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Flexibility: Energy transition and Industry 4.0

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ABSTRACT The energy sector plays a fundamental role in the economy as a key provider for other sectors. To maintain competitiveness, it is crucial for the sector to adapt to market trends. Industry 4.0 has emerged as a solution to improve operational efficiency, reduce costs, and develop smart grids in the energy sector. However, there are still challenges to overcome. This study examines how Industry 4.0 is driving the transformation of the electricity sector, highlighting its benefits and key technologies. It focuses on the concept of flexibility and Demand Response, demonstrating their capacity to address issues in local distribution networks comparing their operation for residential customers and offices. The main objective is to demonstrate the utility of the tools offered by Industry 4.0 in transitioning to a more efficient and sustainable electricity sector, involving all stakeholders.

INDEX TERMS Demand response, Flexibility, Heat Pumps, Industry 4.0 and Tariffs.

I. INTRODUCTION

It is evident that the provision of electricity has been the driving force behind the industrial and social transformation of the world for over a century, becoming one of the most essential services in our society. As a response to the global imperative of combating climate change, there is a growing focus on decarbonizing the economy, positioning electricity as the primary energy vector [1]. In addition to other challenges and demands, such as the need to increase energy efficiency and enhance the resilience of electric grids.

Currently, we witness cities experiencing constant growth and modernization, where households possess mobile devices, security systems, lighting, and other appliances that generate vast volumes of data. The Industry 4.0 is characterized by the intensive use of the internet and new digital technologies, which harness the generated data to enable businesses to develop highly automated and interconnected processes.

The energy sector is not immune to the Industry 4.0 revolution and is undergoing an unprecedented transformation due to associated technological advancements. These advancements have facilitated improvements in energy efficiency, the enhancement of distribution networks, and the maximization of renewable energy utilization through digital systems that optimize energy flows and power substations. These innovations extend to distribution networks with the widespread adoption of smart meters, as well as commercialization through the development of online trading platforms and mobile applications, all with the requirement of cost-effectiveness [2].

In this context, it is crucial to comprehend the scope and benefits of the transformation of the electricity sector driven by the Industry 4.0, as well as the challenges that still need to be overcome. This study aims to provide a detailed analysis of how the Industry 4.0 is aiding the transformation of the electricity sector, emphasizing key technologies and their benefits. Furthermore, one of the proposed solutions, Demand Response, is examined in greater detail to showcase how these tools can address distribution network issues comparing their operation for residential buildings and offices.

With all these aspects in mind, the goal is to offer valuable information to companies in the sector, policymakers, and consumers, with the intention of promoting a transition towards a more efficient electricity sector.

II. INDUSTRY 4.0 IN THE ELECTRIC SECTOR

The Industry 4.0 refers to the 4th Industrial Revolution, characterized by the integration of digital, physical, and biological technologies to transform the way products and services are designed, manufactured, and managed

The Industry 4.0 is based on connectivity and process automation through advanced technologies such as the Internet of Things (IoT), artificial intelligence, machine learning, and cloud computing. The Industry 4.0 encompasses nine technologies, summarized in Figure 1, included in an article by the Boston Consulting Group on Industry 4.0 [3].

These technologies enable the collection and real-time analysis of large volusmes of data, providing valuable information for making more informed decisions and optimizing operational processes.

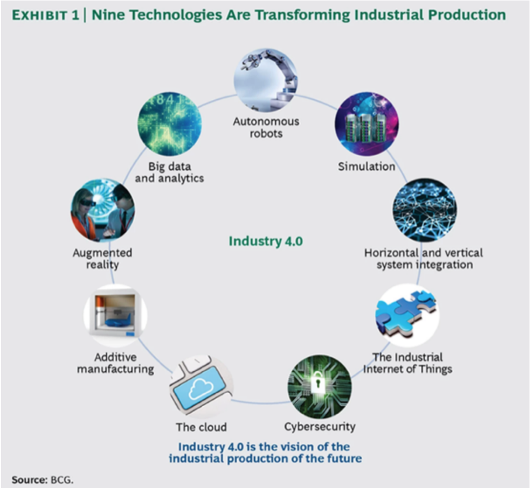

Figure 1: Industry 4.0 technologies. Source: Boston Consulting Group

A. ELECTRIC SECTOR TRANSFORMATION

Before the liberalisation of the electricity sector, initiated in the European Union in 1996, the activity was concentrated in companies characterised by a strong vertical structure. Electricity was generated by centralised producers, transported by unidirectional flows through the grid, and consumed by the end users [4]. However, things are different nowadays, regulatory changes and the development of new technologies (distributed renewable generation, energy storage, electric vehicles, etc.) have altered these assumptions.

According to the report published by the International Energy Agency (IEA) titled *Digitalization & Energy* [5]. The greatest transformational potential for digitalization is its ability to break down boundaries between energy sectors, increasing flexibility and enabling integration across entire systems. The electricity sector is at the heart of this transformation, where digitalization is blurring the distinction between generation and consumption, and enabling four interrelated opportunities:

- **Smart demand response** could provide 185 gigawatts (GW) of system flexibility, roughly equivalent to the current installed electricity supply capacity in Australia and Italy combined. This could save USD 270 billions of investment in new electricity infrastructure that would have otherwise been needed. In the residential sector alone, 1 billion households and 11 billion smart appliances could actively participate in interconnected electricity systems, allowing these households and devices to alter when the draw electricity from the grid.

- Digitalization can help **integrate variable renewables** by enabling grids to better match energy demand to times when the sun is shining and the wind is blowing. In the European Union alone, increased storage and digitally-enabled demand response could reduce the curtailment of solar photovoltaics (PV) and wind power form 7% to 1.6% in 2040, avoiding 30 million tons of carbon dioxide emissions in 2040.

- Rolling out **smart charging technologies for electric vehicles** could help shift charging to periods when electricity demand is low and supply is abundant. This would provide further flexibility to the grid while saving between USD 100 billion and USD 280 billion in avoided investment in new electricity infrastructure between 2016 and 2040.

- Digitalization can facilitate the development of **distributed energy resources,** such as house hold solar PV panels and storage, by creating better incentives and making it easier for producers to store and sell surplus electricity to the grids. New tools such as blockchain could help to facilitate peer-to-peer electricity trade within local energy communities.

Of all these opportunities, this paper intends to focus on demand response. This is further developed in the following chapters.

B. CHALLENGES

Although we have seen that Industry 4.0 and its technologies offer many opportunities to optimize the operation of the electricity sector, there are also challenges. In order to harness the benefits of this transformation, it is important to be aware of and address these challenges. In this section, we have included the main ones.

Cyber-attacks

Although digitalization offers numerous benefits, it also exposes energy systems to increased vulnerability from cyber-attacks. While previous reported cyber-attacks have caused only minor disruptions, the ease and affordability of organizing such attacks are on the rise. Furthermore, the expansion of the Internet of Things (IoT) expands the potential avenues for cyber-attacks in energy systems.

