UNIVERSIDAD PONTIFICIA COMILLAS

ESCUELA TÉCNICA SUPERIOR DE INGENIERÍA (ICAI)

OFFICIAL MASTER'S DEGREE IN THE ELECTRIC POWER INDUSTRY

Master’s Thesis

AN ANALYSIS OF THE ROLE OF DATA CENTERS AS FLEXIBLE ELECTRICITY CONSUMERS IN THE SPANISH POWER SYSTEM

Author: Patricia Rincón Hoyos

Telf: +34 674703519

Email: 201903115@alu.comillas.edu

Company: Endesa

Signature from student:

Supervisor: Javier Rodríguez Domínguez

Telf: +34 691513557

Email: vjavier.rodriguez@enel.com

Company: Endesa

Signature from supervisor:

Madrid, July 16th 2026

Firmado por VENANCIO JAVIER RODRIGUEZ DOMINGUEZ el día 17/07/2026 con un certificado emitido por AC Firmaprofesional - CUALIFICADOS

Master's Thesis Presentation Authorization

THE STUDENT:

Patricia Rincón Hoyos

THE SUPERVISOR

Javier Rodríguez Domínguez

Signed: …………………… Date: ……/ ……/ ……

Firmado por VENANCIO JAVIER RODRIGUEZ DOMINGUEZ el día 17/07/2026
con un certificado emitido por AC Firmaprofesional - CUALIFICADOS

Authorization of the Master's Thesis Coordinator

Dr. Luis Olmos Camacho

Signed: …………………… Date: ……/ ……/ ……

UNIVERSIDAD PONTIFICIA COMILLAS

ESCUELA TÉCNICA SUPERIOR DE INGENIERÍA (ICAI)

OFFICIAL MASTER'S DEGREE IN THE ELECTRIC POWER INDUSTRY

Master's Thesis

AN ANALYSIS OF THE ROLE OF DATA CENTERS AS FLEXIBLE ELECTRICITY CONSUMERS IN THE SPANISH POWER SYSTEM

Author: Patricia Rincón Hoyos

Telf: +34 674703519

Email: 201903115@alu.comillas.edu

Company: Endesa

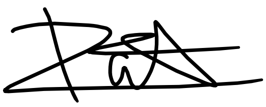
Supervisor: Javier Rodríguez Domínguez

Telf: +34 691513557

Email: vjavier.rodriguez@enel.com

Company: Endesa

Signature from student:



Madrid, July 16th 2026

Abstract

The rapid growth of data centers is creating new challenges for the electricity system. These facilities are essential for cloud computing, artificial intelligence, digital services and technological sovereignty, but they also represent large and concentrated electricity demand. In Spain, this issue is particularly relevant because data center deployment is taking place in a context of increasing grid congestion, limited access capacity, renewable integration and emerging regulatory requirements for large electricity consumers.

This thesis analyses the role of data centers as flexible electricity consumers in the Spanish power system. The aim is not to determine a single optimal design or to minimize costs, but to apply a Pareto-oriented approach that evaluates the trade-off between emissions reduction and economic impact. In particular, the thesis explores which ranges of flexibility requirements could be reasonable for a large data center if future regulation required these facilities to demonstrate emissions reduction, demand flexibility or compatibility with the electricity system, without imposing a disproportionate economic burden on the operator.

The study combines technical, regulatory and quantitative analysis. First, it reviews the energy structure of data centers, including IT load, cooling systems, auxiliary loads, thermal energy storage and battery energy storage systems. Then, it examines the Spanish regulatory context for grid access, flexible access capacity and sustainability requirements. Finally, it develops a hourly model of a representative hyperscale data center with a constant 100 MW IT load.

The model compares a baseline case with two energy storage-based flexibility scenarios: thermal energy storage linked to the cooling system and a battery energy storage system acting on the total net demand of the facility. Both technologies are operated according to hourly emissions intensity, shifting electricity consumption from higher-emission hours to lower-emission hours. The model uses twelve representative days, one for each month of the year, in order to capture seasonal variations in cooling demand, electricity prices and emissions intensity.

The results show that flexibility can reduce the induced emissions of a data center, but only under specific operating conditions. The reduction is not mainly achieved by lowering annual electricity consumption, but by changing when part of that electricity is consumed.

Thermal energy storage provides a limited but useful contribution, since it only affects the cooling component of the load. By contrast, BESS achieves higher emissions reductions because it can act on the full electricity profile of the data center, although it also involves higher investment costs, efficiency losses and greater economic uncertainty.

The thesis concludes that data centers should not be considered fully flexible resources, but neither should they be treated as completely rigid loads. From a regulatory perspective, the key question is not whether flexibility should be imposed without limits, but which technical configurations provide a reasonable balance between environmental benefits and economic impact. In this sense, storage and demand-side flexibility can improve the compatibility of data centers with decarbonization, renewable integration and future flexible access schemes, although they do not eliminate the need for grid capacity and network reinforcement.

Keywords: data centers, flexible demand, Pareto approach, electricity system, BESS, thermal energy storage, induced emissions, grid access, Spain.

Index

Figure index

Table index

Equation index

Chapter 1. INTRODUCTION

1.1 GENERAL CONTEXT

Digital infrastructure has become one of the fundamental pillars of modern economies and societies. The expansion of cloud computing, artificial intelligence, edge computing, digital services, online banking and e-commerce has increased the need to store, process and transmit large volumes of data with high reliability, low latency and efficient connectivity [1]. In this context, data centers have evolved from being a supporting infrastructure for corporate IT systems to becoming strategic assets for economic competitiveness, technological autonomy and digital dominance.

This transformation is particularly relevant in Europe, where data centers are increasingly seen as critical infrastructure for the digital economy and technological transformation [2]. Traditional European data center hubs such as Frankfurt, London, Amsterdam, Paris and Dublin, also known as FLAP-D, continue to play a central role, but growth is increasingly expanding towards Southern Europe due to better availability of land, renewable energy resources and international connectivity [2].

Spain plays a key role in this broad European transformation and expansion. Historically, the Spanish data center market was smaller and more enterprise oriented than the main European hubs. However, recent sectoral studies show that Spain is progressively becoming a relevant digital infrastructure hub, supported by its geographical position, renewable generation potential, land availability, submarine cables and growing demand for cloud and artificial intelligence services [2]. Madrid is consolidating its role as the main national and regional aggregation point, while other regions such as Aragón are gaining relevance for hyperscale campus developments, particularly where renewable energy availability and land conditions are favorable [3].

At the same time, this growth raises a fundamental question for the electricity system. Data centers are not only digital infrastructures, they are also large electricity consumers. Their development interacts directly with the energy transition, grid planning, renewable integration, electricity market design, environmental sustainability and permitting procedures. As data center capacity increases, their role must also be assessed from an energy system perspective, particularly in countries such as Spain, where the electricity system is congested due to the increasing pressure on network capacity and is undergoing a deep transformation driven by electrification, decarbonization and renewable deployment.

1.2 THE ENERGY CHALLENGE: LARGE NEW DEMANDS IN AN ELECTRICITY SYSTEM IN TRANSITION

The Spanish electricity system is currently facing two simultaneous challenges. On one hand, it must continue with the decarbonization strategy through the integration of renewable energy, storage and flexibility. On the other hand, it must accommodate new electricity demand associated with the electrification of transport, buildings, industry and digital infrastructure. The Royal Decree Law (RDL) 7/2026 frames electrification as a strategic tool to reduce fossil fuel dependence and price exposure to volatility, while also recognizing the need to guarantee agile access to electricity networks for new consumers and electrification projects [4].

In this context, RDL 7/2026 represents a relevant turning point for large electricity demand in Spain. The RDL does not only address the general need to accelerate electrification, but also introduces a new approach to demand access, especially relevant for large consumers such as data centers. This approach combines sustainability requirements, economic mechanisms to avoid the speculative reservation of grid capacity, and administrative tools aimed at prioritizing certain projects and ensuring that granted access capacity is effectively used. As a result, data center deployment is increasingly linked to the broader question of how scarce grid capacity should be allocated in a system undergoing rapid electrification.

This context is especially relevant for data centers because they require large amounts of firm electrical capacity, usually concentrated in specific locations and with high reliability requirements. Unlike many traditional electricity consumers, large scale data centers may request tens or hundreds of megawatts of capacity for a single project, creating a significant impact on grid access, connection capacity, network reinforcement needs and constraints. ENTSO-E published report in which they have highlighted that data centers are no longer niche consumers with predictable demand profiles, but increasingly relevant electricity loads whose behavior can affect secure grid operation [5].

However, the challenge is not only limited to electricity consumption. From a power system perspective, what matters is also where the data center is connected, how much capacity it reserves, whether it ramps up gradually or rapidly, whether it operates with a flat profile, and whether it can reduce or shift part of its demand under certain system conditions. All of these factors are key when requesting grid capacity and access and connection permits. ENTSO-E notes that access to power is becoming one of the sector's most frequent concerns, with connection delay times in constrained areas range from several years to more than a decade [5].

In addition, the integration challenge is not limited to the amount of firm capacity requested by the data center. Recent studies show that large AI-oriented data centers may behave as dynamic electrical loads, due to their high dependence on power electronics, UPS-based protection systems and fast variations in computational demand. Therefore, the system operator must also consider how these facilities behave during voltage dips, frequency deviations, rapid load ramps, disconnection events and subsequent reconnection to the grid. In this sense, the integration of data centers raises not only a capacity-allocation problem, but also a stability and robustness problem [6].

In Spain, this concern is reinforced by the debate around access and connection permits, stated in the Royal Decree (RD) 1183/2020. The regulatory framework for access and connection seeks to provide legal certainty, transparency and non-discriminatory treatment, while also avoiding inefficient or speculative use of grid capacity [7]. More recently, the Spanish regulatory debate has focused on how to allocate capacity for demand, how to define firm and flexible access conditions, and how to prevent grid capacity from being blocked by projects that do not end up materialized. This issue was recognized in the RDL 7/2026, which identified the existence of fully allocated nodes where part of the reserved capacity corresponds to projects that may not be executed, creating administrative congestion and slowing down electrification [4].

Therefore, the energy challenge caused by data centers is not simply that they consume huge amounts of electricity. The key issue is whether they are integrated into the electricity system as passive, rigid loads, or whether they can be designed and operated in a way that contributes to system efficiency, flexibility and decarbonization.

1.3 THE SPANISH DEBATE: DEMAND, EMISSIONS, SPECULATION AND GRID CONGESTION

The deployment of data centers in Spain has generated a complex public and regulatory debate, due to their strong presence and rapid increasing deployment. The Spanish data center association SpainDC, estimates that the Spanish commercial data center sector reached 439 MW of installed IT power by the end of 2025 and could reach 2.537 MW by 2030 under a continued growing scenario [1]. These numbers show the relevance data centers have on the system.

Due to this increasing demand and presence, data center growth raises concerns about electricity demand, grid congestion, environmental impact, water consumption, land use and the possible speculative reservation of grid capacity. In regions such as Aragón, the scale of announced investments is particularly significant. It is estimated that 2,900–3,400 MW of electricity demand are being considered to be installed in the region, adding up to 47 billion€ of planned or ongoing investments [3]. This illustrates the magnitude of the investments and energy implications associated with hyperscale data center deployment.

Therefore, the Spanish debate around data centers is not limited to their economic contribution or digital relevance. It is also a debate about access to scarce grid capacity, emissions, territorial impacts, decarbonization and the risk of speculative behavior in the reservation of electricity network capacity. RDL 7/2026 introduces a new model for demand access based on three main pillars: a framework of sustainability requirements for data centers to be developed through regulation, economic mechanisms such as the capacity reservation charge to discourage the blocking of grid capacity, and administrative instruments such as demand tenders, priority categories and new causes for permit expiry.

This means that the regulatory treatment of data centers is moving away from a purely ex-ante approach based only on obtaining an access and connection permit. Instead, the emerging model introduces a form of continuous control, in which the maintenance of the permit may depend on the effective use of capacity, the consistency between the declared activity and the actual use of the connection, and compliance with sustainability requirements. In the case of data centers, these requirements may include energy efficiency, water use, renewable electricity, territorial and socioeconomic contribution, and contribution to digital resilience and sovereignty. This evolution is particularly relevant for the thesis because it shows that the Spanish system is beginning to assess data centers not only as investment projects, but also as large electricity consumers whose integration must be justified from an energy system perspective.

In the case of Spain, data centers are seen as a harmful asset in the system, as the Government has the perception that, due to their large demand, data centers are going to increase the induced emissions due to the need of more fossil fuel generation to keep up with their expansion pace. Therefore, this negative opinion from the government creates issues in the deployment of data centers.

This context explains why data centers are currently subject to both opportunity and suspicion in Spain. They may contribute to digital competitiveness and economic development, but they also represent large new electricity demand in a system where grid capacity is increasingly valuable. Therefore, the central issue is whether data centers can be integrated in a way that is compatible with decarbonization, efficient network use and flexibility. This thesis addresses that question by analyzing data centers as potentially flexible electricity consumers rather than as purely rigid demand.

1.4 DATA CENTERS IN SPAIN

The Spanish data center market is becoming increasingly diversified from a territorial perspective. Madrid remains the main national hub, with 49 data centers according to a research conducted by Colliers, 175 MW IT of current supply and approximately 1,413 MW IT of estimated future supply [8]. Its role is supported by connectivity, existing cloud availability zones and business concentration, although growth is increasingly constrained by power availability in saturated areas such as Alcobendas. Recently, Merlin Properties announced an additional 150 MW IT campus in the south of Madrid.

Figure 1 shows the evolution of the installed capacity and expected installed capacity since 2022 until March 2026. Figure 2 shows the deployment of data centers in the region of Madrid. The northern area has a higher amount of data centers, however, it can also be seen how the southern region is increasingly gaining importance in the deployment. Even though this thesis focuses on large scale data centers, as they are the ones that create the greater impact, it must be said that nowadays in Spain most of the data centers are more enterprise or edge data centers, which have lower IT load values.

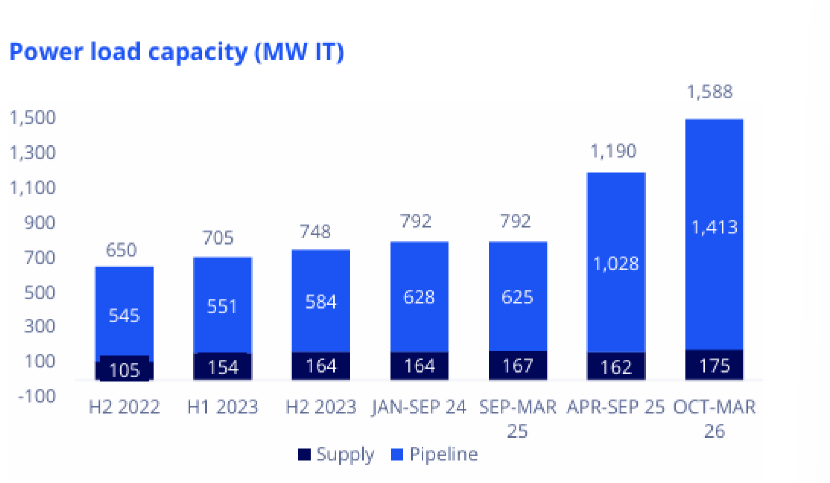


Figure 1. Power load capacity evolution in Madrid (Source: Colliers)

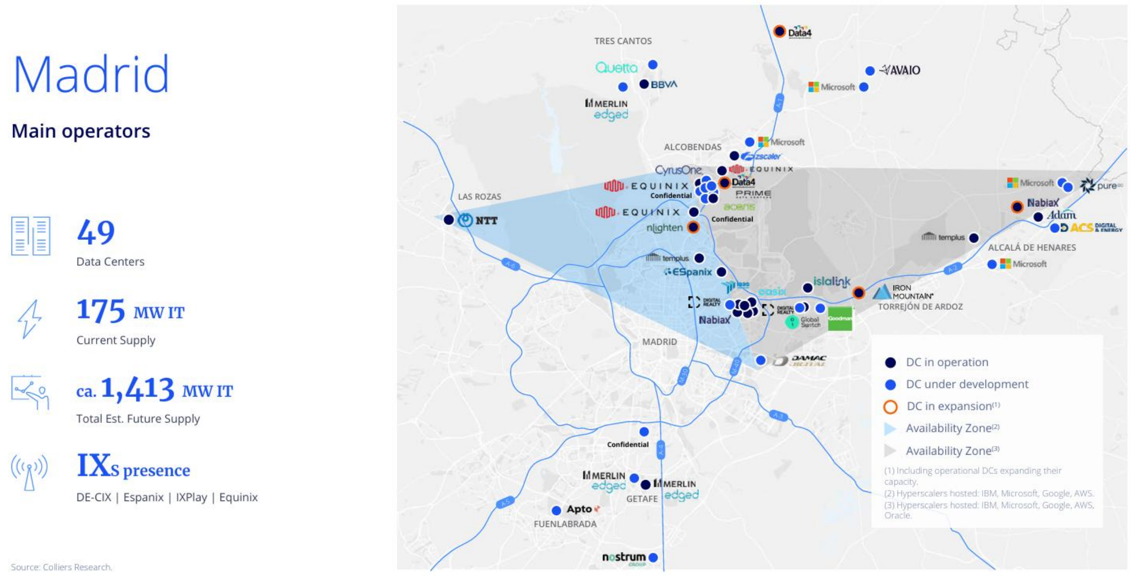


Figure 2.Data centers in Madrid (Source: Colliers)

Barcelona is also gaining relevance, although from a smaller operational base. The city currently has around 42 MW IT of supply and approximately 525 MW IT of estimated future supply [8]. Its growth is supported by submarine cable connectivity, new international operators and increasing AI-related demand. However, the market also shows the relevance of power constraints as some projects have had to reconsider their location or development strategy due to limitations in electricity access.

Aragón represents the clearest example of Spain's transition towards large-scale hyperscale and AI-oriented developments. The region currently has around 108 MW IT in operation, but its estimated future supply reaches approximately 3,461 MW IT. This makes Aragón one of the most significant potential data center hubs in Europe over the coming decade. The pipeline is driven by projects from operators such as AWS, Microsoft, QTS, Merlin Edged and Box2Bit, and is supported by land availability, renewable energy potential and large campus developments [8]. However, the materialization of this pipeline depends heavily on power availability and the execution of the required grid reinforcements.

The pipeline in Aragón comes from hyperscale campuses, with tens and hundreds of MW. This region is expected to host the biggest campuses in Spain.

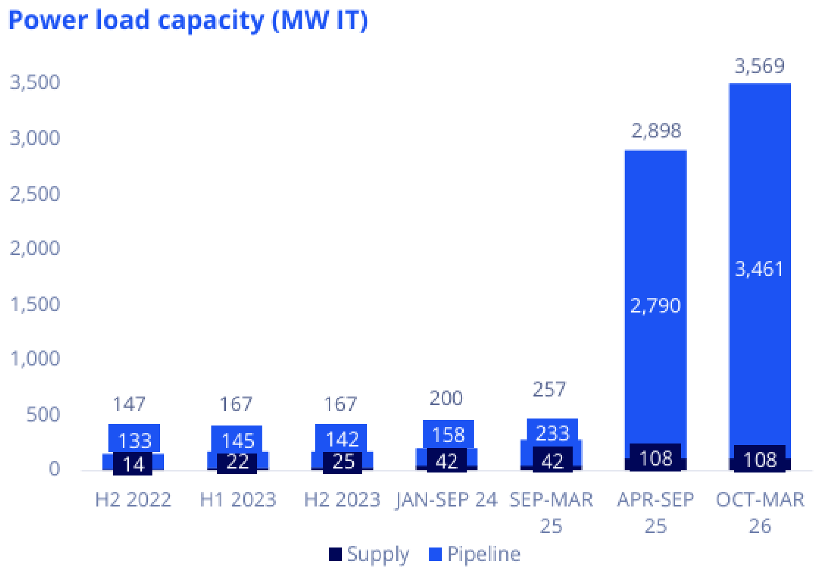


Figure 3. Power load capacity in Aragón (Source: Colliers)

Beyond Madrid, Barcelona and Aragón, data center development is also expanding into other Spanish corridors. These locations account for around 35 MW IT of current supply and approximately 5,755 MW IT of estimated future supply. The largest pipeline is concentrated in Extremadura, with around 3,128 MW IT, mainly driven by Merlin Edged projects, followed by the northern corridor with approximately 996 MW IT, Andalucía with around 832 MW IT and the central corridor with around 780 MW IT. This expansion shows that data centers are moving towards regions with renewable energy availability, industrial land and lower grid congestion, although many of these projects remain at an early stage and depend on securing power, permits and anchor demand.

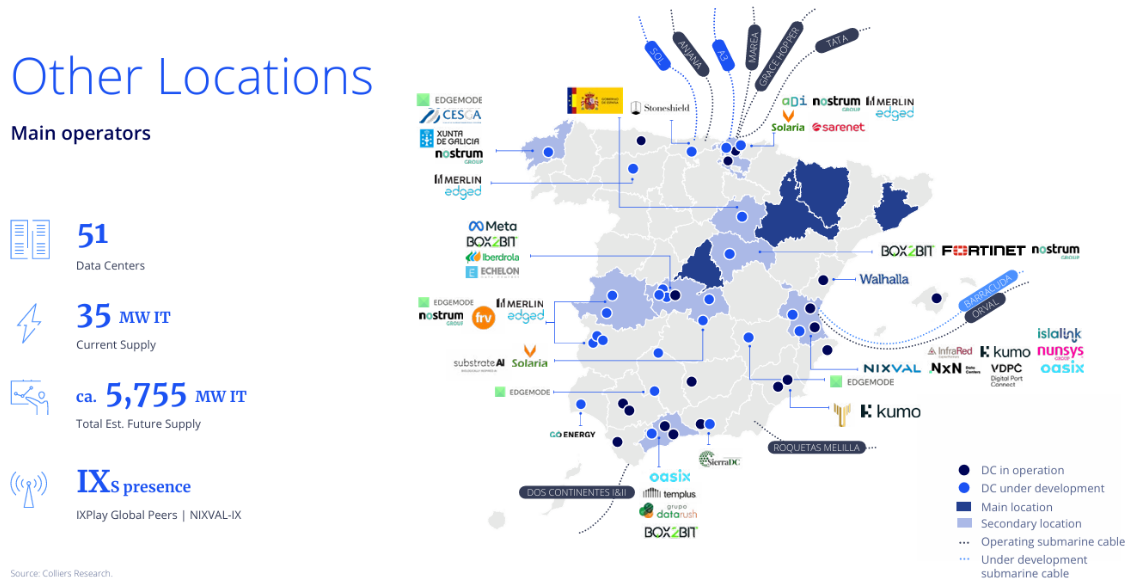


Figure 4. Data centers in Spain (Source: Colliers)

1.5 RESEARCH APPROACH AND OBJECTIVE OF THE THESIS: PARETO-ORIENTED ANALYSIS OF DATA CENTERS AS FLEXIBLE CONSUMERS

The main objective of this thesis is to analyze the role of data centers as flexible electricity consumers in the Spanish power system. Rather than treating the data center only as a new source of solid electricity demand, the thesis examines whether part of its consumption profile can be adapted to the needs of an electricity system in process of decarbonization and to lower the amount of CO_2 emissions they are responsible for. In addition, the thesis adopts a Pareto-oriented approach. The objective is not to identify a single optimal flexibility configuration, but to evaluate the trade-off between emissions reduction and economic impact. In this sense, the model aims to identify a reasonable range of values that could reduce the induced emissions of a data center without creating a disproportionate economic burden for the operator, especially in a future context in which regulation could require data centers to demonstrate flexibility, storage capacity or emissions-reduction capability.

The starting hypothesis is that data centers should not be analysed exclusively as large, inflexible loads. Although their operation requires high reliability and continuous power supply, they include technical systems and operational features that may provide flexibility under certain conditions. Cooling infrastructure, thermal energy storage (TES), battery energy storage systems (BESS), UPS systems and, in some cases, certain IT workloads may allow part of their electricity consumption to be shifted, reduced or managed in response to grid conditions, renewable availability, electricity prices or emissions signals [5].

This regulatory evolution reinforces the relevance of analyzing data centers as flexible consumers. If the Spanish framework is increasingly linking access to the grid with sustainability, efficient use of capacity and the avoidance of speculative reservation, then the technical ability of a data center to adapt part of its demand becomes relevant. Therefore, flexibility can be understood not only as an operational strategy to reduce emissions or electricity costs, but also as a potential element of regulatory acceptability in a context where large new consumers are expected to demonstrate that their connection is compatible with system constraints.

This hypothesis is aligned with the European view that flexibility on the demand side will play an increasingly important role in the electricity system, as if the agent requesting the capacity can provide flexibility services, they can be granted flexible connection arrangements, speeding up the waiting times. The European Network Code on Demand Connection is the baseline for this concept and recognizes demand response as an instrument to increase flexibility in the internal electricity market and to enable a more efficient use of electricity network.

Therefore, the thesis adopts a balanced perspective. It does not assume that data centers are automatically beneficial for the electricity system, nor that their deployment should be promoted without conditions. Instead, it explores whether their technical characteristics can be used to reduce their energy and environmental impact and to improve their compatibility with the Spanish electricity system. In this sense, the data center is analysed not only as a passive consumer connected to the grid, but as a potentially active demand resource.

This balanced perspective is also relevant from a grid-stability point of view. Although this thesis does not perform a dynamic stability simulation, recent literature indicates that data centers should not be evaluated only as large annual energy consumers, but also as large loads whose electrical behavior during disturbances may affect voltage stability, frequency response and power quality. Therefore, the flexibility mechanisms analysed in this thesis are mainly assessed from an emissions and cost perspective, but they may also be understood as part of a broader discussion on how data centers can become more compatible with secure grid operation.

To assess this question, the thesis develops a model of a representative large data center, more known as a hyperscale data center, and evaluates different operating scenarios. The baseline case represents the electricity consumption of the data center without flexibility. Additional scenarios introduce flexibility mechanisms such as thermal energy storage and battery energy storage systems. The purpose is to assess not only the potential emissions reduction associated with these technologies, but also the economic impact of requiring them. Therefore, the model is used as a Pareto-oriented tool to explore which ranges could be technically meaningful and economically acceptable if future regulation imposed certain obligations on data centers.

1.6 METHODOLOGY AND STRUCTURE OF THE THESIS

This thesis combines regulatory, technical and quantitative analysis. The first part of the thesis focuses on the energy behavior of data centers. The analysis considers the main components of electricity consumption in data centers and explains how each of them contributes to the load curve of a data center. This chapter includes the analysis of the metrics data centers use to characterize and report their energy consumption.

The second part of the work presents the context in which data centers are expanding, with particular attention to the European and Spanish markets, the role of data centers as strategic infrastructure, and the challenges created by their electricity demand. This includes the analysis of sectoral reports, European sustainability regulation, Spanish access and connection rules, and recent policy developments affecting demand access, flexible access and data center sustainability.

The third part focuses specifically on the flexibility potential of data centers and explores the mechanisms that can be applied, such as thermal energy storage and battery energy storage systems. The aim of introducing these mechanisms is to shift the time when electricity is consumed to reduce the emissions induced by the data center. It is also important to study to what extent these flexibility mechanisms have a regulatory guarantee of favoring data centers in the assignment of access and connection permits.

Finally, a model has been developed to quantify the impacts of the different flexibility scenarios and mechanisms. In this model, both approaches, TES and BESS have been compared to the baseline scenario in order to study the variation in the emissions and electricity costs.

In order to develop this thesis, several sources of information have been used. Research papers and academic literature have been consulted, as well as reports from companies and associations related to data centers. For the regulatory aspects, Spanish official documentation (Laws, Royal Decrees, Network Codes, etc) have been studied and used. There is also information used that comes from internal meetings with the regulatory team of Endesa, other departments of Endesa, interviews with individuals working directly in the data center sector and even meetings with data center promoters. Therefore, this variety of sources of information have enriched the development of the thesis, as information obtained from researchers has been contrasted and validated with real and reliable data center conducts.

Overall, the thesis aims to connect three dimensions that are often analysed separately: the growth of data centers as strategic digital infrastructure, the increasing difficulty of accessing electricity grid capacity in Spain, and the technical potential of demand side flexibility. By linking these dimensions, the thesis contributes to the debate on how data centers can be integrated into the Spanish electricity system in a way that is not only economically attractive, but also compatible with decarbonization, grid efficiency and sustainable electrification.

Chapter 2. STATE OF THE ART

2.1 DATA CENTERS AS A NEW STRATEGIC ENERGY DEMAND

Data centers have become one of the most visible energy implications of the digital transition. The expansion of cloud computing, artificial intelligence, edge computing, 5G, connected devices and digital public and private services is increasing the need for infrastructure capable of storing, processing and transferring large volumes of data with high reliability and low latency. In this context, data centers are no longer only a technical component of the digital economy, they are becoming strategic infrastructure for economic competitiveness, cybersecurity, digital sovereignty and the continuity of essential services.

This transformation has a direct energy dimension. According to the International Energy Agency, global electricity consumption from data centers is projected to more than double and reach around 945 TWh by 2030 in its base case, driven mainly by artificial intelligence and the growing use of digital services [10]. Although data centers still represent a relatively limited share of global electricity demand, their growth rate is significantly higher than that of many other sectors. Therefore, the energy relevance of data centers lies not only in their absolute consumption, but also in the speed of growth, the concentration of demand in specific locations and the size of individual connection requests.

Almost half of the expected electricity consumption in 2030 comes from data centers located in the United States. Nowadays, United States has the most installed capacity, followed by China and then Europe. In total, as it can be seen in Figure 5, United States and China will represent around the 75% of the total installed capacity worldwide. This represents the strong presence of data centers in these countries and the level of involvement these countries have in the deployment of data centers into their systems.

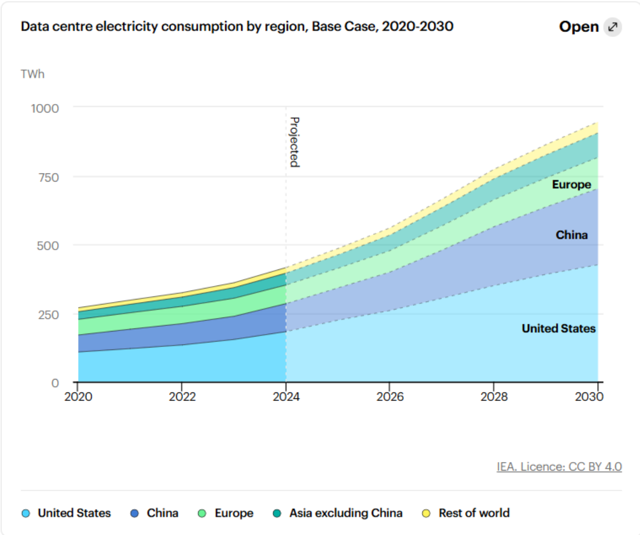


Figure 5. Data center electricity consumption by region (Source: IEA)

2.1.1 DATA CENTERS IN THE EUROPEAN CONTEXT

At European level, the data center sector is undergoing a structural transformation. As it can be seen on Figure 6, data center estimated electricity demand is expected to keep growing at a fast rate in the next five to ten years. The ENTSO-E data center report estimates that there are over 10,500 data center facilities in Europe, which by the end of 2025 had a total capacity of 12,7 GW of IT load [5].

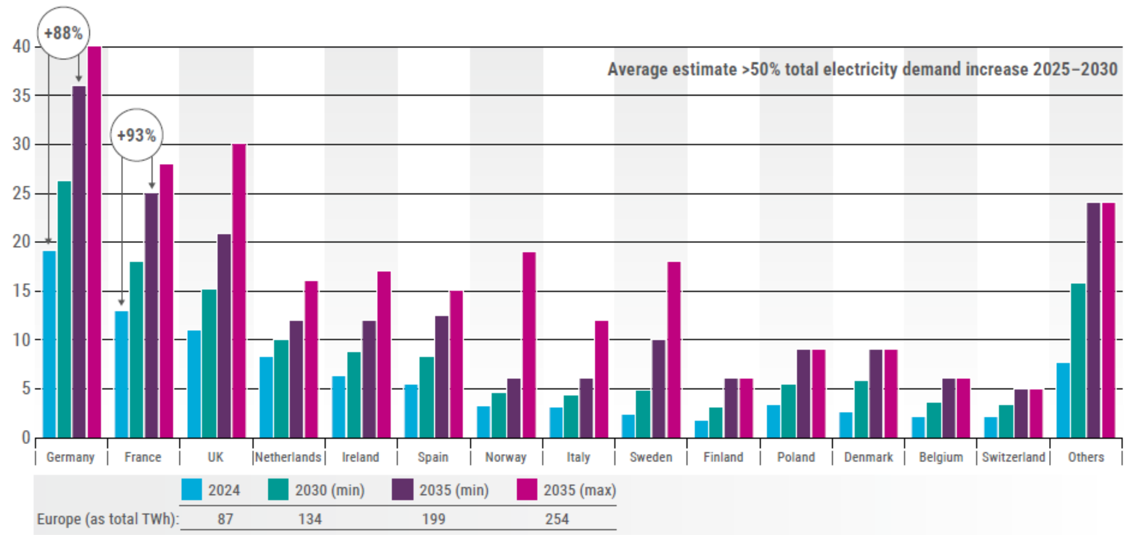


Figure 6. Estimated total data center electricity demand by country (Source: ENTSO-E Data center report)

The traditional FLAP-D markets — Frankfurt, London, Amsterdam, Paris and Dublin — remain the main locations to the European digital infrastructure, but the growth of data centers is increasingly moving beyond these established hubs. The expansion of artificial intelligence, cloud adoption and digital sovereignty requirements is encouraging new data center developments mainly in Southern Europe and the Nordics. This geographical shift is partly explained by the search for available land, energy access, renewable electricity, favorable climate conditions and stronger connectivity routes [2].

