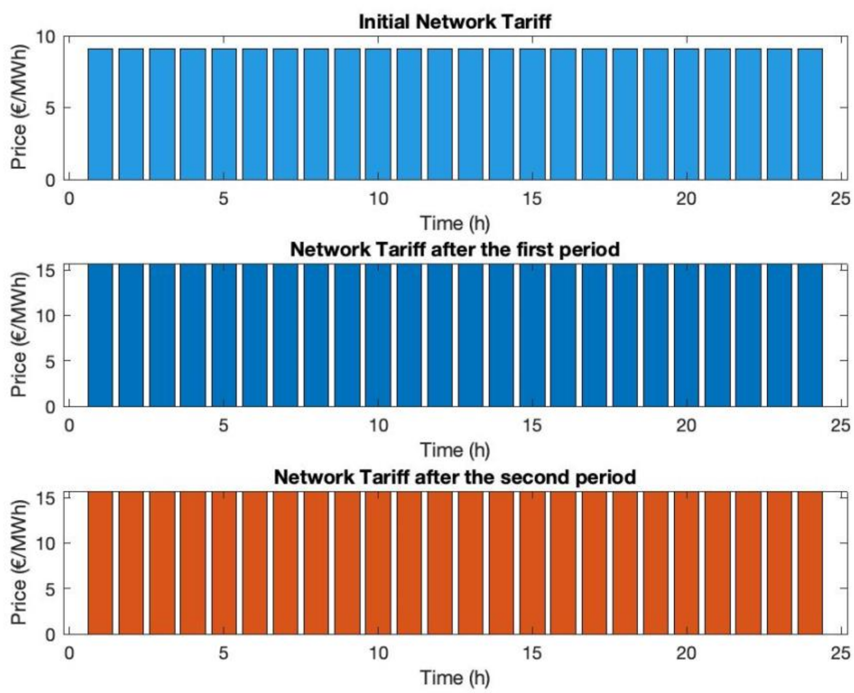

Figure 26. Variation Network Tariff of the user that has a heat pump installed in the Volumetric Tariff scenario.

3.3 CNMC's Tariff

The initial consumption pattern of the consumer with heat pump installed is the one found in Figure 5 (One has to remind that this consumption pattern was set as a predefined one of a common user). Of course, it coincides exactly with the power flow through branch 18, which is shown in Figure 6.

Considering that consumption pattern, the initial network tariff is shown in Figure 27, with higher charges in hours where the consumption is maximum and lower charges where the consumption is lower depending on time blocks, so as to incentive the consumption in those hours where the consumption is lower, noting that hours from 0 to 8 are even free, as they are the ones in which the consumption is lower, which corresponds to period "3".

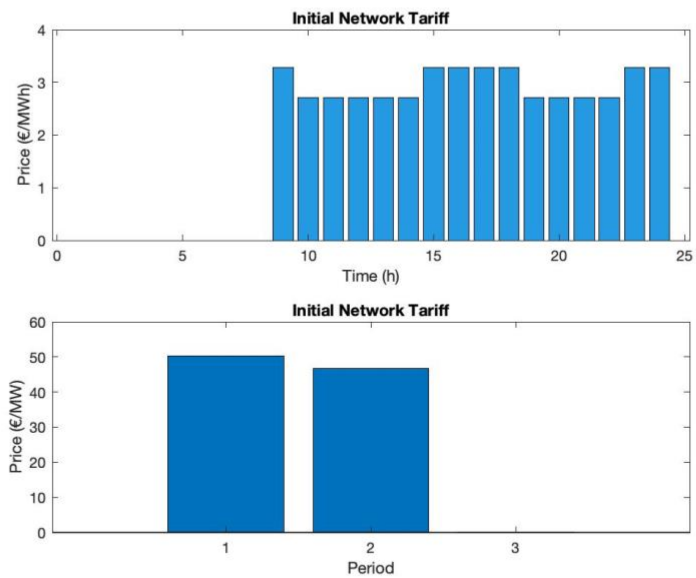

Figure 27. Initial CNMC Network Tariff.

The capacity of the branches, the investment and maintenance costs and the maximum power flow through the different branches are shown in Table 4.

The user decides to install a heat pump, and the consumption changes to the one found in Figure 28.

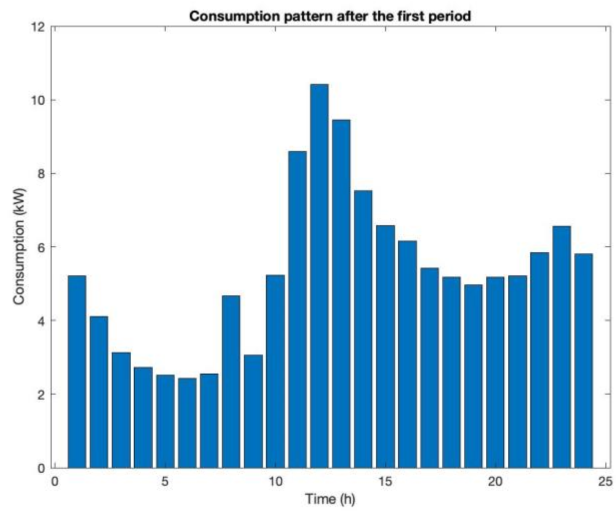

Figure 28. Consumption pattern of the user that installs the heat pump after the first regulatory period under the CNMC Tariff structure.

The difference, depicted in Figure 29, coincides with the consumption of the heat pump. The user is incentivized to use the heat pump in cheap hours, so that is the reason why the consumption increases hours from 0 to 8 (free period) and there is a lack of increase between hours 9 and 13. This is due to the efficient use of the heat pump, as it can be observed in Figures 30 and 31. The temperature inside the house is maintained in the minimum (21ºC) while the price is constant. However, it rises when the heat pump is actioned and that corresponds to the hour 6 when the total price is about to rise. It increases up to the maximum (25ºC) so as to be able to remain within the limits until the price lowers again.

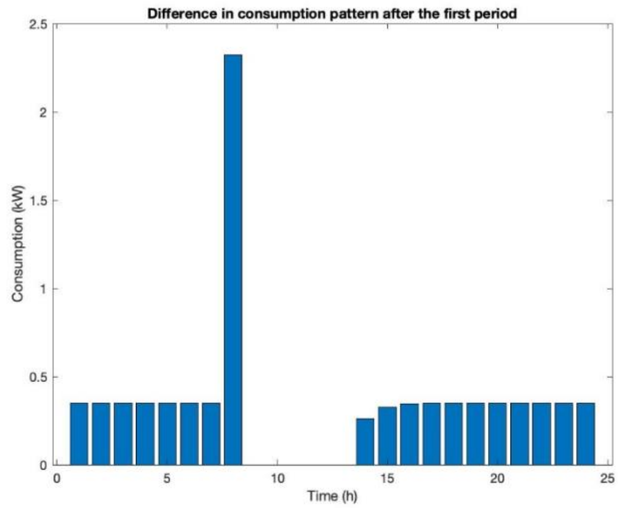

Figure 29. Difference between the consumption pattern after the first regulatory period.