While it is impossible to completely prevent cyber-attacks, their impact can be minimized through effective preparation by countries and companies. Developing system-wide resilience relies on raising awareness among all stakeholders about the associated risks. It is crucial to integrate digital resilience into technology research, development efforts, and policy and market frameworks

Privacy and data ownership

Privacy and ownership of data are significant concerns for consumers, particularly as increasingly detailed data is gathered from a growing array of interconnected devices and appliances. For example, smart meters can collect information about energy usage in households, enabling the identification of activities such as someone being present, using the shower, or making tea. Simultaneously, aggregated and anonymized individual energy consumption data can enhance the understanding of energy systems, including load profiles, and contribute to reducing costs for individual consumers.

Policymakers must strike a balance between addressing privacy concerns and pursuing other objectives, such as fostering innovation and fulfilling the operational requirements of utility companies.

Impact on jobs

Digitalization is impacting the way many businesses operate, thus affecting jobs and required skills in various fields of the energy sector. This is creating new job opportunities in some areas while causing losses in others.

Energy policymakers should actively engage in broader discussions at the government level to assess and address these effects accordingly.

Policy design

The role of legislators in the transformation of the electricity sector through the new technologies of Industry 4.0 is crucial. Legislators have the responsibility of establishing legal and regulatory frameworks that encourage the adoption and implementation of these technologies in the electricity sector. This involves creating incentives for investing in smart infrastructures, promoting open standards and protocols, and ensuring the protection of privacy and data security. Furthermore, legislators can foster collaboration among various stakeholders in the electricity sector, such as electricity companies, technology providers, and consumers, to achieve a successful transition towards a more efficient, sustainable, and resilient electricity system.

III. FLEXIBILITY

As mentioned in the previous chapter, one of the opportunities presented by the transformation of the electricity sector is the ability to provide flexibility to the grid. This document aims to focus on this field. To achieve this, this section explains first what flexibility is and the different types of flexibility available. In the following section, a case study is proposed, and the results are be analysed.

With the increasing adoption of renewable energy and distributed energy resources (DERs), their integration into the distribution grid poses new challenges for system operators. To cope with these challenges, distribution system operators are seeking market tools to enable more active system management and control using flexibility.

Currently the main concepts for flexibility in the network are implicit flexibility and explicit flexibility; both with different approaches on how to bring flexibility to the network.

The explicit flexibility refers to the ability to adjust energy demand or generation in response to price signals or incentives provided through flexibility markets. In these markets, participants actively and voluntarily provide flexible services to the power system [6]. On the other hand, implicit flexibility refers to the inherent response capacity of energy consumers and generators without direct participation in flexibility markets. This flexibility is related to tariff structures imposed by regulators or public service providers, where incentives or charges are established to encourage consumers to adjust their energy consumption during periods of high or low demand [7].

Both types of flexibility play a significant role in demand management and the integration of renewable energies into electrical systems However, in this work, the focus is primarily on implicit flexibility, as it is the aspect that is addressed for the case study.

A. FLEXIBILITY DEFINITION

EURELECTRIC defines flexibility as the possibility of adjusting patterns of generation and consumption in reaction to a signal (price or activation signals) to contribute to different services [8]. In other words, flexibility in the electrical systems refers to the ability of the involved agents (i.e., generators, consumers, system operators, etc.) to adjust their energy production or consumption to adapt to fluctuations in the supply and demand of the electricity market. This flexibility can also be used as a solution for active distribution network management dealing with local network congestion and voltage issues [9].

These fluctuations can be due to multiple factors, such as the variability of intermittent renewable energy production, changes in energy demand or incidents in the electrical grid (i.e., overloads, short circuits, electrical equipment failures, etc.).

B. TARIFFS

As stated in a previous chapter, Demand Response has the potential to emerge as one of the most cost-effective sources of flexibility in a power system, playing a crucial role in facilitating the integration of a high proportion of Variable Renewable Energy (VRE) generation. This Demand Response can be achieved through the implementation of tariffs, leveraging consumer response to price signals [10].

Tariffs definition

Electricity tariffs in the electric sector refer to the price structures established to determine the cost that consumers must pay for electricity supply. These tariffs are designed to cover the operation, maintenance, and expansion costs of the electrical grid, as well as to promote efficiency in electricity usage.

Electricity tariffs are typically set by regulators or electric companies and can vary based on factors such as the type of consumption (residential, commercial, industrial), the time of day (time-of-use tariffs), or geographic location. In addition to covering costs, tariffs may also include components that reflect the economic value of electricity, such as generation costs, capacity charges, or incentives for efficient energy use.

Location based tariffs

There is a type of tariff that is used when there are constraints on the electricity network. These are known as location-based tariffs, which reflect the costs associated with congestion in electrical networks (e.g., nodal pricing). They incentivize consumers and prosumers (participants who can both buy and sell electricity) to reduce electricity consumption from the grid or inject electricity into the grid based on network congestion [10]. The case studies is primarily focus on this type of tariff.

IV. METHODOLOGY

In this section, the methodology used to study the flexibility capacity in problem-solving within the network is explained. To achieve this, the behavior of a heat pump that contributes to the network's flexibility is examined. The first step is to analyze the equations on which this work is based.

The initial equations consist of a series of Python formulas developed by Troncia, M [11]. These formulas calculate the tariff amounts for different hours of the day, considering the issues of various nodes within the network. On the other hand, the second group involves the thermal modeling of a residence (ideally, a 100m2 apartment/office) developed by Morell et al. [12] and Bastida et al. [13]. These formulas describe the evolution of interior temperature in residences with a higher level of detail compared to previous works on the subject, allowing for a more realistic modeling of the heat pump's consumption, closer to reality.

A. NETWORK TARIFFS CALCULATION

As mentioned in the preceding section, the use of tariffs is one of the methods employed to introduce flexibility into the grid. In this thesis, a set of Python equations developed by Troncia, M. [11], are employed to compute the tariffs. These formulas consider the constraints faced by various nodes in the network during different times of the day, along with the corresponding electricity prices. With this information, the equations establish the tariff values for each hour of the day.

The primary purpose of these tariffs is to modify the consumption patterns of devices connected to the network nodes (the heat pumps in this case) and address related issues. The equations can be categorized into three distinct steps:

1) NETWORK COEFFICIENTS: The first step is to calculate the Network coefficients for each hour of the day. To achieve this, the voltages of each bus in the network for each hour of the day are taken into account, and both maximum and minimum voltage values are established, as well as the range within which the coefficients can vary. With all this information, a coefficient is obtained for each hour of the day, so that hours with overvoltage issues have coefficients closer to the lower range, and for undervoltage, closer to the upper range.