Table 1 shows the expected capacity by 2026 in the main European hubs for data centers.

FLAP-D city	***Expected capacity (MW)***
Frankfurt	2.800
London	3.500
Amsterdam	1.200
Paris	1.800
Dublin	1.600

Table 1. FLAP-D expected capacity (Source: Fundación San Basilio report)

Recalling the expected capacities for Madrid and Aragon, which were 1.413 MW and 3.461 MW respectively, it can be seen how these two Spanish hubs are increasing their expected installed capacity, competing fiercely with the European hubs, showing the strong growth expected in Spain.

The Irish case illustrates how quickly this type of demand can become systemically relevant. According to Ireland's Central Statistics Office, data centers increased their share of metered electricity consumption from 5% in 2015 to 22% in 2024 [11]. Over the same period, their electricity consumption increased from 290 GWh in the first quarter of 2015 to 1,829 GWh in the fourth quarter of 2024 [12]. Ireland is, therefore, a useful example of how data center growth can move from being a sectoral issue to becoming a central electricity-system planning concern within less than a decade. The regulatory response has had to evolve. The Irish Commission for Regulation of Utilities (CRU) has adopted a specific connection policy for data centers and other large energy users, including obligations linked to additional renewable electricity and demand flexibility [13]. This confirms that, in some European systems, data centers are already being regulated not only as digital infrastructure, but as large strategic electricity consumers.

The European Union has also recognized that the growth of data centers must be addressed from an energy and sustainability perspective. Delegated Regulation (EU) 2024/1364 establishes a common EU framework for assessing the sustainability of data centers through indicators related to energy consumption, electricity use, temperature settings, waste heat, water use and renewable energy [14]. In parallel, the European Commission has created a reporting framework and database for data centers with significant energy consumption, reinforcing the idea that the sector requires comparable and transparent energy-performance information [15]. This regulatory development reflects the fact that their environmental performance must be measured and monitored.

2.1.2 Data centers in the Spanish context

Spain is increasingly positioned within this European transformation. The country has several structural advantages that support the development of data centers such as a strong fiber network, an expanding submarine cable ecosystem, a strategic geographical position between Europe, Latin America and North Africa, and a high potential for renewable electricity generation. These factors make Spain attractive for cloud, artificial intelligence and digital infrastructure investment, especially since some of the traditional European hubs face limitations related to land availability, grid access and permitting complexity.

The growth of data center deployment is not only linked to the supply of data center capacity, but also to the demand for digital services across the Spanish economy. The Spanish data center association SpainDC identifies sectors such as communications, media and technology, financial services, public administration, healthcare, energy, education, retail, manufacturing and transport as relevant users of data center infrastructure [1]. These sectors depend on data centers for cloud services, real-time transactions, cybersecurity, data storage, digital administration, smart grids, logistics optimization and artificial intelligence applications.

From an electricity-system perspective, the strategic relevance of data centers depends on their scale, location and connection requirements. Unlike many conventional consumers, large data center campuses may require very high levels of firm capacity in specific grid nodes. This means that the challenge is not limited to annual electricity consumption, but also includes issues related with available grid capacity, connection lead times and the ability of the network to accommodate new large loads. In Spain, the Spanish transmission system operator, Red Eléctrica has published demand access capacity information for the transmission grid, indicating that capacity for new demand is available only in part of the transmission network. This shows that the issue is not simply whether Spain has enough electricity generation in aggregate, but whether the grid has available capacity in the specific locations where large new consumers want to connect.

This is precisely the context in which RDL 7/2026 becomes relevant. The Spanish regulatory framework is beginning to treat large new electricity demands, including data centers, as consumers whose access to the grid must be compatible with network planning, sustainability and the efficient use of available capacity. The RDL introduces a new model for demand access based on three elements: sustainability requirements to be developed by regulation, economic mechanisms such as a capacity reservation charge to discourage speculative blocking of grid capacity, and administrative instruments such as priority categories, demand tenders and new causes for permit expiry [4].

2.2 ENERGY SYSTEM IMPLICATIONS OF DATA CENTER GROWTH

The impact of data centers on the electricity system cannot be assessed only through annual electricity consumption. From a power-system perspective, the key variables are the amount of capacity requested, the location of the connection point, the firmness and quality of supply required, the behavior of the facility during disturbances, and the extent to which part of its demand can be managed. Therefore data centers are relevant not only because they consume electricity, but because they may concentrate very large loads in specific grid nodes and require high reliability conditions [5].

Large data center campuses can request tens or hundreds of megawatts in a single location, which may create pressure on substations, transmission-distribution grids and might require adapting the reinforcement plans. In Spain, one of the main bottlenecks is the access to power due to the lack of available capacity.

2.2.1 COMPARISON WITH ELECTRO-INTENSIVE INDUSTRIES

Going beyond, despite being high electricity consumers, they should not be simply compared to traditional electro-intensive industries such as metallurgy or chemical industries due to the differences in the consumption needs and flexibility. In Spain, the industry represents a significant share of national electricity consumption, around one third of final electricity consumption, with approximately 67 TWh out of 223 TWh in 2023. These industries operate normally with stable and continuous profiles due to their high electricity requirements. It is estimated that metallurgy sector has around 5,100-6,900 of full load operating hours, 5,000–6,600 for paper, 5,400–5,900 for chemicals, 4,200–5,900 for food and 4,300–5,000 for cement [16]. These industries need firm and reliable electricity because their production processes are physically continuous as stopping a furnace, a chemical process, a paper machine or a cement line can reduce efficiency, interrupt production or generate significant costs.

In this sense, data centers share with several energy-intensive industries a high, continuous and firm electricity demand profile. However, their economic nature is different. While sectors such as metallurgy, chemicals, cement or paper use electricity as a direct input in physical production processes, data centers provide digital services that are highly capital- and infrastructure-intensive. Traditional energy-intensive industries usually operate in global commodity markets, are often price-takers and have limited ability to pass through energy cost increases to final prices without losing competitiveness. For this reason, they are highly exposed to electricity and gas prices, since energy cost increases can directly reduce margins, production volumes and international competitiveness. On the contrary, the data centers do not have a deep concern regarding electricity prices. The European institutions do not classify data centers as traditional energy-intensive industries. This distinction matters as the economic exposure and technical flexibility are not the same as those of a steel plant, chemical facility or paper mill.

The difference is especially relevant for flexibility. Traditional electro-intensive industries may have relatively flat load profiles, but their ability to shift consumption is often constrained by the physical continuity of production, thermal inertia and process efficiency. In many cases, reducing electricity consumption implies reducing output, interrupting a production line or operating outside optimal technical conditions. In a data center, the IT load also has strict continuity requirements, especially for real-time, mission-critical and latency-sensitive services. However, other elements of the facility such as cooling systems, thermal storage, batteries, UPS infrastructure and some non-real-time workloads may allow partial demand management without necessarily interrupting the digital service [2]. Therefore, the question is not whether the whole data center is flexible, but whether part of its net electricity demand can be shifted or modulated.

In economical terms, the behavior of data centers and electro intensive industries differs substantially. According to a meeting with a data center promoter, they stated that the cost of electricity represents around 40% of the total costs for a data center. In electro intensive industries, the impact of energy costs is assessed in relation to the operating profit rather than OPEX. According to the report of Deloitte on the competitiveness of the industry, energy costs represent on average 25% of the operating profit. However, in some sectors such as chemicals, ceramics, cement, glass, stone and paper this ratio exceeds 35%, and may reach around 95% in metallurgy [16].

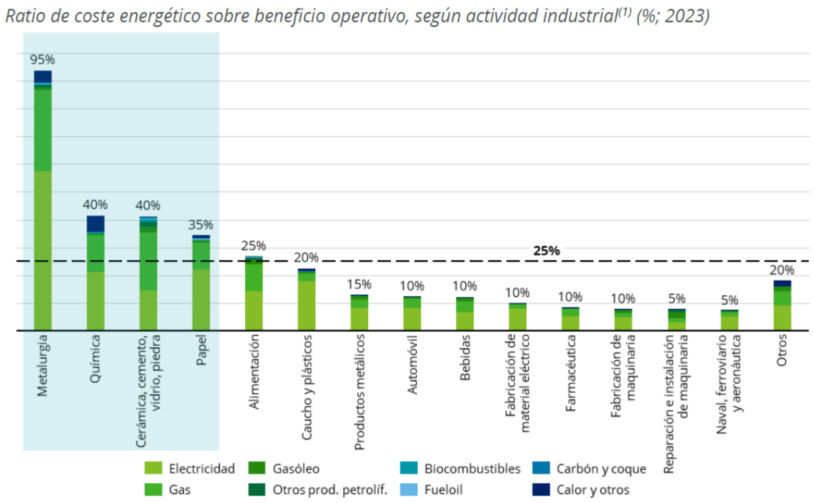


Figure 7. Ratio of energy costs to operational profit (Source: Deloitte)

In addition, electricity represents around 55% of total industrial energy expenditure on average, and in some sectors, it can exceed 80%. Therefore, although both data centers and electro intensive industries are highly exposed to electricity prices, the economic meaning of that exposure is different. In data centers, electricity is a major operating cost, whereas in energy intensive industries it can directly erode production margins, competitiveness and the ability to remain active in internationally exposed markets. Therefore, energy intensive industries are more sensitive to electricity and energy price increases, as they can account for significant losses and reduce the profitability of the business.

The following figure shows how the energy costs for these industries rose significantly in 2022, mainly due to the conflict occurring in Ukraine, which lead to the increase in gas and electricity costs. This price shock is relevant because it illustrates the higher short-term elasticity of energy-intensive industries to energy costs.

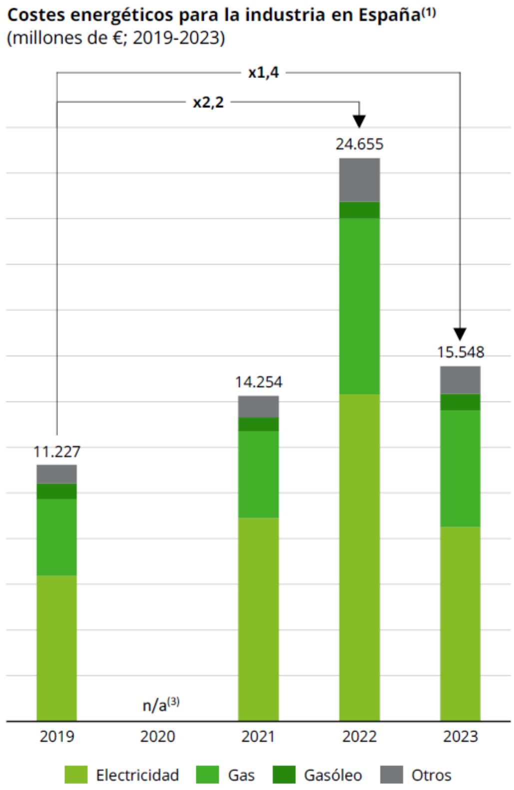


Figure 8. Energy costs by year (Source: Deloitte)

2.2.2 DEMAND IMPACT, SYSTEM STABILITY AND EMISSIONS

Data center demand is also heterogeneous. Edge data centers must be located close to the final users to reduce latency, which tends to place them in urban or metropolitan areas where land and grid capacity may already be constrained. By contrast, compute-intensive facilities, such as those dedicated to AI training or batch processing, may have more geographical and operational flexibility. These facilities can, in principle, be located where renewable generation, land availability or grid capacity are more favorable [1]. This means that the system impact of a latency-sensitive urban data center is not the same as that of a more flexible computing campus located near available renewable resources or grid capacity.

Another implication concerns system stability. Modern data centers rely heavily on power-electronics-based equipment, including UPS systems, converters, servers and cooling infrastructure. UPS-based architectures may disconnect large amounts of demand during minor grid disturbances, potentially amplifying power-quality and system-security problems

[2]. In Spain, the National Comision for Markets and Competence, known as CNMC, has also highlighted the relevance of demand robustness as the dynamic criterion could significantly reduce available access capacity in many transmission nodes if large power-electronics-based loads, such as data centers or electrolyzers, are not able to withstand voltage dips without disconnecting [17]. Robustness is not only a technical requirement, but also a factor that can affect how much demand the network can safely accommodate. A big concern regarding data centers or big consumers in general is that, if they disconnect suddenly, they can create and amplify disturbances in the grid, leading to bigger disturbances compromising the grid stability and security.

This concern is reinforced by recent research on AI-oriented data centers, which identifies them as a new type of large and dynamic digital load [18]. Unlike traditional industrial demand, these facilities may combine a high and continuous baseline consumption with fast variations caused by AI training, inference, workload scheduling and GPU synchronization. These variations can appear as rapid ramps, short power pulses or periodic fluctuations, and may interact with voltage and frequency dynamics in the power system [19]. Therefore, the system impact of a data center depends not only on its requested MW, but also on the speed, magnitude and predictability of its load variations.

Moreover, the use of UPS systems and internal protection schemes can create a tension between the reliability of the individual facility and the reliability of the wider power system [6]. From the data center operator's perspective, disconnecting from the grid during a voltage dip or frequency disturbance protects sensitive IT equipment [20]. However, from the system perspective, the sudden disconnection of hundreds of MW of demand can aggravate the disturbance, producing voltage variations, frequency deviations or even cascading disconnections in areas with high data center concentration [6]. This explains why robustness during disturbances and fault-ride-through capability are becoming increasingly relevant in the assessment of large data center connections.

Finally, the emissions impact of a data center depends on when electricity is consumed. In a power system with high renewable penetration, the carbon intensity of electricity varies over hours depending on renewable output and the marginal generation technology. A data center consuming during hours of high renewable production may induce lower emissions than the same facility consuming during hours when fossil generation is needed. This hourly dimension is central to the thesis as if part of the data center's consumption can be shifted towards lower-emission hours, its annual electricity demand may have a lower climate impact.

This issue is especially relevant in Spain. As it has already been mentioned, one of the biggest concerns of the Spanish government regarding data centers is the concern about increasing the induced emissions. The government believes that, as data centers suppose a big increase in demand, the system will need to accompany this increase by having to dispatch more fossil fuel generation. This belief goes against the energy transition, as the main goal is decarbonization and they believe data centers will go against it. This issue will be addressed in following sections.

In summary, data centers create specific energy-system challenges because they combine large and concentrated connection requests, high reliability needs, power-electronics-based behavior and emissions that depend on the timing of consumption. Compared with traditional electro-intensive industries, their demand is also different in economic function, location drivers and potential sources of flexibility. This duality explains why data centers are challenging loads for the electricity system, but also why they may become more compatible with the energy transition if their connection and operation incorporate robustness, flexibility and sustainability criteria.

2.3 REGULATORY FRAMEWORK FOR DEMAND ACCESS, CONNECTION AND SUSTAINABILITY

Data centers are subject to several provisions of the Spanish electricity sector regulation that applies to electricity consumers connected to the transmission and distribution networks. Data centers are subject, on the one hand, to the general provisions of the Spanish electricity sector regulation applicable to large electricity consumers and, on the other hand, to specific or recently introduced provisions that have a particularly significant impact on their development. Therefore, this section briefly presents the general rules governing electricity demand and access to the networks, while placing greater emphasis on the regulatory measures specifically affecting data centers and other large demand facilities.

First, Law 24/2013 of the Electricity Sector establishes the general principles of the electricity system, including security and quality of supply, electricity planning, third-party access to networks, access and connection rights, demand management and flexibility. Second, the Royal Decree 1183/2020 develops the general procedure for access and connection to transmission and distribution networks. Third, the CNMC Circular 1/2024 introduces the specific methodology and conditions for demand access and connection, including the distinction between firm and flexible access capacity. These national rules are complemented by the European Demand Connection Network Code and, more recently, by Royal Decree Law 7/2026, which introduces a new framework for large electricity demand based on sustainability requirements, capacity reservation mechanisms, administrative prioritization, demand tenders and new causes for permit expiry.

This regulatory framework is especially relevant for data centers because their connection to the grid is no longer a purely administrative matter. Large data centers may require tens or hundreds of megawatts of capacity in specific nodes, may compete with other electrification projects for scarce network capacity, and may require high levels of firmness, quality and continuity of supply. As a result, their regulatory treatment increasingly combines access rights, technical access criteria, efficient use of network capacity, project firmness, technical robustness and sustainability performance.

2.3.1 LAW 24/2013: GENERAL PRINCIPLES OF THE ELECTRICITY SYSTEM

Law 24/2013 of the Electricity Sector provides the legal basis for the Spanish electricity system. Its objective is to regulate the electricity sector in order to guarantee electricity supply under conditions of security, quality, efficiency, objectivity, transparency and minimum cost. It also recognizes electricity supply as a service of general economic interest, which explains why the connection of large new consumers must be assessed not only from the perspective of private investment, but also from the perspective of system security and public interest [21].

The law is relevant for data centers for several reasons. First, it establishes the general right of consumers to access and connect to transmission and distribution networks, but always under the conditions established by law and regulation. This means that access is a regulated right, not an unconditional entitlement to use network capacity in any location or under any technical condition. Second, the law identifies access to networks as one of the pillars of the electricity system, linked to the guarantee of supply and to effective competition. It requires access and connection to be granted under principles of objectivity, transparency and non-discrimination, and to be denied only on technical grounds [21].

Law 24/2013 also gives particular relevance to electricity planning. The planning of the transmission network must anticipate future electricity demand and define the network investments required to guarantee long-term security of supply. This is directly relevant for data centers, because large new demand may require new substations, new transmission positions, reinforcement of existing assets or changes in the intended use of planned infrastructure. The consolidated version of the law now includes mechanisms to adapt transmission planning to new demand, including the possibility of incorporating or modifying positions for demand supply when projects demonstrate maturity and firmness [21].

2.3.2 ROYAL DECREE 1183/2020: GENERAL ACCESS AND CONNECTION PROCEDURE

Royal Decree 1183/2020 develops the access and connection regime established in Article 33 of Law 24/2013. It provides the general procedural framework for obtaining access and connection permits to the transmission and distribution networks. The decree defines the concepts of access capacity, connection point, access permit and connection permit, and regulates the procedure for applications, admission, evaluation, proposal, acceptance, guarantees, contracts and expiry of permits [7].

The distinction between access and connection is central. Access refers to the right to use the network under certain technical and economic conditions, while connection refers to the physical connection of the facility to a specific point of the network. For data centers and other large consumers, both dimensions are essential. A project may need sufficient access capacity to consume the requested power, but it also needs a technically viable connection solution, including the necessary electrical infrastructure and connection works.

Royal Decree 1183/2020 also establishes the principle of chronological priority, or temporal precedence, which is commonly known as the first-come, first-served approach in the processing of access and connection applications. However, this rule is not absolute, because applications must still meet technical requirements and may be affected by specific procedures, exemptions, capacity tenders or later regulatory developments. In practice, the decree provides the general procedural skeleton, while the detailed technical and methodological criteria are developed by the CNMC circulars and specifications.

For data centers, the decree is relevant because it determines when a demand project must request access and connection permits, what guarantees and procedural milestones are required, and when permits may expire. It also provides the basis for subsequent regulatory developments that seek to prevent the speculative reservation of capacity, a concern that becomes particularly important when large demand projects request capacity in constrained nodes but do not materialize within the expected timeframe.

2.3.3 CNMC Circular 1/2024: Methodology for Demand Access and Connection

CNMC Circular 1/2024 is one of the key instruments for data centers because it establishes the methodology and conditions for access and connection to transmission and distribution networks for facilities that demand electricity from the grid.

The circular is particularly important because it introduces a change of paradigm in the treatment of demand. Until its adoption, the regulatory framework was based on the idea that supply to consumers had to be guaranteed at all times. Circular 1/2024 maintains the possibility of access with full guarantee of supply for conventional consumers, but it also allows some demand facilities to opt voluntarily for flexible access. This creates a new regulatory category that is directly relevant for large consumers such as data centers, especially where firm capacity is scarce [22].

Circular 1/2024 distinguishes between firm or ordinary access capacity and flexible access capacity. Firm access capacity is defined as the maximum active power that can be supplied with guarantee of supply during all hours of the year. Flexible access capacity, by contrast, is capacity for which the requirements of firm access are not fully met, because supply is not guaranteed during all hours of the year. To be granted flexible access, the network capacity study must determine that the installation can be supplied during a minimum proportion of the hours of the year. This type of access is voluntary and is intended for consumers willing to accept potential restrictions on supply during certain periods. However, it cannot be requested by installations whose supply must be guaranteed under the applicable regulatory framework [22].

This distinction is central for data centers. On the one hand, data centers usually require high continuity and quality of supply, which makes firm access highly valuable. On the other hand, where firm access is not available or would require long reinforcement periods, flexible access may offer an alternative pathway for phased connection, provided that operational restrictions are predictable, technically manageable and compatible with the facility's reliability requirements.

Circular 1/2024 also regulates the content of access and connection applications. Applicants may request firm and flexible capacity simultaneously and must provide technical information proportional to the power requested and the voltage level of connection. The network operator must assess whether the request affects another network, whether there is access capacity, and whether the connection is technically viable. Where a distribution connected demand has influence on the transmission network or on another upstream network, an acceptability report from the upstream network operator may be required [22].

The proposal issued by the network operator must include both technical and economic conditions. From a technical perspective, it must identify the access capacity granted, distinguishing between firm and flexible capacity, the connection point, voltage level, location, maximum and minimum short-circuit power, technical restrictions, quality-of-service requirements and, where relevant, the control devices associated with flexible access. From an economic perspective, it must include the costs to be borne by the applicant, including connection works and, for flexible access, the costs of reinforcement or devices needed to manage flexible capacity [22]

Finally, Circular 1/2024 regulates refusal and revocation. Access may only be denied due to lack of access capacity, and connection may only be denied if the network owner justifies the technical infeasibility of the connection. In both cases, the refusal must be accompanied by a justified report containing the data, references and calculations supporting the decision. Permits may also be revoked for breach of the technical or economic conditions included in the permits. For data centers, this reinforces the importance of both technical compliance and the credibility of the requested capacity [22].

2.3.4 DETAILED SPECIFICATIONS AND TECHNICAL ACCESS CRITERIA FOR DEMAND CAPACITY

Circular 1/2024 establishes the general methodology for demand access and connection, however the practical calculation of available demand capacity is developed through detailed specifications approved by the CNMC. These specifications translate the general principles of the Circular into concrete technical criteria for determining whether a demand facility can be connected to the transmission or distribution networks. In the case of transmission connected demand, or distribution connected demand requiring an acceptability report from the transmission system operator, the relevant document is the CNMC Resolution of 1 December 2025, which approves the detailed specifications for determining demand access capacity in the transmission grid [23]. The Circular itself anticipates this structure: it states that the evaluation of demand access capacity must be based on technical criteria of security, regularity and quality of supply, and that the detailed specifications will further develop the criteria for capacity assessment.

The detailed specifications make the access process more technical and evidence based. A data center project cannot be assessed only by the amount of capacity requested or by its position in the application queue. The relevant question is whether the grid can safely accommodate that demand under the applicable security criteria. In the transmission network, three criteria are particularly important for large demand: the static criterion, the short-circuit power criterion and the dynamic criterion. Circular 1/2024 already states that the access study must incorporate criteria associated with short-circuit power, static and dynamic stability of the network and power-quality conditions, while the detailed specifications develop how these criteria are applied in practice.

The static criterion assesses whether the additional demand can be supplied without causing overloads or voltage violations in the network under the relevant operating conditions. In other words, it evaluates whether the existing and planned network can transport the requested electricity to the connection point while maintaining secure operating limits. This criterion is linked to the steady-state behavior of the grid: line loading, transformer loading, voltage levels and the ability of the system to supply the demand under normal and relevant contingency conditions. For data centers, this criterion matters because a large load may create congestion not only at the point of connection, but also in upstream elements of the transmission or distribution network.

The short-circuit power criterion focuses on the electrical strength of the network at the connection point. A strong grid has sufficient short-circuit power to maintain voltage stability and power quality when large facilities connect or when disturbances occur. This criterion is particularly relevant for demand connected through power electronics, referred to in the Spanish specifications as CEP. Data centers fall within this category because a significant part of their internal electrical architecture depends on power-electronics-based equipment, including UPS systems, converters, server power supplies and cooling equipment.

The dynamic criterion evaluates the behavior of the power system during transient disturbances, especially voltage dips caused by faults in the transmission network. Unlike the static criterion, which focuses on steady-state operating conditions, the dynamic criterion examines whether the system remains stable during and after a disturbance. For large demand facilities, the critical issue is whether they remain connected and recover correctly after voltage dips, rather than disconnecting simultaneously and suddenly reducing demand. A massive disconnection of demand during a disturbance can aggravate system instability and affect frequency, voltage recovery and system security. Therefore, the dynamic criterion is closely linked to the robustness of demand and to fault-ride-through capability [23].

This point is particularly important for data centers. Their reliability requirements are very high from the perspective of the operator, but from the system perspective it is also necessary to ensure that they behave robustly during grid disturbances. The CNMC documentation for the modification of the transmission demand specifications states that, according to the system operator, approximately 90% of transmission-grid nodes could have zero demand access capacity under the dynamic criterion. This result was associated with the behavior during voltage dips of more than 9 GW of demand with already granted access and connection permits, including data centers and electrolyzes, which may not present sufficient robustness [24]. This issue has aggravated due to the increasing presence of facilities connected through power electronics.

The regulation distinguishes between two dynamic access capacity values: CAD1, applicable to power-electronic connected demand that declares its ability to withstand a voltage dip without disconnection and recover active power afterwards, and CAD2, applicable to installations that do not declare these technical capabilities [23]. In practical terms, this distinction shows that two demand projects requesting the same MW may not have the same impact on the access capacity calculation. A robust project that remains connected during voltage dips may create a lower dynamic impact on the system, whereas a non-robust project may require the system operator to consider a larger dynamic security margin. Therefore, demand robustness can improve the efficient use of the network and may help preserve or unlock access capacity, especially in nodes where the dynamic criterion is the limiting factor.

This distinction is consistent with the concerns identified in recent dynamic modelling studies of data centers. Generic demand models, such as constant PQ or voltage-dependent loads, may not accurately represent the behavior of data centers during faults, because they do not capture UPS switching logic, reconnection delays, protection thresholds, cooling motor dynamics or pulsing load patterns associated with AI workloads. Therefore, a data center that declares robustness against voltage dips should not only be evaluated in terms of steady-state consumption, but also in terms of its actual dynamic response during and after disturbances [20].

In practical terms, the dynamic criterion links the electrical design of the facility with the amount of access capacity that the system can safely accommodate. If large power-electronics-based demand disconnects during voltage dips, the system operator must consider the risk of sudden load loss. If, by contrast, the facility can remain connected or reconnect gradually without causing additional instability, its impact on the dynamic access capacity calculation may be lower. This reinforces the idea that robust data center design can contribute to a more efficient use of scarce grid capacity [25].

The CNMC documentation also indicates that establishing robustness requirements for power electronics connected to demand could make the dynamic criterion less restrictive. In practical terms, this means that a data center capable of withstanding voltage dips without disconnection may have a different impact on system stability from a non-robust facility. The technical design of the data center can therefore influence the amount of access capacity that the network can safely grant.

The relevance of these criteria is that they connect access regulation with the electrical design of the facility. For a data center, obtaining access is not only a matter of requesting capacity and waiting for chronological allocation. It also depends on whether the facility can be integrated into the grid without creating overloads, voltage problems, short-circuit limitations or dynamic stability risks. This is why the technical access criteria are directly linked to the central question of this thesis: data centers may be large and difficult loads to integrate, but their impact can be reduced if their design incorporates robustness, flexibility and system-compatible operation.

This technical discussion is also consistent with the European Demand Connection Network Code, established by Regulation (EU) 2016/1388. This regulation defines harmonized grid-connection requirements for demand facilities. Its objective is to contribute to system security, support the integration of renewable energy sources, facilitate the internal electricity market and ensure that network operators use the capabilities of demand facilities in a transparent and non-discriminatory manner [9].

The relevance of this code for data centers is twofold. First, it confirms that demand facilities may be subject to technical connection requirements when their behavior can affect system operation. This is particularly important for large loads connected at high voltage or with influence on the transmission system. Second, it recognizes that demand can provide system services through demand response, meaning that large consumers are not necessarily passive users of the grid, they may also become active agents if their technical capabilities are properly defined, verified and coordinated with network operators.

2.3.5 Royal Decree-Law 7/2026: new access framework for large demand

The Royal Decree-Law 7/2026 represents the central regulatory development for the analysis of data centers as large electricity consumers in Spain. Its relevance lies in the fact that it addresses two of the main concerns associated with data center deployment which are the risk that large demand projects reserve scarce grid capacity without materializing, and the need to ensure that new electricity demand is compatible with sustainability, electrification and system planning objectives. Therefore, the decree should be understood not only as an emergency energy measure, but also as a regulatory response to the growing pressure of large demand on the electricity network [4].

One of the main measures is the introduction of sustainability requirements for data centers. The decree establishes that data centers connected to electricity networks will be subject to requirements related to energy, environmental performance and resilience. These requirements may include energy efficiency, renewable electricity consumption, additionality and hourly matching, sustainable water use and waste heat reuse. This is a significant development because it links the deployment of data centers to regulatory criteria that go beyond the traditional availability of grid capacity, as they are required to demonstrate sustainability requirements.

A second key measure is the capacity reservation charge. This mechanism applies to holders of demand access and connection permits at voltage levels equal to or above 1 kV, from the granting of the permit until the consumer starts activity through the corresponding third-party access contract [4]. The charge is calculated by reference to the granted access capacity and the power term of the applicable network tariff, adjusted by a factor. It is treated as an advance payment of network tariffs, but non-payment above the applicable threshold may trigger automatic expiry of the access and connection permits.

The purpose of this measure is to discourage capacity hoarding. If holding an unused demand permit has no cost, large consumers may reserve scarce grid capacity without materializing the project, preventing other demand from connecting. This is particularly relevant for data centers, because their capacity requests may be very large and may block network nodes that could otherwise be used for industrial electrification, residential development, transport electrification or other strategic uses.

A third measure is the link between the access permit and the economic activity of the consumer through the CNAE code. RDL 7/2026 requires demand access and connection applications at voltage levels equal to or above 1 kV to identify the CNAE code associated with the activity of the consumption facility. Once the permit is granted, changes affecting the division or group of the CNAE are restricted [4]. Existing permits must also be updated, and failure to update or maintain consistency between the declared activity and the actual use of the connection may lead to permit expiry.

The CNAE requirement is important because it limits the possibility of transforming a demand permit into a speculative asset detached from the original project. This reinforces traceability and aligns the access permit with the real economic activity that justified the demand request.

The prioritization of certain types of electricity demand had already become visible before the adoption of RDL 7/2026. An important precedent was the first demand access capacity tenders launched through the Resolution of 11 July 2025. These tenders did not establish a single ranking in which all large demand projects competed under identical conditions.

Applicants were classified into three consumption categories: the production of hydrogen and renewable gases, the electrification of industry and mining, and data centers [26]. Projects belonging to the first two categories were expressly given priority in the allocation order over data center projects. The subsequent scoring criteria were only used to rank projects within the same priority group, rather than allowing a data center to overtake an industrial electrification or renewable hydrogen project.

Within each applicable priority group, projects were assessed according to three main criteria: the proposed date for starting electricity consumption, the volume of investment and the greenhouse gas emissions avoided. The environmental assessment considered the emissions avoided by the productive process and throughout the value chain, while renewable self-consumption and long-term renewable electricity supply arrangements could also improve the project's score. However, guarantees of origin alone were not considered sufficient to demonstrate renewable electricity coverage.

This design placed data centers in a comparatively less favorable position. The Resolution justified this distinction on the basis that industrial electrification and renewable hydrogen production may directly replace processes based on fossil fuels and therefore generate identifiable avoided emissions. By contrast, data centers were generally considered additional baseload electricity demand which could increase generation requirements during periods of low renewable availability. Consequently, even a mature data center project with a high investment volume and renewable electricity procurement remained behind projects classified as industrial electrification or renewable gas production in the initial ordering stage.