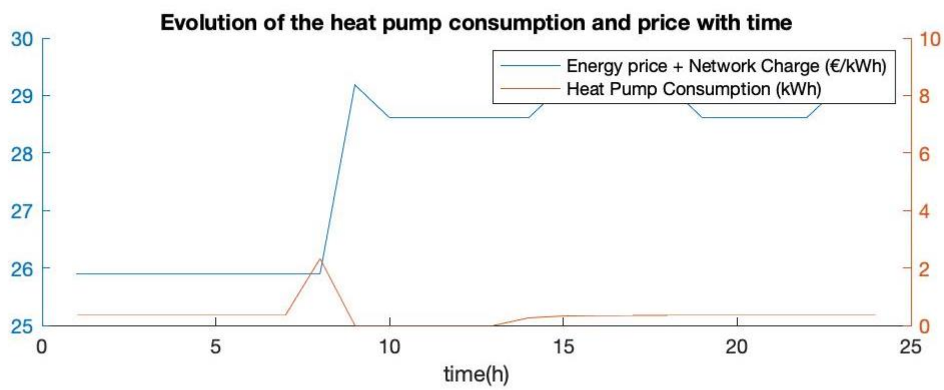

Figure 30. Behavior of the consumption in time with respect to price when the CNMC's tariff is applied

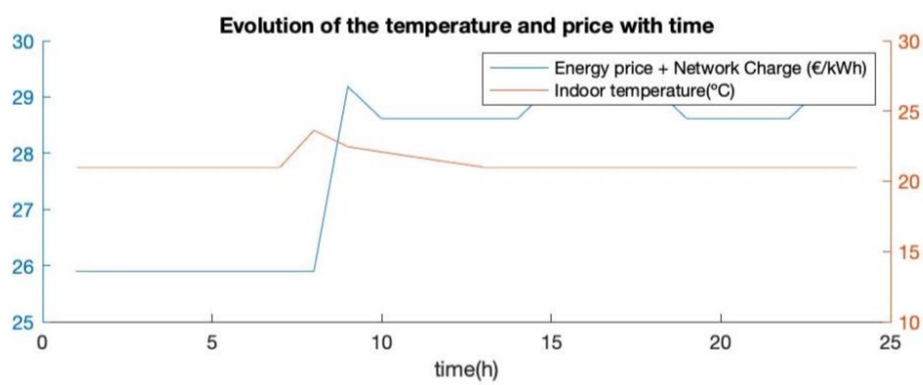

Figure 31. Behavior of the indoors temperature in time with respect to price when the CNMC's tariff is applied

Once the first regulatory period has ended and considering that consumption, the network tariff is again computed, as shown in Figure 32.

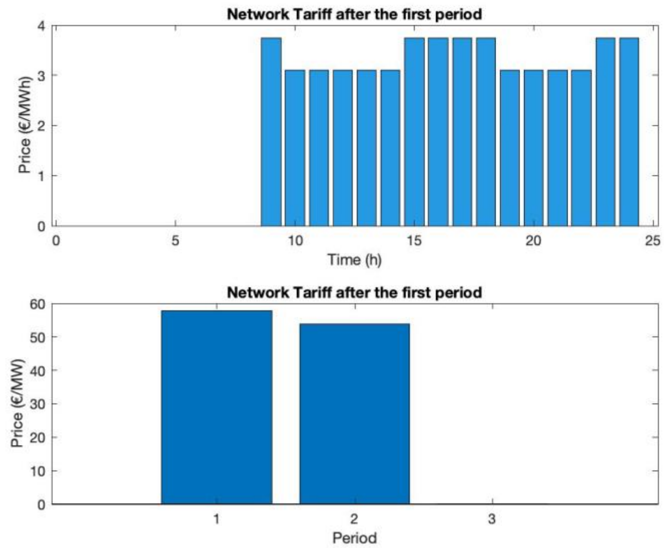

Figure 32. Network Tariff in the case of the CNMC tariff structure after the first regulatory period.

The network tariff increases for this user in periods 1 and 2 as the consumption has increased, as is depicted in Figure 33.

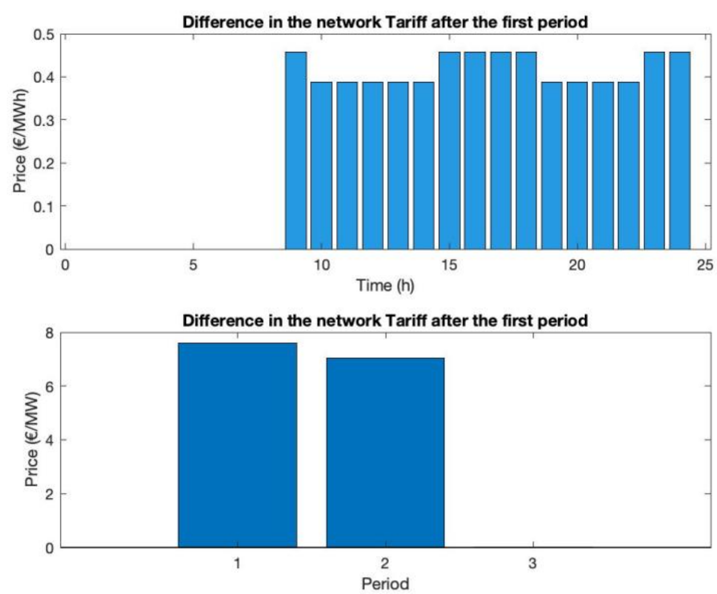

Figure 33. Difference in the network tariff after the first period under the CNMC Tariff Structure

In theory, if the costs would have remained stable, the price per MWh, must have been reduced. However, as the maximum power flow after the first regulatory period has changed in several lines (as it is shown in Table 9), the costs in those lines increased, and consumer 9 (the one that has the heat pump installed) bear part of those costs.

Table 9. Branch data after the first regulatory period under the CNMC Tariff structure

Nº of branch	Capacity of the line (MW)	Max power flow after first period (MW)	Percentage of total capacity (%)	Initial Maint. cost (€)	Maint. Cost after first period (€)
1	20.36	16.084	79.00%	60	60
2	21.94	17.335	79.00%	30	30
3	9.52	7.522	79.00%	30	30
4	3.62	2.855	78.98%	5360	5360
5	6.33	4.998	79.00%	180	180
6	4.84	3.827	79.01%	180	180
7	4.80	3.795	79.00%	180	180
8	2.07	1.638	79.00%	180	180
9	0.05	0.040	79.70%	710	710
10	0.08	0.000	0.00%	90	90
11	0.05	0.040	79.70%	300	300
12	0.04	0.029	79.96%	120	120
13	0.03	0.023	80.20%	120	420
14	0.01	0.010	79.00%	450	450
15	0.02	0.017	79.00%	30	30
16	0.01	0.010	79.00%	30	30
17	0.01	0.010	79.00%	30	30
18	0.01	0.010	79.00%	30	30
19	0.08	0.000	0.00%	30	30

Finally, the second regulatory period occurs. With that new network tariff, the user changes slightly its consumption pattern. The difference is depicted in Figure 34.