2) ENERGY COEFFICIENT: In order to transform the Network coefficients into tariffs, there is a need for a parameter that establishes a connection between power and price, known as the Energy coefficient. This Energy coefficient represents a certain percentage of the selected average electricity price used in the case study.

3) NETWORK COST: Finally, the amount of the tariffs to be applied to each hour of the day is calculated as follows: if the Network coefficient for that hour is greater than 1, the tariff is obtained by multiplying the Network coefficient by the Energy coefficient. If the Network coefficient is less than 1, the tariff is calculated by subtracting 2 from the coefficient and multiplying it by the Energy coefficient. In

the case that the Network coefficient is 0, the tariff amount is also 0.

If different tariffs are desired within the same network, either for each node or certain groups of nodes, the same process would need to be repeated as many times as there are groups, inputting the voltages of the respective nodes. By doing so, the tariffs have a higher level of detail, aligning more closely with the issues specific to each group. Furthermore, if there is a need to increase the tariff amounts, it would simply require expanding the range of variation for the Network coefficients.

This section briefly outlines the process of tariff calculation. For a more comprehensive understanding of all the mentioned formulas, readers can refer to Troncia, M. GitHub repository [11].

B. DYNAMIC THERMAL MODEL

Number equations consecutively with equation numbers in parentheses flush with t

As mentioned earlier, to model the behavior of the heat pump, a thermal model proposed by Morell et al. [12] is used as a reference, based on the one developed by Bastida et al. [13]. This paper introduces a method for modeling the thermal dynamics of a building using equivalent thermal parameters. The approach involves employing resistive and capacitive (RC) networks to represent the heat flow through various solid surfaces, such as walls, roof, and windows. By using this approach, the design process is simplified, as demonstrated in Figure 2.

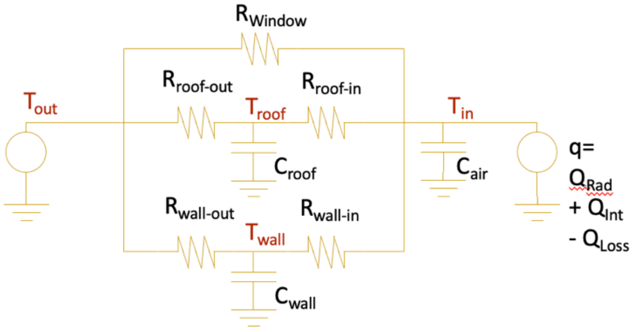

Figure 2: New thermal model. Source: Morell, N.

In this Figure, can be observed the different variables considered when modeling the evolution of the temperature inside the dwelling (t_{in}). These variables include: outside temperature (t_{out}), introduced heat (q), and the different layers taken into account (walls, roofs, and windows).

Thanks to this scheme, it is possible to develop formulas that define the temperature behavior inside the house. Starting with the thermal layers the following for the roof ($t_{R,h}$) is obtained, which also depends on the neighbor's temperature ($t_{neighbor}$):

$$t_{R,h} = t_{R,th-1} + \left(T_{neighbor} - t_{R,h-1}\right)\frac{R_{Rout}}{C_R}\Delta + \left(t_{int,h-1} - t_{R,h-1}\right)\frac{R_{Rin}}{C_R}\Delta h$$

And the formulas for the walls ($t_{W,h}$)

$$t_{W,h} = t_{W,h-1} + \left(T_{out,h-1} - t_{W,h-1}\right)\frac{R_{Wout}}{C_W} + \left(t_{int,h-1} - t_{W,h-1}\right)\frac{R_{Win}}{C_W}\Delta h$$

In both equations, you can observe how the temperature of both the roof and the walls depends on the temperature at the previous time step ($t_{X,h-1}$), along with the temperature differences with adjacent elements, multiplied by the ratio of thermal resistance (R) to thermal capacitance (C).

It's worth noting that the windows of the dwelling are not considered a layer because they cannot store heat (as shown in Figure 2). This is because they are very poor thermal insulators.

When formulating the evolution of the temperature inside the dwelling, the windows (R_{WW}), are taken into account, as well as the rest of the layers and the net heat received by the dwelling (q). Thus, the equations are as follows:

$$t_{in,h} = t_{in,h-1} + \left(t_{R,h-1} - t_{in,h-1}\right)\frac{R_{Rin}}{C_{air}}\Delta h + \left(T_{out,h-1} - t_{in,h-1}\right)\frac{R_{Ww}}{C_{air}}\Delta h + \left(t_{W,h-1} - t_{in,h-1}\right)\frac{R_{Win}}{C_{air}}\Delta h + \frac{q_{h-1}}{C_{air}}\Delta h$$

The heat received by the dwelling is not the same as the heat provided by the heat pump ($q_{in,h-1}$), as it is necessary to consider losses ($Q_{Loss,h-1}$) and the solar radiation received ($Q_{Rad,h-1}$):

$$q_{h-1} = Q_{Rad,h-1} + q_{in,h-1} - Q_{Loss,h-1}$$

Using these equations, it becomes feasible to predict the indoor temperature in the house at the next time step ($t_{in,h+1}$), based on the heat supplied through the heat pump (q_h). This prediction is crucial for assessing the heat pump's capacity to offer flexibility to the network.

C. PROPOSED MODEL

Taking into account the two solutions presented previously, the objective of this section is to present the developed formulation for optimizing the heat pump's consumption. This section is divided into two parts: the first part explains the modeling of the heat pump without considering flexibility, aiming to minimize the cost based solely on the PVPC prices; and the second part explains the model of the heat pump that takes into account demand response tariffs.

Table 1 provides a summary of the nomenclature used:

Table 1: Nomenclature used for the proposed model

INDICES AND SETS	
$h \in H$	Hour
$f \in F$	Feeder
H	Set of hours
F	Set of feeders
PARAMETERS	
Ce_h	Cost of electricity in day-ahead market
Ct_h	Cost tariffs for demand response
$Ct_{f,h}$	Cost tariffs for demand response per feeder *f*
$T_{out,h}$	Temperature outside the building in period *h*
$T_{neighbor}$	Temperature of the neighbour's house
T_{in}^{min}	Minimum temperature that can be inside
$Q_{loss,h}$	Heat losses in period *h*
$Q_{rad,h}$	Solar radiation received by the building
COP	Coefficient of Performance
VARIABLES	
$t_{in,h}$	Temperature inside the house in period *h*
$t_{in\ f,h}$	Temperature inside the house in period *h* per feeder *f*
$t_{W,h}$	Temperature of the walls in period *h*
$t_{W\ f,h}$	Temperature of the walls in period *h* per feeder *f*
$t_{R,h}$	Temperature of the roof in period *h*
$t_{R\ f,h}$	Temperature of the roof in period *h* per feeder *f*
p_h	Power consumed in period *h*
p_h^i	Power consumed in period *h*
$p_{f,h}^i$	Power consumed in period *h* per feeder *f*
q_h	Heat introduced inside in period *h*
$q_{f,h}$	Heat introduced inside in period *h* per feeder *f*
$q_{in,h}$	Heat introduced by the pump in period *h*
$q_{in\ f,h}$	Heat introduced by the pump in period *h* per feeder *f*

1) NO NETWORK REPRESENTATION IN TARIFFS

Following the formulation proposed by Morell et al. [12] and Bastida et al. [13], the objective of this section is to define a set of formulas that model the behavior of a heat pump for a dwelling. In this case, the objective function aims to minimize the operational cost for a day, which is simply the sum of the power consumed (p_h^i) multiplied by the PVPC electricity price (Ce_h) for all 24 hours.