Overall, RDL 7/2026 shifts the treatment of large demand from a purely ex-ante permitting model towards a model of continuous control. The relevant regulatory question is no longer only whether the applicant submitted the request correctly and obtained a permit. It is also whether the project is firm, whether it effectively uses the granted capacity, whether its declared activity is maintained, whether it complies with sustainability requirements and whether it contributes to the efficient use of the network.

For this thesis, the relevance of RDL 7/2026 is that it connects the regulatory discussion on grid access with the technical and environmental behavior of the data center. If access to scarce capacity increasingly depends on project maturity, sustainability and efficient use of the network, then the ability of a data center to reduce induced emissions, integrate storage or adapt part of its net demand becomes relevant not only as an operational strategy, but also as a potential element of regulatory acceptability.

2.3.6 Energy Efficiency Directive (EU) 2023/1791

The Energy Efficiency Directive (EU) 2023/1791 introduces a specific transparency framework for data centers within the European energy efficiency policy. Article 12 requires Member States to ensure that data centers with an installed IT power demand of at least 500 kW make publicly available a set of information related to their energy performance [27]. This obligation reflects the increasing relevance of data centers as electricity consumers and the need to monitor their impact on the energy system.

The Directive focuses on measurable indicators rather than general sustainability claims. The information to be reported includes energy consumption, installed power, data traffic, storage capacity and indicators such as Power Usage Effectiveness (PUE), Water Usage Effectiveness (WUE), Energy Reuse Factor (ERF) and Renewable Energy Factor (REF), further specified by Commission Delegated Regulation (EU) 2024/1364. In this sense, the European framework links data center sustainability with efficiency, water use, heat recovery and renewable electricity consumption.

For this thesis, the Directive is relevant because it establishes data centers as monitored energy consumers under EU energy efficiency policy. However, its approach is mainly based on annual performance and reporting indicators. It does not directly address the hourly modulation of electricity demand, which is the specific flexibility dimension analysed in this work.

2.3.7 EU Code of Conduct on Data Center Energy Efficiency

The EU Code of Conduct on Data Centre Energy Efficiency is a voluntary technical framework promoted by the European Commission and the Joint Research Centre to improve energy efficiency in data centers. Unlike the Energy Efficiency Directive, it is not a binding regulatory instrument, but it provides recognized best practices for the design, operation and management of data center facilities.

The Code of Conduct addresses the main systems that determine total facility consumption: IT equipment, cooling systems, airflow management, UPS and power distribution, monitoring, temperature control and auxiliary services. Its best practices include the optimization of temperature set points, separation of hot and cold airflows, use of free cooling, efficient UPS operation, reduction of electrical losses and continuous energy monitoring. These measures are mainly aimed at reducing non-IT consumption and improving indicators such as PUE [28].

In the context of this thesis, the Code of Conduct provides technical reference for efficient data center operation. Nevertheless, its focus is primarily energy efficiency, while this work analyses an additional operational dimension: the potential use of cooling systems, batteries and other flexible resources to shift electricity consumption across hours without compromising the core digital service.

In conclusion, the particular characteristics of data center electricity demand have significant regulatory implications. Data centers may require very large volumes of access capacity, generally present relatively low price sensitivity due to the priority given to service continuity and rely extensively on power-electronic equipment, whose response during network disturbances may affect the operation and stability of the electricity system. These characteristics differentiate large data centers from conventional demand facilities and explain why their regulatory treatment is progressively extending beyond the general access and connection procedure.

As a result, the emerging regulatory framework establishes, or anticipates the introduction of, numerous sustainability, technical and indirect economic requirements. These include conditions related to energy efficiency, renewable electricity consumption, water use, waste heat recovery and resilience, as well as stricter technical requirements for network behavior and economic mechanisms intended to discourage the reservation of unused capacity. Access to the network may also be influenced by the maturity, strategic value and environmental contribution of the project, as demonstrated by the prioritization mechanisms and demand tenders introduced in recent years.

However, many of these regulatory provisions are recent, remain subject to further development or have not yet been consolidated through practical application. This makes it particularly relevant to assess the extent to which the proposed requirements generate positive effects for the electricity system, the level at which they remain proportionate and the capabilities that data centers may incorporate to respond to them. Flexibility mechanisms, energy storage, improved disturbance-response capabilities and the adaptation of consumption to network, price or emissions signals may become relevant instruments for regulatory compliance. Therefore, the current context provides an appropriate opportunity to evaluate not only which obligations should apply to data centers, but also how stringent they should be and which technical capabilities could allow these facilities to meet them without imposing disproportionate operational or economic impacts.

2.4 EXISTING STRATEGIES TO REDUCE ENERGY AND ENVIRONMENTAL IMPACT

The discussion on energy efficiency and sustainability is central to the data center debate because, under the emerging Spanish regulatory framework, these elements are no longer only voluntary corporate commitments. The RDL 7/2026 expressly anticipates the development of specific environmental requirements for data centers connected to electricity networks. This means that data centers may increasingly be assessed by their ability to demonstrate efficient energy use, responsible water management, renewable electricity procurement, waste heat reuse and compatibility with the wider objectives of the energy transition. Therefore, efficiency and sustainability are not only technical or reputational issues as they may become part of the regulatory conditions under which large data centers obtain and maintain access to scarce grid capacity

Energy efficiency has traditionally been the dominant strategy to reduce the electricity footprint of data centers. The most widely used metric is Power Usage Effectiveness (PUE), which compares total facility energy consumption with IT energy consumption. In this chapter, PUE is considered only as a sustainability indicator, since the detailed energy structure of the data center and the role of PUE in the model are developed later. The relevant point is that PUE has helped standardize the measurement of infrastructure efficiency, but it does not capture all dimensions of sustainability. A data center may have a low PUE and still represent a very large electricity demand if its IT capacity is high. Similarly, PUE does not indicate whether the electricity consumed is renewable, whether water use is sustainable, whether waste heat is reused or whether consumption takes place during low-emission hours.

This limitation explains why European sustainability regulation increasingly combines PUE with additional indicators. Delegated Regulation (EU) 2024/1364 establishes a reporting framework that includes indicators such as Water Usage Effectiveness, Energy Reuse Factor and Renewable Energy Factor, together with information on energy consumption, electricity use, temperature settings, waste heat, water use and renewable energy [14]. This broader approach reflects a shift from a narrow focus on infrastructure efficiency towards a more multidimensional assessment of data center sustainability.

Cooling optimization is one of the most frequently identified areas for efficiency improvement, because cooling can represent a significant share of non-IT energy consumption. The EU Code of Conduct for Data Centre Energy Efficiency includes best practices related to airflow management, temperature settings, efficient cooling systems and operational monitoring [15]. However, the technical description of cooling systems is not developed in detail here, since it belongs to the characterization of the data center energy model. In this section, the relevant point is that cooling efficiency can reduce baseline consumption, but it does not automatically solve the system-level issue created by large, continuous and geographically concentrated demand.

Renewable electricity procurement is another central strategy. Data center operators increasingly use power purchase agreements (PPAs), Guarantees of Origin (GdO) and, in some cases, on-site renewable generation to reduce their reported carbon footprint. This is particularly relevant in Europe, where the sector is highly electrified and where sustainability reporting requires information on renewable energy use [2]. However, renewable procurement can be interpreted in different ways. Annual matching means that the data center procures an amount of renewable electricity equivalent to its annual consumption, but it does not necessarily ensure that renewable generation and consumption occur at the same time or in the same location. Hourly or location-based matching is more demanding because it seeks a closer relationship between the data center's consumption profile and the availability of low-carbon electricity. This distinction is increasingly important for large consumers because annual renewable procurement may reduce reported emissions while still allowing consumption during high-emission hours.

Water use and waste heat reuse are also increasingly relevant. Some cooling strategies may reduce electricity consumption but increase water consumption, while other technologies may reduce water use but require more electricity. The EU reporting framework includes water and energy reuse indicators, reflecting the need to evaluate trade-offs between electricity, water and heat recovery [28]. Waste heat reuse can improve the overall resource efficiency of a data center, but its feasibility depends on local heat demand, nearby consumers, temperature levels and district heating infrastructure. This means that heat reuse is not only a technical measure, but also a territorial and urban-planning issue.

To sum up, sustainability reporting has become a regulatory tool in itself. Delegated Regulation (EU) 2024/1364 requires data center operators above the relevant threshold to report information on energy consumption, water use, renewable energy and waste heat. This improves transparency and comparability across facilities and provides a basis for future benchmarking or minimum performance requirements [14]. In Spain, this approach is reinforced by RDL 7/2026, which links data center deployment to future sustainability requirements related to energy, environmental performance, resilience and digital sovereignty [4].

2.5 DEMAND-SIDE FLEXIBILITY AND GRID-INTERACTIVE DATA CENTERS

Energy efficiency and sustainability measures reduce the environmental footprint of data centers. However, a data center may be efficient, may procure renewable electricity and may comply with reporting obligations, while still requesting scarce firm capacity in a constrained node or consuming during hours of high system stress. For this reason, the debate is moving from efficiency alone towards demand side flexibility. This is understood as the ability of large consumers to adapt part of their electricity consumption in response to grid conditions, electricity prices, renewable availability or emissions signals.

Demand side flexibility is already recognized in European electricity regulation. The European Demand Connection Network Code identifies demand response as an instrument that can contribute to system security, improve the functioning of the internal electricity market and support a more efficient use of electricity networks [9]. In the Spanish framework, this logic is also reflected in the CNMC Circular 1/2024, which introduces the possibility for certain demand installations to request flexible access capacity, and in RDL 7/2026, which reinforces the need to integrate large new demands in a way that is compatible with network planning, sustainability and efficient use of available capacity.

In this context, data centers are increasingly discussed as potential grid-interactive consumers. Traditionally, they have been treated as critical loads requiring continuous, high-quality and highly reliable electricity supply. This remains true. Not all data center consumption can be interrupted or shifted, and many services require strict continuity. However, the internal energy architecture of data centers includes several systems that may provide some degree of operational flexibility. These include battery energy storage systems, UPS infrastructure, cooling systems, thermal energy storage and, in some cases, IT workloads that are not strictly real-time or latency-sensitive [5].

The first source of flexibility is electrical storage. Data centers already include backup and power-conditioning systems to ensure continuity of supply, especially through UPS infrastructure and batteries. Traditionally, these systems are designed for reliability rather than market or grid services. However, ENTSO-E highlights that battery systems and UPS infrastructure could, under appropriate technical and regulatory conditions, contribute to grid support by reducing demand peaks, providing short-duration flexibility or helping manage connection constraints [5]. In this thesis, this idea is translated into the analysis of battery energy storage systems (BESS) as a technology capable of modifying the net electricity demand of a data center by charging in selected hours and discharging in others.

A second source of flexibility is cooling. Cooling demand is not identical to IT load, it depends on outdoor temperature, cooling technology, operating conditions and the ability to store or shift cooling production. This creates the possibility of using thermal energy storage to decouple, at least partially, the time at which cooling is produced from the time at which cooling is needed. In practice, thermal storage can allow the data center to produce cooling during lower-emission or lower-price hours and use stored cooling during less favorable periods. This type of flexibility is more limited than electrical storage because it is constrained by cooling demand, but it is relevant because cooling is one of the main non-IT electricity consuming loads in data centers.

A third source of flexibility may come from workload management. Some IT tasks, especially batch processing, artificial intelligence training, data analytics or non-urgent computational workloads, may be more flexible than real-time applications such as financial transactions, cloud services with strict service-level agreements or latency-sensitive inference. In principle, flexible workloads can be delayed, rescheduled or geographically shifted to periods or locations with lower electricity prices, higher renewable availability or lower emissions. However, this flexibility is highly dependent on the type of service, contractual obligations, data localization requirements, latency, and operational priorities. Therefore, workload flexibility should not be assumed for all data centers, but it represents an additional potential source of flexibility in specific cases.

These flexibility options make it possible to distinguish between a mere grid-safe data center and a grid-supporting data center. A grid-safe data center is designed not to harm the electricity system as it complies with technical connection requirements, withstands disturbances, avoids unacceptable power-quality impacts and respects access conditions. A grid-supporting data center goes further as it can actively adapt part of its net demand to support system needs [5].

From an emissions perspective, flexibility is relevant because the carbon intensity of electricity generation varies across hours. If a data center can shift part of its electricity consumption from more carbon-intensive hours to hours with higher renewable generation, the same annual energy consumption may induce lower emissions. This is different from annual renewable procurement, which may reduce reported emissions but does not necessarily change the physical timing of consumption. Flexibility therefore links the operational behavior of the data center with the hourly conditions of the electricity system.

The potential contribution of data center flexibility is real but bounded. Data centers cannot be treated as fully interruptible loads, and their reliability requirements limit the extent to which they can respond to grid signals. At the same time, they are not necessarily completely rigid. Their internal systems may allow partial modulation of net demand without compromising service continuity. The key analytical question is not whether a data center can become fully flexible, but which part of its consumption can be shifted, under what technical limits, and with what effect on emissions, costs and grid integration.

2.6 RESEARCH GAP AND JUSTIFICATION OF THESIS

The existing literature and regulatory framework provide a broad understanding of the role of data centers in the energy transition. Sectoral reports describe the rapid growth of data center capacity, the expansion of cloud computing and artificial intelligence, and the increasing strategic relevance of digital infrastructure for economic competitiveness and digital sovereignty. At the same time, power system studies identify data centers as large and increasingly relevant electricity loads whose integration depends on grid availability, connection lead times, operational security and technical robustness [5].

The literature also identifies the main environmental and system level concerns associated with data center growth. These include high electricity demand, concentration of large connection requests in specific network nodes, cooling requirements, water use, land-use implications and the need to ensure that new demand is compatible with decarbonization. The case of Aragón illustrates that the scale of planned data center deployment may become significant not only at national level, but also at regional level, with implications for electricity planning, network reinforcement and territorial development [3]. Similarly, the Irish case shows that, in some electricity systems, data centers have already become a relevant share of total electricity consumption, leading to specific regulatory responses for large energy users.

From the regulatory perspective, the Spanish and European framework is also evolving quickly. Law 24/2013, Royal Decree 1183/2020 and CNMC Circular 1/2024 provide the general legal and methodological framework for access and connection of demand to electricity networks. The detailed specifications for demand access capacity introduce technical criteria to assess whether new demand can be accommodated safely, including static, short-circuit and dynamic criteria. RDL 7/2026 adds a further layer by linking large demand, and specifically data centers, to sustainability requirements, capacity reservation mechanisms, administrative prioritisation, demand tenders and new causes for permit expiry.

In parallel, European regulation increasingly requires data centers to report sustainability indicators. Delegated Regulation (EU) 2024/1364 establishes a common reporting framework based on indicators such as energy consumption, water use, renewable energy use and waste heat reuse. This shows that the policy debate has moved beyond the mere existence of data centers as digital infrastructure. The sector is now expected to provide measurable information on its energy and environmental performance, and future regulatory treatment may increasingly depend on efficiency, sustainability and compatibility with system objectives.

However, despite this growing body of literature and regulation, several gaps remain. First, many reports describe the expected growth of data centers and their aggregate demand, but few studies analyze their operation at an hourly level. Annual energy consumption is useful to estimate the size of the sector, but it does not capture the temporal interaction between data center demand and the electricity system. In a power system with variable renewable generation, electricity prices and emissions factors change significantly across hours.

Therefore, two data centers with the same annual consumption may have different daily load consumption profiles and climate impacts depending on when they consume electricity and in which power system they are located as depending on the different generation mix from each country, the share of renewable energy varies.

Second, existing sustainability approaches often focus on reducing total energy consumption or improving reported environmental indicators, but they do not necessarily assess the potential of data centers to modify their load profile. Metrics such as PUE and WUE are useful to evaluate, but they do not directly measure whether a data center can shift consumption away from high-emission or constrained hours. This distinction is important because an efficient data center may still request scarce firm capacity or consume during periods of high emissions.

Third, while ENTSO-E and other studies identify data centers as potential grid-interactive consumers, there is still a need for applied quantitative analysis of specific flexibility options. The concept of a grid-supporting data center is increasingly discussed, but its practical contribution depends on the technology considered, the operational constraints of the facility and the electricity system conditions in which it operates. Batteries, UPS systems, thermal storage, cooling flexibility and workload management do not provide the same type of flexibility and cannot be assumed to have the same impact. Their effects must be assessed under different assumptions.

Fourth, the Spanish context creates a specific research need. Spain combines high renewable penetration, increasing pressure on grid access, and a regulatory framework that is beginning to link access to sustainability and robustness. However, there is limited analysis of how a representative data center could operate as a flexible electricity consumer in the Spanish power system. This is particularly relevant after RDL 7/2026, which reinforces the idea that large demand should not only be connected, but integrated under conditions that are compatible with the energy transition and the efficient allocation of scarce network capacity.

This thesis addresses these gaps by analyzing data centers not only as large electricity consumers, but as potential flexible consumers that can adapt their consumption profile to reduce the induced emissions in the system. The approach combines the energy characterization of a representative data center with hourly electricity prices and hourly emissions indicators. A baseline case without is compared with scenarios that include thermal energy storage and battery energy storage systems. This allows the thesis to evaluate whether profile modelling can modify and reduce induced emissions or change electricity costs.

Therefore, the contribution of the thesis is twofold. From a technical perspective, it provides a quantitative assessment of flexibility mechanisms applied to a data center load profile. From a regulatory perspective, it provides a qualitative assessment of how data centers can be integrated in the Spanish power system under future access, sustainability and flexibility requirements. The objective is not to claim that data centers are fully flexible or automatically beneficial for the electricity system, nor to define a single optimal storage size. Rather, the thesis investigates which parts of their energy system can be operated in a way that improves their compatibility with decarbonization, efficient network use and the emerging regulatory framework for large demand in Spain. In this sense, the model provides an indicative range of values that could inform future regulatory discussions, by showing where emissions reductions become meaningful and where additional flexibility may start to generate disproportionate economic impacts.

A further gap concerns the regulatory interpretation of flexibility requirements. Existing studies often evaluate technical solutions such as batteries, thermal storage or workload shifting from the perspective of feasibility, emissions reduction or cost savings. However, fewer studies address the question of proportionality: if regulation were to require large data centers to include flexibility or emissions-reduction capabilities, it would be necessary to understand what level of requirement could be considered reasonable. A requirement that is too low may have limited system value, while a requirement that is too ambitious may impose excessive costs on the data center without providing proportional additional emissions reductions. Therefore, this thesis uses a Pareto-oriented approach to explore the range of flexibility configurations that balance environmental benefits and economic impact.

Chapter 3. ENERGY CHARACTERIZATION OF DATA CENTERS

This chapter provides the technical basis for understanding how electricity is consumed inside a data center and which components determine its energy performance. Data centers are not homogeneous facilities: their electricity demand depends on their scale, ownership model, workload type, cooling architecture and geographical location. This distinction is particularly relevant given the growing role of data centers as large electricity consumers.

The chapter first introduces the main typologies of data centers and then reviews the metrics used to assess their energy and environmental performance. It subsequently analyses the main electricity-consuming components which are the IT equipment, cooling systems, electrical infrastructure and auxiliary loads, and describes the cooling and backup systems required to ensure continuous operation.

3.1 DATA CENTER TYPOLOGIES

Data centers can be defined as facilities designed to host, operate and interconnect information and communication technology equipment, including servers, storage systems and networking devices. However, from an energy perspective, this definition must be understood differently. A data center is not only the physical space where IT equipment is installed, but also the set of supporting systems required to guarantee service availability and ensure continuous, secure and reliable operation. These include power distribution infrastructure, uninterruptible power supply systems, backup generation, cooling systems, fire protection, monitoring equipment and physical security systems [29]. Therefore, the electricity demand of a data center is not limited to the power consumed by servers, but it also includes the energy required to maintain adequate operating conditions and service availability.

The energy performance of data centers depends on several factors, including their size, ownership model, workload type, utilization rate, redundancy requirements, cooling architecture and geographical location. Therefore, there is a need to have harmonized definitions to be able to compare data center energy consumption across countries and facility types [30].

Nowadays, data centers are classified in the following typologies according to their characteristics, size and use.

3.1.1 Enterprise data centers

The first category is the enterprise data center. These facilities are usually owned and operated by a company, public administration, financial institution, university or large organization to support their own internal digital services. Enterprise data centers may range from small server rooms to larger corporate facilities, and they tend to be more heterogeneous than larger scale facilities. Their equipment may differ in age, efficiency and utilization rate, and their cooling and power distribution systems may not always be optimised. As a result, their energy performance can vary significantly. In particular, older or smaller enterprise facilities may present less efficient airflow management and higher losses in cooling or electrical infrastructure [31].

3.1.2 Edge data centers

The second category is the edge data center. Edge data centers are smaller and more distributed facilities located closer to users or to the point where data are generated. Their purpose is to reduce latency and support applications requiring rapid response, such as 5G, industrial Internet of Things (IoT) or real-time analytics. Although each edge facility usually has a much lower electricity demand than a hyperscale data center, their aggregate demand may become relevant if deployment is widespread. In addition, edge facilities may not always benefit from the same economies of scale in cooling, monitoring, maintenance and energy optimization as large centralized data centers. Therefore, their distributed nature may create different efficiency, reporting and regulatory challenges compared with large facilities [31].

3.1.3 COLOCATION DATA CENTERS

A third category is the colocation data center. In this model, a specialized operator leases the physical space and provides electricity supply, cooling, connectivity, security and other facility services required by multiple customers. The clients may install and operate their own IT equipment, while the colocation provider manages the shared infrastructure. From an energy perspective, this model can benefit from economies of scale, since several users share the same cooling systems, power infrastructure and backup systems. However, the overall energy performance of a colocation facility also depends on the efficiency and utilization patterns of the equipment installed by each customer. This means that the operator may have direct control over building-level systems, such as cooling and power distribution, but more limited control over the IT load itself [32].

3.1.4 HYPERSCALE DATA CENTERS

The final category is the hyperscale data center, which refers to very large facilities designed to support massive computing, storage and cloud service requirements. Hyperscale data centers are normally associated with major cloud providers, digital platforms and, increasingly, artificial intelligence workloads. These facilities are typically highly standardized, allowing for more efficient design of electrical architecture, cooling systems, server deployment and operational management. Due to their scale and level of optimization, hyperscale facilities often achieve better infrastructure efficiency than smaller or older data centers. Nevertheless, their absolute electricity demand can be very large. New data centers associated with cloud computing and artificial intelligence can reach capacities in the range of hundreds of megawatts, creating significant challenges for electricity supply, grid connection and local infrastructure planning [33]. This typology of data center is the one this thesis is focusing on.

3.1.5 CLOUD, INTERNET AND COMPUTE DATA CENTERS

Aside from the previous four categories of data centers, we can distinguish between three specific types of data centers cloud, internet and compute data centers. This distinction is relevant because each of the characteristics they have makes them vary their behavior.

The first one is cloud data center, which is closely related to the hyperscale category, but both concepts should not be treated as exact synonyms. Cloud refers primarily to the service model: the provision of on-demand computing, storage, databases, software, analytics, machine learning and other digital services. Hyperscale, by contrast, refers to the physical scale and standardized architecture of the facility. Many cloud data centers are hyperscale, but a facility can provide cloud services without necessarily reaching the scale of the largest global campuses. This distinction matters because the energy profile of a cloud data center depends not only on installed capacity, but also on the workloads it serves. Data center energy consumption can be modelled from both hardware-centric and software-centric perspectives, since power demand is shaped by servers, components, virtual machines and applications [34].

Another useful distinction is between internet data centers and compute data centers. Internet data centers mainly support services such as streaming, user data storage, web applications, database queries and online gaming, where low latency, networking throughput and reliability are central requirements. Compute data centers, by contrast, are oriented towards more computationally intensive activities such as numerical simulations, AI training and inference, cryptocurrency mining or large-scale dataset processing [35]. This distinction is relevant because compute-intensive workloads can lead to higher rack power densities, greater cooling requirements and different flexibility opportunities compared with more latency-sensitive internet services.

Overall, the typology of the data center determines how its electricity demand should be interpreted. Enterprise data centers tend to be more heterogeneous: colocation facilities concentrate the demand of multiple customers under shared infrastructure, hyperscale and cloud data centers can achieve high levels of efficiency but create very large point loads and edge data centers respond to latency needs through smaller and more distributed infrastructure. The classification is useful because it identifies the main characteristics that shape energy consumption: scale, ownership, workload type, redundancy requirements, cooling architecture and degree of infrastructure optimization. This distinction provides the starting point for the following sections, where energy performance metrics, electricity consumption breakdown, cooling systems and backup infrastructure are analysed in greater detail.

3.2 *ENERGY AND ENVIRONMENTAL PERFORMANCE METRICS*

The energy and environmental performance of a data center is usually assessed through a set of indicators that relate the electricity used by IT equipment to the energy, water and emissions associated with the supporting infrastructure. These indicators are useful because data centers are complex facilities where the final electricity consumption is not determined only by servers, storage and networking equipment, but also by cooling systems, power distribution, backup infrastructure and auxiliary services. However, energy metrics must be interpreted carefully, since each indicator captures only one dimension of performance and may omit relevant aspects such as carbon intensity, water consumption, local grid impacts or the temporal profile of electricity demand [29].

3.2.1 POWER USAGE EFFECTIVENESS

The most widely used indicator is Power Usage Effectiveness (PUE). The PUE is defined as the ratio between the total electricity consumption of the data center and the electricity consumption of the IT equipment.

$$PUE = \frac{Total\ consumption}{IT\ consumption}$$

Equation 1. PUE calculation

In simplified terms, it measures how much additional electricity is required by the facility infrastructure for each unit of electricity consumed by servers and IT loads. A PUE of 1 would represent an ideal situation in which all electricity is used directly by IT equipment, with no losses or auxiliary consumption. In practice, PUE is always above 1, because cooling systems, UPS losses, power distribution equipment, lighting, monitoring and other auxiliary systems also consume electricity [36].

PUE is particularly useful because it provides a simple and comparable measure of infrastructure efficiency. Therefore, PUE is directly relevant for modelling total electricity consumption from a given IT load. In this thesis, the PUE concept is used as one of the key parameters to derive total data center consumption from the reference IT load.

Nevertheless, PUE has important limitations. First, it does not measure the efficiency of the IT equipment itself. A facility may have a low PUE while operating inefficient or underutilized servers. Second, PUE does not indicate the carbon intensity of the electricity consumed. Two data centers with the same PUE may have very different emissions depending on the electricity mix and the hours in which they consume electricity. Third, PUE does not account for water consumption, land use, local grid constraints or the environmental impact of backup generation. For this reason, PUE should not be interpreted as a complete sustainability indicator, but rather as a metric of facility-level energy efficiency.

Although PUE is often reported as a single annual or design value, it should not be interpreted as a completely fixed parameter. In practice, PUE can vary over time because part of the non-IT electricity consumption depends on external conditions and operating requirements. This is particularly relevant for cooling. During warmer months, higher outdoor temperatures increase the cooling effort required to maintain IT equipment within safe operating ranges, which may raise the electricity consumed by chillers, pumps, fans or other thermal management systems [37]. As a result, monthly PUE values may be higher in summer than in winter, especially in locations where free cooling is less available during hot periods. Therefore, using a single representative PUE is useful for annual modelling, but a monthly PUE profile provides a more accurate representation of the relationship between IT load, cooling demand and total electricity consumption according to the seasonal effect of temperature on cooling electricity demand.

3.2.1.1 PUE values

It has already been stated the importance of PUE. However, the values of the PUE vary significantly depending on several factors such as the typology and size of the data center, the technical and technological equipment, the location and the cooling systems.

These values depend on the source of information used. This section covers the different types of sources used to determine PUE values.

3.2.1.1.1 PUE according to data center enterprises

The first source for PUE values is the public disclosed values published on the websites of data center developers and operators. In this case, four data center developers based in Madrid, Spain, have been used as a reference.

The first developer, Edged Energy, in partnership with Merlin Properties, represents a new generation of high-efficiency data center infrastructure aimed at cloud, high-performance computing and AI-related workloads. Its facility located in Getafe, Madrid, is described as having 20 MW of IT load capacity and a guaranteed design PUE of 1.15, supported by waterless cooling and high-density configurations. This type of project is not a traditional enterprise data center, but rather a facility designed for large-scale, high-density digital infrastructure.

Other operators in Madrid correspond more clearly to colocation or edge models. nLighten operates an edge data center in Madrid, with approximately 3,300 m^2 of edge data center space, an end-state site capacity of 1.5 MW and a design PUE of 1.29. This makes it a useful reference for smaller, latency-oriented facilities rather than hyperscale campuses. DATA4, by contrast, is a campus-based colocation operator. Its Madrid campus in Alcobendas is presented as a secure digital campus with 10.7 ha of land and 100 MW of electrical reserves. Equinix is also primarily a global colocation and interconnection provider in Madrid, with several facilities for hyperscale deployments. Finally, Arsys should be treated differently: it is mainly a cloud, hosting and managed services provider. Although it has corporate presence in Madrid, its main data center is located in Logroño, with 6,000 m^2 of total area and a 1,000 m^2 IT floor. Therefore, Arsys is useful as a reference for Spanish hosting/cloud infrastructure, but not as a Madrid data center campus comparable to DATA4, Equinix or Edged.

The following table shows the name of the data center developer and the corresponding PUE value they state on their corporate websites. It must be said that they state this PUE value is an average of the PUE values for the facilities they own.

Data center developer/operator	***PUE value***
Edged Energy	1,15
nLighten	1,29
DATA4	1,3
Equinix	1,39
Arsys	1,32
Average	**1,29**

Table 2. Data center developers and PUE values. Sources: each operator's website

These operator-level references are not used as direct inputs for the model, but as a benchmark to understand the range of PUE values publicly announced for different types of facilities operating or developing capacity in Spain.

3.2.1.1.2 PUE according to official data center projects information

In addition to academic literature and company disclosures, this thesis uses public project documentation from the Government of Aragón's portal for *Planes y Proyectos de Interés General de Aragón* (PIGA). This source is particularly valuable because, unlike most public information on data centers in Spain, it provides access to detailed project files, including justificatory memoranda, environmental impact assessments and technical documentation submitted during the planning and authorization process. These documents make it possible to extract information that is usually not available in corporate announcements, such as total electrical capacity, IT capacity, cooling technologies, backup systems, photovoltaic installations, redundancy criteria and, in some cases, design PUE values.

The review carried out for this thesis covers several large-scale data center projects published through the Aragón PIGA portal, including Rhodes, La Puebla de Alfindén, Microsoft, Green IT Aragón and AWS-related developments. The information was systematized in a dedicated database in order to compare the technical characteristics of different projects. Although the level of detail is not homogeneous across promoters, the documentation provides a useful empirical basis for understanding the scale and design features of data centers currently being developed in Spain. In this sense, the PIGA files complement international literature by grounding the analysis in real Spanish projects rather than relying only on generic benchmark values.

The projects reviewed show that new data center developments in Aragón are large electricity consumers, with declared total electrical capacities ranging from around 100 MW in some individual Green IT sites to more than 600 MW in projects such as Rhodes or Microsoft's campuses. Where IT capacity is disclosed, the ratio between IT load and total electrical capacity varies significantly. Some projects, such as Rhodes and La Puebla de Alfindén, indicate an IT capacity equivalent to approximately two thirds of total electrical capacity, while Green IT projects report 72 MW of IT capacity out of 100 MW of total capacity. Microsoft's Aragón campuses show lower IT-to-total ratios, reflecting a larger share of infrastructure, cooling, redundancy or auxiliary capacity. AWS projects, by contrast, disclose total electrical capacity but do not provide exact IT power values, which illustrates the uneven transparency of public project documentation.

Table 3 shows the data center promoters, their location, the IT load and total consumption they state and the corresponding PUE according to these values.

Promoter / Project	*Location*	*Total electrical power (MW)*	*IT load (MW)*	*PUE*
Rhodes	Aragón	648	432	1,5
Puebla de Alfindén	Puebla de Alfindén	150	100	1,5
Microsoft	La Muela	652	345,6	1,9
Microsoft	Villamayor de Gállego	651	345,6	1,9
Microsoft	Zaragoza	543	288	1,9
Green IT	Ribera Alta del Ebro I	100	72	1,4
Green IT	Ribera Alta del Ebro II	100	72	1,4
Green IT	Atalaya del Ebro	100	72	1,4
AWS	Villanueva de Gállego 1	115,75	Not disclosed	N/A
AWS	Villanueva de Gállego 2	414,2	Not disclosed	N/A
AWS	Huesca	340,65	Not disclosed	N/A
AWS	El Burgo de Ebro	265,6	Not disclosed	N/A
AWS	Zaragoza La Cartuja	487	Not disclosed	N/A

Table 3. PIGAs published information (Source: each project's documentation)

The average value for the PUE is 1,6 according to these PUE values.