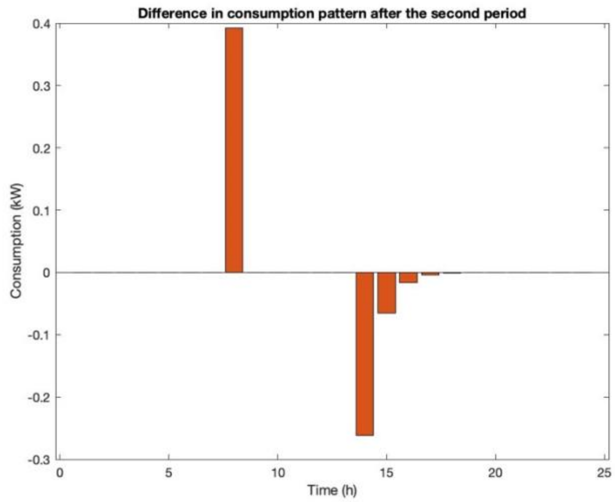

Figure 34. Difference in consumption after the second regulatory period under the CNMC's tariff structure

The consumption increases in hour 8, when network charges are free, and it is reduced from 14:00h to 18:00h, where the higher charges are encountered, taking also into consideration the that the indoors temperature has to be maintained between 21ºC and 25ºC.

Finally, the capacity of the line in which the system has invested is 20% higher, meaning that the capacity is below the threshold set, as seen in Table 10, so the tariff that is again computed, remains the same than in the previous period.

Table 10. Change of capacity and congestion after the second regulatory period under the CNMC's Tariff Structure

Nº of branch	Capacity of the line (MW)	Percentage of total capacity (%)	New capacity of the line (MW)	Percentage of total capacity after the second regulatory period (%)
1	20.359	79.00%	20.359	79.00%
2	21.943	79.00%	21.943	79.00%
3	9.521	79.00%	9.521	79.00%
4	3.615	78.98%	3.615	78.98%
5	6.327	79.00%	6.327	79.00%
6	4.844	79.01%	4.844	79.01%
7	4.803	79.00%	4.803	79.00%
8	2.074	79.00%	2.074	79.00%
9	0.050	79.70%	0.050	79.70%
10	0.080	0.00%	0.080	0.00%
11	0.050	79.70%	0.050	79.70%
12	0.036	79.96%	0.036	79.96%
13	0.029	80.20%	0.035	66.83%
14	0.013	79.00%	0.013	79.00%
15	0.021	79.00%	0.021	79.00%
16	0.013	79.00%	0.013	79.00%
17	0.013	79.00%	0.013	79.00%
18	0.013	79.00%	0.013	79.00%
19	0.080	0.00%	0.080	0.00%

All this behavior proves that the CNMC send more efficient signals than volumetric tariff, but some reinforcements cannot be avoided, in the sense that the consumer is incentivized to consume in cheaper hours, but he would have to bear the same costs of the reinforcements either way.

The results for the CNMC Tariff in the different periods are summarized in Figures 35 and 36. While Figure 35 represents the changes in the consumption pattern of the user that has the heat pump installed, Figure 36 represent the difference in the price of the tariff.

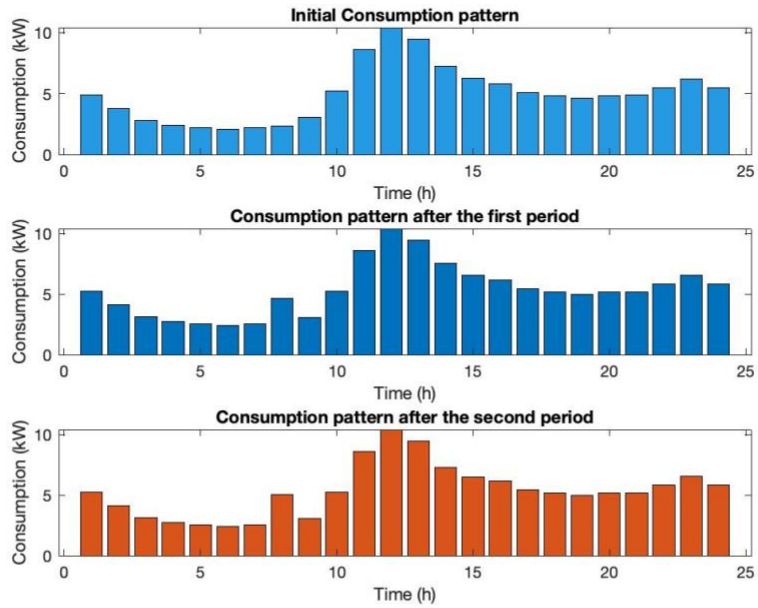

Figure 35. Variation of the consumption pattern of the user that has a heat pump installed in the CNMC Tariff scenario.

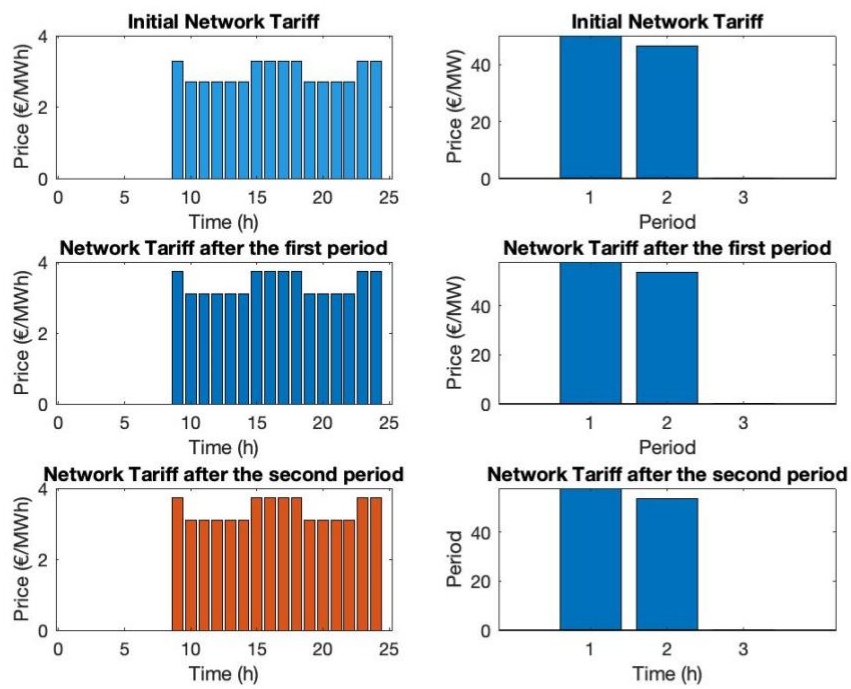

Figure 36. Variation Network Tariff of the user that has a heat pump installed in the CNMC Tariff scenario.