Another aspect to consider is the temperature constraints set by the residents of the dwelling (T_{in}^{min} and T_{in}^{max}), which are the main factors for providing flexibility.

As seen in the previous section, the indoor temperature depends on the temperature of the walls ($t_{W,h}$) and the roof ($t_{R,h}$), as well as the net introduced heat.

To determine the power consumed by the heat pump, its Coefficient of Performance (COP) needs to be known, as it relates the generated heat to the consumed power:

$$p_h = \frac{q_{in,h}}{COP}$$

The model defined is as follows:

$$\min \sum_{h \in H} p_h^i \, Ce_h$$

s.t.

$$p_h^i = \frac{q_{in,h}}{COP}, \qquad \forall_h \in H$$

$$q_{in,h} = q_h + Q_{loss,h} - Q_{rad,h}\,, \qquad \forall_h \in H$$

$$t_{in,h+1} = t_{in,h} + \left(t_{R,h} - t_{in,h}\right)\frac{R_{Rin}}{C_{air}}\Delta h + \left(T_{out,h} - t_{in,h}\right)\frac{R_{Ww}}{C_{air}}\Delta h + \left(t_{W,h} - t_{in,h}\right)\frac{R_{Win}}{C_{air}}\Delta h + \frac{q_h}{C_{air}}\Delta h\,, \qquad \forall_h \in H$$

$$t_{W,h+1} = t_{W,h} + \left(T_{out,h} - t_{W,h}\right)\frac{R_{Wout}}{C_W}\Delta h + \left(t_{int,h} - t_{W,h}\right)\frac{R_{Win}}{C_W}\Delta h\,, \qquad \forall_h \in H$$

$$t_{R,h+1} = t_{R,h} + \left(T_{neighbor} - t_{R,h}\right)\frac{R_{Rout}}{C_R}\Delta h + \left(t_{int,h} - t_{R,h}\right)\frac{R_{Rin}}{C_R}\Delta h\,, \qquad \forall_h \in H$$

$$T_{in}^{min} \le t_{in,h} \le T_{in}^{max}, \qquad \forall_h \in H$$

2) NETWORK REPRESENTATION IN TARIFFS

In this section, two models is developed that, like the previous model, have the objective of minimizing the operational cost of the heat pump. However, the difference is that these models consider demand response tariffs. These tariffs are calculated based on the issues that arise in the network and aim to modify the consumption curve.

Although both models consider the tariffs, the first model only has a single tariff for all nodes in the network (which evolves throughout the 24 hours of the day). On the other hand, the second model considers the different feeders in which the network is divided and their respective tariffs.

<u>*Tariffs for DR with no local differentiation*</u>

This model is very similar to the previous one, but with the difference that the Demand Response tariffs () are added to the electricity price. In this case, the tariff amount is the same for all nodes.

The resulting model is as follows:

$$\min \sum_{h \in H} p_h^i \left(Ce_h + Ct_h\right)$$

s.t.

$$p_h^i = \frac{q_{in,h}}{COP}, \qquad \forall_h \in H$$

$$q_{in,h} = q_h + Q_{loss,h} - Q_{rad,h}\,, \qquad \forall_h \in H$$

$$t_{in,h+1} = t_{in,h} + \left(t_{R,h} - t_{in,h}\right)\frac{R_{Rin}}{C_{air}}\Delta h + \left(T_{out,h} - t_{in,h}\right)\frac{R_{Ww}}{C_{air}}\Delta h + \left(t_{W,h} - t_{in,h}\right)\frac{R_{Win}}{C_{air}}\Delta h + \frac{q_h}{C_{air}}\Delta h\,, \qquad \forall_h \in H$$

$$t_{W,h+1} = t_{W,h} + \left(T_{out,h} - t_{W,h}\right)\frac{R_{Wout}}{C_W}\Delta h + \left(t_{int,h} - t_{W,h}\right)\frac{R_{Win}}{C_W}\Delta h\,, \qquad \forall_h \in H$$

$$t_{R,h+1} = t_{R,h} + \left(T_{neighbor} - t_{R,h}\right)\frac{R_{Rout}}{C_R}\Delta h + \left(t_{int,h} - t_{R,h}\right)\frac{R_{Rin}}{C_R}\Delta h\,, \qquad \forall_h \in H$$

$$T_{in}^{min} \le t_{in,h} \le T_{in}^{max}, \qquad \forall_h \in H$$

Tariffs for DR with local differentiation

Being able to differentiate by groups of nodes or by individual nodes directly allows obtaining tariffs that reflect the issues of those specific buses in greater detail. To achieve this, the previous model needs to be modified, considering that now the heat pumps operating in different feeders have different consumption profiles ($p^i_{f,h}$) due to the varying tariff amounts ($Ct_{f,h}$).

Another significant change is adding an additional summation to the objective function to account for the different feeders.

The resulting model is as follows:

$$\min \sum_{h\in H}\sum_{f\in F} p^i_{f,h}\left(Ce_h + Ct_{f,h}\right)$$

s.t.

$$p^i_{f,h} = \frac{q_{in\,f,h}}{COP}\,, \qquad \forall_h \in H;\ \forall_f \in \mathrm{F}$$

$$q_{in\,f,h} = q_{f,h} + Q_{loss,h} - Q_{rad,h}\,, \qquad \forall_h \in H;\ \forall_f \in \mathrm{F}$$

$$t_{in\,f,h+1} = t_{in\,f,h} + \left(t_{R\,f,h} - t_{in\,f,h}\right)\frac{R_{Rin}}{C_{air}}\Delta h + \left(T_{out,h} - t_{in\,f,h}\right)\frac{R_{Ww}}{C_{air}}\Delta h + \left(t_{W\,f,h} - t_{in\,f,h}\right)\frac{R_{Win}}{C_{air}}\Delta h + \frac{q_{f,h}}{C_{air}}\Delta h\,, \qquad \forall_h \in H;\ \forall_f \in \mathrm{F}$$

$$t_{W\,f,h+1} = t_{W\,f,h} + \left(T_{out,h} - t_{W\,f,h}\right)\frac{R_{Wout}}{C_W}\Delta h + \left(t_{int\,f,h} - t_{W\,f,h}\right)\frac{R_{Win}}{C_W}\Delta h\,, \qquad \forall_h \in H;\ \forall_f \in \mathrm{F}$$

$$t_{R\,f,h+1} = t_{R\,f,h} + \left(T_{neighbor} - t_{R\,f,h}\right)\frac{R_{Rout}}{C_R}\Delta h + \left(t_{int\,f,h} - t_{R\,f,h}\right)\frac{R_{Rin}}{C_R}\Delta h\,, \qquad \forall_h \in H;\ \forall_f \in \mathrm{F}$$

$$T_{in}^{min} \le t_{in,h} \le T_{in}^{max}, \qquad \forall_h \in H;\ \forall_f \in \mathrm{F}$$

V. CASE OF STUDY

The objective of this section is to demonstrate the utility of flexibility in resolving overvoltage and undervoltage issues in a low-voltage network. To achieve this, the previously presented models have been translated into Python, and the low-voltage network has been defined. Figure 3 displays the network along with its nodes.