3.2.1.1.3 PUE according to experts and consulted literature

According to some meetings with experts working on the data center sector, nowadays the PUE values data centers in Spain are handling go around from 1,4 to 1,8, depending on the weather temperature. During warmer months in July and August, PUE values rise to 1,8 due to the intensive cooling demand and requirements. In the cooler months, the values range around 1,4. These values can also be found in academic literature and papers.

3.2.2 WATER USAGE EFFECTIVENESS

A second relevant indicator is Water Usage Effectiveness (WUE). WUE measures the amount of water consumed by the data center in relation to the energy used by IT equipment, usually expressed in liters per kilowatt-hour of IT energy (l/kWh) [38]. This metric is especially relevant for facilities that rely on evaporative cooling, cooling towers or other water-intensive thermal management systems. From an environmental perspective, WUE is important because improving energy efficiency through certain cooling technologies may increase water consumption. Therefore, a low PUE does not necessarily imply a low environmental impact if the cooling strategy requires significant water use. This is particularly relevant in regions exposed to water scarcity or high summer temperatures, where cooling demand and water stress may coincide.

This thesis does not focus on WUE as water usage optimization is not on the scope of the thesis. It is important to know the existence and relevance of this metric, but it is not going to be a focus in model development.

3.2.3 CARBON USAGE EFFECTIVENESS

A third indicator is Carbon Usage Effectiveness (CUE). CUE relates the greenhouse gas emissions associated with data center energy consumption to the electricity consumed by IT equipment. It is typically expressed as kilograms of CO_2 equivalent per kilowatt-hour of IT energy [38]. Unlike PUE, which focuses on the internal efficiency of the facility, CUE introduces the carbon intensity of the electricity supply. This makes it more suitable for analyzing the climate impact of data centers, especially in power systems where the hourly emissions factor varies significantly depending on renewable generation, fossil fuel generation and electricity imports. In this sense, CUE is particularly relevant for this thesis because the objective is not only to estimate total electricity consumption, but also to analyze how the timing of consumption affects induced emissions.

However, in this thesis the CUE is used from a slightly different approach. Instead of considering only IT consumption, it is considered total consumption. The reason is that, when introducing a battery, the energy consumption increases a little bit due to the efficiency of the battery. In order to discharge a certain amount of energy, it is needed to charge a little extra energy to compensate for efficiency losses.

The distinction between PUE and CUE is central to the analysis of data centers as flexible electricity consumers. A data center can improve its PUE by reducing cooling or electrical demand, but this does not necessarily reduce emissions if the remaining electricity consumption takes place during hours with high carbon intensity generation mix. Conversely, operational strategies that shift part of the electricity demand towards hours with lower emissions may reduce total carbon impact even if the annual PUE remains unchanged. This means that energy efficiency and emissions optimization are related but not equivalent objectives. PUE captures how efficiently the facility uses electricity internally, while CUE captures the emissions associated with the electricity consumed.

The issue found, which is one of the main focus and scopes of the thesis is that flexible data center operation can reduce system costs but may increase emissions if the shifting strategy is not carbon-aware, which confirms that price optimization and emissions optimization are not always aligned [39].

3.2.4 OTHER METRICS

In addition to these indicators, some studies consider complementary metrics related to renewable energy use, waste heat recovery or overall resource efficiency. For example, indicators such as Renewable Energy Factor (REF) or Energy Reuse Factor (ERF) can be used to assess the share of electricity supplied by renewable sources or the extent to which waste heat is recovered for useful applications. These metrics are relevant in broader sustainability assessments, especially where data centers are integrated with district heating networks or long-term renewable procurement strategies. However, they are not always available in public project documentation and are less directly connected to the operational modelling developed in this thesis. For this reason, the analysis focuses primarily on PUE and CUE.

Publicly available project documentation in Spain also shows why these metrics require careful interpretation. In several large data center projects reviewed through the Government of Aragón's PIGA documentation, promoters report target or expected PUE values, often reflecting efficient design assumptions and advanced cooling configurations. These values are useful because they provide evidence from real projects under development in Spain. However, they should be treated as design or expected values rather than necessarily as verified operational performance. Actual PUE may vary depending on final occupancy, IT load utilization, external temperature, cooling operation, redundancy use and the evolution of workloads over time. Therefore, PIGA documentation is useful to define realistic assumptions, but it must be complemented with literature values and sensitivity analysis.

For the purposes of this thesis, PUE is used as the main parameter to translate IT load into total electricity demand, while CUE and hourly emissions factors are used to assess the climate impact of that consumption. WUE is included as an important environmental indicator, but it is not modelled quantitatively because the thesis focuses on electricity consumption, emissions and flexibility. This methodological choice reflects the central research question: whether data centers can reduce their induced emissions by modifying the timing of part of their electricity demand. As a result, the following sections first describe the internal components of electricity consumption and then analyze the systems, especially cooling and backup infrastructure, that determine how much of that demand may be technically adjustable.

3.3 ELECTRICITY CONSUMPTION BREAKDOWN AND TECHNICAL SYSTEMS

Data center electricity consumption is not limited to IT equipment, but also includes the cooling, power supply, backup and auxiliary systems required to ensure continuous operation. This section breaks down total electricity demand into its main technical components: IT load, cooling systems, electrical infrastructure and auxiliary loads, in order to identify the role of each component in the overall consumption balance and to provide the basis for the modelling framework developed later in the thesis.

Figure 9 shows the main infrastructure of data centers.

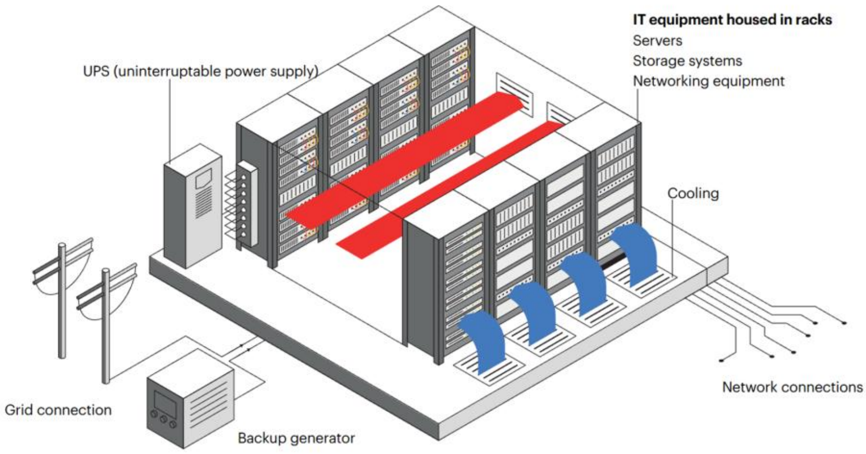


Figure 9. Data center structure (Source: IEA)

3.3.1 IT EQUIPMENT AND COMPUTATIONAL LOAD

The IT load represents the core electricity-consuming function of a data center. It includes the equipment directly responsible for processing, storing and transmitting digital information, mainly servers, storage systems and networking devices. Within this category, servers usually account for the largest share of IT electricity demand, since they contain the processors, memory, accelerators and internal power supply units required to execute computational workloads. IT equipment are accountable for approximately 55% of the total electricity use of data centers [40]. This value is useful as an order of magnitude because it shows that more than half of the electricity consumed by a data center is directly associated with computing and data services, while the remaining share corresponds to cooling, power supply systems and other supporting infrastructure.

The electricity demand of IT equipment depends on both installed capacity and utilization. A data center may have a large installed IT capacity, but its actual power consumption depends on how intensively servers are used, the type of processors deployed, the efficiency of power supply units and the characteristics of the workloads being executed.

In energy modelling, the IT load is often treated as a relatively stable base demand, especially in large cloud, colocation and hyperscale facilities that operate 24 hours a day. This assumption is reasonable because many data center services require high availability and because the facility must remain operational continuously. However, a stable IT load should not be interpreted as a completely inflexible load. IT load can be distinguished between delay-sensitive and delay-tolerant computational tasks, which is central to understanding the flexibility potential of IT demand [40]. Delay-sensitive tasks, such as real-time cloud applications, financial transactions, streaming, industrial control or latency-critical inference, must be processed almost immediately and therefore offer limited scope for temporal shifting.

However, this modelling simplification should be interpreted carefully. For energy and emissions analysis over hourly representative days, assuming a constant IT load is a reasonable approach because it reflects the continuous operation of a hyperscale facility. Nevertheless, at shorter time scales, AI-oriented workloads may produce rapid and structured variations in power demand. Large GPU clusters can alternate between compute-intensive phases and communication or synchronization phases, creating power fluctuations that are not visible in an hourly energy model but may be relevant for grid stability and power quality studies [19].

By contrast, delay-tolerant workloads can potentially be scheduled or shifted in time without significantly affecting service quality. These may include batch processing, some data analytics, backups, software updates, internal maintenance processes and certain training or non-urgent computational tasks.

For the purposes of this thesis, the IT load is treated as the base electricity demand of the reference data center. This reflects the continuous operation and high availability requirements of data centers, while keeping the model transparent. Nevertheless, the literature shows that part of the computational load may be technically adjustable depending on workload type, latency requirements and operational constraints [40]. This distinction is important for later chapters: the IT load is not modelled as a fully flexible demand in the baseline case, but the existence of delay-tolerant workloads helps justify why data centers may become relevant flexible consumers in the power system under specific technical and operational conditions.

3.3.2 COOLING SYSTEMS AND THERMAL MANAGEMENT

Cooling systems are one of the most important technical components of data center electricity consumption. Almost all the electricity consumed by IT equipment is ultimately converted into heat, which must be continuously removed to maintain servers, storage systems and networking equipment within safe operating conditions. More than 95% of the total cooling load in a data center is attributable to the heat generated by IT equipment, which explains why cooling demand is directly linked to the IT load even when the cooling equipment itself is part of the non-IT infrastructure [37].

Cooling can represent a very significant share of total electricity consumption. Several studies use representative breakdowns in which IT equipment accounts for 52% of electricity use, cooling systems for 38% and the remaining 10% for other infrastructure such as power distribution and UPS systems [41]. Other studies indicate that it can account for around 30% of total power consumption, depending on the facility design, climate conditions and control strategy [42]. These values are consistent with the idea that cooling is usually the largest non-IT load and that it accounts for the 30-40% of the electricity consumption.

The purpose of cooling is not simply to reduce temperature, but to maintain IT equipment within acceptable thermal and humidity ranges. The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) thermal guidelines provide recommended and allowable environmental envelopes for data center equipment because data centers have specific Heat, Ventilation and Air-Conditioning (HVAC) requirements. Unlike conventional buildings, they are designed primarily to cool information technology equipment rather than occupants [43].

The electricity required for cooling is strongly influenced by external conditions. Even if the IT load is treated as constant, the cooling electricity demand may vary according to outdoor temperature, humidity and the availability of free cooling, and by consequence, PUE differs, showing that outdoor air conditions can have a direct effect on cooling energy consumption

[37]. For this reason, the effective PUE of a data centre can vary throughout the year: in colder months, free cooling can reduce the need for mechanical refrigeration, while in summer, chillers, pumps and fans may operate more intensively.

3.3.2.1 Cooling architecture

The main cooling architecture can be grouped into air cooling, liquid cooling, free cooling and hybrid systems.

3.3.2.1.1 Air cooling systems

Traditional air-cooled facilities rely on the movement of cold and hot air through the data hall, often using hot aisle/cold aisle layouts, containment systems, computer room air conditioning units (CRACs), computer room air handler units (CRAHs) and air handling units (AHUs). The traditional air-cooling systems can be divided into two systems, a system in charge of moving air and a system in charge of cooling or heating water. In the case of refrigerating data centers, the system cools water. Air cooling remains widely used because of its maturity and operational simplicity, although its efficiency becomes more limited as rack power density increases [44]. Airflow management is therefore a central efficiency measure, since poor separation of hot and cold air can increase fan power and mechanical cooling requirements.

3.3.2.1.2 Free cooling

Free cooling uses favorable outdoor conditions to reduce or replace mechanical refrigeration. The way free cooling works is using outdoor temperature to use that cool air for refrigerating while still relying on mechanical components for moving that air. Free cooling reduces the refrigerating consumption by 68% because the system used for cooling water is not needed [44]. Free cooling is stated to be used completely when outdoor temperatures is below 18ºC and partially when temperature is between 18ºC and 22ºC [43]. Above 22ºC free cooling is less used because the outdoor temperature is not cold enough to refrigerate.

3.3.2.1.3 Liquid cooling

Liquid cooling is becoming increasingly important as rack power densities rise, especially in AI and high-performance computing data centers. In liquid-cooled systems, heat is removed closer to the source, for example through immersion cooling. Liquid cooling can improve thermal management where air cooling becomes insufficient. This is relevant for future data centers because AI accelerators and high-density servers increase the need for more advanced thermal management.

3.3.2.1.4 PIGA documentation for cooling systems

The PIGA documentation reviewed for this thesis confirms that the main cooling technologies identified in the literature are also present in Spanish data center projects. The Aragón projects include references to chillers, air handling units, dry coolers, free cooling, closed water circuits and, in some cases, liquid cooling.

Table 4 shows the disclosed information regarding cooling systems for the PIGA projects analyzed.

Promoter / Project	*Location*	*Total electrical power (MW)*	*IT load (MW)*	*Cooling information*
Rhodes	Aragón	648	432	216 MW; free cooling; dry coolers; closed circuit
Puebla de Alfindén	Puebla de Alfindén	150	100	Chillers, dry coolers, free cooling and liquid cooling; closed circuit
Microsoft	La Muela	652	345,6	Chillers: 288 MW; free cooling; liquid cooling; AHUs; closed water circuit
Microsoft	Villamayor de Gállego	651	345,6	Chillers: 288 MW; free cooling; liquid cooling; AHUs; closed water circuit
Microsoft	Zaragoza	543	288	Chillers: 240 MW; free cooling; liquid cooling; AHUs; closed water circuit
Green IT	Ribera Alta del Ebro I	100	72	Infrastructure/cooling load: 28 MW; 28 air-cooled water

				chillers; free cooling; closed system
Green IT	Ribera Alta del Ebro II	100	72	28 MW; 28 air-cooled water chillers; free cooling; closed system
Green IT	Atalaya del Ebro	100	72	28 MW; 28 air-cooled water chillers; free cooling; closed system
AWS	Villanueva de Gállego 1	115,75	Not disclosed	AHUs with water; free cooling
AWS	Villanueva de Gállego 2	414,2	Not disclosed	AHUs with water; free cooling
AWS	Huesca	340,65	Not disclosed	AHUs with water; free cooling
AWS	El Burgo de Ebro	265,6	Not disclosed	AHUs with water; free cooling
AWS	Zaragoza La Cartuja	487	Not disclosed	AHUs with water; free cooling

Table 4. PIGAs cooling information (Source: each project's documentation)

3.3.2.2 Coefficient of performance

The efficiency of mechanical cooling equipment is commonly described through the coefficient of performance (COP). Unlike PUE, which is a facility-level metric, COP is a technical parameter that measures the efficiency of a cooling system. It is defined as the ratio between the cooling energy delivered and the electrical energy consumed by the cooling equipment. For example, a chiller with a COP of 5 delivers 5 MWh of cooling for each 1 MWh of electricity consumed. This distinction is important for modelling because cooling demand can be expressed in thermal terms, while the data center electricity balance requires converting that cooling requirement into electrical consumption.

3.3.2.3 Thermal energy storage

Thermal energy storage can be understood as an extension of the cooling system that allows part of the cooling demand to be shifted over time. In a conventional configuration, cooling must be produced almost simultaneously at the same time heat is generated by IT equipment. As a result, chillers, pumps and fans tend to operate when the cooling demand occurs, regardless of whether those hours coincide with high electricity prices, grid stress or higher carbon intensity [45]. By contrast, thermal energy storage can decouple, at least partially, the production of cooling from its final use time. Cooling can be generated in advance, stored in the form of chilled water, ice, phase-change materials or underground thermal storage, and later discharged when the data hall requires it [46].

In data centers, this distinction is particularly relevant because the IT service must remain continuous, but the electricity consumption associated with cooling does not always need to occur at the same time as the heat is produced. Thermal storage therefore does not make the servers themselves flexible. Instead, it creates flexibility in the cooling system while maintaining the thermal conditions required for reliable IT operation. This makes it different from direct IT load shifting, which may be constrained by latency, service level agreements or workload availability [47].

The technical value of TES is usually associated with peak shaving, lower electricity bills, improved use of cooling equipment and additional operational resilience. By producing cooling during off-peak periods and using stored cooling during peak periods, data centers can reduce the operation of mechanical cooling when electricity demand is highest. In some configurations, stored chilled water can also provide emergency cooling if the main cooling plant is temporarily unavailable, helping avoid overheating while IT equipment continues to be supplied by UPS systems [48]. Larger-scale configurations, such as underground thermal energy storage, can also reduce peak cooling demand in large facilities with high and continuous cooling requirements [49].

In this thesis, however, thermal energy storage is mainly interpreted as a carbon-oriented flexibility mechanism. The objective is not limited to reducing peak demand or lowering electricity costs, but to shift part of the electricity required for cooling from hours with higher emission intensity to hours with lower emission intensity [50]. In operational terms, this means charging the thermal storage system by producing cooling during cleaner hours and discharging it during more carbon-intensive hours, thereby reducing mechanical cooling consumption when the electricity mix is more emissive. This approach is consistent with carbon-aware data center operation, where the environmental impact depends not only on the amount of electricity consumed, but also on the timing of that [51].

The potential of TES is therefore bound by the size and temporal profile of cooling demand. It cannot shift the entire electricity consumption of the data center, because IT equipment, networking, storage and many auxiliary systems continue to operate. Its effect is limited to the portion of the load associated with cooling, and even that component depends on storage capacity, charging and discharging power, cooling equipment efficiency, outdoor temperature and thermal constraints inside the data hall. For this reason, TES is treated later in the model as a partial flexibility option: it reduces cooling electricity consumption during selected high-emission hours by transferring part of that cooling production to lower-emission hours, while preserving the continuity of the IT service.

For the purposes of this thesis, cooling is modelled as the main variable non-IT component of electricity consumption. The IT load is treated as the primary source of heat and remains relatively stable, while cooling electricity demand varies by month according to PUE assumptions and temperature-related cooling requirements. This approach reflects the technical literature, which links cooling energy to IT heat, external climate and cooling system efficiency, while also allowing the model to represent the seasonal increase in cooling demand during warmer months. Thermal energy storage is therefore analysed later as a potential flexibility option that can shift part of the cooling electricity demand without directly interrupting the IT service.

3.3.3 ELECTRICAL INFRASTRUCTURE, UPS AND BACKUP SYSTEMS

The electrical infrastructure of a data center includes all the systems required to deliver electricity from the grid connection to the final IT equipment. This normally involves medium- or high-voltage connection equipment, transformers, switchgear, uninterruptible power supply systems and power distribution units. Electricity therefore passes through several conversion and distribution stages before reaching processors, memory, storage devices and networking equipment. Each stage introduces some electrical losses, so the design of the power supply architecture affects both the reliability and the overall energy efficiency of the facility [52]

Uninterruptible power supply systems (UPS) are a central element of this architecture. Their main function is to protect IT equipment from short interruptions, voltage disturbances or frequency deviations, ensuring that the load remains supplied until the grid recovers or backup generation starts. In most data centers, UPS systems are supported by batteries, traditionally lead-acid but also lithium-ion batteries are becoming more common [53]. These batteries are primarily designed for continuity of supply rather than for ordinary energy arbitrage, although the existence of storage within the power architecture has led to growing interest in using data center energy storage for demand response and grid services [54].

From a grid-integration perspective, UPS systems are not only internal reliability assets. They also determine how the data center interacts with the grid during disturbances. During voltage dips, frequency deviations or short interruptions, the UPS may isolate the IT load from the external grid and supply it from internal energy storage or backup systems [20]. This behavior protects the data center, but it may also produce a sudden reduction in grid demand if a large share of the facility disconnects simultaneously.

The reconnection process is also relevant. If the data center reconnects abruptly after a fault, the sudden restoration of a large load can create additional voltage or frequency stress [20]. If reconnection is delayed, staged or coordinated, the impact on the system may be reduced. Therefore, the technical design of UPS protections, ride-through settings and reconnection logic is an important element of data center grid integration, even if it is not explicitly represented in the model developed in this thesis.

For longer interruptions, data centers usually rely on backup generators, commonly diesel units, although alternative backup technologies are increasingly being discussed in the context of decarbonization. These systems are necessary because data centers have very high availability requirements and cannot normally tolerate prolonged electricity supply interruptions. Redundancy configurations such as N+1, N+2 or 2N increase resilience by ensuring that critical loads can remain supplied even if part of the electrical infrastructure fails [38]. However, redundancy also increases installed capacity and can affect energy performance, since some equipment may operate at part load or remain available as reserve capacity [55].

3.3.3.1 PIGA documentation for electrical infrastructure, UPS and backup systems

The PIGA documentation reviewed for this thesis confirms the importance of backup and electrical infrastructure in large Spanish data center projects. Several projects include large numbers of backup generators, lithium-ion batteries associated with UPS systems, dedicated substations, transformers and explicit redundancy criteria. This shows that the electricity demand of a data center is not only determined by the IT load and cooling systems, but also by the infrastructure required to guarantee uninterrupted operation.

Table 5 shows the disclosed information regarding electrical systems, UPS and backup systems for the PIGA projects analyzed.

Promoter / Project	***Location***	***Total electrical power (MW)***	***IT load (MW)***	***Backup systems***	***Renewable generation***
Rhodes	Aragón	648	432	Diesel generators; Li-ion UPS; thermal backup 2,360 MWht	PV: 2,600 kWp
Puebla de Alfindén	Puebla de Alfindén	150	100	3,750 kVA / 3,000 kW generators per module; UPS; N+1/N+2 redundancy	PV: 407.5 kWp
Microsoft	La Muela	652	345,6	216 server generators (3 MWe each) + 4 admin generators; 48 h autonomy; Li-ion UPS	PV: 1,439 kWp
Microsoft	Villamayor de Gállego	651	345,6	216 server generators (3 MWe each) + 3 admin generators; 48 h autonomy; Li-ion UPS	PV: 1,497 kWp
Microsoft	Zaragoza	543	288	180 server generators (3 MWe each) + 3 admin generators;	PV: 1,259 kWp

				48 h autonomy; Li-ion UPS	
Green IT	Ribera Alta del Ebro I	100	72	42 diesel generators; gas turbine plant; black-start diesel; UPS	Associated wind + PV hybrid parks; not owned
Green IT	Ribera Alta del Ebro II	100	72	42 diesel generators; gas turbine plant; black-start diesel; UPS	Associated wind + PV hybrid parks; not owned
Green IT	Atalaya del Ebro	100	72	42 diesel generators; gas turbine plant; black-start diesel; UPS	Associated wind + PV hybrid parks; not owned
AWS	Villanueva de Gállego 1	115,75	Not disclosed	45 generators; Li-ion UPS and VRA batteries; thermal backup 327 MWht	PV: >410.8 kWp
AWS	Villanueva de Gállego 2	414,2	Not disclosed	158 generators; Li-ion UPS and VRA batteries; thermal backup 1,169.46 MWht	PV: >1,541.5 kWp
AWS	Huesca	340,65	Not disclosed	131 generators; Li-ion UPS and VRA batteries; thermal backup 962.58 MWht	PV: >1,254.1 kWp
AWS	El Burgo de Ebro	265,6	Not disclosed	102 generators; Li-ion UPS and VRA batteries; thermal backup 750.66 MWht	PV: >998.1 kWp
AWS	Zaragoza La Cartuja	487	Not disclosed	184 generators; Li-ion UPS and VRA batteries; thermal backup 1,373.82 MWht	PV: >1,735.4 kWp

Table 5.PIGA information of electrical infrastructure, ups and backup systems (Source: each project's documentation)

In the modelling framework of this thesis, these systems are not represented as flexible loads in themselves; rather, their effect is captured through the non-IT consumption included in the overall electricity balance, while battery storage is analysed separately as a specific flexibility scenario.

3.3.4 AUXILIARY LOADS AND CONSUMPTION BALANCE

In addition to IT equipment, cooling systems and electrical infrastructure, data centers also include a set of auxiliary loads required for normal facility operation. These may include lighting, monitoring and control systems, security equipment, fire protection systems, offices and other building services. Although these loads are usually smaller than IT and cooling consumption, they must be included in the total electricity balance because they contribute to the difference between IT electricity demand and total facility demand [56]

For modelling purposes, it is useful to separate this non-IT component into cooling and other auxiliary loads, because they do not behave in the same way over time. In this thesis, the reference data center is therefore modelled through three main components: a constant IT load, a variable cooling load and a smaller constant auxiliary load. The IT load represents the continuous digital service, the cooling load captures the seasonal variation associated with temperature and PUE, and the auxiliary load represents general facility services such as lighting, monitoring and security. This simplified structure does not reproduce every internal subsystem in detail, but it provides a transparent electricity balance for calculating total consumption, emissions and costs in the baseline and flexibility scenarios.

Chapter 4. GRID ACCESS AND CONNECTION SITUATION IN SPAIN

This chapter analyses the current situation of grid access and connection for new electricity demand in Spain, with a particular focus on data centers. After briefly describing the applicable regulatory framework, it examines how the scarcity of available capacity, node congestion and technical constraints are becoming central factors in the development of large demand projects. The chapter also discusses the risk of speculative capacity reservation, the emerging role of firm and flexible access capacity, and the technical requirements that may condition the connection of large consumers. Overall, it provides the context needed to understand why data center location and operation can no longer be assessed only from a digital or economic perspective but must also be considered in relation to the physical and operational limits of the electricity system.

4.1 REGULATORY FRAMEWORK FOR GRID ACCESS AND CONNECTION

As already discussed in the state of the art chapter, grid access and connection in Spain is governed by a set of legal and regulatory instruments that define who can connect to the network, under what conditions, and how available capacity is assessed. This section therefore does not aim to repeat the full regulatory analysis, but to briefly recall the elements that are most relevant for understanding the current situation of grid access for new large demand projects such as data centers.

The general legal basis is the Spanish Electricity Sector Law 24/2013, which establishes the principles of access and connection to electricity networks. This framework is developed later on by the Royal Decree 1183/2020, which regulates the access and connection procedure, including the submission of applications, the granting of permits, economic guarantees, deadlines and the expiry of permits. This is relevant because access rights are not only administrative authorizations but determine whether a project can effectively reserve capacity in a specific network node.

For demand facilities, the key regulatory instrument is CNMC Circular 1/2024, which establishes the methodology and conditions for access and connection of installations that demand electricity from transmission and distribution networks. In practical terms, this CNMC Circular is the basis for assessing whether a new demand project can be connected, whether there is sufficient access capacity, and whether the proposed connection is technically viable. It also introduces the distinction between firm and flexible access capacity, which is especially relevant when network capacity is limited or subject to operational constraints and these concepts will be developed further in following sections.

The most recent regulatory rule is the Royal Decree-law 7/2026 which has introduced additional pressure on projects that reserve capacity but do not end up materialized. This RDL creates a capacity reservation payment for consumers holding demand access and connection permits at voltage levels equal to or above 1 kV, from the moment the permits are obtained until the activity starts. This measure is particularly important in a context where network capacity is scarce, as the measure seeks to discourage the long-term blocking of grid capacity by projects that are not yet operational.

The same RDL is directly relevant for data centers, since anticipates specific sustainability requirements for future data center connections. These may include renewable additionality, hourly correlation between consumption and renewable supply, energy efficiency, sustainable water use, social and economic benefits, and contribution to digital resilience and sovereignty. However, these requirements are not yet fully defined, as they must be developed in the upcoming future.

Overall, this framework is important because it shows that grid access is no longer only a question of requesting capacity in chronological order. For large demand projects, access is increasingly linked to technical feasibility, effective project materialization, use of reserved capacity and, in the case of data centers, future sustainability conditions.

4.2 NODE CONGESTION AND AVAILABLE CAPACITY

The availability of access capacity for new demand in Spain is increasingly constrained by the physical and operational limits of the transmission network. The Spanish transmission system operator (TSO) Red Eléctrica (REE) publishes monthly information on demand access capacity at transmission nodes. REE has been publishing these capacity files since February 2026. These files distinguish between capacity already granted, capacity available for new applications under the general procedure, and capacity that is technically calculated but cannot be granted in the transmission network. However, these values are not obtained through a single calculation. They result from the application of several technical criteria that determine the maximum additional capacity that can be safely connected at each node.

The publication of demand access capacity by Red Eléctrica in June 2026 reflects a significant change in the grid access situation for new demand projects in Spain. The issue is not only that some nodes have limited technical capacity, but that a relevant volume of capacity that had previously appeared as available under the general procedure is now shown as non-grantable or reserved. This change is especially relevant for large new consumers, such as data centers, because one aspect of their ability to connect depends on the regulatory status of that capacity.

4.2.1 REE DEMAND ACCESS CAPACITY FILES STRUCTURE

The Red Eléctrica files distinguish several layers of information. First, they show the technical capacity resulting from the application of different access criteria, including the short-circuit power criterion, the static criterion for demand and storage and the dynamic criterion. These criteria determine the maximum additional demand that can be connected without compromising system security. For each criterion, the files also indicate the non-occupied margin, which represents the remaining capacity once already granted or committed capacity has been considered. The effective available capacity for each node is determined by the most restrictive criterion, meaning the lowest margin among the criteria.

Second, the files classify the resulting capacity according to its regulatory situation. Capacity may be already granted, available for new applications under the general procedure, or not grantable in the transmission network, which also means that the capacity is reserved. This last category is particularly important in the June 2026 publication, where 48 nodes include the note: *"Capacidad liberada reservada conforme a lo establecido en el artículo 13.6 del RDL-7/2026"*. This means that the capacity is not immediately available for ordinary access requests but is reserved under the mechanism introduced by Royal Decree-law 7/2026.

The effect of RDL 7/2026 is relevant because it changes what happens when capacity that had already been granted to a demand project is later released, for example because the permit holder renounces the permit or reduces the requested capacity. If the released capacity in a node is higher than 5 MW, that capacity is not automatically returned to the ordinary access procedure; instead, it is temporarily reserved so that the administration can identify the affected nodes and open a specific process for receiving and evaluating new demand access applications. This explains why, in the June 2026 publication, several nodes appear with the note *"Capacidad liberada reservada conforme a lo establecido en el artículo 13.6 del RDL-7/2026"*. The issue is not necessarily that the network has lost technical capacity, but that capacity above the 5 MW threshold has changed regulatory status and is no longer immediately available under the general procedure.

4.2.2 February and June 2026 comparison

The comparison between the February and June 2026 publications shows the effect of this mechanism. As mentioned above, 48 nodes have no available capacity in June 2026 due to the application of the article 13.6 of the RDL 7/2026. These nodes had available capacity in February 2026 but no available capacity in June 2026. Not only the available capacity has gone to cero, but these nodes appear to have not grantable capacity, even higher capacity than what was available in February 2026. An analysis was conducted in order to understand not only the disappearance of the available capacity, but also the increase in the reserved capacity. The following table shows all the nodes affected due to the article 13.6 of the RDL 7/2026. Table 6 shows the granted available capacity in February of 2026 and the reserved capacity in June 2026. It must be said that in June 2026 the available capacity is cero for all the nodes and that the reserved capacity in February 2026 was mostly cero in most of the nodes. As it can be seen, the non-grantable capacity has increased considerably in most of the cases. A few considerations must be taken into account. First is that demand and storage are treated differently, although they are affected by each other if changes occur. Second is that we are focusing on CEP demands which CEP stands for *Conectados con Electrónica de Potencia*, which means connected by power electronics. CH stands for *Con Huecos*, which means that the demand connected withstands voltage dips and MPE stands for Módulo de Parque Eléctrico, which means electric park module.