4. Conclusions

In this thesis, three distribution network tariffs have been analyzed under a scenario of 20% heat pump penetration, to evaluate how tariff changes in terms of efficient signals for the user to behave according to the needs of the system, preventing congestion of the network, and therefore, avoiding new costs.

These network tariffs are a volumetric tariff structure, with just volumetric charges, the current Spanish tariff structure, with volumetric and contracted capacity charges that consider three different time blocks, and a proposed tariff, with uses a fixed charge per customer and a volumetric charge.

For this purpose, mathematical models have been developed to emulate the optimal behavior that the end-user would follow using heat pumps. Results have shown different particularities in each tariff.

On the one hand, the proposed tariff acts in the most efficient way possible: the consumption is increased in a way that the user that installs the heat pump does not contribute to increasing the maximum power flow running through the network, and therefore the network costs do not increase. For the second regulatory period, the consumption is modified efficiently, as the user has been provided with the necessary signals to modify his pattern wisely. However, on the other hand, neither the Spanish tariff structure, nor the volumetric tariff structure work this way, on the contrary, under these tariff structures, the use of the heat pump is incentivized during hours when the consumer would contribute to the congestion of a line, therefore increasing the network costs, as a consequence, increasing the costs for the user that has installed this device, and for the others at the same voltage level.

In conclusion, the proposed tariff outperforms the other tariff structures in the presented case study. However, more research has to be done to prove this point under other circumstances.

4.1 Future works

Although profound research has been carried out, different possible future developments could be made, such as, but not limited to:

- Results show that neither the profile of the volumetric tariff structure, nor the one applied in Spain change if 20% of the LV consumers install a heat pump. Future works could study whether an increasing penetration would make these profiles change.
- This thesis has studied the impact on one customer, but another analysis that could be done is to see how the installation of heat pumps by some users has impacted the other consumers of the network. Also, the total system savings could be calculated.
- Moreover, as pointed out in [3], the time blocks scheduled in this thesis for the Spanish tariff are static. That is to say, the hours belonging to the time blocks (peak, flat and valley) do not vary. Therefore, in tariff recalculation, the first-time block may be cheaper than the second-time block. For future research, the hours belonging to each time block in the CNMC tariff could be made variable.
- The mathematical model for the thesis is simplified: it just considers one day, and the network is simplified. A more complex network could be used, and other time frames could be proposed.
- Just one case (with the capacity and the congestion of the lines) has been studied. It will be interesting to try the model under different circumstances.