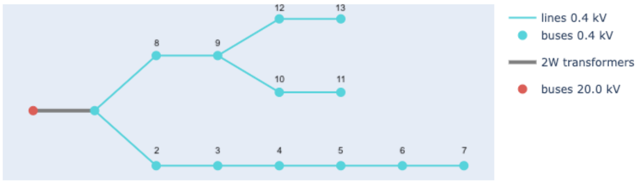

Figure 3: Low voltage electricity network for the case study. Source: Own elaboration

The study involves the analysis of three distinct scenarios:

- **Base Scenario**: no network representation in tariffs.
- **Scenario A**: tariffs for Demand Response but with no local differentiation.
- **Scenario B**: tariffs for Demand Response but with local differentiation.

Additionally, to demonstrate the capacity of flexibility in resolving constraint problems in the low-voltage network, two different scenarios are compared. The first case study involves an analysis for a network with connected dwellings, where the residents have set temperature ranges between 20 and 25ºC. On the other hand, the second case study involves an analysis for a network with connected offices, where the temperature range from 9 am to 5 pm is set according to the RITE regulations between 21 and 23ºC for winter [14]; while there are no limitations for the rest of the hours.

For all scenarios, the outside temperature has been selected as that of a winter day in Madrid. To observe the solutions offered by flexibility markets, the connection of 15 heat pumps to the designated nodes (3, 5, 7, 9, 11, and 13) has been decided upon. The PVPC prices used are those corresponding to June 30th, 2023, obtained from Red Eléctrica website [15].

A. BASE SCENARIO: NO NETWORK REPRESENTATION IN TARIFFS

The following results are obtained when running the model considering only PVPC prices:

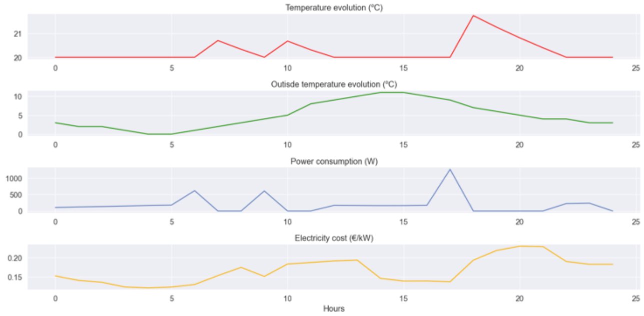

Figure 5: Summary heat pump modelling result | Base Scenario (residential). Source: Own elaboration

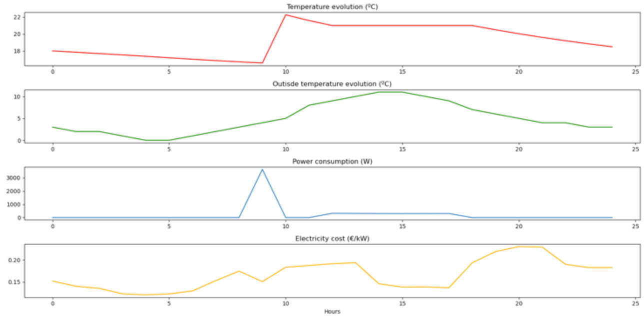

Figure 4: Summary heat pump modelling result | Base Scenario (Offices). Source: Own elaboration

Looking at Figures 4 and 5, in the first graph, the evolution of the indoor temperature can be observed, which remains within the specified ranges for each case. The green line represents the outside temperature, ranging between 0 and 12°C.

The third graph displays the heat pump's consumption profile, while the last one shows the evolution of electricity prices throughout the day.

Differences can already be observed in the consumption profiles for both cases. In the case of residential customers, consumption is more evenly distributed during the day, with three prominent consumption peaks coinciding with price decreases. On the other hand, in the case of offices, the temperature peak occurs at 9 a.m., corresponding to the activation of the RITE regulation, and then the pump maintains a constant consumption until 5 p.m.

In Figures 6 and 7, the issues generated by these consumption profiles on the grid can be observed.

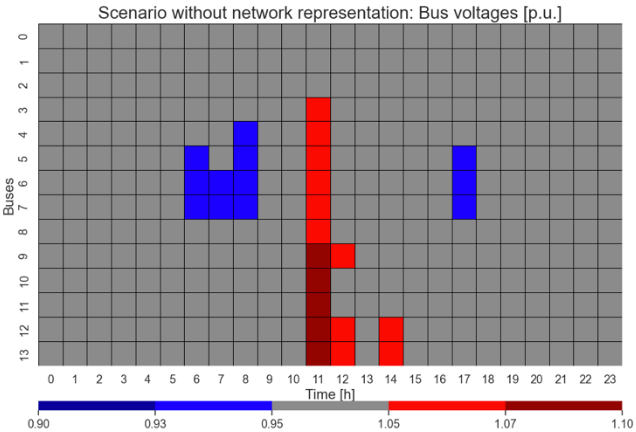

Figure 6: Network problems per bus and time | Base Scenario (residential). Source: Own elaboration

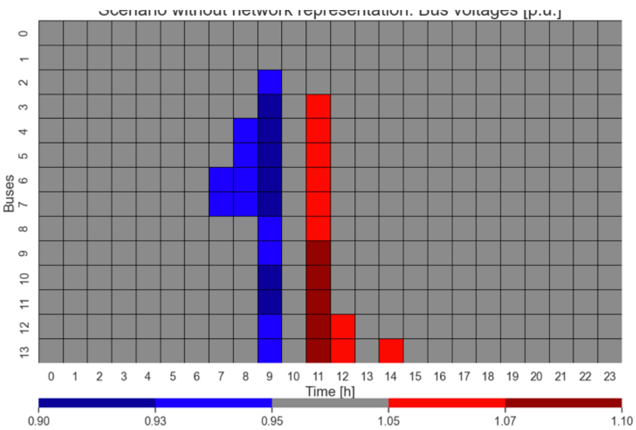

Figure 7: Network problems per bus and time | Base Scenario (Offices). Source: Own elaboration

These graphs display the status of different buses in the network for each hour, with blue cells representing undervoltage issues and red cells indicating overvoltage problems. The legend at the bottom indicates that darker shades correspond to higher magnitudes of the problem.