Node name and voltage level	***Region***	***Available access capacity for general requests in February***		***Non grantable access capacity in transmission network in June***	
		Demand CEP CH	**Storage CEP MPE**	**Demand CEP CH**	**Storage CEP MPE**
Aguayo 400	Cantabria	0	0	0	0
Aguayo 220	Cantabria	98	98	423	423
Cicero 220	Cantabria	65	197	65	522
Penagos 400	Cantabria	306	306	631	631
Penagos 220	Cantabria				
Puente S.Miguel 220	Cantabria	217	453	217	453
Solorzano 400	Cantabria	197	197	278	522
Solorzano 220	Cantabria	54	197	54	522
Cotorros 400	Castilla y León	416	416	468	722
Fuentebureba 400	Castilla y León	447	580	447	905
Garoña 220	Castilla y León	55	556	55	881
Montearenas 220	Castilla y León	47	155	47	526
Velilla 400	Castilla y León	0	0	134	134
Villalbilla 220	Castilla y León			72	870
Villameca 400	Castilla y León	0	0	48	48
Villimar 220	Castilla y León	2	564	2	564
Virtus 400	Castilla y León	255	297	255	622
San Servan 220	Extremadura	339	839	339	901
Belesar 220	Galicia	215	451	215	468

Boimente 400	Galicia	73	261	73	586
Puentes G.R. 400	Galicia	58	58	346	383
Quereño 220	Galicia	19	155	19	220
Trives 400	Galicia	0	0	61	61
Trives 220	Galicia	308	710	308	710
Xove 400	Galicia	0	0	243	243
Alonsotegui 220	País Vasco	0	16	0	51
Amorebieta 400	País Vasco	140	140	192	465
Azpeitia 400	País Vasco	469	469	494	794
Basauri 220	País Vasco			23	374
Gatica 400	País Vasco	0	0	192	282
Gueñes 400	País Vasco	0	0	0	0
Gueñes 220	País Vasco	0	16	0	341
Hernani 400	País Vasco			414	414
Itxaso 220	País Vasco	103	335	103	507
Jundiz 220	País Vasco	21	21	188	492
La Jara 220	País Vasco	16	16	223	341
Ortuella 220	País Vasco			60	60
Santurce 400	País Vasco			106	106
Santurce 220	País Vasco			60	60
Vitoria 400	País Vasco	505	505	569	830
El Palo 400	Principado de Asturias	261	261	542	586
Lada 400	Principado de Asturias	13	121	13	446
Narcea 400	Principado de Asturias	14	226	14	551
Pesoz 400	Principado de Asturias	0	0	73	303
Salas 400	Principado de Asturias	153	226	153	551
Santa Maria De Grado 400	Principado de Asturias	96	96	155	421
Soto De Ribera 400	Principado de Asturias	0	0	100	100
Soto De Ribera 220	Principado de Asturias	28	470	28	707

Table 6. Nodes affected by article 13.6 of the RDL 7/2026 (Source: REE published capacity files)

The analysis suggested that a significant part of this change may be linked to the release or reduction of previously granted capacity. The case of Ziérbena 400 kV appears especially important and can be relevant for this thesis because, although it is unknown why the granted capacity was released, it is believed that the granted capacity in Ziérbana 400 kV corresponded to a planned project of a data center. Two factors have great importance in this specific case. In February 2026, the node Ziérbana 400 kV had 450 MW of granted capacity. There were other nodes that renounced capacity or reduced the requested capacity, however the renounced capacity compared to Ziérbana 400 kV was lower, with a maximum decrease of 53 MW, compared to the 450 MW. This is shown in Table 7.

Node name and voltage level	*Region*	*Granted demand access capacity in transmission network February 2026*	*Granted demand access capacity in transmission network June 2026*
Los Arenales 220	Extremadura	53	0
Los Vientos 220	Aragón	147	146
Peñaflor 400	Aragón	350	300
Perafort 220	Cataluña	91	90
Villares del Saz 220	Castilla-La Mancha	8	0
Ziérbana 400	País Vasco	450	0

Table 7. Nodes with reduced granted capacity (Source: REE published capacity files)

The second factor is related to the dynamic zones. The analysis of the dynamic zone shows that Ziérbana shares dynamic zones with almost all the 48 affected nodes by the RDL 7/2026. This indicates that the effect of released capacity may not be limited to the individual node where the renunciation occurs. When the limiting criterion is dynamic, a change in one electrically significant node can affect the capacity shown in a broader group of related nodes.

However, the issue is not only technical. It also raises an important regulatory interpretation problem: whether the reserved capacity should correspond only to the capacity actually released by individual renunciations or reductions, or whether the reservation has also affected capacity that was already available before the RDL 7/2026 mechanism was applied. This distinction is relevant because, if previously available capacity is also classified as reserved, the effect of the regulation would be broader than simply managing newly released capacity.

This point is central to understanding the current situation. The purpose of RDL 7/2026 is to avoid inefficient blocking of scarce grid capacity and to ensure that released capacity can be allocated to priority demand projects. However, if the publication of June 2026 has moved previously available capacity into the non-grantable category, the practical consequence is a sharp reduction in capacity accessible through the general procedure. In other words, the regulation does not only affect speculative projects that renounce capacity; it may also temporarily reduce the capacity visible to ordinary new applicants in affected nodes.

For data centers, this creates a more complex access environment. A project cannot rely only on the apparent technical capacity of a node. It must assess whether the capacity is actually grantable, whether it is affected by released-capacity reservation under RDL 7/2026 and whether the node where the required capacity is belongs to a shared dynamic zone.

Overall, the February-June 2026 comparison shows that node congestion in Spain is not only a physical grid issue. It is also shaped by the way capacity is classified, reserved and reallocated after regulatory changes. This is relevant for the thesis because it shows why data center location cannot be analysed only through land, fiber connectivity or market attractiveness. The question is whether there is usable and grantable grid capacity in the node or zone where the project intends to connect.

4.3 ISSUES RELATED TO SPECULATIVE PROJECTS

One of the main problems associated with grid access in Spain is the risk that scarce network capacity is reserved by projects that are not sufficiently mature or that may not ultimately materialize. This issue is particularly relevant in the case of new large demand projects, because access capacity in the transmission network is limited and once it is granted, it can prevent other projects from connecting to the same node or to electrically related areas. Red Eléctrica has highlighted that, since 2022, 11.8 GW of capacity for new demand had been granted in the transmission network without any of these projects having yet entered into service, which illustrates the gap that may exist between access permits and actual project deployment [57].

This concern has also been recognized in the regulatory framework. The Resolution of 11 July 2025 on demand access capacity tenders explicitly refers to the risk of speculative behavior, describing situations in which access requests may lead to the accumulation of network capacity without being justified by the real interest or maturity of the planned investments [26]. In this context, speculation does not necessarily mean that the project is not legitimate, but that the reservation of capacity may occur before there is sufficient certainty regarding land availability, financing, permits, construction timetable or actual consumption.

Data centers are especially relevant in this debate because they require large amounts of firm electrical capacity and tend to concentrate in specific areas where fiber connectivity, land availability and proximity to demand are favorable. RDL 7/2026 explicitly notes that the access permits already granted to data center projects exceed even the most ambitious deployment forecasts, and links this to the need to ensure that these new loads do not undermine electrification and decarbonization objectives. Therefore, the issue is not only the volume of electricity that data centers may consume once operational, but also the amount of grid capacity they may reserve before reaching operation.

The RDL 7/2026 responds to this problem through several mechanisms. First, it introduces a capacity reservation payment for demand access and connection permits at voltage levels equal to or above 1 kV, applicable from the moment the permit is obtained until the activity starts. This payment acts as an economic signal as projects that reserve capacity but do not advance towards operation face a cost for keeping that capacity blocked. Second, the regulation links non-payment to the possible automatic expiry of the access and connection permits, reinforcing the idea that capacity should not remain indefinitely assigned to inactive projects.

Speculative access requests create three main risks for the electricity system. First, they reduce the capacity available for other consumers that may be more advanced or strategically relevant. Second, they distort the apparent level of network saturation, because the system may look fully booked even if part of the granted capacity is unlikely to be materialized. Third, they complicate planning decisions, since network reinforcements may be assessed against a pipeline of projects that is larger than the demand that will actually connect. For data centers, this means that access to the grid is becoming increasingly linked to project credibility, timing and effective materialization, rather than only to the formal submission of an access request.

4.4 FIRM CAPACITY, FLEXIBLE CAPACITY, AND INTERRUPTIBILITY

The introduction of flexible access represents one of the main regulatory responses to the increasing pressure created by new large electricity consumers. Traditionally, access capacity has been understood as firm capacity. Once the capacity is granted, the consumer has the right to use that capacity under regular operating conditions, being subject only to the general technical and operational rules of the system. However, the rapid growth of demand requests has made this model more difficult to sustain in congested areas. In this context, the CNMC Circular 1/2024 is particularly relevant because it establishes the methodology and conditions for demand access and connection, applying both to new requests and to modifications or increases of existing permits [22]. This circular introduces the distinction between firm and flexible access.

Flexible capacity does not mean that the grid physically has more capacity. Instead, it allows demand to connect under conditions in which its access may be limited in certain circumstances. The CNMC explicitly links this approach to the need to facilitate demand electrification and improve network utilization, since flexible access can enable the connection of consumers that would otherwise not be able to obtain firm access in constrained nodes. In this sense, flexible access is particularly relevant for large consumers such as data centers, whose load is generally continuous but may incorporate flexibility through batteries, thermal storage, backup systems or operational adjustments.

This distinction is also important in the context of RDL 7/2026. The regulation confirms that access prioritisation mechanisms may apply not only to firm access capacity but also to flexible access capacity, especially when capacity values are updated as a consequence of new technical specifications for determining demand access capacity. Therefore, the regulatory framework is moving towards a more differentiated treatment of demand as not all consumers necessarily require the same degree of firmness, and projects capable of adapting their consumption may be easier to integrate into the system.

For data centers, this creates both an opportunity and a constraint. On the one hand, flexible access could facilitate connection in areas where firm capacity is scarce, especially if the facility can reduce or shift part of its demand during network stress events. On the other hand, data centers are critical digital infrastructures with high reliability requirements, so any kind of interruptibility or limitation of access must be compatible with the continuity of their service.

4.5 VOLTAGE DIPS, DYNAMIC CRITERIA, AND TECHNICAL REQUIREMENTS

Beyond the formal availability of access capacity, the connection of large demand facilities is conditioned by technical security criteria and power quality requirements. The CNMC detailed specifications for demand access to the transmission grid establish that available capacity must be calculated through three main criteria: short-circuit power, static behavior and dynamic behavior, which may apply at nodal or zonal level. Therefore, the limitation of a node is not only related to the thermal capacity of lines or transformers, but also to the ability of the system to maintain voltage stability, withstand disturbances and preserve acceptable power quality. The available capacity comes from applying the most restrictive criteria.

This is particularly relevant for data centers because a significant part of their electrical equipment is connected through power electronics, including UPS systems, power converters, battery systems and cooling drives. The CNMC specifications define consumers with power electronic interfaces, known as CEP demand, as demand facilities in which the total consumption connected through power electronics reaches at least 20 MW in the peninsular system, or 5 MW in non-peninsular territories [22]. This definition is important because large converter-based loads may affect the electrical strength of the node and interact with voltage stability, short-circuit power and harmonic behavior.

Voltage dips are sudden short duration drops in voltage. These voltage dips are addressed within the dynamic behavior criterion. The regulation distinguishes between two dynamic access capacity values: CAD1, applicable to CEP installations that declare their ability to withstand a voltage dip without disconnection and recover active power afterwards, and CAD2, applicable to CEP installations that do not declare these technical capabilities [22]. In other words, the robustness of the connected load directly affects how its access capacity is evaluated. For example, a data center capable of remaining connected during voltage disturbances may be treated differently from a facility whose equipment disconnects during such events.

Voltage dips are particularly relevant for data centers because their internal electrical architecture is designed to protect highly sensitive IT equipment. In many facilities, UPS systems, converters and internal protections may react very quickly to deviations in voltage or frequency. This behavior improves service continuity from the data center perspective, but it may also create risks for the power system if a large amount of demand disconnects almost simultaneously. This issue is especially important in the transmission network because voltage dips are not necessarily local events. A fault in a high-voltage network can produce a voltage depression that propagates electrically across a wider area, affecting several nodes at the same time. The sudden loss of a large amount of demand may modify power flows, affect voltage recovery and create additional stress for the system. For this reason, the dynamic criterion may be assessed at zonal level and not only at the individual node level, since the relevant question is how the system behaves when several electrically related nodes are affected by the same disturbance. Recent dynamic studies show that the response of data centers during faults cannot be fully captured with generic static load models, since UPS switching logic, ride-through thresholds, reconnection delays and internal load dynamics strongly influence their impact on transient stability [20].

A second issue is the reconnection process after the disturbance has been cleared. If a large data center reconnects too quickly, the sudden recovery of a large load may cause a new voltage or frequency deviation, potentially triggering repeated connection and disconnection cycles. This phenomenon, sometimes described as flapping, shows that the relevant technical requirement is not only that the facility survives the initial voltage dip, but also that it returns to normal operation in a controlled way. Therefore, fault-ride-through and reconnection behavior should be considered together when assessing the dynamic compatibility of large data centers with the transmission network [20].

A third concern is power quality. Data centers include a high concentration of power-electronics-based equipment, including UPS rectifiers, server power supplies, cooling drives and converters. These devices can produce harmonic distortion, reactive power variations, voltage flicker and waveform-quality issues, particularly when combined with fast load changes from AI workloads or cooling ramp-up [25]. In weak or congested nodes, these effects may become more relevant because the local short-circuit strength is lower and the same load variation can produce a larger voltage impact.

Finally, AI-oriented data centers may introduce an additional stability concern: periodic or semi-periodic power fluctuations. Large GPU clusters can operate in synchronized computation and communication cycles, producing structured load variations at short time scales. If the frequency content of these fluctuations interacts with local or inter-area oscillation modes of the power system, the data center may act as a persistent forcing source rather than as a conventional passive load [19]. This does not mean that all data centers create oscillatory problems, but it shows why dynamic modelling and monitoring become increasingly important as AI workloads grow.

For data centers this means that grid connection also depends on whether the facility can demonstrate adequate electrical behavior under disturbances, acceptable harmonic emissions, balanced operation, suitable protection systems and sufficient robustness of power-electronic loads. This reinforces the idea that future data centers may need to be designed not only as reliable consumers from an internal perspective, but also as grid-compatible loads capable of supporting system security and power quality.

Chapter 5. FLEXIBILITY POTENTIAL OF DATA CENTERS

After analyzing the energy characterization of data centers and the current grid access situation in Spain, this chapter focuses on the flexibility potential of data centers as large electricity consumers. Data centers are commonly perceived as rigid loads because they require continuous operation, high reliability and strict power quality conditions. However, their internal energy structure shows that not all electricity consumption has the same degree of criticality. While the IT load must normally remain continuously supplied, other systems such as cooling, thermal storage, batteries, UPS infrastructure and some non-critical workloads may provide partial flexibility under specific technical and operational conditions.

The objective of this chapter is therefore to identify which parts of a data center can be technically managed without compromising the continuity of the digital service. Flexibility is understood not as the complete interruption of the facility, but as the ability to modify part of its net electricity demand in response to system conditions, such as emissions intensity, renewable availability, electricity prices or network constraints. This distinction is important because the potential contribution of data centers to the electricity system depends on the type of flexible resource, its activation time, its duration, and the operational limits imposed by reliability, redundancy and contractual obligations.

The chapter first defines the concept of the data center as a flexible consumer and then analyses the main sources of flexibility: cooling and thermal energy storage, BESS and UPS systems, IT workload management and technical flexibility services. It also discusses whether flexibility can partially reduce pressure on grid reinforcement needs and introduces the concept of grid-interactive data centers. This provides the technical basis for the modelling chapter, where thermal storage and BESS are selected as the two flexibility options to be quantitatively assessed.

5.1 CONCEPT OF THE DATA CENTER AS A FLEXIBLE CONSUMER

Data centers are usually perceived as large and continuous electricity consumers because their operation requires firm supply, high power quality and uninterrupted service. However, this does not mean that the whole facility behaves as an inflexible load. A data center combines critical IT demand with cooling systems, UPS infrastructure, batteries and auxiliary services, each with different operational constraints and flexibility potential [32].

In this thesis, flexibility is not understood as the complete interruption of the data center, since their critical digital service must remain available [58]. Instead, data center flexibility refers to the ability to modify part of the facility's net electricity demand without compromising its core function. This can be achieved by shifting cooling production, using electrical storage, reducing grid withdrawal during selected hours or rescheduling non-critical workloads [35].

From a regulatory perspective, it is necessary to distinguish between firm and flexible access capacity. Firm access capacity refers to the maximum active power that can be supplied with guarantee during all hours of the year, while flexible access capacity refers to capacity that cannot be guaranteed in all hours and may therefore be subject to temporary limitations or operating conditions [22].

Furthermore, it is also necessary to distinguish between three layers of flexibility. Technical flexibility potential refers to the physical capability of the facility to modify part of its electricity profile [58]. Available flexibility refers to the part of that technical potential that the operator can actually make available after preserving redundancy margins, backup requirements, cooling safety limits and contractual obligations [58]. Market activation refers to the flexibility that is finally activated in response to an external signal, such as electricity prices, emissions intensity, grid constraints, flexibility mechanisms or regulatory instructions [32]. This distinction is important because the existence of flexible assets does not imply that all technical flexibility is actually usable or economically activated.

Technically, this flexibility can arise from three different layers. The first is thermal flexibility, where cooling production can be shifted through thermal inertia, pre-cooling or thermal energy storage [46]. The second is electrical flexibility, where UPS batteries or dedicated BESS can modify the net electricity withdrawn from the grid, although UPS systems remain primarily designed for backup and continuity of supply [54]. The third is IT flexibility, where non-critical or delay-tolerant workloads can be postponed, rescheduled or relocated, although this depends on latency requirements, customer contracts and the degree of control that the operator has over the computational load [59].

The existence of these assets does not imply that all technical flexibility is actually usable. A data center may have batteries, thermal storage or schedulable workloads, but the amount of flexibility that can be offered depends on several factors such as redundancy margins and the operator's willingness to accept operational risk [32]. For this reason, data center flexibility should be understood as partial and conditional as it affects specific subsystems and time windows, not the entire facility.

Therefore, for the purposes of this thesis, flexibility is defined as the ability of a data center to modify part of its hourly electricity profile in response to system conditions, especially emissions intensity, without reducing its useful digital output. This approach focuses on the timing of consumption rather than only on annual electricity use, since shifting demand from more carbon-intensive hours to lower-emission hours can reduce induced emissions [32]. This also aligns with the recent Spanish regulatory direction, where new data center connections are expected to comply with future requirements on energy, environmental sustainability, resilience and digital sovereignty [4].

However, beyond the aim of this thesis, the flexibility mechanisms can also be useful in order to have regulatory advantages regarding access permit granting.

Additionally, some meetings with data centers promoters have been carried out during the development of this thesis. The aim of these meetings was to back up the research literature with actual performance and operational actions carried out nowadays by data centers.

From these meetings several takeaways were considered. The first one is that flexibility is not the main priority data centers are considering when designing and operating the data centers. Although they are aware of the potential and advantages flexibility can provide them, especially regarding access permit granting, they stated they are not considering flexibility as a main topic. However, they believe it is an interesting addition, and they are aware they will need to guarantee flexibility mechanisms when required by regulatory authorities.

The reason they stated was behind flexibility is not a primary priority is that it goes against their business model. Data centers need to guarantee continuous supply and operation, therefore, having their electricity consumption constraint is not a viable option for the moment. They mentioned that the typical data center contracts the promoters have with the data center operators guarantee they can cover 120% of the guaranteed demand. This reflects the sensitivity they have regarding continuity of supply and stable service. The promoters also stated that one of the aims of the digital infrastructure is to maximize its use, therefore they are not interested in being flexible to see their power supply interrupted.

5.2 FLEXIBILITY IN COOLING AND THERMAL STORAGE

Cooling is one of the most relevant sources of flexibility in a data center because it is a large and controllable electricity-consuming subsystem, but it is not part of the critical IT load itself. The cooling system must maintain safe operating temperatures for servers, yet the production of cooling does not always need to occur exactly at the same time as the heat is generated if thermal inertia, pre-cooling or thermal energy storage are available [60]. This creates a limited but technically clear flexibility margin.

Thermal flexibility is based on the partial decoupling between cooling production and cooling demand. In a conventional configuration, chillers operate according to the instantaneous thermal load. With thermal energy storage, part of the cooling demand can be produced in advance and stored as chilled water, ice or another storage [60]. During discharge, the stored cooling replaces or reduces chiller operation, lowering the electricity consumed by the cooling system during selected hours [45].

This mechanism is especially relevant for data centers because cooling demand is linked to both IT heat dissipation and external temperature. In warmer hours or months, mechanical cooling requirements increase and the scope for shifting cooling consumption becomes larger. However, the flexibility is not unlimited as the system must respect server temperature limits, minimum mechanical cooling requirements, storage capacity, discharge power and chiller efficiency [61]. Therefore, TES should be understood as a bounded flexibility resource rather than a fully dispatchable load.

From a system perspective, TES can be used for different objectives. It can reduce peak electricity demand by shifting cooling production away from high-load periods [46], reduce cooling costs under time-varying electricity prices [45], provide thermal backup during short disruptions of mechanical cooling [48], and support grid operation by moving demand away from constrained or carbon-intensive hours [62]. In this thesis, the relevant objective is not cost reduction, but the reduction of induced emissions through hourly load shifting.

For the quantitative model, TES is applied only to the cooling component of the data center demand. The IT load and auxiliary demand remain unchanged, while cooling electricity consumption is shifted from hours with higher emissions intensity to hours with lower emissions intensity. This assumption reflects the main advantage of TES which is that it can provide flexibility without directly affecting the digital service. At the same time, it also explains its main limitation which is that its impact is restricted to the share of electricity consumption associated with cooling and to the amount of cooling that can be safely displaced.

It is also important to mention that thermal energy storage can only shift part of the cooling load, as there is still some mechanical load to move the air to cool. The only part that can be shifted is when the cooling of the air occurs.

Consequently, thermal storage is modelled as a partial flexibility option. It reduces or shifts cooling-related electricity demand, but it does not modify the full net demand profile of the data center. This distinction is important for the later comparison with BESS, which can act on the total electricity withdrawn from the grid rather than only on cooling demand.

5.3 USE OF BESS AND UPS AS ENERGY RESOURCES

The electrical storage is a second source of flexibility in data centers, but it is important to distinguish between UPS systems and BESS. UPS batteries are included in the electrical architecture of the facility to ensure continuity of supply during outages, voltage disturbances or short interruptions [54]. Their primary function is reliability, not energy optimization. For this reason, although UPS systems can technically provide fast response or short-duration flexibility, their use is limited by the need to preserve backup capacity for critical IT loads [58].

A BESS has a different role. Instead of being reserved mainly for emergency supply, it can be operated as an energy management asset, charging when electricity is cheaper, less carbon-intensive or less constrained, and discharging when grid withdrawal should be reduced. This allows the data center to modify its net demand at the point of connection without changing the underlying IT load.

The flexibility provided by BESS depends on both power and energy capacity. Power capacity determines the maximum reduction of grid withdrawal during discharge, while energy capacity determines how long that reduction can be sustained. This distinction is essential because different services require different storage configurations. Backup requires high reliability and limited cycling, peak shaving requires repeated discharge during high-demand periods, power regulation requires fast response, and renewable integration or emissions-based shifting requires sufficient energy duration [60].

For this thesis, the BESS is not modelled exclusively as a backup resource, but as a flexibility asset used to shift the data center's hourly net electricity demand. The battery charges during hours with lower emissions intensity and discharges during hours with higher emissions intensity. Unlike TES, which only affects cooling demand, BESS can act on the total electricity profile of the facility, including IT load, cooling and auxiliary consumption. This gives it a broader potential impact on induced emissions but also exposes the model to additional constraints such as round-trip efficiency, cycling losses, battery degradation and investment cost.

In addition to emissions-based shifting, BESS can also provide value during grid contingencies or temporary access restrictions. If a network problem occurs, the battery can reduce the electricity withdrawn from the grid while maintaining part of the data center supply for a limited period. This capability is especially relevant for flexible access schemes, because it allows the facility to demonstrate that part of its demand can be temporarily covered internally instead of being fully supplied by the grid during critical moments. However, this contribution depends on the available state of charge, the power rating of the battery, the duration of the restriction and the need to preserve backup margins for critical IT loads.

BESS flexibility also has limits. The battery cannot reduce grid demand beyond its discharge power, cannot discharge for longer than its energy capacity allows, and must recover its state of charge through later charging. In addition, repeated cycling may accelerate degradation, while the economic value of arbitrage may decrease if price spreads flatten as storage deployment increases [32]. Therefore, BESS should be understood as a flexible energy resource with higher scope than TES, but also with higher cost, operational and modelling complexity.

In the context of the thesis, BESS is selected because it provides a clear and measurable mechanism to modify the hourly demand profile of a data center. It allows the analysis to quantify how much consumption can be moved from high-emission hours to low-emission hours, and how this affects total emissions and electricity costs. This makes BESS a suitable flexibility option for comparison with TES, since both technologies shift electricity consumption over time but act on different parts of the data center load.

Beyond this emissions-oriented operation, BESS and UPS systems may also be relevant from a dynamic grid-integration perspective. In AI-oriented data centers, storage can potentially help smooth abrupt variations in net demand, limit the speed of load ramps and support the facility during short grid disturbances. However, this additional value must be treated as complementary to the main scope of this thesis. [6].

5.4 IT LOAD MANAGEMENT AND WORKLOAD SHIFTING

A third source of flexibility is the IT load itself. Unlike conventional industrial demand, part of the electricity consumption of a data center is software-defined and depends on how, when and where computational tasks are executed. This creates a specific form of flexibility that is not based on storage, but on modifying the timing or location of digital workloads [5].

IT flexibility can take two main forms. The first is time shifting, where delay-tolerant tasks are postponed to hours that are more favorable for the power system [35]. The second is geographical shifting, where workloads are moved between different data centers or regions when the same computation can be executed elsewhere without affecting service quality [59].

The flexibility potential depends strongly on the type of workload. AI training, batch processing, data analytics and backups are generally more suitable for time shifting because they are not always subject to immediate latency requirements[5]. By contrast, AI inference, web services, content delivery, financial transactions and other real-time applications have much lower flexibility because they are closely linked to user activity, response time and service availability [5]. Therefore, the flexible share of the IT load cannot be assumed to be equal to the full IT demand.

Table 8 summarizes the different workload types and their sensitivity and potential to latency, time and geo-shift and their overall flexibility potential.

Workload Type	Latency Sensitivity	Time-Shift Potential	Geo-Shift Potential	Load Profile	Dominant Business Model	Overall Flexibility Potential
AI / ML Training	Low	High	High	Sustained, bursty step-loads	Hyperscale	High[51]
Batch / Data Processing	Low	High	Medium–High	Schedulable, periodic	Hyperscale, Enterprise	Medium–High
Backup / Disaster Recovery	Low (until failover)	High	Low	Low baseline, surge on failover	Enterprise, Colocation	Medium
AI Inference	Medium–High	Low–Medium	Medium	Variable, diurnal pattern	Hyperscale, Colocation	Medium-Low
Web / SaaS / Content Delivery	Medium–High	Low	Medium–High	Diurnal, traffic-driven	Hyperscale, Colocation	Low
Transactional / Real-Time	Very High	Very Low	Very Low	Steady, mission-critical	Enterprise, Colocation	Very Low

Table 8. Evaluation of flexibility potential of IT workload types (Source: ENTSO-E report)

The business model of the data center is also relevant. Hyperscale operators usually have more capacity to shift workloads because they control both the digital platform and the physical infrastructure. Colocation data centers face stronger barriers because the facility operator manages power, cooling and space, but customers control their own servers and applications. Enterprise data centers may have full internal control, but their workloads can be linked to critical business processes, which limits the practical willingness to provide flexibility [5].

IT load management can therefore provide valuable flexibility, but it is highly dependent on workload characteristics, latency constraints, customer contracts, data residency requirements and the operator's control architecture. In addition, the economic or environmental signal must be strong enough to justify modifying the execution of digital tasks, since service quality remains the main priority [63].

For these reasons, IT workload shifting is considered in this thesis as a relevant but non-modelled flexibility option. It is technically important because it can reduce or relocate part of the demand without requiring physical energy storage. However, it is not included in the quantitative model because it requires detailed operational information on workload mix, latency sensitivity, contractual conditions, utilization rates and the geographical distribution of computing resources. The model therefore focuses on TES and BESS, which can be represented with clearer physical constraints and publicly available technical assumptions.

5.5 TECHNICAL FLEXIBILITY SERVICES FROM DATA CENTERS

The flexibility resources described in the previous sections can provide different technical services to the power system. ENTSO-E distinguishes data center flexibility resources according to their ability to reduce peak power, shift energy, remain operationally available and respond within different activation timeframes.

5.5.1 FAST POWER RESPONSE

The first type of service is fast power response. UPS batteries and power-electronic interfaces are technically suitable for very fast response because they can react within seconds or even milliseconds. This makes them more appropriate for grid-safe behavior, fast frequency response or short-duration reserve products. However, this capability should be interpreted as a fast and short-duration response, suitable for events lasting from seconds to minutes, rather than as a substitute for prolonged energy supply during long grid interruptions.

5.5.2 ENERGY SHIFTING

The second type of service is energy shifting. BESS and thermal energy storage are more appropriate for this function because they can move electricity consumption across hours. BESS can charge during low-emission or low-price periods and discharge when grid withdrawal should be reduced, affecting the total net demand of the facility. TES performs a similar function, but only for the cooling component, by producing cooling in advance and using it later to reduce chiller electricity consumption. Therefore, BESS provides broader flexibility, while TES provides a more specific but less intrusive form of flexibility.

5.5.3 PEAK REDUCTION AND CONGESTION SUPPORT

The third type of service is peak reduction and congestion support. Large data centers can contribute to reducing demand during stressed network periods if part of their load is controllable or backed by storage. This may be achieved through battery discharge, temporary cooling load reduction, thermal storage discharge or workload shifting. These mechanisms are especially relevant in constrained grid areas, where the value of flexibility is linked not only to system-wide energy prices, but also to local network conditions.

5.5.4 RENEWABLE MATCHING AND EMISSIONS REDUCTION

The fourth type of service is renewable matching and emissions reduction. In systems with high renewable penetration, the environmental value of flexibility depends on the ability to move consumption towards hours with lower emissions intensity or higher renewable availability. This is the main perspective adopted in this thesis. Under this approach, flexibility is not only an economic arbitrage mechanism, but also a way to reduce induced emissions by changing the timing of electricity consumption.

Table 9 provides a qualitative assessment of each type of flexibility source and their adequateness according to different flexibility actions.

Flexivility Source	Power peak reduction	Energy shift	Operational availability	Business contraints
IT UPS battery	High	Moderate	Moderate	Very low
OT Load Shift	Very high	Low	Moderate	Very low
Cooling UPS Battery	High	Moderate	High (seasonal)	High
Cooling Load Shift	Low	Moderate	Very high (seasonal)	Very high
Thermal storage	Moderate	High	Very high	Very high

Table 9. Flexibility source capabilities (Source: ENTSO-E report)

Table 10 summarizes the main flexibility resources and their most suitable technical applications.

Flexibility resource	***Main technical contribution***	***Typical activation / duration***	***Most suitable use***	***Main limitation***
UPS batteries	Fast power response	Seconds to minutes	Fast response, short reserve, grid-safe operation	Must preserve backup function

Dedicated BESS	Power reduction and energy shifting	Minutes to hours	Peak shaving, emissions-based shifting, congestion support	CAPEX, degradation and round-trip losses
Cooling load shifting	Temporary reduction of cooling electricity	Minutes to hours	Short-term demand modulation and peak reduction	Thermal safety and ambient temperature
Thermal energy storage	Cooling energy shifting	Hours	Shifting cooling demand away from high-emission hours	Only affects cooling demand
IT workload shifting	Temporal or geographical relocation of computing tasks	Minutes to hours or days	Renewable matching, congestion management and demand reduction	Latency, SLAs and customer control
On-site generation	Local supply during constrained periods	Minutes to hours	Flexible connection support and backup	Emissions, permits and fuel constraints

Table 10. Flexibility sources and suitability (Source: own elaboration from ENTSO-E report)

This classification shows that data center flexibility is not a single product, but a portfolio of technical capabilities. UPS systems are more suitable for fast and short-duration power response, TES is better suited to cooling-related energy shifting, BESS can modify the total net demand profile, and IT workload shifting depends on the type of digital task and the operator's control over it. Therefore, the value of flexibility depends on matching each internal resource with the service for which it is technically appropriate.

5.6 FLEXIBILITY AS A PARTIAL ALTERNATIVE TO GRID REINFORCEMENT

The deployment of large data centers creates pressure on electricity networks because these facilities request large connection capacity at specific nodes. If the full demand is treated as firm and inflexible, the network must be planned to supply the maximum requested power under all relevant operating conditions. This can require additional grid reinforcements, longer connection lead times and stricter capacity allocation processes, especially in already constrained areas [5].

Flexibility can partially reduce this pressure by lowering the amount of demand that needs to be supplied as firm capacity in every hour. In this sense, a data center with controllable load, storage or conditional operation can reduce its grid withdrawal during selected periods of network stress. Flexible connection arrangements follow this logic. The facility receives firm capacity for the part of the demand that must be guaranteed, while an additional share may be disconnected under operating conditions, curtailment limits or temporary restrictions [22].

This does not mean that flexibility replaces grid reinforcement. Data centers still require a significant level of firm supply to guarantee service continuity, and the network must remain capable of supplying critical loads safely. However, flexibility can reduce peak demand, improve the utilization of existing infrastructure and defer some reinforcements when constraints occur only during a limited number of hours. ENTSO-E identifies flexible connection agreements as a way to close the "time-to-power" gap, allowing earlier connection when full firm capacity is not immediately available [5].