Appendix A. Code for the mathematical formulation of the Forward-Looking Tariff’s model

```
%% Modelo de FORWARD-LOOKING TARIFF Heat Pump
%%
function [x]=f_HPump(C,ProposedTariff,n)

%% Par√°metros
C.Cons=C.Cons*1000; %Hay que multiplicar el consumo por 1000 porque no estaba en kWh
POWERHP=5;
%TOUT=[-2 -2 -2 -2 -2 -2 -2 -1 -1 0 1 1 1 2 2 2 2 2 2 1 1 0 -1 -1];
TOUT=[2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2];
COP=2.5;
HPLOSS=0.15;
R1=0.5;
R2=20;
Cv=2.73;
A=1/(Cv*R2);
B=COP*(1-HPLOSS)/0.8;
D=(R1+R2)/(Cv*R2) - R1;

%% M√°ximos y m√≠nimos de las variables
consumomaximo=max(max(C.Cons));
TherHPmin=0;
TherHPmax=POWERHP;
TempHPmin=0;
TempHPmax=POWERHP;
Compramin=0;
Compramax=POWERHP+consumomaximo; %El consumo m√°ximo del cliente y la capacidad de la heatpump
tIndmin=21;
tIndmax=25;

%% Precio Energ√≠a
Energy_Price=[27.55;25.90;24.90;24.48;24.48;25.01;31.24;34.54;37.64;37.01;34.02;33.13;32.10;30.45;28.14;27.61;28.21;30.82;35.71;42.17;41.75;41.31;35.51;33.68];

%% Precio Potencia
Network_Power_Price=ProposedTariff.ConsCapacity(n,:)/365;

%% Precio total
Total_Price=Energy_Price+Network_Power_Price';

%% IGUALDADES: Recordatorio variables de decision x= therHP, tempHP, Compra, tInd
Aeq = [-1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0  -1 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0  1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
       0 -1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0  0 -1 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0  0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
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    0 0 -1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0  0 0 -1 0 0 0 0 0 0 0
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    0 0 0 0 -1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0  0 0 0 0 -1 0 0 0 0 0
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-R1*B 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
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D*B -R1*B 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
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D*B -R1*B 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
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0 0  0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 (A-1) 1];

Beq=[C.Cons(n,1);C.Cons(n,2);C.Cons(n,3);C.Cons(n,4);C.Cons(n,5);C.Cons(n,6);
C.Cons(n,7);C.Cons(n,8);C.Cons(n,9);C.Cons(n,10);C.Cons(n,11);C.Cons(n,12);C.
Cons(n,13);C.Cons(n,14);C.Cons(n,15);C.Cons(n,16);C.Cons(n,17);C.Cons(n,18);C
.Cons(n,19);C.Cons(n,20);C.Cons(n,21);C.Cons(n,22);C.Cons(n,23);C.Cons(n,24);

A*TOUT(1);A*TOUT(2);A*TOUT(3);A*TOUT(4);A*TOUT(5);A*TOUT(6);A*TOUT(7);A*TOUT(
8);A*TOUT(9);A*TOUT(10);A*TOUT(11);A*TOUT(12);A*TOUT(13);A*TOUT(14);A*TOUT(15
);A*TOUT(16);A*TOUT(17);A*TOUT(18);A*TOUT(19);A*TOUT(20);A*TOUT(21);A*TOUT(22
);A*TOUT(23);A*TOUT(24)];

%% DESIGUALDADES: Recordatorio variables de decision x= therHP, tempHP,
Compra, tInd
A1=A;
B1=B;
A= [1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0  1 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0  0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0  0 0
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0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0
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0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0

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    0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1  0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 1  0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0  0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0];

B=
[POWERHP;POWERHP;POWERHP;POWERHP;POWERHP;POWERHP;POWERHP;POWERHP;POWERHP;POWE
RHP;POWERHP;POWERHP;POWERHP;POWERHP;POWERHP;POWERHP;POWERHP;POWERHP;POWERHP;P
OWERHP;POWERHP;POWERHP;POWERHP;POWERHP];

lb=[TherHPmin;TherHPmin;TherHPmin;TherHPmin;TherHPmin;TherHPmin;TherHPmin;The
rHPmin;TherHPmin;TherHPmin;TherHPmin;TherHPmin;TherHPmin;TherHPmin;TherHPmin;
TherHPmin;TherHPmin;TherHPmin;TherHPmin;TherHPmin;TherHPmin;TherHPmin;TherHPm
in;TherHPmin;

TempHPmin;TempHPmin;TempHPmin;TempHPmin;TempHPmin;TempHPmin;TempHPmin;TempHPm
in;TempHPmin;TempHPmin;TempHPmin;TempHPmin;TempHPmin;TempHPmin;TempHPmin;Temp
HPmin;TempHPmin;TempHPmin;TempHPmin;TempHPmin;TempHPmin;TempHPmin;TempHPmin;T
empHPmin;

Compramin;Compramin;Compramin;Compramin;Compramin;Compramin;Compramin;Compram
in;Compramin;Compramin;Compramin;Compramin;Compramin;Compramin;Compramin;Comp
ramin;Compramin;Compramin;Compramin;Compramin;Compramin;Compramin;Compramin;C
ompramin;

tIndmin;tIndmin;tIndmin;tIndmin;tIndmin;tIndmin;tIndmin;tIndmin;tIndmin;tIndm
in;tIndmin;tIndmin;tIndmin;tIndmin;tIndmin;tIndmin;tIndmin;tIndmin;tIndmin;tI
ndmin;tIndmin;tIndmin;tIndmin;tIndmin];

ub=[TherHPmax;TherHPmax;TherHPmax;TherHPmax;TherHPmax;TherHPmax;TherHPmax;The
rHPmax;TherHPmax;TherHPmax;TherHPmax;TherHPmax;TherHPmax;TherHPmax;TherHPmax;
TherHPmax;TherHPmax;TherHPmax;TherHPmax;TherHPmax;TherHPmax;TherHPmax;TherHPm
ax;TherHPmax;

TempHPmax;TempHPmax;TempHPmax;TempHPmax;TempHPmax;TempHPmax;TempHPmax;TempHPm
ax;TempHPmax;TempHPmax;TempHPmax;TempHPmax;TempHPmax;TempHPmax;TempHPmax;Temp
HPmax;TempHPmax;TempHPmax;TempHPmax;TempHPmax;TempHPmax;TempHPmax;TempHPmax;T
empHPmax;

Compramax;Compramax;Compramax;Compramax;Compramax;Compramax;Compramax;Compram
ax;Compramax;Compramax;Compramax;Compramax;Compramax;Compramax;Compramax;Comp
ramax;Compramax;Compramax;Compramax;Compramax;Compramax;Compramax;Compramax;C
ompramax;

tIndmax;tIndmax;tIndmax;tIndmax;tIndmax;tIndmax;tIndmax;tIndmax;tIndmax;tIndm
ax;tIndmax;tIndmax;tIndmax;tIndmax;tIndmax;tIndmax;tIndmax;tIndmax;tIndmax;tI
ndmax;tIndmax;tIndmax;tIndmax;tIndmax];

%% Funci√≥n Objetivo
f=[0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;
   0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;

Total_Price(1);Total_Price(2);Total_Price(3);Total_Price(4);Total_Price(5);To
tal_Price(6);Total_Price(7);Total_Price(8);Total_Price(9);Total_Price(10);Tot
al_Price(11);Total_Price(12);Total_Price(13);Total_Price(14);Total_Price(15);
Total_Price(16);Total_Price(17);Total_Price(18);Total_Price(19);Total_Price(2
0);Total_Price(21);Total_Price(22);Total_Price(23);Total_Price(24);
```

```
   0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0];

%% Programa
[x,fval] = linprog(f,A,B,Aeq,Beq,lb,ub);

Variable_TherHP=x(1:24)
Variable_TempHP=x(25:48)
Variable_Compra=x(49:72)
Variable_tInd=x(73:96)

figure;
subplot(2,1,1);
title('Evolution of the temperature and price with time');
hold on;
x=[0:1:23]
y1=Total_Price;
yyaxis left;
plot(x,y1);
hold on;

yyaxis right;
ylim([10,30]);
plot(x,Variable_tInd);
hold on;
legend('Total price (,Ç¨)','Indoor temperature(¬∫C)');
xlabel('time(h)');

subplot(2,1,2);
title('Evolution of the heat pump consumption and price with time');
yyaxis left;
plot(x,y1);
hold on;
yyaxis right;
ylim([0,10]);
plot(x,Variable_TempHP);
legend('Total price (,Ç¨)','Heat Pump Consumption (kWh)');
xlabel('time(h)');
```