Analyzing the issues in both Figures, it can be observed that when using the same network for both cases, the lack of demand problems are almost identical. However, the issues of excess demand are different. In the case of offices, the excess demand problems are much more significant and concentrated between 7 a.m. and 9 a.m., which corresponds to the time when office temperatures need to be adjusted. On the other hand, in the case of residential customers, undervoltage issues are much smaller and distributed throughout the morning and afternoon.

These problems observed in different buses are used to determine the network cost coefficients for Demand Response. These tariffs are added to the PVPC prices to incentivize or disincentivize consumption during different hours and solve the problems accordingly.

B. SCENARIO A: TARIFFS FOR DR BUT WITH NO LOCAL DIFFERENTIATION

In this scenario, the tariffs for demand response are added to the PVPC prices, but without distinguishing them by feeder. The results for the case of residential customers and offices can be seen in Figures 8 and 11.

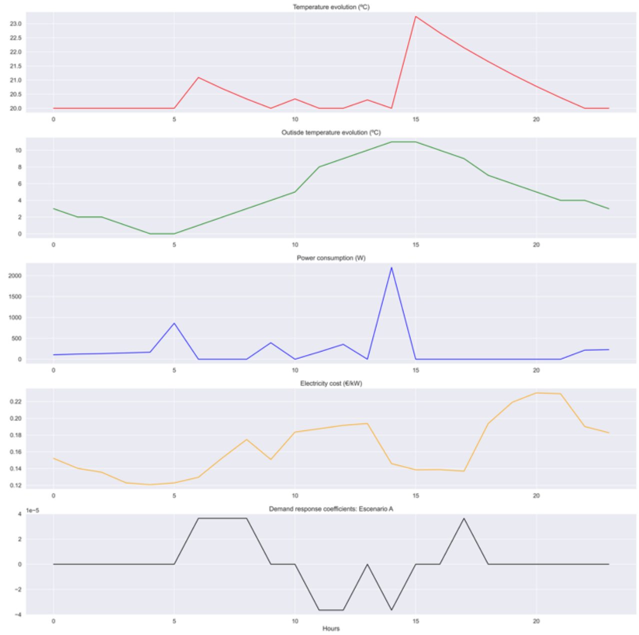

Figure 8: Summary heat pump modelling result | Scenario A (residential). Source: Own elaboration

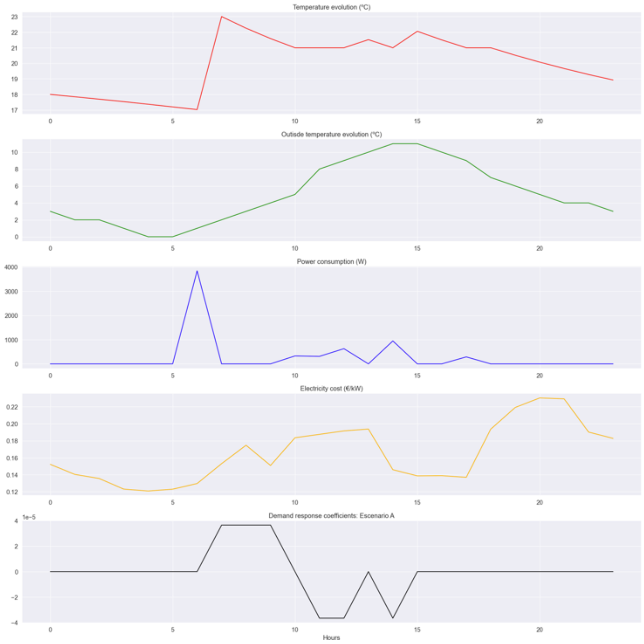

Figure 11: Summary heat pump modelling result | Scenario A (Offices). Source: Own elaboration

In these graphs, changes in the different analyzed parameters can already be observed. Starting with the home temperature, in the case of residential customers, there are more temperature peaks, and the maximum temperature reached is higher compared to the Base Scenario. In the case of offices, the temperature peak now occurs earlier (from 10 a.m. to 7 a.m.), and it is no longer maintained constantly during office hours.

All these changes in temperature are driven by changes in consumption profiles. In the case of residential customers, four consumption peaks can now be observed, whereas previously there were three peaks and higher consumption at 2 p.m., resulting in an increase in the maximum temperature. In the case of offices, it can be seen that the consumption peak has shifted to 6 a.m., causing the earlier peak in consumption and some oscillation in consumption during working hours, whereas previously it remained constant.

Another aspect to observe is the tariffs, which are the cause of the changes in consumption profiles. In the case of residential customers, two peaks and two valleys can be observed in the tariff profile. The peaks aim to disincentivize consumption during those hours to solve undervoltage problems, while the valleys aim to incentivize consumption during those hours to address overvoltage problems. For the case of offices, the valleys are the same as in the previous case, but only one peak is present in the morning, where undervoltage issues were observed.

In Figures 9 and 10, a more detailed view of the changes in consumption profiles can be observed.

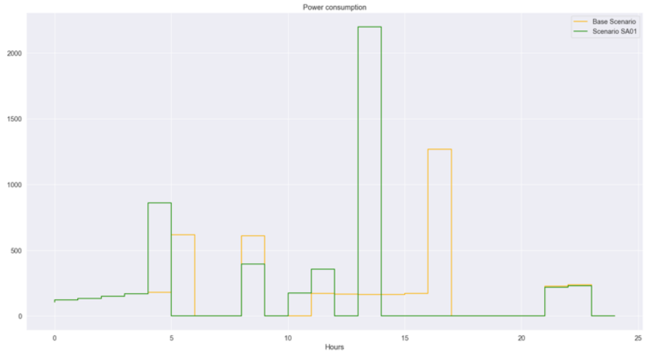

Figure 9: Comparison between consumption profiles | Base Scenario vs Scenario A (residential). Source: Own elaboration

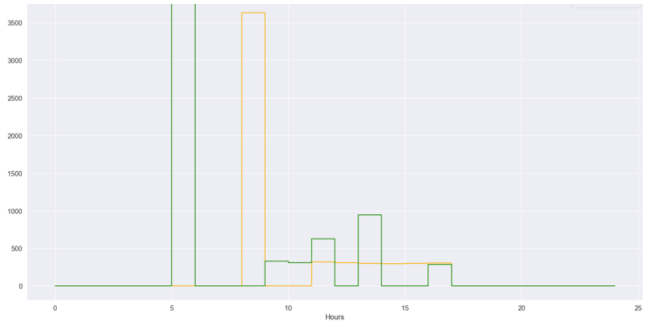

Figure 10: Comparison between consumption profiles | Base Scenario vs Scenario A (Offices). Source: Own elaboration

In these graphs, the yellow line represents the consumption profile of the Base Scenario, while the green line represents Scenario A.