The usefulness of flexibility for grid planning depends on its reliability and verifiability. A flexible demand profile can only be considered in access or planning studies if the modulation is technically enforceable, predictable and compatible with system operation. This requires clear operating rules, real-time measurement, controllability and coordination with the network operator. Otherwise, the theoretical flexibility potential of the data center cannot be translated into actual hosting capacity.

For data centers, this creates a link between technical design and grid access. Assets such as BESS, TES, controllable cooling systems and workload management tools do not only reduce emissions or electricity costs, they can also improve the compatibility of the facility with constrained networks. This is particularly relevant under the recent Spanish regulatory direction, where large demand projects and data centers are increasingly expected to demonstrate maturity, sustainability and operational compatibility with the electricity system [4].

5.7 GRID-INTERACTIVE DATA CENTERS

The previous sections have shown that data center flexibility is not based on a single resource, but on the coordinated operation of thermal energy systems, electrical storage, UPS infrastructure, controllable IT workloads and, in some cases, on-site generation. A grid-interactive data center can therefore be understood as a facility that does not only consume electricity efficiently, but also adapts part of its demand profile to external power-system conditions, such as grid constraints, renewable availability, electricity prices or emissions intensity [5].

This concept goes beyond conventional energy efficiency. An efficient data center reduces the amount of electricity required to deliver a given digital service, mainly through lower PUE, improved cooling systems and more efficient IT equipment. A flexible data center can also modify when part of that electricity is consumed. A grid-interactive data center adds a further layer. It coordinates internal assets through an energy management system so that the facility can operate safely while responding to system needs.

ENTSO-E describes this transition as a progression from grid-safe to grid-supporting operation. The first step is ensuring that large data centers do not create risks for system stability, which requires robust behavior during voltage dips, controlled reconnection, ramp-rate control and adequate interaction with the grid. Once this control architecture exists, the same capabilities can support more active operation, including demand modulation, storage dispatch, cooling optimization and participation in flexibility services [5].

The concept of grid-interactive data centers is therefore directly related to the objective of this thesis. If data centers remain passive consumers, their impact on the electricity system is mainly determined by the size and location of their firm demand. If part of their demand becomes controllable, the timing of consumption can be adapted to reduce induced emissions and, potentially, to relieve pressure on the grid during critical periods. The quantitative analysis developed in the following chapters focuses on this second perspective by comparing an inflexible baseline with flexible scenarios based on TES and BESS.

Overall, data centers should not be understood as fully dispatchable resources, but neither should they be treated as completely passive loads. Their role in the electricity system will depend on how much of their technical flexibility potential can become available and how much of that available flexibility can actually be activated through operational, regulatory or market signals. This chapter has established the technical basis for analyzing data centers as partial, conditional and technology-specific flexible consumers.

Chapter 6. TECHNOLOGICAL AND REGULATORY SOLUTIONS

The previous chapter showed that data centers may provide partial and conditional flexibility through specific internal systems. However, technical flexibility alone is not sufficient for data centers to become useful resources for the electricity system. Flexibility must also be recognized, controlled and integrated within the regulatory framework. This chapter analyses the main technological and regulatory solutions that can enable data centers to move from being passive large consumers to regulated and controllable demand resources.

In Spain, this transition is particularly relevant because the growth of large demand is taking place in a context of grid congestion, limited access capacity and increasing regulatory concern about the efficient use of network capacity. The chapter first examines the shift from passive demand to regulated flexible demand, with emphasis on robustness, controllability and behavior during grid disturbances. It then analyses flexible access to the grid, distinguishing between different types of flexible permits and the operational conditions that may apply to demand connected to distribution or transmission networks.

The chapter also explains the role of automatic power reduction mechanisms, especially the difference between SRAP and SRAD. SRAP is presented as an operational obligation linked to Type 3 flexible access in the transmission grid, while SRAD is treated as a voluntary and remunerated demand response service. Finally, the chapter addresses the emerging sustainability requirements for data centers, including renewable additionality, hourly matching, energy efficiency reporting, sustainable water use, waste heat recovery, resilience and digital sovereignty. These elements show that the future integration of data centers in Spain will depend not only on their ability to obtain grid capacity, but also on their capacity to demonstrate technical robustness, operational flexibility and environmental compatibility.

6.1 FROM PASSIVE DEMAND TO REGULATED FLEXIBLE DEMAND

Large electricity consumers have traditionally been treated mainly as passive loads whose integration depends on the availability of access and connection capacity. However, this approach is less sufficient for large data centers, because their impact on the system depends not only on the MW requested, but also on their dynamic behavior during disturbances.

This is especially relevant for data centers connected through UPS systems and other power-electronic equipment. Data centers can differ from conventional industrial loads because may disconnect large blocks of load during voltage or frequency disturbances. Therefore, large power-electronic connected demand must be assessed according to its robustness, voltage-dip behavior and impact on power quality.

The regulatory focus is shifting towards how large demand behaves under disturbed grid conditions and how they can connect without affecting system stability. Abrupt disconnection during a voltage dip, or uncontrolled reconnection after the fault is cleared, can amplify the original event and create additional stress for system. For this reason, requirements such as fault ride-through capability and controlled active power recovery become relevant for large demand facilities.

6.2 FLEXIBLE ACCESS TO THE GRID

Flexible access is being developed in Spain as a specific regulatory tool for new demand connections and expansions in constrained networks. It is not intended to convert existing firm access permits into flexible ones, but to allow new consumers to connect when full firm capacity is not available, provided that they accept predefined operating limitations. This approach is consistent with CNMC Circular 1/2024, which introduces flexible access capacity for demand facilities as a voluntary alternative where the network cannot guarantee supply during all hours of the year [22].

Therefore, flexible access is a tool for new supplies or expansions in constrained areas, where consumers may connect without waiting for all reinforcements, provided that they accept temporary power limitations or disconnection under defined risk scenarios.

For data centers, BESS can make flexible access more technically feasible. If part of the requested capacity is granted as flexible rather than firm, the battery can help the facility reduce its grid withdrawal during the periods in which the system operator requires a limitation. In this case, the data center would not necessarily interrupt its digital service, but would temporarily supply part of its demand from the battery. This reinforces the role of BESS not only as an emissions-reduction asset, but also as a technical enabler of flexible access. Nevertheless, this capability must be limited by the battery duration, available state of charge, discharge power and the need to maintain sufficient backup for critical loads.

The key logic is that the network may be able to supply the full demand in normal operation, but not under certain contingencies or saturated network conditions, such as N-1 contigencies. In that case, granting only firm capacity would reduce the amount of demand that can be connected, while granting a firm and flexible combination allows the grid to host additional demand without oversizing the network for conditions that occur only during limited periods.

6.2.1 FLEXIBLE ACCESS PERMITS

The CNMC Circular 1/2024 establishes the base for distinguishing four types of flexible access permits. The first three types, type 0, 1 and 2, correspond to the distribution grid, while access type 3 belongs to the transmission grid.

6.2.1.1 Type 0

Type 0 applies to distribution-connected demand above 1 kV and allows the same installation to have firm and flexible capacity [64]. It is based on predefined consumption patterns, which may reflect seasonality and network saturation. The flexible capacity is limited if the approved pattern is not respected. The control is local, through a PLC, smart relay or remote-control meter. In this type of permit real-time measurement is not required, except for BESS above 1 kV and 100 kW.

Therefore, Type 0 is the least dynamic modality as it does not rely on real-time instructions from the distribution network operator, but on compliance with an agreed consumption pattern.

6.2.1.2 Type 1

Type 1 applies to distribution-connected demand above 36 kV. The demand for this type of access is fully flexible and cannot combine firm and flexible capacity within the same installation. It applies when the installation can be supplied under normal network operation, but not if an N-1 contingency affects the substation where it is connected. Unlike Type 0, the facility must send real-time measurements to the distribution network operator and the reduction condition may lead to complete remote disconnection of demand installation [64]. Its expected consumption availability is around 90% of the hours of the year, although this does not represent a firm supply guarantee.

6.2.1.3 Type 2

Type 2 applies to distribution-connected demand above 36 kV and above 1 MW, and allows firm and flexible capacity to coexist in the same installation [64]. The flexible part may be limited partially or totally through day-ahead D-1 programmed limitations, preventive real-time instructions with a 30-minute horizon, or corrective real-time instructions with immediate or sub-three-minute activation. If the installation does not comply with the programmed limitation or setpoint, the distribution network operator may remotely disconnect the installation through the corresponding control device. This makes Type 2 a more active form of distribution operation.

6.2.1.4 Type 3

Type 3 applies to transmission-connected demand and is the most relevant modality for very large consumers. It allows firm and flexible capacity to be combined, but the flexible part has no supply guarantee and is subject to the operational requirements of the transmission system operator [64]. The consumer must participate in the Automatic Power Reduction System (SRAP in Spanish, Sistema de Redución Automática de Potencia), receiving predisposition or activation signals from the system operator. In contingency, unavailability or overload situations, the system operator may require immediate reduction of the flexible demand, including reduction to 0 MW, and consumption cannot be increased again until the order is deactivated.

All types require that flexible demand is measurable, controllable and verifiable. The obligations the consumers must follow are essential because flexible access only has regulatory value if the limitation can actually be executed when the network contingency occurs. In this sense, metering and telecontrol are necessary.

The economic treatment of flexible access is also relevant. Since flexible capacity does not have the same guarantee of supply as firm capacity, flexible access has a differentiated economic treatment, including the concept of a flexible network tariff or flexible access charge. The logic is that a consumer accepting lower supply guarantees and operating restrictions may be subject to a different tariff treatment.

6.3 AUTOMATIC POWER REDUCTION SCHEMES: SRAP AND SRAD

The activation of demand flexibility in Spain can occur through two different mechanisms that should not be confused, the Automatic Power Reduction System (SRAP) and the Active Demand Response Service (SRAD). Both involve a reduction of demand, but their regulatory nature, activation logic and economic treatment are different.

6.3.1 SRAP

The SRAP is an operational security mechanism regulated by Operational Procedure PO 3.11. Participation in the mechanism is generally voluntary and is not limited to electricity demand, since PO 3.11 also covers generation, storage and pumping facilities that meet the applicable participation requirements [65]. However, in the context of flexible demand access, participation becomes mandatory when it is established as a condition of a Type 3 flexible access permit. In this case, the installation must be capable of receiving predisposition and activation signals from the system operator and reducing the flexible part of its demand when required to preserve system security.

Operational Procedure (PO) 3.11 belongs to the regulatory framework for operational procedures stablished by the Spanish TSO, REE. These procedures regulate different aspects of electricity system operation with the objective of ensuring the secure and adequate operation of the system and the transmission network

The amount of power subject to SRAP is defined ex ante by the flexible capacity granted in the access permit. Therefore, the consumer does not decide in real time how much it is willing to reduce, nor is this amount determined through an auction. If a data center has, for example, 100 MW of firm capacity and 40 MW of Type 3 flexible capacity, the SRAP obligation applies to the 40 MW flexible block, not to the firm capacity. In case of activation, the system operator may require the reduction of the flexible demand to 0 MW, or to another value established by the operator, and the consumer cannot increase consumption again until the activation order is deactivated [66].

This mechanism is not remunerated like an ordinary flexibility market product. The reduction of the flexible capacity under SRAP is part of the conditions accepted by the consumer when obtaining a flexible access permit. Consequently, SRAP activation should be understood as the enforcement of a flexible access condition for security purposes rather than as the voluntary provision of a remunerated demand-response service.

6.3.2 SRAD

The SRAD, by contrast, is a market-based balancing service and a specific product associated with manual Frequency Restoration Reserve (mFRR) under the European balancing framework. It is regulated in P.O. 7.5 and allows demand facilities to offer consumption reductions to the system operator when there is insufficient upward tertiary reserve [67]. Its purpose is to provide additional upward balancing reserve and contribute to correcting system imbalances, rather than to manage local network congestion. The participation is voluntary and remunerated. The service is assigned through auctions, in which demand-side resources offer reduction capacity for a defined delivery period. Red Eléctrica has already used this mechanism in the Spanish peninsular system, with 1,725 MW awarded for the first half of 2026 and 1,775 MW for the second half of 2026 [68].

The remuneration structure of SRAD is also different from SRAP. In SRAD, the provider receives a payment for availability when its offer is assigned, and, if activated, the energy reduction is settled according to the rules of P.O. 7.5 [67]. Therefore, SRAD is a demand-response service that contributes to the provision of upward mFRR, while SRAP is an operational security mechanism that becomes mandatory when it is included as a condition of the flexible capacity granted under a Type 3 access permit.

For data centers, this distinction is essential. A data center with Type 3 flexible access would be required to comply with SRAP for the flexible portion of its connection capacity, independently of whether it participates in markets. Participation in SRAD would be a separate decision, subject to qualification, operational capability and the willingness of the operator to offer demand reduction as a remunerated balancing service. Therefore, SRAP defines an operational obligation linked to access, whereas SRAD represents a potential additional revenue opportunity for demand flexibility through the provision of balancing reserves.

6.4 SUSTAINABILITY REQUIREMENTS FOR DATA CENTERS

One of the initial hypotheses was that future regulation would go beyond access rights and network security and would eventually impose requirements influencing how data centers consume electricity. In Spain, the approval of RDL 7/2026 strongly supports that hypothesis as it explicitly foresees specific requirements on energy sustainability, environmental sustainability, resilience and digital sovereignty for newly connected data centers to transmission and distribution networks [4].

The provision does not define the final technical thresholds yet, but it anticipates the main areas that may be regulated, including renewable additionality and hourly matching, energy efficiency, sustainable water use, economic and social benefits, and the contribution of the project to Spanish or European digital resilience and sovereignty [4].

Therefore, the future regulatory framework is expected to make sustainability a mandatory condition linked to the development and operation of new data center projects, rather than only a voluntary performance attribute. However, these requirements will apply to data centers that connect to the transmission or distribution networks after the entry into force of the future Royal Decree. Consequently, data centers already connected before that date would not fall within the scope established by this provision, unless subsequent regulation provides otherwise. This is particularly relevant because non-compliance with these requirements may lead to penalties or even the loss of access and connection permits, under the terms to be defined by the future regulation [4].

6.4.1 RENEWABLE ADDITIONALITY AND HOURLY MATCHING

One of the most relevant elements of the future Spanish framework is the expected link between data center electricity consumption and renewable generation. The RDL 7/2026 expressly states that the future Royal Decree may include criteria of additionality and hourly matching in relation to the consumption of electricity from renewable sources [4].

6.4.1.1 Additionality

Additionality is understood as the idea that renewable electricity associated with new large consumers should contribute to increasing renewable generation available to the system, rather than simply reallocating existing renewable production through certificates or guarantees of origin. This means that the data center should demonstrate that its electricity procurement contributes to the deployment of new renewable capacity, for example through a long-term PPA with a new renewable project, direct investment in renewable generation, or another mechanism that increases the amount of renewable electricity available in the system. The objective is to avoid a situation in which a large new electricity consumer claims renewable supply on an annual accounting basis while the physical system still needs additional non-renewable generation to meet its real-time demand.

6.4.1.2 Hourly matching

Hourly matching means that renewable generation associated with the data center consumption should be produced in the same hours. This goes beyond an annual renewable procurement approach as under this approach, a data center could consume electricity continuously throughout the year and buy enough renewable certificates or renewable energy volumes to match its total annual consumption, even if a significant part of its real-time consumption occurs during hours with low renewable generation. Hourly matching seeks to avoid this mismatch by requiring a closer temporal relationship between renewable production and electricity demand.

Hourly matching is particularly relevant because one of the objectives of this thesis is to assess whether future regulation should influence not only the access conditions of data centres, but also the way they consume electricity. The explicit reference in RDL 7/2026 to additionality and hourly matching provides strong evidence that Spanish policymakers are already considering such an approach. However, one of the questions explored in this work is whether a strict hourly matching requirement would be proportionate. Preliminary results suggest that meaningful incentives can already be created by encouraging data centres to increase consumption during periods of abundant renewable generation, particularly during solar surplus hours, without necessarily requiring a one-to-one hourly correspondence between consumption and renewable production. This distinction is important because the period of significant solar surplus is often concentrated in a limited number of hours per day, which may make less granular matching approaches capable of delivering many of the intended system benefits while preserving greater operational flexibility for data centres

6.4.2 Energy efficiency and environmental reporting

Energy efficiency is also identified as one of the criteria that may be included in the future Royal Decree for data centers [4]. The regulatory relevance of energy efficiency is not limited to setting performance requirements, but it is also linked to the obligation to measure, report and monitor the energy and environmental performance of data centers. At European level, the Energy Efficiency Directive (EU) 2023/1791 requires the creation of a framework for monitoring the energy performance of data centers, in which they require Member States to ensure the collection and publication of data relevant to energy performance of data centers [27]. The Delegated Regulation (EU) 2024/1364 establishes the first phase of a common Union rating scheme for data centers in which they develop the obligation by defining the information and key performance indicators that operators must report [14]. This information will be reported by data centers with an installed IT power demand of at least 500 kW to the European database on data centers ReportENER. The purpose is to allow the European Commission and Member States to be transparent and to assess the sustainability of data centers using comparable information.

In Spain, the regulatory process opened by MITECO for the Royal Decree on energy efficiency and sustainability for data centers builds on this European framework. The draft of the Royal Decree provides that operators of data centers with an installed IT power demand of at least 500 kW must submit, every year and no later than 15 May, the information required under Annexes I and II of Delegated Regulation (EU) 2024/1364 to the Directorate-General for Energy Planning and Coordination [69]. The Spanish draft requires reporting on strategies to minimize impacts related to total energy consumption, electricity grid functions, water use, potable water use and reused waste heat, as well as information on employment and socioeconomic impact

6.4.3 Sustainable water use

Sustainable water use is another environmental dimension expressly mentioned in RDL 7/2026. This is particularly relevant for cooling technologies that rely on evaporative processes or operate in areas with water stress. Some cooling solutions may reduce electricity consumption but increase water consumption, creating a trade-off between energy and water performance. Therefore, this requirement does not necessarily imply excluding specific cooling technologies, but it requires the project to justify that its cooling design is compatible with local water availability, climate conditions and territorial constraints. In this context, indicators such as WUE become relevant not only as technical performance metrics, but also as part of the assessment of whether a data center can be considered environmentally sustainable.

6.4.4 Waste heat recovery and territorial integration

Waste heat recovery is not expressly listed in the RDL 7/2026 on data center sustainability requirements. The specific regulatory treatment of waste heat appears more clearly in the draft project of Royal Decree on the energy efficiency and sustainability of data centers. This draft project includes the better use of waste heat among its objectives, defines waste heat as the heat generated by servers and IT equipment during operation that is not used for the main purpose of the facility, and requires data centers with a total rated energy input above 1 MW to use waste heat for heating, cooling or other heat applications [69].

The draft project of Royal Decree links this obligation to the planning as data center developers and owners would have to prepare a waste heat utilization plan supported by a cost-benefit analysis, assessing the technical, economic, financial and socio-environmental viability of the project [69]. Therefore, reused waste heat is included in the information to be reported annually, which means that heat recovery is not treated only as a voluntary efficiency practice, but as a measurable sustainability indicator. This is also consistent with the European efficiency framework.

This requirement is relevant because data centers continuously reject heat from servers and cooling systems. Although this heat is usually low-temperature and therefore not always easy to reuse, it may be valuable for nearby district heating networks, buildings, swimming pools, industrial processes or urban developments. The feasibility of waste heat recovery therefore depends strongly on territorial conditions. A data center located close to a heat demand center or to an existing district heating network is more likely to reuse its residual heat than an isolated facility with no nearby thermal demand.

There are some real practical examples, such as the use of residual heat from Google's Hamina data center in Finland for nearby buildings and public facilities [70].

For this reason, waste heat recovery should be understood not only as an energy efficiency measure, but also as a territorial integration mechanism. It can help data centers provide a local benefit to the surrounding area, reduce primary energy needs in nearby thermal uses and improve the social acceptability of large electricity-consuming projects.

6.4.5 RESILIENCE AND DIGITAL SOVEREIGNTY

Finally, the RDL 7/2026 also identifies resilience and digital sovereignty as areas that may be regulated by the future Royal Decree [4]. Resilience refers to the capacity of the data center to maintain critical digital services under electrical, operational, cyber or external disruptions. Digital sovereignty refers to the strategic value of data center infrastructure for Spanish and European digital autonomy. These requirements show that the regulation of data centers is not only an electricity sector issue, but it is also part of a broader industrial, digital and security policy.

Overall, the sustainability framework for data centers should be understood as a complement to grid access regulation. Access and connection rules determine whether the network can technically host the demand, while sustainability requirements determine whether the project is compatible with broader energy, environmental and strategic objectives. RDL 7/2026 reinforces this link by allowing the future requirements to lead to penalties or even the loss of access and connection permits, under the terms to be defined by future regulation. For the purposes of this thesis, this reinforces the relevance of flexibility and renewable integration because these resources may help data centers align their consumption with cleaner electricity, reduce environmental impact and improve their integration into the Spanish power system.

Chapter 7. MODELING

This chapter presents the model developed to analyze the daily energy load behavior of a hyperscale data center. The main purpose of the model is to assess whether a data center, which is considered as a high stable and inflexible load, can incorporate energy flexibility strategies. The analysis focuses on storage-based solutions, a thermal storage scenario linked to the cooling system and an electrical storage through battery energy storage systems (BESS). These solutions are used to shift part of the electricity demand from hours with higher emission intensity to hours with a lower share of emitting generation.

The aim of the model is not to optimize or minimize electricity costs, but to evaluate the trade-off between emissions reduction and economic impact. In the regulatory context described in previous chapters, data centers may increasingly be required to demonstrate sustainability, flexibility or compatibility with the electricity system in order to obtain or maintain access to grid capacity. Therefore, the model explores whether technologies such as TES and BESS could reduce induced emissions, and what cost this would imply for the data center.

The analysis follows a Pareto-oriented approach. Each flexibility configuration represents a different balance between avoided emissions and additional or reduced costs. The objective is not to identify a single optimal solution, but to determine which ranges of storage capacity could be reasonable if flexibility requirements were imposed on data centers. In this sense, the model helps assess whether certain technical requirements would provide meaningful environmental benefits without creating a disproportionate economic burden for the facility.

This model does not aim to reproduce in full detail the internal technical operation of a real data center as such approach would require highly detailed information on electrical architecture, cooling design, redundancy levels, IT workload management and operational constraints. Instead, the model adopts a more simplified but representative approach, suitable for comparing different flexibility scenarios and quantifying their impact on electricity consumption and emissions.

A key modelling decision is the use of twelve representative days, one for each month of the year. Each day is modelled with an hourly resolution, which results in a total of 288 hourly time steps. The model does not simulate every hour of the year directly but rather uses one representative day per month to approximate the annual behavior of the data center. The representative day of each month is built by averaging all the disaggregated hours of the same month, obtaining 24 hourly average values. This approach allows the model to capture seasonal and hourly differences in cooling demand, electricity generation mix and emissions intensity, while keeping the level of complexity manageable. The results obtained from the twelve representative days are then annualized in order to estimate the yearly parameters.

These simplifications are relevant as the objective of the thesis is not to forecast exact annual operation of a data center, but to compare performance of different flexibility strategies.

An important note to take into account: when talking about total consumption or cooling consumption, it refers to the consumption obtained by the energy withdrawn from the grid.

7.1 OBJECTIVE

This model is designed to compare several scenarios. The first scenario represents the reference case, in which the data center operates without any flexibility mechanism. In this case, the hourly electricity consumption is determined by the IT load, the cooling demand and the auxiliary loads. This scenario provides the baseline against which all flexibility options are compared.

The second and third scenarios introduce flexibility technologies. In the case of thermal storage, part of the cooling demand is shifted from high-emission hours to low-emission hours by pre-producing and storing cooling energy. In the case of the BESS, electricity is charged during hours with a lower emissions factor and discharged during hours with a higher emissions factor. It must be said that in many hours, low-emission periods tend to coincide with lower spot prices, especially when renewable generation is abundant. However, this relationship is not assumed to be perfect. For this reason, the model identifies charging and discharging hours primarily according to the emissions factor, while electricity prices are used later to assess the economic impact of the flexibility strategies.

The model aims to answer the following questions and represent the core pillars:

- What is the hourly electricity consumption profile of a representative large-scale data center?
- How does this profile vary across the year due to changes in cooling demand?
- Which hours present the highest and lowest emissions intensity within the Spanish electricity mix?
- How much demand can be shifted using thermal storage or battery storage?
- What emissions reductions can be achieved through these flexibility strategies?
- What are the associated economic implications, considering investment costs and electricity costs variations?

The main outputs include annual electricity consumption, hourly demand profiles, total CO2 emissions, avoided emissions, storage charging and discharging patterns, investment costs and average electricity costs. These indicators allow the different scenarios to be compared from both an environmental and an economic perspective.

The model follows a sequential structure. First, the electricity consumption of the reference data center is estimated from the IT load, the monthly PUE and the auxiliary consumption assumptions. Second, this consumption profile is combined with hourly electricity system data, including the generation mix, emissions intensity, spot prices, network tariffs and regulated charges. Finally, different flexibility scenarios are introduced in order to assess how thermal storage and battery storage modify the hourly demand profile, total emissions and electricity costs.

Figure 10 shows the methodology followed in the model, in order to illustrate the steps followed.

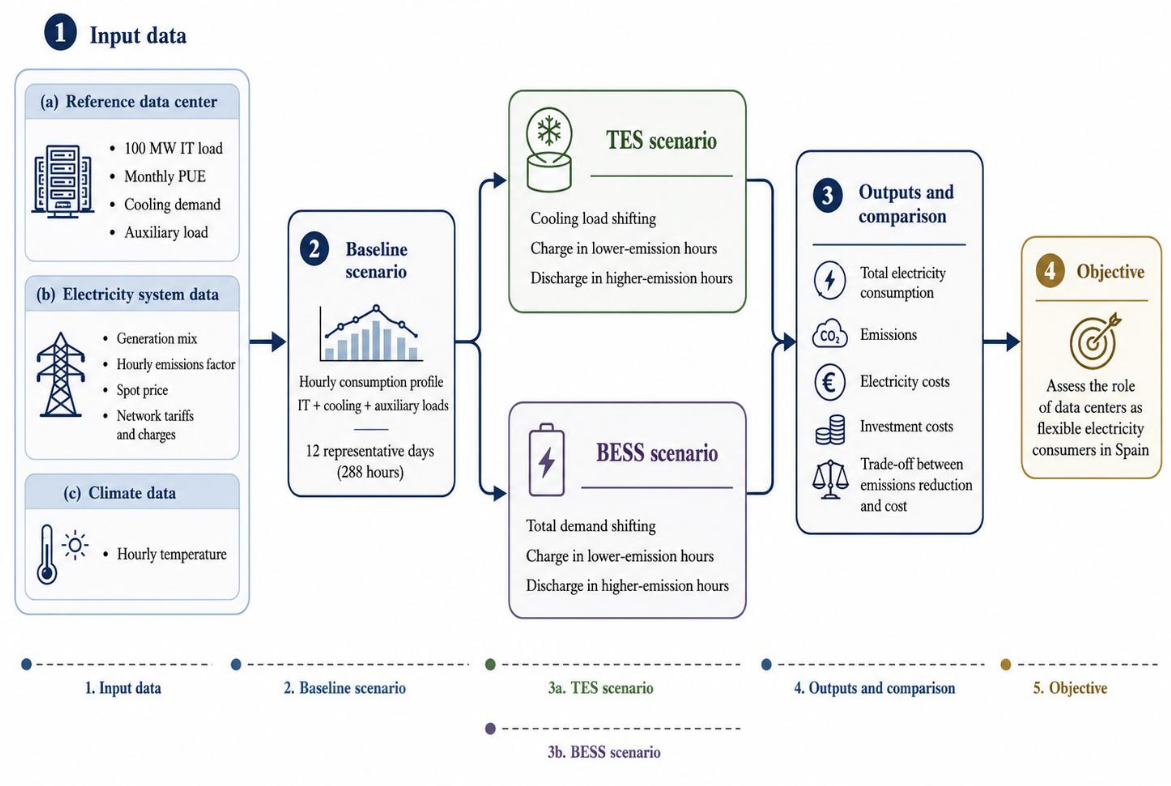


Figure 10. Methodology followed for modeling a data center consumption profile (Source: generated by AI)

7.2 DEFINITION OF THE REFERENCE DATA CENTER

The reference case considered for the modelling is a hyperscale data center with an IT power demand of 100 MW. This value represents the electrical power required by the IT load, mainly by the servers, that perform the core digital functions of the facility. The IT load is considered the main driver of electricity consumption and is assumed to operate continuously throughout the year, if disturbances do not occur. The assumption of the IT load operating continuously is due to not considering the different types of workloads. As it has been seen in chapters 3 and 5, there are different types of IT workloads and each of them carry out different functions. However, these detailed differences are not considered, therefore, it is assumed that IT workloads operate continuously with a flat profile to avoid complexity that would not add much value to this analysis.

The choice of a 100 MW IT load is intended to represent a big load rather than a small or medium-sized data center as the hyperscale data centers are becoming increasingly important electricity consumers and can have significant impact on connection capacity, electricity demand growth and transmission grid. At the same time, their large and relatively predictable consumption profiles make them suitable for flexibility strategies.

The total electricity demand of the data center is not only based on the IT load. In addition to the electricity consumed by IT equipment, the facility requires energy for cooling systems, lighting, security systems, backup systems and other auxiliary services. Among these additional loads, cooling is the most relevant in terms of power consumption as it accounts for around 40% of the total consumption and also in terms of flexibility, because part of its cooling demand can be shifted through thermal energy storage (TES).

As stated in previous chapters, the overall performance of the data center is represented though the concept of Power Usage Effectiveness, known as PUE, which is defined as the ratio between the total electricity consumed by the data center and the electricity consumed by the IT equipment. In this model, the PUE varies by month in order to reflect the seasonal influence of ambient temperature on the cooling needs. During colder months, cooling requirements are lower, and free cooling can be used, lowering the PUE. By contrast, during warmer months, cooling demand increases and the PUE becomes higher.

The reference data center of the model is represented as the combination of the three main electricity consumption components:

- **IT consumption:** associated with servers and digital infrastructure.
- **Cooling consumption:** associated with the refrigeration system.
- **Other auxiliary consumption:** lighting, security, monitoring systems and backup systems. Usually linked to operational safety and service continuity.

The IT load is assumed to be relatively stable and continuous, as large data centers are designed to provide high availability and continuous services. Although some IT workloads can be shifted in time due to peak shaving for example, this is out of the scope of this model.

The cooling demand is modelled as a variable component that depends on the monthly PUE. This represents the variations in the cooling demands depending on the time of the year. A PUE value of 1,5 is used as the mean value and is used in mild temperature months. During the winter months, the PUE decreases to 1,3 and in the summer the PUE increases up to 1,8.

The other auxiliary loads are not treated as flexible loads since their contribution is really small in comparison to the other components.

The total electricity consumption is obtained by multiplying the IT electricity consumption by the monthly PUE. Therefore, the difference between total consumption and IT consumption represents the non-IT demand, mainly cooling and auxiliary services.

The reference data center is used as the baseline for the following flexibility analysis. All storage scenarios are compared against this base load case in order to determine how the introduction of flexibility strategy modifies the demand profile, emissions and economic performance of the data center.

7.3 INPUT DATA

The model requires several types of input data to represent the operation of the data center and its interaction with the electricity system. Aside from the data regarding the characteristics of the data center like already mentioned before (IT load, PUE, cooling demand…), it is necessary to obtain data from the system. More specifically hourly generation mix, system emissions factor, hourly spot prices, network tariffs and regulated charges and hourly temperature.

It is important to explain how this data has been treated. The raw format of the obtained data had an hourly resolution for a complete year. Therefore, each variable considered had initially 8760 hourly values. However, since the model is based on twelve representative days, one for each month of the year, the original hourly data had to be aggregated. To do this, an hourly profile was calculated for each month, this means that, for every month, the average value of each disaggregated hour of the day was obtained using all corresponding days of that month.

An example to illustrate is the following. The value assigned to the hour 00:00 in January corresponds to the average value of all the 31 00:00 in January. The same procedure has been applied to the remaining hours of the days for the 12 months. As a result, each month is represented by a 24 hour-profile, reducing from 8760 hours to 288 representative average hourly values.

The data is all obtained for the year 2025, as it is the last full year of recorded values. The selection of this year is because, as more renewable energy is being introduced in the system, the year 2025 was going to be the most representative year for the following year, which resembles more accurately the current situation. However, the values from the last years down to 2020 were also analyzed in order to confirm that 2025 had not been an extraordinary year with abnormal or unexpected values. The results concluded that 2025 did not have considerable outliers that could influence the results of the model, in terms of electricity spot price or temperature values.