Appendix B. Code for the mathematical formulation of the Volumetric Tariff's model

```
%% Modelo VOLUMETRIC TARIFF Heat Pump
%%
function [x]=f_HPump(C,VolumetricTariff,n)

%% Par√°metros
C.Cons=C.Cons*1000; %Hay que multiplicar el consumo por 1000 porque no estaba
en kWh
POWERHP=5;
TOUT=[2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2];
COP=2.5;
HPLOSS=0.15;
R1=0.5;
R2=20;
Cv=2.73;
A=1/(Cv*R2);
B=COP*(1-HPLOSS)/0.8;
D=(R1+R2)/(Cv*R2) - R1;

%% M√°ximos y m√≠nimos de las variables
consumomaximo=max(max(C.Cons));
TherHPmin=0;
TherHPmax=POWERHP;
TempHPmin=0;
TempHPmax=POWERHP;
Compramin=0;
Compramax=POWERHP+consumomaximo; %El consumo m√°ximo del cliente y la
capacidad de la heatpump
tIndmin=21;
tIndmax=25;

%% Precio Energ√≠a
Energy_Price=[27.55;25.90;24.90;24.48;24.48;25.01;31.24;34.54;37.64;37.01;34.
02;33.13;32.10;30.45;28.14;27.61;28.21;30.82;35.71;42.17;41.75;41.31;35.51;33
.68];

%% Precio de la Red
Network_Power_Price=VolumetricTariff.ConsEnergy(n,:)/365; %Este es el √öNICO
cambio con respecto a la eficiente

%% Precio total
Total_Price=Energy_Price+Network_Power_Price';

%% IGUALDADES: Recordatorio variables de decision x= therHP, tempHP, Compra,
tInd
Aeq = [-1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0  -1 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0  1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
       0 -1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0  0 -1 0 0 0 0 0 0 0 0
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       0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 -1 0  0 0 0 0 0 0 0 0 0 0
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       0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 -1  0 0 0 0 0 0 0 0 0 0
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0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0

       0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0  -R1*B 0 0 0 0 0 0 0 0
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       0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0  0 -D*B -R1*B 0 0 0 0
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       0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0  0 0 -D*B -R1*B 0 0 0
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       0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0  0 0 0 -D*B -R1*B 0 0
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       0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0  0 0 0 0 -D*B -R1*B 0
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       0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0  0 0 0 0 0 -D*B -R1*B
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       0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0  0 0 0 0 0 0 -D*B -
R1*B 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0  0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
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0 0 0 0 -D*B -R1*B 0 0 0 0 0 0 0  0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
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       0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0  0 0 0 0 0 0 0 0 0 0 0
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0 0  0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 (A-1) 1 0 0 0 0
       0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0  0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 -D*B -R1*B 0 0 0  0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0  0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 (A-1) 1 0 0 0
       0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0  0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 -D*B -R1*B 0 0  0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0  0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 (A-1) 1 0 0
       0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0  0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 -D*B -R1*B 0  0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0  0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 (A-1) 1 0
       0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0  0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 -D*B -R1*B  0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0  0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 (A-1) 1];

Beq=[C.Cons(n,1);C.Cons(n,2);C.Cons(n,3);C.Cons(n,4);C.Cons(n,5);C.Cons(n,6);
C.Cons(n,7);C.Cons(n,8);C.Cons(n,9);C.Cons(n,10);C.Cons(n,11);C.Cons(n,12);C.
Cons(n,13);C.Cons(n,14);C.Cons(n,15);C.Cons(n,16);C.Cons(n,17);C.Cons(n,18);C
.Cons(n,19);C.Cons(n,20);C.Cons(n,21);C.Cons(n,22);C.Cons(n,23);C.Cons(n,24);

A*TOUT(1);A*TOUT(2);A*TOUT(3);A*TOUT(4);A*TOUT(5);A*TOUT(6);A*TOUT(7);A*TOUT(
8);A*TOUT(9);A*TOUT(10);A*TOUT(11);A*TOUT(12);A*TOUT(13);A*TOUT(14);A*TOUT(15
);A*TOUT(16);A*TOUT(17);A*TOUT(18);A*TOUT(19);A*TOUT(20);A*TOUT(21);A*TOUT(22
);A*TOUT(23);A*TOUT(24)];

%% DESIGUALDADES: Recordatorio variables de decision x= therHP, tempHP,
Compra, tInd
A1=A;
B1=B;
A= [1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0  1 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0  0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0  0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
     0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0  0 1 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0  0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0  0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
     0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0  0 0 1 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0  0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0  0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
     0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0  0 0 0 1 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0  0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0  0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
```

0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0
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0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0
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0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
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0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
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0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
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0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
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0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
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0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0

```
    0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1  0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 1  0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0  0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0];

B=
[POWERHP;POWERHP;POWERHP;POWERHP;POWERHP;POWERHP;POWERHP;POWERHP;POWERHP;POWE
RHP;POWERHP;POWERHP;POWERHP;POWERHP;POWERHP;POWERHP;POWERHP;POWERHP;POWERHP;P
OWERHP;POWERHP;POWERHP;POWERHP;POWERHP];

lb=[TherHPmin;TherHPmin;TherHPmin;TherHPmin;TherHPmin;TherHPmin;TherHPmin;The
rHPmin;TherHPmin;TherHPmin;TherHPmin;TherHPmin;TherHPmin;TherHPmin;TherHPmin;
TherHPmin;TherHPmin;TherHPmin;TherHPmin;TherHPmin;TherHPmin;TherHPmin;TherHPm
in;TherHPmin;

TempHPmin;TempHPmin;TempHPmin;TempHPmin;TempHPmin;TempHPmin;TempHPmin;TempHPm
in;TempHPmin;TempHPmin;TempHPmin;TempHPmin;TempHPmin;TempHPmin;TempHPmin;Temp
HPmin;TempHPmin;TempHPmin;TempHPmin;TempHPmin;TempHPmin;TempHPmin;TempHPmin;T
empHPmin;

Compramin;Compramin;Compramin;Compramin;Compramin;Compramin;Compramin;Compram
in;Compramin;Compramin;Compramin;Compramin;Compramin;Compramin;Compramin;Comp
ramin;Compramin;Compramin;Compramin;Compramin;Compramin;Compramin;Compramin;C
ompramin;

tIndmin;tIndmin;tIndmin;tIndmin;tIndmin;tIndmin;tIndmin;tIndmin;tIndmin;tIndm
in;tIndmin;tIndmin;tIndmin;tIndmin;tIndmin;tIndmin;tIndmin;tIndmin;tIndmin;tI
ndmin;tIndmin;tIndmin;tIndmin;tIndmin];

ub=[TherHPmax;TherHPmax;TherHPmax;TherHPmax;TherHPmax;TherHPmax;TherHPmax;The
rHPmax;TherHPmax;TherHPmax;TherHPmax;TherHPmax;TherHPmax;TherHPmax;TherHPmax;
TherHPmax;TherHPmax;TherHPmax;TherHPmax;TherHPmax;TherHPmax;TherHPmax;TherHPm
ax;TherHPmax;

TempHPmax;TempHPmax;TempHPmax;TempHPmax;TempHPmax;TempHPmax;TempHPmax;TempHPm
ax;TempHPmax;TempHPmax;TempHPmax;TempHPmax;TempHPmax;TempHPmax;TempHPmax;Temp
HPmax;TempHPmax;TempHPmax;TempHPmax;TempHPmax;TempHPmax;TempHPmax;TempHPmax;T
empHPmax;

Compramax;Compramax;Compramax;Compramax;Compramax;Compramax;Compramax;Compram
ax;Compramax;Compramax;Compramax;Compramax;Compramax;Compramax;Compramax;Comp
ramax;Compramax;Compramax;Compramax;Compramax;Compramax;Compramax;Compramax;C
ompramax;

tIndmax;tIndmax;tIndmax;tIndmax;tIndmax;tIndmax;tIndmax;tIndmax;tIndmax;tIndm
ax;tIndmax;tIndmax;tIndmax;tIndmax;tIndmax;tIndmax;tIndmax;tIndmax;tIndmax;tI
ndmax;tIndmax;tIndmax;tIndmax;tIndmax];

%% Funci√≥n Objetivo
f=[0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;
   0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;

Total_Price(1);Total_Price(2);Total_Price(3);Total_Price(4);Total_Price(5);To
tal_Price(6);Total_Price(7);Total_Price(8);Total_Price(9);Total_Price(10);Tot
al_Price(11);Total_Price(12);Total_Price(13);Total_Price(14);Total_Price(15);
Total_Price(16);Total_Price(17);Total_Price(18);Total_Price(19);Total_Price(2
0);Total_Price(21);Total_Price(22);Total_Price(23);Total_Price(24);
```

```
   0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0];

%% Programa
[x,fval] = linprog(f,A,B,Aeq,Beq,lb,ub);

Variable_TherHP=x(1:24)
Variable_TempHP=x(25:48)
Variable_Compra=x(49:72)
Variable_tInd=x(73:96)

figure;
subplot(2,1,1);
title('Evolution of the temperature and price with time');
hold on;
x=[0:1:23]
y1=Total_Price;
yyaxis left;
plot(x,y1);
hold on;

yyaxis right;
ylim([10,30]);
plot(x,Variable_tInd);
hold on;
legend('Total price (‚Ç¨)','Indoor temperature(¬∫C)');
xlabel('time(h)');

subplot(2,1,2);
title('Evolution of the heat pump consumption and price with time');
yyaxis left;
plot(x,y1);
hold on;
yyaxis right;
ylim([0,10]);
plot(x,Variable_TempHP);
legend('Total price (‚Ç¨)','Heat Pump Consumption (kWh)');
xlabel('time(h)');
```