In the case of residential customers, it can be observed that there is an advance in the consumption peak, as well as an increase in power consumption at 2 p.m. For offices, a clear advancement of the consumption peak can be seen (with almost the same power consumption), and consumption is less constant between 10 a.m. and 3 p.m.

In Figures 12 and 13, we can analyze whether these changes in consumption have solved the network problems observed before:

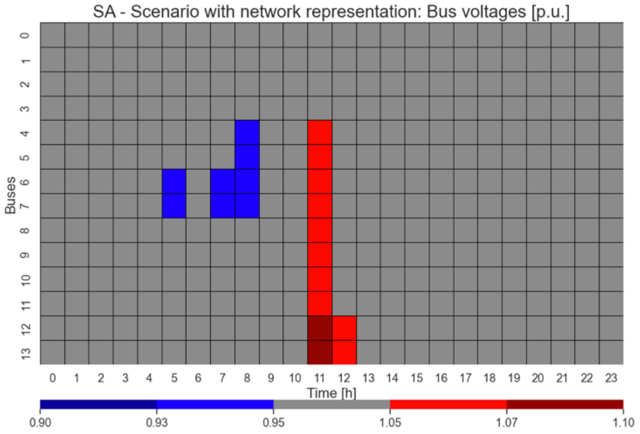

Figure 12: Network problems per bus and time | Scenario A (residential). Source: Own elaboration

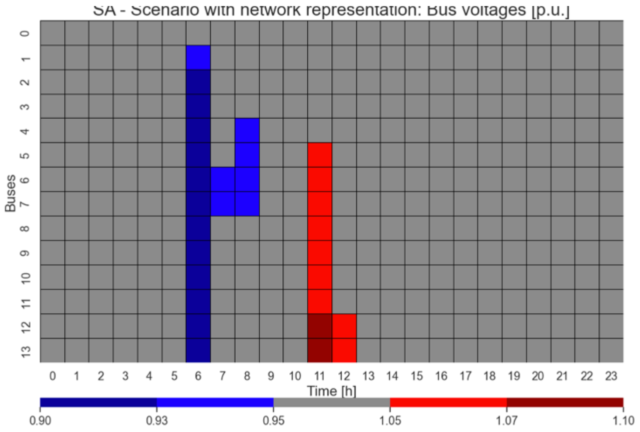

Figure 14: Network problems per bus and time | Scenario A (offices). Source: Own elaboration

Based on the Figures, we can indeed affirm that some of the network problems have been resolved to a certain extent.

Starting with the case of residential customers, thanks to the DR coefficients, the excess demand problems at 6 AM and 5 PM have been resolved (although new issues have appeared at 5 AM). Additionally, part of the overvoltage problems at 11 AM (reducing the intensity of red), 12 PM (bus 9), and all the issues at 2 PM have been addressed.

On the other hand, in the case of offices, part of the overvoltage problems at 11 PM has been resolved, specifically for buses 3 and 4, and the intensity of the red has been reduced. The issue at 2 PM for bus 13 has also been addressed. However, concerning the undervoltage problems, although the ones at 9 PM have been completely resolved, by advancing the consumption from 9 PM to 6 PM, the problems have shifted to that hour (and with greater intensity).

C. SCENARIO B: TARIFFS FOR DR BUT WITH LOCAL DIFFERENTIATION

In this latest scenario, similar to the previous one, demand response tariffs are considered. The difference is that in this Scenario, the location is considered. To achieve this, the network has been divided into two feeders (F0 and F1), each having distinct tariffs tailored to address specific issues observed in those groups of nodes during the Base Scenario. Feeder 0 covers nodes 2 to 7, while feeder 1 covers nodes 8 to 13.

When running the model with differentiated demand response tariffs based on feeders, the following results are obtained:

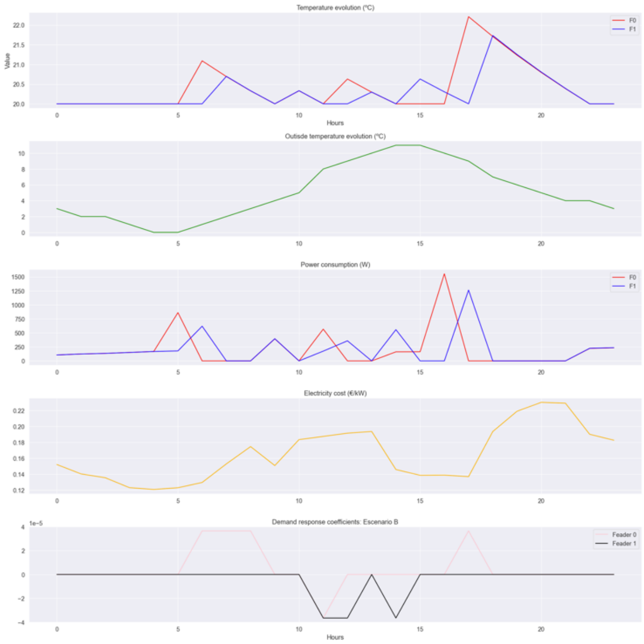

Figure 13: Summary heat pump modelling result | Scenario B (residential). Source: Own elaboration

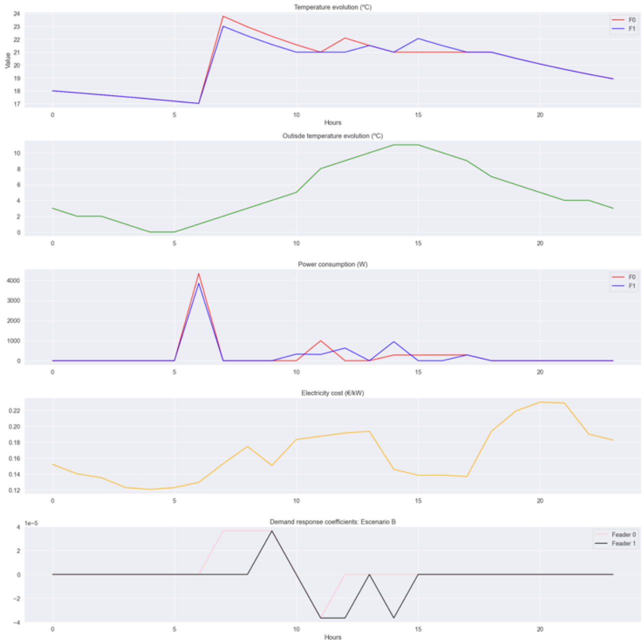

Figure 15: Summary heat pump modelling result | Scenario B (Offices). Source: Own elaboration

In Figures 14 and 15, the same information as in the previous scenarios is presented, but this time distinguishing between feeders for indoor temperature, power consumption, and tariffs. The red color represents Feeder F0, while the blue color represents Feeder F1.