7.3.1 ELECTRICITY GENERATION MIX

The first group of input data corresponds to the Spanish electricity generation mix. The model uses the calculated aggregated data of the hourly generation by each technology. This data for the year 2025 was provided by a member of the Endesa team, which obtained this data from official sources from the system operator. The emitting generation included combined cycle gas turbines, coal, cogeneration and other fossil-based sources. The non-emitting generation includes renewable generation, solar photovoltaic and thermal and wind generation, nuclear power, hydro and pumping. For each representative hour, the share of emitting and non-emitting generation is calculated. This allows the model to identify the hours in which the electricity system has a higher or lower carbon intensity. These hourly values are essential for the operation of the storage systems, since both the battery and the thermal storage are designed to charge during cleaner hours and discharge during more emitting hours.

7.3.2 EMISSIONS COMPUTATION

The second group is the emissions. This group rather than obtaining raw data, it was calculated using the electricity generation mix and the average tons of CO_2 equivalent per MWh, since the hourly values of tons of CO_2 were not available. The methodology followed is the following. First, once the emitting and non-emitting generation was differentiated, their representative percentage of each of them in the system was calculated. During the central hours of the day, the percentage of emitting generation decreases down to 9%, however during the night, with little renewable generation, the emitting generation can represent up to 36% in the electricity mix in the worst case scenario. However, this value ranges from around 17% to 27% approximately during night hours. With all the percentage values for the 288 representative hours, it was obtained that the mean value of generating mix is around 21,2% of the total system.

The annual average emissions factor for the Spanish electricity system in 2025 was obtained from Red Eléctrica de España. Since hourly emissions factors were not available, the daily values were used to calculate an annual average emissions factor of 0.108 tCO_2 eq/MWh for the year 2025. This annual average value was then used as the reference emissions factor of the model. Therefore, when the emitting generation share is equal to 21.2%, the model assumes an emissions factor of 0.108 tCO_2 eq/MWh.

For each representative hour, the emissions factor was adjusted proportionally according to the corresponding share of emitting generation. If the hourly emitting share is higher than 21.2%, the emissions factor increases in the same proportion. Conversely, if the hourly emitting share is lower than 21.2%, the emissions factor decreases proportionally. As a result, the model obtains a table of 288 hourly emissions factors, expressed in tCO_2 eq/MWh, corresponding to each representative hour of each month.

7.3.3 SPOT PRICE, NETWORK TARIFFS AND REGULATED CHARGES

The third group of input data is the spot price for the Spanish electricity system. These values were obtained from the day-ahead Spanish market and as they were values for the whole year, the same aggregation procedure to the average hourly values for each month was made.

An assumption was made for this data, as the purpose of the model is to compare flexibility scenarios rather than to reproduce the exact electricity bill of a particular facility. The electricity cost of the data center is estimated using only the hourly spot price, network tariffs and regulated charges. Other components of the final electricity bill, such as supplier margins, taxes, bilateral contract conditions, hedging strategies, imbalance costs or guarantees of origin, are not explicitly considered and they have been dismissed. This simplification is justified because these elements are highly dependent on the specific contractual situation of each consumer and are not directly linked to the hourly operation of the data center. Therefore, the calculated cost should be understood as a representative approximation, not as a full retail bill simulation.

The fourth group of input data are the network tariffs and regulated charges. Since network tariffs and regulated charges are structured by time periods, it was necessary to adapt them to the representative-day approach used in the model. In the Spanish peninsula, these periods are not distributed in the same way across all months: weekdays are classified into different seasonal types depending on the month, while Saturdays, Sundays and national holidays are assigned to the same period for the whole day [71]. For this reason, a monthly average value was calculated for each hour taking into account all the periods present during that representative hour and the corresponding tariff and charge. This allows the model to capture, in a simplified way, the effect of different tariff periods within each month while remaining consistent with the use of twelve representative days.

7.3.4 TEMPERATURE

The fifth group is the temperature data. The temperature was an important factor to consider as depending on the ambient temperature, the cooling necessities of the data center vary. Also, depending on the temperature, free cooling could be done or not. The temperature was taken from two different cities, Madrid and Sevilla, for reasons explained later on. However, Madrid is used as the main reference location, while Sevilla is introduced as a high-temperature case in order to test sensitivity of cooling demand under warmer climate conditions. For the case of Madrid, the temperature was taken from the meteorological database of the Autonomous Community of Madrid, and the chosen data is from the meteorological station of Alcobendas. The selection of this city is relevant as it is in that area at the north of the city of Madrid where many projects of data center are being deployed, and therefore these temperatures resemble the ones that many data centers are going to deal with. As usual, the hourly average for each month was obtained.

The temperature for the year 2025 was compared with the temperature of the previous 5 years in order to see whether 2025 did not have any considerable outliers. This analysis concluded that 2025 was a perfectly representative year

Table 11 summarizes the input data handled.

Input	***Resolution before treatment***	***Final resolution in the model***	***Source***	***Use in the model***
IT load	Assumption	Hourly constant	100 MW IT	Base electricity demand
PUE	Monthly assumption	Monthly	Own assumption based on seasonality	Total consumption calculation
Generation mix	Hourly annual data	288 representative hours	REE data	Emissions profile
Emissions factor	Annual average + hourly proxy	288 representative hours	REE + own calculation	CO_2 emissions

Spot price	Hourly annual data	288 representative hours	Day-ahead market	Electricity cost
Network tariffs and regulated charges	Period-base	288 representative hours	MITECO and e-distribución	Regulated cost component
Temperature	Hourly annual data	288 representative hours	Meteorological databases	Cooling and free cooling analysis

Table 11. Input data summary

7.4 BASELINE SCENARIO

7.4.1 PARAMETERS DEFINITION

The baseline scenario represents the operation of the reference data center without any flexibility mechanism. In this case, the data center operates as a conventional electricity consumer. The main assumptions considered in this scenario are that the IT load remains constant 24/7 at 100 MW, the cooling demand varies accordingly to the monthly cooling requirements and that the remaining auxiliary loads have a constant consumption of 6,5 MW.

The first step in the construction of the baseline scenario consists of estimating the monthly electricity consumption of the data center. The starting point is the IT load, which has been defined as 100 MW.

The second fixed parameter is the electricity consumption of the loads classified under the "other auxiliary loads" category. In the model. These loads are assumed to be independent from climatic conditions. Therefore, their consumption is considered constant throughout the year, with a value of 6,5 MW. It has to be said that the value of 6,5 MW is an arbitrary but reasonable value obtained from previous estimations and calculations made assuming a theoretical 40% of cooling demand with a fixed PUE value.

The third parameter established was PUE. Several sources of information were analyzed and were already explained in chapter 3, concluding that the average PUE is 1,5 for mild temperature months. However, since the cooling needs of a data center vary significantly throughout the year, a single constant PUE would not properly represent the seasonal behavior of the facility. For this reason, the PUE was defined on a monthly basis according to ambient temperature and cooling requirements.

The highest PUE values are assigned to the warmest months, when mechanical cooling requirements are higher. In particular, August is assigned a PUE of 1.8, while July is assigned a PUE of 1.7. These values reflect the higher electricity consumption required by the cooling system during periods of high ambient temperature. By contrast, the lowest PUE values are assigned to the coldest months, when the data center can make greater use of free cooling and therefore requires less mechanical refrigeration. For this reason, January and December are assigned a PUE of 1.3. For the remaining months, a linear variation between these values is considered, in order to represent a gradual transition between winter, mild and summer operating conditions.

With these three parameters, the rest of the monthly table can be computed. Having the PUE and the IT load, the total consumption can be obtained by multiplying the corresponding monthly PUE by the IT load:

$$Total\ consumption\ (MW) = PUE\ x\ IT\ load\ (MW)$$

Equation 2. Total data center consumption calculation

Having fixed the consumption of the auxiliary loads, the cooling demand can be calculated by subtracting the IT load and auxiliary consumptions to the total consumption.

$$Cooling\ demand\ (MW) = Total\ consumption\ (MW) - IT\ load\ (MW) - Auxiliary\ load\ (MW)$$

Equation 3. Cooling demand calculation

Now that all the consumptions in MW have been calculated, the percentage for each type of load can be computed. It can be seen in Table 12 how the auxiliary consumption represents the 4-5% and the IT load and cooling consumption vary from 55% to 75% and from 20% to 40% respectively, depending on the cooling needs. These values align according to the stated, as IT load represents around 55%, cooling 40% and auxiliary services 5% of the total consumption.

Table 12 shows all the percentages, PUE values and the consumptions for the twelve months.

Month	*PUE*	*%IT*	*%Cooling*	*%Others*	*Total consumption (MW)*	*IT load (MW)*	*Cooling (MW)*	*Others (MW)*
January	1,3	76,9	18,1	5	130	100	23,5	6,5
February	1,35	74,1	21,1	5	135	100	28,5	6,5
March	1,4	71,4	23,9	5	140	100	33,5	6,5
April	1,5	66,7	29,0	4	150	100	43,5	6,5
May	1,6	62,5	33,4	4	160	100	53,5	6,5
June	1,65	60,6	35,5	4	165	100	58,5	6,5
July	1,7	58,8	37,4	4	170	100	63,5	6,5
August	1,8	55,6	40,8	4	180	100	73,5	6,5
September	1,6	62,5	33,4	4	160	100	53,5	6,5
October	1,5	66,7	29,0	4	150	100	43,5	6,5
November	1,4	71,4	23,9	5	140	100	33,5	6,5

December	1,3	76,9	18,1	5	130	100	23,5	6,5

Table 12. Consumption in baseline scenario

7.4.2 Baseline cooling consumption

The second step is defining the real cooling consumption across the 24 representative hours of each month. This was done using the hourly temperature profile, since the electricity required for cooling depends strongly on the ambient temperature.

Even within the same representative day, the model assumes cooling consumption does not remain constant as the cooling needs are not the same during colder night-time hours as during the hottest hours of the afternoon. For this reason, the model introduces two temperature-dependent factors: a free cooling factor and a cooling load factor.

7.4.2.1 Free cooling factor

This factor represents the extent to which the data center can rely on free cooling instead of mechanical refrigeration. This model is constructed in a way that when the ambient temperature is below 18ºC, free cooling can be fully used. In this case, the free cooling factor is 1. Whenever the temperature increases above 22º, free cooling is no longer available, and the free cooling factor becomes 0. For temperatures between 18ºC and 22ºC, a partial free cooling operation is done. In this intermediate range, the free cooling factor decreases linearly from 1 to 0.

This can be expressed as:

$$FC_h = \begin{cases} 1, & T_h \leq 18^\circ C \\ 1 - \frac{T_h - 18}{4}, & 18^\circ C < T_h \leq 22^\circ C \\ 0, & T_h > 22^\circ C \end{cases}$$

Equation 4. Free cooling factor calculation

where FC_h is the free cooling factor in hour h, and T_h is the ambient temperature in that hour.

Table 13 shows the free cooling factor for each hour. The cells in green with the number 1 represent the hours in which free cooling is completely available due to temperatures being lower than 18ºC, the cells in red with the number 0 represent when free cooling is not available due to temperatures being higher than 22ºC. Meanwhile, there are few cells with values different from 1 and 0 in which the temperatures are between 18ºC and 22ºC.

	January	*February*	*March*	*April*	*May*	*June*	*July*	*August*	*September*	*October*	*November*	*December*
h0	1	1	1	1	1	0	0	0	0,81	1	1	1
h1	1	1	1	1	1	0,01	0,06	0	0,98	1	1	1
h2	1	1	1	1	1	0,15	0,26	0	1	1	1	1
h3	1	1	1	1	1	0,33	0,44	0	1	1	1	1
h4	1	1	1	1	1	0,47	0,61	0,04	1	1	1	1
h5	1	1	1	1	1	0,51	0,66	0,16	1	1	1	1
h6	1	1	1	1	1	0,30	0,48	0,12	1	1	1	1
h7	1	1	1	1	1	0	0,09	0	1	1	1	1
h8	1	1	1	1	1	0	0	0	0,85	1	1	1
h9	1	1	1	1	1	0	0	0	0,39	1	1	1
h10	1	1	1	1	0,98	0	0	0	0,01	1	1	1
h11	1	1	1	1	0,69	0	0	0	0	0,69	1	1
h12	1	1	1	1	0,41	0	0	0	0	0,42	1	1
h13	1	1	1	1	0,19	0	0	0	0	0,22	1	1
h14	1	1	1	1	0,13	0	0	0	0	0,10	1	1
h15	1	1	1	1	0,10	0	0	0	0	0,06	1	1
h16	1	1	1	1	0,12	0	0	0	0	0,17	1	1
h17	1	1	1	1	0,22	0	0	0	0	0,41	1	1
h18	1	1	1	1	0,41	0	0	0	0	0,66	1	1
h19	1	1	1	1	0,74	0	0	0	0	0,92	1	1
h20	1	1	1	1	1	0	0	0	0	1	1	1
h21	1	1	1	1	1	0	0	0	0,19	1	1	1
h22	1	1	1	1	1	0	0	0	0,42	1	1	1
h23	1	1	1	1	1	0	0	0	0,64	1	1	1

Table 13. Free cooling factor

7.4.2.2 Cooling load factor

This factor is used to reflect that once temperature increases, the cooling system increases the effort it needs to refrigerate the data center. The cooling requirements are not the same for 22º C than for 35ºC, therefore the cooling load factor increases with temperature.

To build this factor, the model takes the highest hourly average temperature as reference. This temperature is 33ºC for Madrid. Therefore, the cooling factor is equal to 0 when the temperature is below the minimum free cooling temperature threshold, and it increases linearly as temperature rises, reaching 1 at the reference temperature of 33º.

The cooling load factor is calculated as:

$$Cooling\ load\ factor = \begin{cases} 0, & T_a \leq 18ºC \\ \dfrac{T_a - 18}{T_{max} - 18}, & T_a > 18ºC \end{cases}$$

Equation 5. Cooling load factor calculation

Where T_a is the ambient temperature hourly and T_{max} is the maximum temperature of 33ºC taken as reference.

Table 14 shows the cooling factor for each hour. The cells in red with the number 0 represent the hours in which free cooling is completely available due to temperatures being lower than 18ºC. The rest of the cells have the respective values according to the linear relationship between the temperature of that hour and maximum temperature.

	January	*February*	*March*	*April*	*May*	*June*	*July*	*August*	*September*	*October*	*November*	*December*
h0	0	0	0	0	0	0,31	0,31	0,44	0	0	0	0
h1	0	0	0	0	0	0	0	0,38	0	0	0	0
h2	0	0	0	0	0	0	0	0,34	0	0	0	0
h3	0	0	0	0	0	0	0	0,30	0	0	0	0
h4	0	0	0	0	0	0	0	0	0	0	0	0
h5	0	0	0	0	0	0	0	0	0	0	0	0

h6	0	0	0	0	0	0	0	0	0	0	0	0
h7	0	0	0	0	0	0,28	0	0,31	0	0	0	0
h8	0	0	0	0	0	0,41	0,37	0,44	0	0	0	0
h9	0	0	0	0	0	0,53	0,50	0,58	0	0	0	0
h10	0	0	0	0	0	0,64	0,60	0,69	0	0	0	0
h11	0	0	0	0	0	0,73	0,70	0,80	0,36	0	0	0
h12	0	0	0	0	0	0,81	0,77	0,89	0,45	0	0	0
h13	0	0	0	0	0	0,86	0,84	0,96	0,51	0	0	0
h14	0	0	0	0	0	0,88	0,89	0,99	0,56	0	0	0
h15	0	0	0	0	0	0,88	0,92	1,00	0,57	0	0	0
h16	0	0	0	0	0	0,85	0,93	0,98	0,56	0	0	0
h17	0	0	0	0	0	0,84	0,91	0,94	0,52	0	0	0
h18	0	0	0	0	0	0,79	0,86	0,88	0,43	0	0	0
h19	0	0	0	0	0	0,70	0,76	0,80	0,34	0	0	0
h20	0	0	0	0	0	0,59	0,64	0,70	0,27	0	0	0
h21	0	0	0	0	0	0,50	0,54	0,62	0	0	0	0
h22	0	0	0	0	0	0,43	0,45	0,54	0	0	0	0
h23	0	0	0	0	0	0,37	0,38	0,48	0	0	0	0

Table 14. Cooling load factor

7.4.2.3 Baseline cooling consumption calculations

Once these two factors have been calculated, they are used to estimate the hourly cooling consumption. First, each hour of each representative day is assigned the monthly calculated cooling consumption from Table 12, however this value has to be adjusted according to the free cooling factor and the cooling load factor.

The first factor applied is the free cooling factor because if the temperature is below 18ºC, the cooling consumption only depends on it. Free cooling does not reduce the cooling electricity consumption to zero, since part of the mechanical system still needs to operate. Fans, pumps, air handling units and other mechanical auxiliary components still consume electricity. For this reason, free cooling can only cover 68% of the total consumption of the cooling requirements and the cooling consumption will be 32% of the monthly stated cooling demand [44].

Therefore, the first step is to calculate the hourly consumption if free cooling is available:

$$E_{cooling,h} = 0{,}32\ x\ E_{cooling,m}$$

Equation 6. Cooling consumption calculation with total free cooling reduction

Where $E_{cooling,h}$ is the cooling electricity consumption in hour h, and $E_{cooling,m}$ is the monthly cooling demand.

For temperatures between 18ºC and 22ºC, when only partial free cooling is available, the cooling system still benefits from favorable outdoor conditions, but more mechanical cooling progressively becomes more relevant, according to the cooling load factor. To avoid an abrupt transition between full free cooling and fully mechanical cooling, the cooling factor is assumed to increase linearly from 0.32 at 18 ºC to 0.50 at 22 ºC. The resulting calculations are the following:

$$E_{cooling,h} = E_{cooling,m}\ x\ (0{,}32\ + (0{,}50 - 0{,}32\ x\ FC_h)$$

Equation 7. Cooling consumption calculation with partial free cooling reduction

Finally, when the ambient temperature is above 22ºC, free cooling is no longer available and half of the cooling demand is fixed, and the other half increases accordingly to the cooling load factor. This allows to represent the increase in the cooling demand during peak temperature hours, especially in summer months like July and August.

The calculations when there is no free cooling follow the following formula:

$$E_{cooling,h} = E_{cooling,m}\ x\ (0{,}5\ +\ 0{,}5\ x\ Cooling\ load\ factor_h)$$

Equation 8. Cooling consumption calculation without free cooling with lineal increase due to temperatures

With all this into consideration, the cooling consumption table of the twelve hourly representative days can be computed.

(MW)	***January***	***February***	***March***	***April***	***May***	***June***	***July***	***August***	***September***	***October***	***November***	***December***
h0	7,5	9,1	10,7	13,9	17,1	38,3	41,5	52,8	18,9	13,9	10,7	7,5
h1	7,5	9,1	10,7	13,9	17,1	29,1	31,0	50,8	17,4	13,9	10,7	7,5
h2	7,5	9,1	10,7	13,9	17,1	27,7	28,8	49,2	17,1	13,9	10,7	7,5
h3	7,5	9,1	10,7	13,9	17,1	25,8	26,7	47,6	17,1	13,9	10,7	7,5
h4	7,5	9,1	10,7	13,9	17,1	24,3	24,8	36,2	17,1	13,9	10,7	7,5
h5	7,5	9,1	10,7	13,9	17,1	23,9	24,2	34,7	17,1	13,9	10,7	7,5
h6	7,5	9,1	10,7	13,9	17,1	26,0	26,2	35,1	17,1	13,9	10,7	7,5
h7	7,5	9,1	10,7	13,9	17,1	37,4	30,8	48,3	17,1	13,9	10,7	7,5
h8	7,5	9,1	10,7	13,9	17,1	41,1	43,6	53,0	18,6	13,9	10,7	7,5
h9	7,5	9,1	10,7	13,9	17,1	44,9	47,5	58,1	23,0	13,9	10,7	7,5
h10	7,5	9,1	10,7	13,9	17,3	48,1	50,9	62,2	26,7	13,9	10,7	7,5
h11	7,5	9,1	10,7	13,9	20,1	50,7	53,8	66,0	36,4	16,3	10,7	7,5
h12	7,5	9,1	10,7	13,9	22,8	52,8	56,3	69,4	38,8	18,5	10,7	7,5
h13	7,5	9,1	10,7	13,9	24,9	54,4	58,5	72,0	40,4	20,0	10,7	7,5
h14	7,5	9,1	10,7	13,9	25,5	55,0	60,0	73,0	41,6	21,0	10,7	7,5
h15	7,5	9,1	10,7	13,9	25,8	55,0	60,8	73,5	41,9	21,3	10,7	7,5
h16	7,5	9,1	10,7	13,9	25,6	54,2	61,1	72,8	41,7	20,4	10,7	7,5
h17	7,5	9,1	10,7	13,9	24,7	53,7	60,6	71,3	40,6	18,6	10,7	7,5
h18	7,5	9,1	10,7	13,9	22,8	52,4	58,9	69,0	38,3	16,6	10,7	7,5
h19	7,5	9,1	10,7	13,9	19,6	49,9	55,9	66,2	35,9	14,6	10,7	7,5
h20	7,5	9,1	10,7	13,9	17,1	46,6	52,0	62,5	34,1	13,9	10,7	7,5
h21	7,5	9,1	10,7	13,9	17,1	43,9	48,8	59,5	24,9	13,9	10,7	7,5
h22	7,5	9,1	10,7	13,9	17,1	41,8	46,1	56,7	22,7	13,9	10,7	7,5
h23	7,5	9,1	10,7	13,9	17,1	40,1	43,7	54,4	20,6	13,9	10,7	7,5

Table 15. Cooling consumption (MW)

This approach is a simplified representation of the cooling behavior of the data center. It does not model the detailed thermodynamic performance of chillers, pumps or air handling units. Instead, it uses temperature-dependent factors to approximate how cooling electricity consumption changes with ambient conditions and with the availability of free cooling.

7.4.3 BASELINE TOTAL CONSUMPTION CALCULATION

Once the hourly cooling consumption has been calculated, the total hourly electricity consumption of the data center in the baseline scenario can be obtained. The baseline demand is composed of the three main components: the IT load, the cooling consumption and the auxiliary loads.

Both the IT and auxiliary loads are assumed to remain constant throughout the year at 100 MW and 6,5 MW respectively. Since the model works with hourly values, these values correspond to the electricity consumption in every representative hour.

The only variable component is the cooling consumption, which is the one that makes the load profile not constant.

Therefore, for each representative hour, the total electricity consumption of the data center is calculated as:

$$E_{total,h} = E_{IT,h} + E_{cooling,h} + E_{aux,h}$$

Equation 9. Total consumption calculation of the data center due to calculated components

Where $E_{total,h}$ is the total electricity consumption in hour h, $E_{IT,h}$ is the IT electricity consumption, $E_{cooling,h}$ is the cooling electricity consumption and $E_{aux,h}$ is the auxiliary electricity consumption.

Figure 11 shows the total consumption for each of the twelve representative days. As it can be seen, in the cooler months, the consumption profile is stable due to the use of free cooling. For the warmer months, the profile varies, increasing its consumption load in the central hours of the day, in which the temperatures are higher and therefore, the cooling consumption is higher.

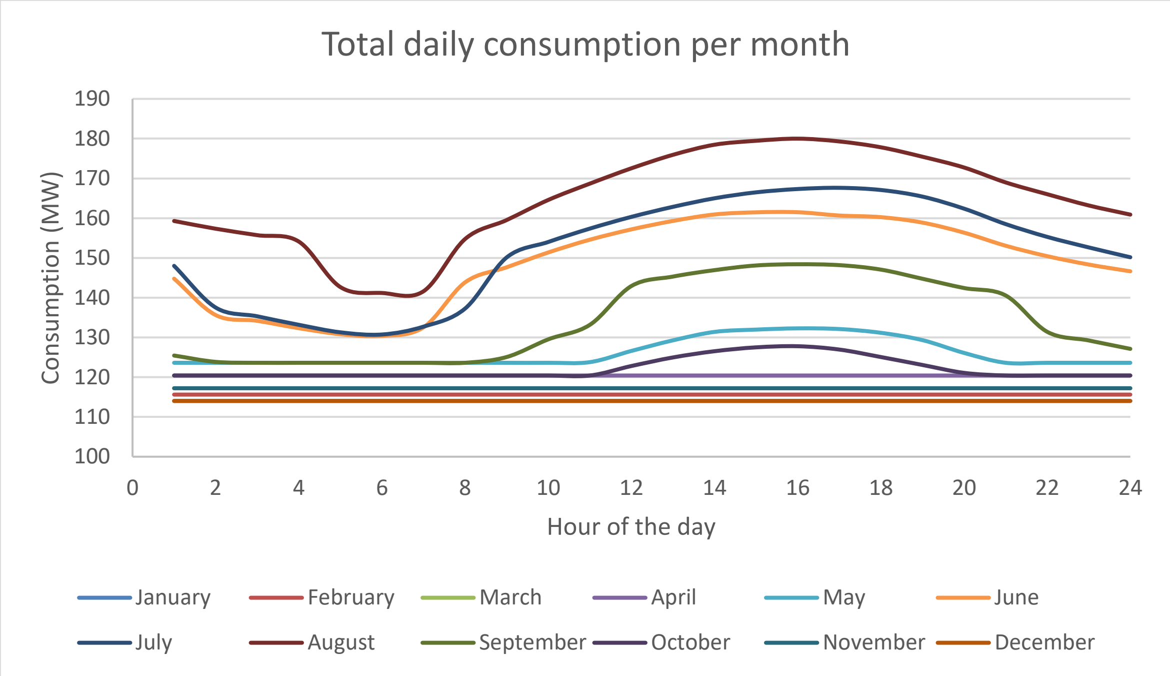


Figure 11. Total daily consumption profiles

In this baseline scenario, no flexibility mechanism is applied. This means that electricity consumption occurs at the same hour in which it is required. Cooling demand is not shifted to other periods, and no battery is used to modify the net electricity demand of the facility. As a result, the baseline hourly profile represents the natural electricity consumption of the data center before introducing any flexibility strategy.

The resulting profile is a table of 288 representative hours, which can be annualized by multiplying each representative day by the number of days in the corresponding month. Knowing the total annual consumption is important for the future comparison with the flexibility scenarios, in order to analyze the total cost variations.

The resulting daily, monthly and annual consumption are shown in Table 16:

Months	***Total daily consumption (MW)***	***Total monthly consumption (MW)***
January	2736,5	84830,9
February	2774,9	77696,6
March	2813,3	87211,7

April	2890,1	86702,4
May	3024,7	93764,8
June	3573,0	107190,6
July	3648,6	113106,5
August	3950,3	122458,7
September	3221,2	96635,8
October	2932,1	90894,2
November	2813,3	84398,4
December	2736,5	84830,9
Total		**1129722**

Table 16. Baseline scenario total consumption

It can be seen how during warmer months the total consumption increases due to the higher cooling requirements.

7.4.4 BASELINE ELECTRICITY COST

After obtaining the total hourly electricity consumption, the next step is to calculate the electricity cost of the baseline scenario. The model estimates the electricity cost using the three components: the hourly average spot market price, network tariffs and regulated charges.

These values had been previously averaged according to the representative hourly approach the model uses.

The hourly electricity cost in the baseline scenario is calculated as:

$$Cost_h = E_{total,h} \ x \ (P_{spot,h} + NT_h + RC_h)$$

Equation 10. Cost calculation

Where $Cost_h$ is the electricity cost in hour h, $E_{total,h}$ is the total electricity consumption of the data center, $P_{spot,h}$ is the hourly spot price, NT_h represents the network tariffs, and RC_h represents the regulated charges.

Exactly as the electricity consumption, the total costs can be annualized by multiplying each representative day by the number of days in the corresponding month. Knowing the total annual cost is important for the future comparison with the flexibility scenarios, in order to analyze the total cost variations.

The resulting daily, monthly and annual costs are shown in Table 17:

Months	*Total daily consumption (€)*	*Total monthly consumption (€)*
January	277.080 €	8.589.483 €
February	312.759 €	8.757.258 €
March	159.369 €	4.940.426 €
April	86.789 €	2.603.681 €
May	60.092 €	1.862.843 €
June	265.889 €	7.976.667 €
July	267.447 €	8.290.845 €
August	277.347 €	8.597.768 €
September	204.215 €	6.126.449 €
October	230.525 €	7.146.285 €
November	174.710 €	5.241.306 €
December	225.676 €	6.995.971 €
Total		**77.128.983 €**

Table 17. Baseline scenario total costs

With the total consumption and the total cost, the total cost per MWh is calculated, resulting in 68,3 €/MWh. This reference value will be used in the future analysis comparing it with the flexibility scenarios.

7.4.5 BASELINE EMISSIONS

The final step in the construction of the baseline scenario is the calculation of the associated CO_2 emissions. The total hourly electricity consumption has been obtained, it is multiplied by the hourly emissions factor previously calculated from the Spanish electricity mix. This value is 0.108 tCO_2 eq/MWh.

The hourly emissions of the data center are calculated as:

$$Emissions_h = E_{total,h} \ x \ EF$$

Equation 11. Emissions calculation

Where $Emissions_h$ is the total emissions associated with hour h, $E_{total,h}$ is the total electricity consumption of the data center in that hour, and EF is the estimates hourly emissions factor, expressed in tCO_2 eq/MWh.

Figure 12 shows the daily induced emissions profile for each representative day. From this graph, there are some observations. The first is that it can be seen how emissions lower during daylight hours due to the big share of renewable energy generation during the day, mainly by solar photovoltaic generation. The second is that, as warmer temperature months require more consumption due to cooling needs, this implies more generation and therefore, more induced emissions. The cooler months due to their lower generation induce less emissions.

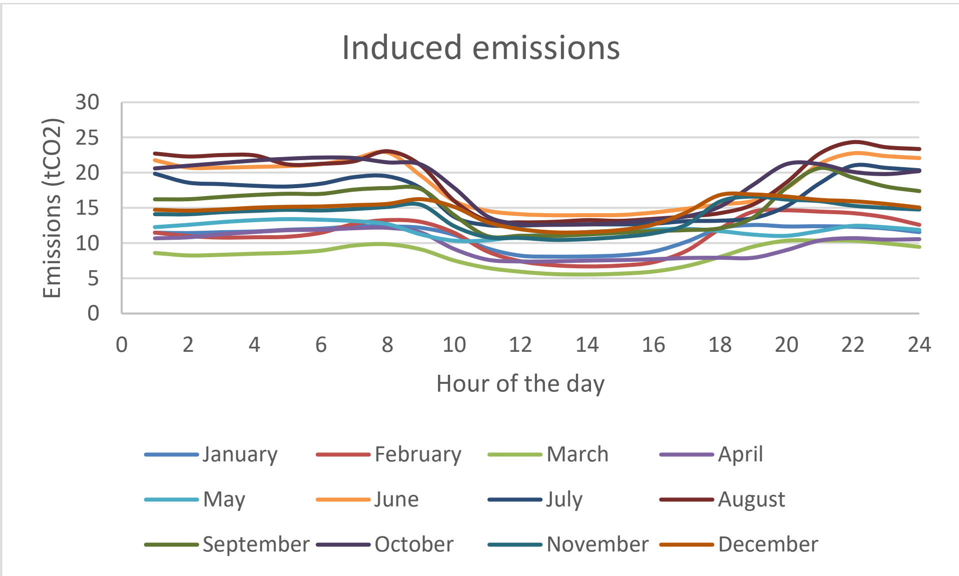


Figure 12. Induced emissions profile

Exactly as the electricity consumption and total costs, the total emissions can be annualized by multiplying each representative day by the number of days in the corresponding month. Knowing the total annual emissions is important for the future comparison with the flexibility scenarios, in order to analyze the total emissions variations.

The resulting daily, monthly and annual emissions are shown in Table 18:

Months	*Total daily emissions (tCO_2)*	*Total monthly emissions (tCO_2)*
January	264	8199
February	266	7444
March	197	6116
April	233	6994
May	287	8907
June	444	13327
July	393	12190
August	449	13930
September	365	10957
October	439	13616
November	332	9948
December	352	10907
Total		**122534**

Table 18. Baseline scenario total emissions

With the total consumption and the total emissions, the total emissions per MWh is calculated, resulting in 0,108 tCO_2 eq/MWh. This reference value will be used in the future analysis comparing it with the flexibility scenarios.

This baseline emissions value represents the estimated annual carbon footprint associated with the electricity consumption of the data center under normal operation, without flexibility. It is used as the reference case for calculating avoided emissions in the thermal storage and BESS scenarios.

7.4.6 Baseline scenario summary

Table 19 summarizes all the important values that will be used to compare the thermal energy storage and BESS cases.

Energy	
Total energy cost (€)	77.128.983 €
Total energy (MWh)	1129722
Average cost (€/MWh)	68,3

Emissions	
Total emissions (tCO_2)	122534
Average emissions (tCO_2/MWh)	0,108

Table 19. Baseline scenario reference values

7.4.6.1 Baseline scenario summary for Seville

The following table shows the same outputs for the Seville case.