Appendix C. Code for the mathematical formulation of the CNMC's Tariff's Model

```
%% Modelo CNMC Tariff Heat Pump
function [x]=f_HPump_CNMC(C,TariffCNMC,n)

%% Par√°metros
C.Cons=C.Cons*1000; %Multiplicar el consumo por 1000 porque est√° en MWh
POWERHP=5;
TOUT=[2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2];
COP=2.5;
HPLOSS=0.15;
R1=0.5;
R2=20;
Cv=2.73;
A=1/(Cv*R2);
B=COP*(1-HPLOSS)/0.8;
D=(R1+R2)/(Cv*R2) - R1;
a1=1;
a2=1;
a3=1;

%% M√°ximos y m√≠nimos de las variables
consumomaximo=max(C.Cons(9,:));
TherHPmin=0;
TherHPmax=POWERHP;
TempHPmin=0;
TempHPmax=POWERHP;
Compramin=0;
Compramax=POWERHP+consumomaximo; %El consumo m√°ximo del cliente y la
capacidad de la heatpump
tIndmin=21;
tIndmax=25;
CapacityBoughtmax=POWERHP+consumomaximo;
CapacityBoughtmin=0.001;

%% Precio Energ√≠a
Energy_Price=[27.55;25.90;24.90;24.48;24.48;25.01;31.24;34.54;37.64;37.01;34.
02;33.13;32.10;30.45;28.14;27.61;28.21;30.82;35.71;42.17;41.75;41.31;35.51;33
.68];
Energy_Price=Energy_Price'+TariffCNMC.ConsEnergy(n,:)/365;

%% Precio Potencia
Network_Power_Price=TariffCNMC.ConsCapacity(n,:)/365;

%% IGUALDADES: Recordatorio variables de decision x= therHP, tempHP, Compra,
tInd, CapacityBought
Aeq = [-1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0  -1 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0  1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0  0 0 0
       0 -1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0  0 -1 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0  0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0  0 0 0
```

```
    0 0 -1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0   0 0 -1 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0   0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0   0 0 0
    0 0 0 -1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0   0 0 0 -1 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0   0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0   0 0 0
    0 0 0 0 -1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0   0 0 0 0 -1 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0   0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0   0 0 0
    0 0 0 0 0 -1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0   0 0 0 0 0 -1 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0   0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0   0 0 0
    0 0 0 0 0 0 -1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0   0 0 0 0 0 0 -1 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0   0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0   0 0 0
    0 0 0 0 0 0 0 -1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0   0 0 0 0 0 0 0 -1 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0   0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0   0 0 0
    0 0 0 0 0 0 0 0 -1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0   0 0 0 0 0 0 0 0 -1 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0   0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0   0 0 0
    0 0 0 0 0 0 0 0 0 -1 0 0 0 0 0 0 0 0 0 0 0 0 0 0   0 0 0 0 0 0 0 0 0 -1
0 0 0 0 0 0 0 0 0 0 0 0 0 0   0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0   0 0 0
    0 0 0 0 0 0 0 0 0 0 -1 0 0 0 0 0 0 0 0 0 0 0 0 0   0 0 0 0 0 0 0 0 0 0
-1 0 0 0 0 0 0 0 0 0 0 0 0 0   0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0   0 0 0
    0 0 0 0 0 0 0 0 0 0 0 -1 0 0 0 0 0 0 0 0 0 0 0 0   0 0 0 0 0 0 0 0 0 0
0 -1 0 0 0 0 0 0 0 0 0 0 0 0   0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0   0 0 0
    0 0 0 0 0 0 0 0 0 0 0 0 -1 0 0 0 0 0 0 0 0 0 0 0   0 0 0 0 0 0 0 0 0 0
0 0 -1 0 0 0 0 0 0 0 0 0 0 0   0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0   0 0 0
    0 0 0 0 0 0 0 0 0 0 0 0 0 -1 0 0 0 0 0 0 0 0 0 0   0 0 0 0 0 0 0 0 0 0
0 0 0 -1 0 0 0 0 0 0 0 0 0 0   0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0
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    0 0 0 0 0 0 0 0 0 0 0 0 0 0 -1 0 0 0 0 0 0 0 0 0   0 0 0 0 0 0 0 0 0 0
0 0 0 0 -1 0 0 0 0 0 0 0 0 0   0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0   0 0 0
    0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 -1 0 0 0 0 0 0 0 0   0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 -1 0 0 0 0 0 0 0 0   0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0   0 0 0
    0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 -1 0 0 0 0 0 0 0   0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 -1 0 0 0 0 0 0 0   0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0   0 0 0
    0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 -1 0 0 0 0 0 0   0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 -1 0 0 0 0 0 0   0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0   0 0 0
    0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 -1 0 0 0 0 0   0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 -1 0 0 0 0 0   0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0   0 0 0
    0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 -1 0 0 0 0   0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 -1 0 0 0 0   0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0   0 0 0
    0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 -1 0 0 0   0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 -1 0 0 0   0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0   0 0 0
```

0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 -1 0 0 0 0 0 0 0 0 0 0 0 0
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0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
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Beq=[C.Cons(n,1);C.Cons(n,2);C.Cons(n,3);C.Cons(n,4);C.Cons(n,5);C.Cons(n,6);
C.Cons(n,7);C.Cons(n,8);C.Cons(n,9);C.Cons(n,10);C.Cons(n,11);C.Cons(n,12);C.
Cons(n,13);C.Cons(n,14);C.Cons(n,15);C.Cons(n,16);C.Cons(n,17);C.Cons(n,18);C
.Cons(n,19);C.Cons(n,20);C.Cons(n,21);C.Cons(n,22);C.Cons(n,23);C.Cons(n,24);

A*TOUT(1);A*TOUT(2);A*TOUT(3);A*TOUT(4);A*TOUT(5);A*TOUT(6);A*TOUT(7);A*TOUT(
8);A*TOUT(9);A*TOUT(10);A*TOUT(11);A*TOUT(12);A*TOUT(13);A*TOUT(14);A*TOUT(15
);A*TOUT(16);A*TOUT(17);A*TOUT(18);A*TOUT(19);A*TOUT(20);A*TOUT(21);A*TOUT(22
);A*TOUT(23);A*TOUT(24)];