In the case of residential customers, certain differences between the feeders can be observed, particularly in the fact that the consumption is more advanced in Feeder F0 than in F1. However, for offices, all the graphs are similar for both feeders.

In Figures 16 and 18, a more detailed view of these differences can be observed.

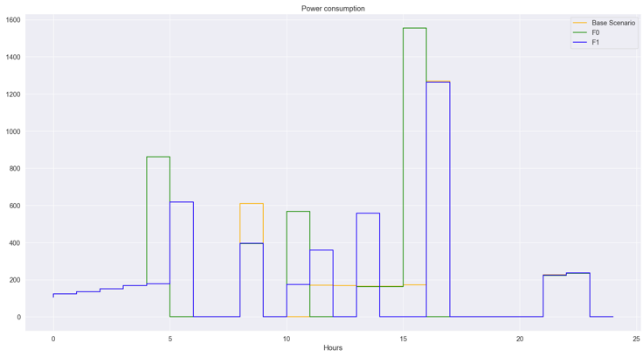

Figure 16: Comparison between consumption profiles | Scenario B vs Base Scenario (residential). Source: Own elaboration

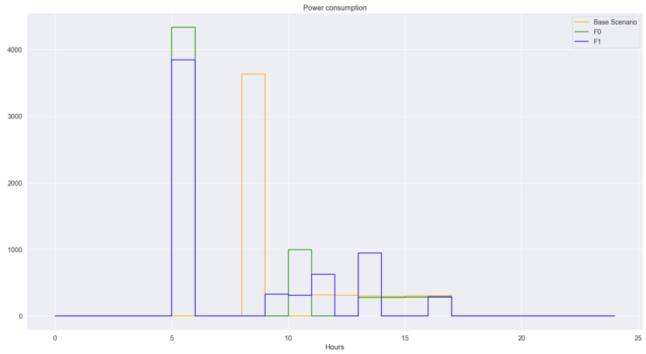

Figure 17: Comparison between consumption profiles | Scenario B vs Base Scenario (Offices). Source: Own elaboration

In these figures, yellow represents the consumption profile of the Base Scenario, while green corresponds to Feeder F0, and blue to Feeder F1.

Starting with the case of residential customers, unlike Scenario A where the consumption profile was entirely different from the Base Scenario, in this case, can be seen that none of the profiles entirely match the base, but they each coincide at different hours. These differences allow for greater adaptability to the specific problems of each group of nodes, enhancing the ability to address localized issues effectively.

On the other hand, in the case of offices, can be observed that there is not much difference between Feeder F0 and F1 (except for a distinction between 4 p.m. and 5 p.m.). Moreover, these consumption profiles are very similar to those obtained in Scenario A. This suggests that there hasn't been much adaptation by considering location in the tariff calculation.

In Figures 17 and 19, can be further observed whether the differentiation between feeders has resolved more issues.

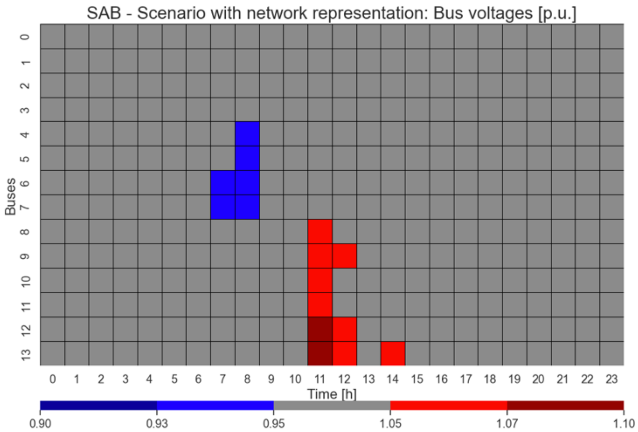

Figure 18: Network problems per bus and time | Scenario B – (residential). Source: Own elaboration

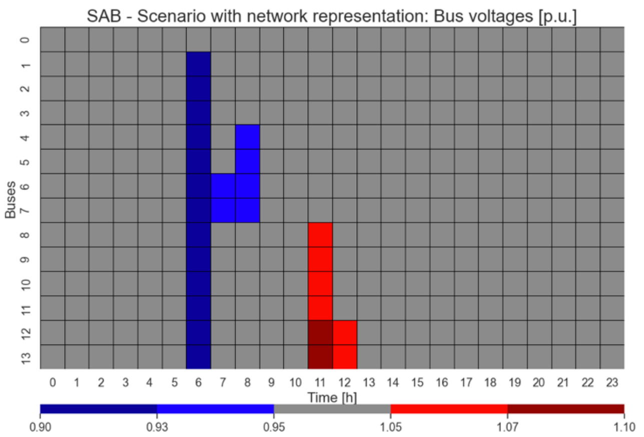

Figure 19: Network problems per bus and time | Scenario B – (Offices). Source: Own elaboration

Indeed, despite not resolving all the problems, it can be affirmed that using different tariffs for the two selected groups of nodes has resolved more issues than the scenario with a single tariff.

Starting with the case of residential customers, it can be seen that the excess demand (undervoltage) problems at 6 AM and 5 PM have been resolved, as well as a significant portion of the issues at 11 AM and half of those at 2 PM.

In the case of offices, the undervoltage problems have remained the same as in Scenario A, likely due to the absence of significant changes in consumption profiles. However, concerning the overvoltage problems, a substantial portion of them has been resolved (half of those at 11 PM and all of those at 2 PM).

VI. CONCLUSIONS

Based on the analysis conducted in the previous section regarding the resolution of network issues through the modeling of a heat pump operating in a network with demand response tariffs, this chapter aims to summarize the conclusions that have been reached.

Regarding the analysis conducted for residential customers, it has been observed that the best configuration has been the one that takes into account the node's location when calculating tariffs. This is because the higher level of detail allows for the application of accurate tariffs, leading to the resolution of a greater number of problems.

Regarding the case of offices, it has been noticed that the network problem resolution has been the same for both Scenario A, which uses a homogeneous tariff, and Scenario B, which differentiates tariffs based on node location. In this case, a lack of flexibility due to greater restrictions has limited the capacity to solve problems, particularly when dealing with undervoltage issues, as the overvoltage problems have remained almost unchanged.

Overall, the study demonstrated the potential of demand response solutions using heat pumps to address network problems. The results emphasized the importance of considering tariff structures, differentiating by node location, and being sensitive to tariff amounts to achieve optimal network performance. However, it was acknowledged that implementing granular tariffs based on location may present challenges. Further research and optimization efforts, such as incorporating other flexible service providers into the simulation, are necessary to fully address all network problems and maximize the benefits of flexibility markets.

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