%% DESIGUALDADES: Recordatorio variables de decision x= therHP, tempHP,
Compra, tInd, CapacityBought
A1=A;
B1=B;
A= [1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0  1 0 0 0 0 0 0 0 0 0 0 0
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    0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0  0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0  0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 a2 0 0 0 0 0 0  0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0  0 -a2 0
    0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0  0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0  0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 a1 0 0 0 0 0  0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0  -a1 0 0
    0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0  0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0  0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 a1 0 0 0 0  0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0  -a1 0 0
    0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0  0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0  0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 a1 0 0 0  0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0  -a1 0 0
    0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0  0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0  0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 a1 0 0  0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0  -a1 0 0
    0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0  0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0  0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 a2 0  0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0  0 -a2 0
    0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0  0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0  0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 a2  0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0  0 -a2 0];

B=
[POWERHP;POWERHP;POWERHP;POWERHP;POWERHP;POWERHP;POWERHP;POWERHP;POWERHP;POWE
RHP;POWERHP;POWERHP;POWERHP;POWERHP;POWERHP;POWERHP;POWERHP;POWERHP;POWERHP;P
OWERHP;POWERHP;POWERHP;POWERHP;POWERHP;0;0;0; 0; 0; 0; 0; 0; 0; 0; 0; 0;
0; 0; 0; 0; 0; 0; 0; 0; 0; 0; 0; 0];

%% L√≠mites
lb=[TherHPmin;TherHPmin;TherHPmin;TherHPmin;TherHPmin;TherHPmin;TherHPmin;The
rHPmin;TherHPmin;TherHPmin;TherHPmin;TherHPmin;TherHPmin;TherHPmin;TherHPmin;
TherHPmin;TherHPmin;TherHPmin;TherHPmin;TherHPmin;TherHPmin;TherHPmin;TherHPm
in;TherHPmin;

TempHPmin;TempHPmin;TempHPmin;TempHPmin;TempHPmin;TempHPmin;TempHPmin;TempHPm
in;TempHPmin;TempHPmin;TempHPmin;TempHPmin;TempHPmin;TempHPmin;TempHPmin;Temp
HPmin;TempHPmin;TempHPmin;TempHPmin;TempHPmin;TempHPmin;TempHPmin;TempHPmin;T
empHPmin;

Compramin;Compramin;Compramin;Compramin;Compramin;Compramin;Compramin;Compram
in;Compramin;Compramin;Compramin;Compramin;Compramin;Compramin;Compramin;Comp
ramin;Compramin;Compramin;Compramin;Compramin;Compramin;Compramin;Compramin;C
ompramin;

tIndmin;tIndmin;tIndmin;tIndmin;tIndmin;tIndmin;tIndmin;tIndmin;tIndmin;tIndm
in;tIndmin;tIndmin;tIndmin;tIndmin;tIndmin;tIndmin;tIndmin;tIndmin;tIndmin;tI
ndmin;tIndmin;tIndmin;tIndmin;tIndmin;
    CapacityBoughtmin; CapacityBoughtmin; CapacityBoughtmin];
```

```
ub=[TherHPmax;TherHPmax;TherHPmax;TherHPmax;TherHPmax;TherHPmax;TherHPmax;The
rHPmax;TherHPmax;TherHPmax;TherHPmax;TherHPmax;TherHPmax;TherHPmax;TherHPmax;
TherHPmax;TherHPmax;TherHPmax;TherHPmax;TherHPmax;TherHPmax;TherHPmax;TherHPm
ax;TherHPmax;

TempHPmax;TempHPmax;TempHPmax;TempHPmax;TempHPmax;TempHPmax;TempHPmax;TempHPm
ax;TempHPmax;TempHPmax;TempHPmax;TempHPmax;TempHPmax;TempHPmax;TempHPmax;Temp
HPmax;TempHPmax;TempHPmax;TempHPmax;TempHPmax;TempHPmax;TempHPmax;TempHPmax;T
empHPmax;

Compramax;Compramax;Compramax;Compramax;Compramax;Compramax;Compramax;Compram
ax;Compramax;Compramax;Compramax;Compramax;Compramax;Compramax;Compramax;Comp
ramax;Compramax;Compramax;Compramax;Compramax;Compramax;Compramax;Compramax;C
ompramax;

tIndmax;tIndmax;tIndmax;tIndmax;tIndmax;tIndmax;tIndmax;tIndmax;tIndmax;tIndm
ax;tIndmax;tIndmax;tIndmax;tIndmax;tIndmax;tIndmax;tIndmax;tIndmax;tIndmax;tI
ndmax;tIndmax;tIndmax;tIndmax;tIndmax;
    CapacityBoughtmax; CapacityBoughtmax; CapacityBoughtmax];

%% Funci√≥n objetivo: Recordatorio variables de decision x= therHP, tempHP,
Compra, tInd, CapacityBought
f=[0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;
   0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;

Energy_Price(1);Energy_Price(2);Energy_Price(3);Energy_Price(4);Energy_Price(
5);Energy_Price(6);Energy_Price(7);Energy_Price(8);Energy_Price(9);Energy_Pri
ce(10);Energy_Price(11);Energy_Price(12);Energy_Price(13);Energy_Price(14);En
ergy_Price(15);Energy_Price(16);Energy_Price(17);Energy_Price(18);Energy_Pric
e(19);Energy_Price(20);Energy_Price(21);Energy_Price(22);Energy_Price(23);Ene
rgy_Price(24);
   0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;
   Network_Power_Price(1); Network_Power_Price(2); Network_Power_Price(3)];

%% Programa
[x,fval] = linprog(f,A,B,Aeq,Beq,lb,ub);

Variable_TherHP=x(1:24)
Variable_TempHP=x(25:48)
Variable_Compra=x(49:72)
Variable_tInd=x(73:96)
Variable_PotenciaContratada=x(97:99);

figure;
subplot(2,1,1);
title('Evolution of the temperature and price with time');
hold on;
x=[0:1:23]
y1=Energy_Price;
yyaxis left;
plot(x,y1);
hold on;

yyaxis right;
ylim([10,30]);
plot(x,Variable_tInd);
```

```
hold on;
legend('Total price (‚Ç¨)','Indoor temperature(¬∫C)');
xlabel('time(h)');

subplot(2,1,2);
title('Evolution of the heat pump consumption and price with time');
yyaxis left;
plot(x,y1);
hold on;
yyaxis right;
ylim([0,10]);
plot(x,Variable_TempHP);
legend('Total price (‚Ç¨)','Heat Pump Consumption (kWh)');
xlabel('time(h)');
```

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