Energy	
Total energy cost (€)	79.302.656 €
Total energy (MWh)	1158436
Average cost (€/MWh)	68,5

Emissions	
Total emissions (tCO_2)	126277
Average emissions (tCO_2/MWh)	0,109

Table 20. Baseline scenario reference values for Seville

7.5 SCENARIO WITH THERMAL STORAGE

The first flexibility strategy analyzed in the model is the implementation of a Thermal Energy Storage system (TES) associated with the cooling system of the data center. The TES only affects the electricity consumption linked to cooling, while the IT load and auxiliary loads remain unchanged with respect to the baseline scenario.

The objective of the TES is to charge the TES during low-emission hours and use the stored cooling during high-emission hours. Therefore, the system modifies the timing of cooling electricity consumption, but not the cooling requirements of the data center.

Four TES scenarios are analyzed in the model. The first three scenarios correspond to the reference data center located in Madrid, considering 3-hour, 2-hour and 1-hour TES durations. These different storage durations are included in order to evaluate how the size of the thermal storage system affects the amount of cooling demand that can be shifted, the electricity cost, the investment required and the emissions displaced. A larger TES can move more cooling consumption away from high-emission hours and therefore increase the avoided emissions, but it also requires a higher investment cost. For this reason, comparing different storage sizes makes it possible to assess whether additional TES capacity provides proportional environmental and economic benefits, or whether the value becomes limited beyond a certain size. This also allows the relationship between investment cost and emissions reduction to be evaluated.

The fourth scenario corresponds to a 3-hour TES configuration in Seville. This case is introduced as a sensitivity analysis to represent a more extreme temperature context. Since Seville presents higher temperatures than Madrid, especially during summer, the cooling demand of the data center is expected to be higher and the availability of free cooling lower. This scenario allows the model to assess how TES performance changes under more demanding climatic conditions and whether thermal storage becomes more relevant when cooling requirements increase.

Overall, these four scenarios allow the analysis to compare the effect of storage size, climatic conditions, electricity cost impact and emissions reduction potential on the performance of thermal storage as a flexibility strategy for data centers.

7.5.1 TES SIZING APPROACH

The The TES is sized using the hourly cooling consumption profile obtained in the baseline scenario. The sizing approach is based on August, since this is the month with the highest cooling consumption in the model and therefore represents the most demanding operating conditions for the cooling system. Using August as the reference month ensures that the TES is dimensioned according to the period in which the potential need for thermal flexibility is highest.

However, the TES is not sized according to the total cooling consumption of the data center. It is sized according to the part of the cooling demand that can actually be shifted. This distinction is important because thermal storage cannot completely replace the operation of the cooling system. Even when stored cooling is discharged, part of the mechanical system must continue operating in order to maintain safe thermal conditions inside the data center. Fans, pumps, air handling units and other auxiliary cooling components still require electricity. Therefore, the model defines a minimum cooling consumption level that must always be maintained.

The maximum shiftable cooling power is calculated as the difference between the maximum hourly cooling consumption in August and the minimum technical cooling consumption that must remain active. This value represents the maximum amount of cooling electricity consumption that the TES can reduce in a single hour:

$$P_{TES} = E_{cooling,max,Aug} - E_{cooling,min,Aug}$$

Equation 12. TES power value calculation

Where P_{TES} is the maximum TES discharge power, $E_{cooling,max,Aug}$ is the maximum cooling consumption in August and $E_{cooling,min,Aug}$ is the maximum cooling consumption in August and $E_{cooling,min,Aug}$ is the minimum consumption in August.

Applying this criterion to the August cooling profile, the maximum TES discharge power is approximately 50 MW. This means that, in the most favorable case, the TES can reduce up to 50 MW of cooling electricity consumption in one hour, but only if the cooling demand in that hour is high enough to allow this reduction without falling below the minimum technical cooling level.

$$P_{TES}(MW) = 73{,}5 - 23{,}5$$

$$P_{TES} = 50\ MW$$

The energy capacity of each TES scenario depends on the number of storage hours considered. Therefore, the storage energy capacity is calculated as:

$$E_{TES} = P_{TES}\ x\ N_{hours}$$

Equation 13. TES energy calculation

Where E_{TES} is the energy storage capacity in MWh, P_{TES} is the discharge power calculated previously and N_{hours} is the number of storage hours.

Based on this approach, three TES durations are analysed for the Madrid case: 1 hour, 2 hours and 3 hours. These correspond to energy capacities of approximately 50 MWh, 100 MWh and 150 MWh, respectively.

Hours	***Energy capacity (MWh)***
1	50
2	100
3	150

Table 21. TES energy storage capacity

Although August is used for sizing, the TES is applied to all representative months. This allows the model to evaluate how a system designed for peak cooling conditions performs throughout the year. In colder months, the TES may be underused because cooling demand is lower and free cooling is more available. By contrast, in summer months, the TES has greater potential to shift cooling consumption because mechanical cooling requirements are higher. This approach therefore makes it possible to assess both the maximum potential and the seasonal limitations of thermal storage.

7.5.2 SELECTION OF DISCHARGE AND CHARGE HOURS

The selection of charge and discharge hours is based on the hourly emissions factor calculated for each representative day. The objective of the TES is to reduce cooling electricity consumption during the hours in which the electricity mix is more carbon intensive, and to move that consumption to hours with lower emissions. Therefore, the storage system is operated according to an emissions-based criterion rather than a cost-minimization criterion.

For each representative day, the model calculates the average emissions factor and the TES is discharged only during hours in which the emissions factor is higher than the representative daily average. Conversely, the TES is charged only during hours in which the emissions factor is lower than the representative daily average. Therefore, the operation of the TES follows an emissions-based criterion rather than a cost-minimization criterion.

7.5.2.1 Discharge hours

The TES is discharged during the hours with the highest emissions intensity, since these are the periods in which reducing electricity consumption provides the greatest environmental benefit. Within the hours above the average emissions factor, the model prioritizes the hours with the highest emissions first. This means that the TES is not discharged in all high-emission hours equally, but is allocated first to the hours where the avoided cooling electricity consumption has the greatest environmental value.

For example, in the 3-hour TES case, the system has a maximum discharge power of approximately 50 MW and a total storage capacity of around 150 MWh. The value of 50 MW represents the maximum amount of cooling electricity consumption that the TES can reduce in a single hour. However, this does not mean that the TES will always discharge 50 MW in every discharge hour.

The actual discharge in each hour depends on the cooling consumption available in that month. The cooling system must always maintain a minimum operating level, so the TES can only reduce the part of the cooling demand that is above this minimum value. Therefore, if the available reducible cooling demand in a given hour is lower than 50 MW, the TES discharges only the amount that can be reduced in that hour. This avoids assuming that thermal storage can replace the entire cooling system, since fans, pumps, air handling units and other auxiliary components must continue operating to maintain safe thermal conditions inside the data center.

The discharge available in each selected hour can be expressed as:

$$TES_{discharge,h} = \min\left(P_{TES}, E_{cooling,h}^{baseline} - E_{cooling,min,m}\right)$$

Equation 14. TES discharge calculation

Where $TES_{discharge,h}$ is the discharged energy in hour h, P_{TES} is the maximum discharge power of the TES, $E_{cooling,h}^{baseline}$ is the original cooling consumption in that hour and $E_{cooling,min,m}$ is the minimum cooling consumption of month m.

This expression ensures that the hourly discharge is limited not only by the TES power rating, but also by the cooling demand that is actually shiftable in that hour.

The remaining stored energy is not lost or forced into that same hour. Instead, the model continues allocating the available TES energy to the following high-emission hours, always respecting the maximum discharge power and the minimum cooling consumption constraint. In this way, the TES may discharge at less than its maximum power in some hours, but the total available energy, for example 150 MWh in the 3-hour case, is distributed across as many high-emission hours as necessary and technically possible.

This condition is modeled under the following constraint:

$$\sum TES_{discharge,h} \leq E_{TES}$$

Equation 15. TES discharging constraint

This approach allows the TES to use its stored energy realistically. The system prioritizes the most emitting hours, but the hourly discharge is adapted to the actual cooling profile of each month. As a result, in summer months the TES may operate closer to its maximum power, while in months with lower cooling demand the same energy may need to be spread over a larger number of hours or may be limited by the available cooling demand.

7.5.2.2 Charge hours

Once the discharge potential has been calculated, the model determines the TES charging hours. These are selected among the hours with the lowest emissions factors of each representative day. This order is important because the model first identifies how much energy can actually be discharged and only then allocates the corresponding charge. In this way, the TES is not charged according to its full theoretical capacity if that energy cannot later be used during discharge hours.

During charging hours, the cooling system produces additional cooling energy and stores it in the TES. This increases electricity consumption in those hours, but the additional consumption takes place when the electricity mix is cleaner. Therefore, the TES does not reduce total cooling needs; it changes the timing of the electricity consumption required to provide the same cooling service.

The energy charged is not necessarily equal to the full theoretical capacity of the TES. Instead, charging energy is linked to the amount of energy that can actually be discharged later. This prevents the model from charging energy that cannot be used. Therefore, if the discharge potential in a month is lower than the full TES capacity, the model reduces the charging accordingly.

This approach avoids leaving unused stored energy at the end of the representative day and keeps the daily TES cycle balanced. Thermal losses during storage are not explicitly modelled. This simplification is considered acceptable because the TES is operated within the same representative day and the objective of the model is to compare the relative effect of different TES sizes rather than to reproduce the detailed thermal behavior of the storage tank.

Table 22 shows the power charged and discharged and the corresponding hours in which they occur for the TES of 3 hours. Positive values represent TES charging, which increases cooling electricity consumption in that hour, while negative values represent TES discharge, which reduces cooling electricity consumption.

(MW)	***January***	***February***	***March***	***April***	***May***	***June***	***July***	***August***	***September***	***October***	***November***	***December***
h0	0	0	0	0	0	-14,1	-16,8	-17,3	-0,88	0	0	0
h1	0	0	0	0	0	-5,1	-6,8	-15,3	0	0	0	0
h2	0	0	0	0	0	-3,1	-3,8	-14,3	0	0	0	0
h3	0	0	0	0	0	-1,1	-1,8	-12,3	0	0	0	0
h4	0	0	0	0	0	-0,1	0,0	-1,3	0	0	0	0
h5	0	0	0	0	0	0	0	0	0	0	0	0
h6	0	0	0	0	0	-2,1	-1,8	-0,3	0	0	0	0
h7	0	0	0	0	0	-13,1	-5,8	-13,3	0	0	0	0
h8	0	0	0	0	0	-17,1	-18,8	-18,3	-0,9	0	0	0
h9	0	0	0	0	0	0	0	0	0	0	0	0
h10	0	0	0	0	0	0	0	0	0	0	0	0
h11	0	0	0	0	0	0	0	0	0	0	0	0
h12	0	0	0	0	0	30,5	0	50,0	50,0	0	0	0
h13	0	0	0	0	0	50,0	47,5	50,0	1,2	0,1	0	0
h14	0	0	0	0	0	50,0	50,0	50,0	0	0	0	0
h15	0	0	0	0	0	0	50,0	0	0	0	0	0
h16	0	0	0	0	0	0	0	0	0	0	0	0
h17	0	0	0	0	0	0	0	0	0	0	0	0
h18	0	0	0	0	0	0	0	0	0	0	0	0
h19	0	0	0	0	0	0	0	0	-17,9	-0,1	0	0
h20	0	0	0	0	0	-22,1	-27,8	-27,3	-16,9	0	0	0
h21	0	0	0	0	0	-19,1	-23,8	-24,3	-6,9	0	0	0
h22	0	0	0	0	0	-17,1	-21,8	-5,7	-4,9	0	0	0
h23	0	0	0	0	0	-16,1	-18,8	0	-2,9	0	0	0

Table 22. Charge and discharge power for TES of 3 hours

7.5.3 COOLING CONSUMPTION WITH TES

The cooling consumption with TES is obtained by modifying the baseline cooling profile. During discharge hours, the stored cooling reduces the electricity consumption of the cooling system. During charge hours, electricity consumption increases because additional cooling is produced and stored.

For each representative hour, the cooling consumption with TES is calculated as:

$$E_{cooling,h}^{TES} = E_{cooling,h}^{baseline} - TES_{discharge,h} + TES_{charge,h}$$

Equation 16. Total consumption calculation including TES discharge and charge power

Where $E_{cooling,h}^{TES}$ is the cooling consumption after applying TES, $E_{cooling,h}^{baseline}$ is the original cooling consumption, $TES_{discharge,h}$ is the reduction during discharge hours, and $TES_{charge,h}$ is the additional consumption during charge hours.

As a result, the TES modifies the hourly cooling profile without changing the cooling needs of the data center. The cooling service remains the same, but part of the electricity consumption required to provide it is moved from high-emission hours to low-emission hours.

Table 23 shows the cooling consumption for each representative day. It can be seen how during the hours when the TES charges, the cooling consumption has increased considerably, meanwhile, during discharge hours, the cooling consumption is considerably lower.

(MW)	***January***	***February***	***March***	***April***	***May***	***June***	***July***	***August***	***September***	***October***	***November***	***December***
h0	7,5	9,1	10,7	13,9	17,1	24,2	24,7	35,5	18,1	13,9	10,7	7,5
h1	7,5	9,1	10,7	13,9	17,1	24,0	24,2	35,5	17,4	13,9	10,7	7,5
h2	7,5	9,1	10,7	13,9	17,1	24,6	25,0	34,9	17,1	13,9	10,7	7,5
h3	7,5	9,1	10,7	13,9	17,1	24,7	24,9	35,3	17,1	13,9	10,7	7,5
h4	7,5	9,1	10,7	13,9	17,1	24,2	24,8	34,8	17,1	13,9	10,7	7,5
h5	7,5	9,1	10,7	13,9	17,1	23,9	24,2	34,7	17,1	13,9	10,7	7,5
h6	7,5	9,1	10,7	13,9	17,1	23,9	24,4	34,8	17,1	13,9	10,7	7,5
h7	7,5	9,1	10,7	13,9	17,1	24,2	25,0	34,9	17,1	13,9	10,7	7,5
h8	7,5	9,1	10,7	13,9	17,1	24,0	24,9	34,7	17,7	13,9	10,7	7,5
h9	7,5	9,1	10,7	13,9	17,1	44,9	47,5	58,1	23,0	13,9	10,7	7,5
h10	7,5	9,1	10,7	13,9	17,3	48,1	50,9	62,2	26,7	13,9	10,7	7,5
h11	7,5	9,1	10,7	13,9	20,1	50,7	53,8	66,0	36,4	16,3	10,7	7,5

h12	7,5	9,1	10,7	13,9	22,8	83,3	56,3	119,4	88,8	18,5	10,7	7,5
h13	7,5	9,1	10,7	13,9	24,9	104,4	106,0	122,0	41,6	20,1	10,7	7,5
h14	7,5	9,1	10,7	13,9	25,5	104,9	110,0	122,9	41,6	21,0	10,7	7,5
h15	7,5	9,1	10,7	13,9	25,8	55,0	110,8	73,5	41,9	21,3	10,7	7,5
h16	7,5	9,1	10,7	13,9	25,6	54,2	61,1	72,8	41,7	20,4	10,7	7,5
h17	7,5	9,1	10,7	13,9	24,7	53,7	60,6	71,3	40,6	18,6	10,7	7,5
h18	7,5	9,1	10,7	13,9	22,8	52,4	58,9	69,0	38,3	16,6	10,7	7,5
h19	7,5	9,1	10,7	13,9	19,6	49,9	55,9	66,2	18,0	14,5	10,7	7,5
h20	7,5	9,1	10,7	13,9	17,1	24,4	24,2	35,2	17,2	13,9	10,7	7,5
h21	7,5	9,1	10,7	13,9	17,1	24,8	25,0	35,2	18,0	13,9	10,7	7,5
h22	7,5	9,1	10,7	13,9	17,1	24,7	24,4	51,0	17,9	13,9	10,7	7,5
h23	7,5	9,1	10,7	13,9	17,1	24,0	24,9	54,4	17,7	13,9	10,7	7,5

Table 23. Cooling consumption with TES of 3 hours

7.5.3.1 Cooling consumption with TES for the case of Seville

Analyzing the case of Seville is interesting because due to having higher temperatures in Seville than in Madrid, at first sight, it can be intuitive that a thermal storage can be more useful in areas with higher temperatures. This is because, due to higher temperatures, free cooling is less available during more hours and therefore thermal storage can be used more frequently.

Table 24 shows the temperature difference between Seville and Madrid. It can be seen how, in most of the hours, the temperature in Seville is higher than the temperature in Madrid. The temperature increase can be up to 9ºC. This shows why free cooling is less used in Seville, leading to an increase in the use of the TES.

(MW)	***January***	***February***	***March***	***April***	***May***	***June***	***July***	***August***	***September***	***October***	***November***	***December***
h0	5	5	6	5	6	5	5	4	7	7	6	4
h1	5	5	5	5	6	4	5	4	6	7	5	4
h2	5	5	5	5	6	4	5	4	6	7	6	4
h3	5	5	6	5	6	4	5	4	6	7	5	4
h4	5	5	6	5	6	4	5	4	6	7	5	4

h5	5	5	5	5	5	3	4	3	6	7	5	3
h6	5	5	5	4	4	2	3	3	5	6	5	3
h7	5	4	4	3	2	0	1	1	4	5	4	3
h8	4	3	3	1	0	-2	-1	-1	2	3	3	3
h9	3	1	3	0	0	-2	-1	-3	0	2	2	2
h10	2	0	3	1	1	-2	-1	-2	0	1	1	1
h11	1	0	3	1	2	-1	0	-1	1	2	1	1
h12	2	0	4	2	3	0	1	0	2	3	2	2
h13	3	1	5	3	4	1	2	1	3	4	3	2
h14	4	2	5	4	5	2	3	2	4	5	4	4
h15	5	3	6	5	5	3	3	3	5	6	5	5
h16	6	4	6	5	6	4	4	4	6	7	6	5
h17	7	5	7	6	7	5	5	5	7	8	7	6
h18	7	6	7	6	7	5	5	6	8	9	7	6
h19	7	6	7	7	8	6	6	6	9	9	7	6
h20	6	5	7	6	8	7	7	7	9	8	6	5
h21	6	5	6	6	8	6	6	6	8	8	6	5
h22	5	5	6	5	7	5	5	5	7	7	6	5
h23	5	5	6	5	6	5	5	5	7	7	6	4

Table 24. Temperature difference between Seville and Madrid

Table 25 shows the free cooling factor for Seville. It shows whether free cooling can be used totally, partially or not. The Seville case is included to test the sensitivity of TES performance under warmer climatic conditions. Higher ambient temperatures reduce the availability of free cooling and increase the number of hours in which mechanical cooling is required. As a result, a larger share of the cooling demand becomes potentially shiftable through TES. Comparing it to the case of Madrid, there are differences that can be considered. In general, free cooling is used during less months. There are many more hours in which it cannot be used. For example, in the case of Madrid, during April, free cooling could be used the whole time. However, in the case of Seville, during the central hours of the day, free cooling cannot be used completely. In May, in Seville, free cooling can only be used during early morning hours, whereas in Madrid it can be used during the whole day except for few central hours of the day. During the warmer months of June, July, August and September, free cooling availability is substantially reduced in Seville, especially during summer months, while in Madrid there were few hours in the early morning in which it could be used partially because the temperature is below 22ºC. October and November show interesting results as in Madrid, there are some hours in which free cooling can be done completely in October and in all hours of November. In Seville, free cooling is more limited and can only be used partially in some hours, while in the remaining hours mechanical cooling is still required.

This table shows why the cooling consumption for data centers in Seville, an area with higher temperatures, is greater than in cooler areas.

(MW)	***January***	***February***	***March***	***April***	***May***	***June***	***July***	***August***	***September***	***October***	***November***	***December***
h0	1	1	1	1	0,5	0	0	0	0	0	1	1
h1	1	1	1	1	0,7	0	0	0	0	0,2	1	1
h2	1	1	1	1	0,8	0	0	0	0	0,3	1	1
h3	1	1	1	1	1,0	0	0	0	0	0,5	1	1
h4	1	1	1	1	1	0	0	0	0	0,6	1	1
h5	1	1	1	1	1	0	0	0	0,1	0,7	1	1
h6	1	1	1	1	1	0	0	0	0,2	0,8	1	1
h7	1	1	1	1	1	0	0	0	0,3	0,9	1	1
h8	1	1	1	1	1	0	0	0	0,5	0,9	1	1
h9	1	1	1	1	1	0	0	0	0,4	1,0	1	1
h10	1	1	1	1	0,7	0	0	0	0	0,7	1	1
h11	1	1	1	1	0,2	0	0	0	0	0,2	1	1
h12	1	1	1	0,9	0	0	0	0	0	0	1	1
h13	1	1	1	0,5	0	0	0	0	0	0	1	1
h14	1	1	1	0,3	0	0	0	0	0	0	1	1
h15	1	1	1	0,0	0	0	0	0	0	0	1,0	1
h16	1	1	1	0	0	0	0	0	0	0	0,9	1
h17	1	1	1	0	0	0	0	0	0	0	0,9	1
h18	1	1	1	0,0	0	0	0	0	0	0	1	1
h19	1	1	1	0,2	0	0	0	0	0	0	1	1
h20	1	1	1	0,4	0	0	0	0	0	0	1	1
h21	1	1	1	0,8	0	0	0	0	0	0	1	1
h22	1	1	1	1	0	0	0	0	0	0	1	1

h23	1	1	1	1	0,1	0	0	0	0	0	1	1

Table 25. Free cooling factor in Seville

7.5.4 TES INTEGRATION INTO TOTAL DATA CENTER CONSUMPTION

After obtaining the new cooling profile, the total electricity consumption of the data center is recalculated. The IT load remains constant at 100 MW, and the auxiliary loads remain constant at 6.5 MW. Therefore, the TES only modifies the cooling component.

The total electricity consumption with TES is calculated as:

$$E_{total,h}^{TES} = E_{IT,h} + E_{aux,h} + E_{cooling,h}^{TES}$$

Equation 17. Total consumption calculation with TES cooling consumption

Where $E_{total,h}^{TES}$ is the total electricity consumption of the data center with thermal storage, $E_{IT,h}$ is the IT electricity consumption, $E_{aux,h}$ is the auxiliary electricity consumption, and $E_{cooling,h}^{TES}$ is the cooling consumption after applying TES.

This results in a new table of 288 representative hourly values for each TES scenario, which can be directly compared with the baseline scenario.

Figure 13 shows the daily electricity consumption profiles of the data center after implementing the 3 hour TES. The storage shifts part of the cooling demand towards the central hours of the day, increasing consumption during charging periods while reducing it during the hours selected for discharge. This effect is more pronounced during the summer months, when cooling demand is higher, whereas during the colder months, the TES cannot be used at all.

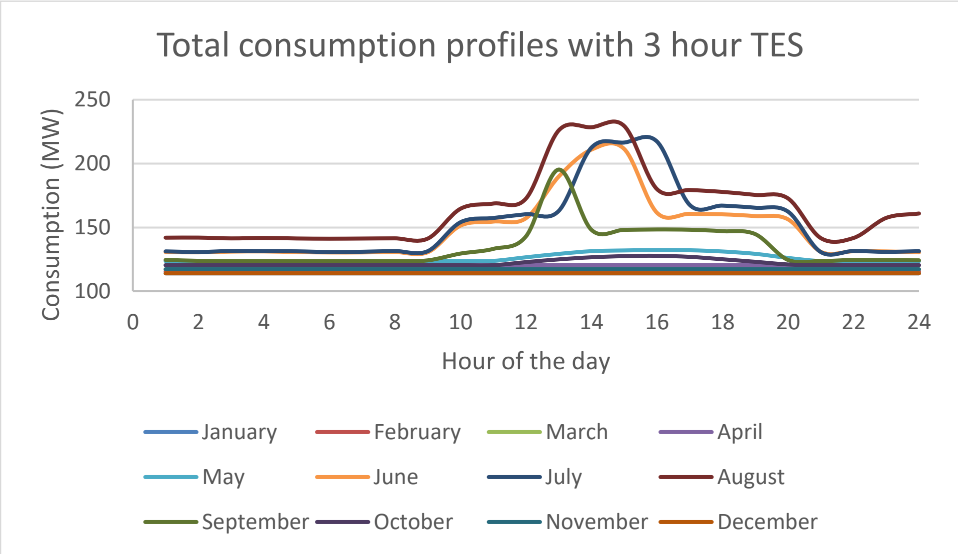


Figure 13. Total consumption profiles with 3 hour TES

7.5.5 Cost calculations in TES scenario

The electricity costs of the TES scenario is calculated using the same cost structure as in the baseline scenario. For each representative hour, the total electricity consumption with TES is multiplied by the sum of the spot price, network tariffs and regulated charges:

$$Cost_h^{TES} = E_{total,h}^{TES} \times (P_{spot,h} + NT_h + RC_h)$$

Equation 18. TES cost calculation

where $Cost_h^{TES}$ is the electricity cost in hour h, $E_{total,h}^{TES}$ is the total electricity consumption with TES, $P_{spot,h}$ is the hourly spot price, T_h represents network tariffs, and C_h represents regulated charges.

The annual cost is then obtained by multiplying each representative day by the number of days in the corresponding month and adding the twelve monthly results.

Although knowing the total electricity cost is important, the relevance is to compare it with the baseline scenario to assess whether the cost has decreased or not.

The cost difference with respect to the baseline is calculated as:

$$\Delta Cost = Cost^{TES} - Cost^{baseline}$$

The electricity cost of the baseline scenario is 77.128.983 € and for the case of Seville is 79.302.656 €.

For each of the four scenarios considered, the total cost and the variation respect to the baseline costs is shown in Table 26:

TES scenario	***Total costs with TES (€)***	***ΔCost (€)***
3 hour – 150 MWh	75.979.910 €	-1.149.073 €
2 hour – 100 MWh	76.208.738 €	-920.245 €
1 hour – 50 MWh	76.599.494 €	-529.489 €
3 hour – 150 MWh Seville	77.575.730 €	-1.726.926 €

Table 26. Total costs for TES scenarios

The table shows the annual electricity cost obtained for each TES scenario and the corresponding variation with respect to the baseline case. As can be observed, all TES configurations reduce the electricity cost compared with the case without flexibility, since part of the cooling consumption is shifted from more expensive hours to hours with lower electricity prices. However, it should be noted that the TES is not dispatched according to electricity prices, but according to the hourly emissions intensity. Therefore, the cost reduction observed in these scenarios is an indirect effect of the partial correlation between low-emission hours and low-price hours, rather than the result of a cost-minimization strategy.

For Madrid, the most favorable case from the electricity cost perspective is the 3-hour TES scenario, which provides the largest annual cost reduction. Nevertheless, the difference between the TES configurations should not be interpreted only from a cost perspective, since the main objective of the storage operation is to reduce induced emissions. This suggests that, once the most valuable hours have already been shifted, adding more TES capacity does not necessarily lead to proportional additional cost savings. In this case, the extra energy may be charged or discharged in hours with a lower price difference, reducing the marginal economic benefit of the larger system.

The Seville case also shows a reduction in electricity cost, and the saving is higher than in the Madrid 3-hour case. This is consistent with the higher cooling demand caused by warmer temperatures, which increases the amount of cooling consumption that can potentially be shifted. As a result, TES operation is more frequent and more valuable in warmer locations, although the dispatch logic remains based on emissions rather than electricity price.

However, these results only represent the operational electricity cost savings. They do not yet determine whether the TES is economically profitable. To assess the final attractiveness of each option, these savings must later be compared with the investment cost of each TES configuration. In particular, the analysis should evaluate whether the additional cost of installing more storage capacity is justified by the additional savings and emissions reductions obtained. For this reason, the cost results should be interpreted as one part of the trade-off between economic impact and emissions reduction, rather than as the main criterion used to operate the TES.

7.5.6 EMISSIONS CALCULATION IN TES SCENARIO

The emissions of the TES scenario are calculated by multiplying the total hourly electricity consumption with TES by the hourly emissions factor:

$$Emissions_h^{TES} = E_{total,h}^{TES} \times EF_h$$

Equation 19. TES emissions calculation where $Emissions_h^{TES}$ represents the emissions in hour h, $E_{total,h}^{TES}$ is the total electricity consumption with TES, and EF_h is the estimated hourly emissions factor.

The total emissions of the baseline scenario were 122.534 tCO_2 and for the case of Seville is 126.227 tCO_2.

For each of the four scenarios considered, the total emissions and the variation respect to the baseline emissions is shown in Table 27:

TES scenario	***Total emissions with TES (tons CO2)***	***Avoided emissions (tons CO2)***
3 hour – 150 MWh	*121.642*	*892*
2 hour – 90,1 MWh	*121.823*	*711*
1 hour – 50 MWh	*122.127*	*407*
3 hour – 150 MWh Seville	*125.033*	*1.244*

Table 27. Total emissions for TES scenarios

The table presents the total annual emissions obtained for each TES scenario and their variation with respect to the baseline case. The results show that the introduction of thermal storage has a relatively limited impact on total annual emissions, since the TES only affects the cooling component of the data center and shifts a small part of the total electricity consumption.

For the Madrid scenarios, the 3-hour TES case achieves the largest emissions reduction, followed by the 2-hour and 1-hour cases. This result is consistent with the logic of the model: a larger TES capacity allows a greater amount of cooling consumption to be shifted away from high-emission hours. However, the difference between the scenarios is small, which suggests that the emissions reduction potential of TES is limited once the most relevant cooling load has already been shifted.

The Seville case shows the highest emissions reduction among the scenarios analysed. This is coherent with the higher cooling requirements associated with warmer temperatures. Since the data center in Seville relies less on free cooling and has a higher cooling demand, there is more consumption available to be shifted through TES. As a result, thermal storage has a slightly greater environmental impact in this location.

Overall, the results indicate that TES can contribute to reducing emissions, but the magnitude of the reduction is modest compared with the total annual emissions of the data center. Therefore, the environmental benefit of TES should not be assessed only in absolute terms, but also in relation to the investment required. This will be analysed later through indicators such as the cost per tonne of CO_2 avoided.

7.5.7 Investment costs

The investment cost of the thermal energy storage system is estimated through three CAPEX scenarios: 40 €/kWh_t, 60 €/kWh_t and 100 €/kWh_t. For this type of system, the storage tank is usually the main cost component, with typical installed costs for chilled-water tanks in the range of 100–200 $/ton-hour [46]. Since one refrigeration ton is defined as 12,000 Btu/h and 1 kWh is equivalent to approximately 3,412 Btu, one ton-hour corresponds to 12,000/3,412 = 3.516 kWh_t. Therefore, the reported range of 100–200 $/ton-hour is equivalent to 28.4–56.9 $/$kWh_t$, or approximately 26–52 €/kWh_t when applying an exchange rate of 0.92 €/USD. This conversion is used only to express the original cost references in the same thermal energy unit adopted in the model.

The 100–200 $/ton-hour range is used as a reference for the installed cost of chilled-water TES tanks. However, this value should not be interpreted as the full investment cost of the TES system in the data center model. It mainly represents the storage tank itself, which is usually the largest cost component, but additional costs must be considered when the system is integrated into a real cooling infrastructure. These include civil work, foundations, hydraulic connections, pumps, valves, heat exchangers, control systems, engineering, commissioning and reliability requirements. For this reason, the cost obtained from the 100–200 $/ton-hour reference is used as a lower technical benchmark, while the CAPEX assumptions adopted in the model are increased to 40, 60 and 100 €/kWh$_t$ to represent a complete and integrated TES system.

The low-cost scenario of 40 €/kWh$_t$ is interpreted as an optimistic future case, reflecting potential reductions from economies of scale, standardization and wider deployment of thermal storage technologies. The central scenario of 60 €/kWh$_t$ is adopted as a conservative reference value, assuming that part of these cost reductions can be achieved in a medium-term future. Finally, the high-cost scenario of 100 €/kWh$_t$ is used to represent a more conservative cost case with the level of deployment and integration that thermal energy storage has nowadays.

It is estimated that the useful life of a TES is around 40 years.

The TES capacity obtained in the model is expressed as electrical-equivalent cooling consumption, because it represents the electricity consumption of the cooling system that can be shifted. However, TES investment costs are expressed in €/kWh$_t$. Therefore, the electrical-equivalent storage capacity is converted into thermal energy by multiplying it by the assumed COP of the cooling system, equal to 5.

Table 28 shows the required investments for each TES size and each CAPEX value.

TES size	***Electrical energy (MWh)***	***Thermal energy (MWh$_t$)***	***Low CAPEX - 40 €/kWh$_t$***	***Medium CAPEX - 60 €/kWh$_t$***	***High CAPEX- 100 €/kWh$_t$***
150 MWh – 3 hours	150	750	29,988 M€	44,982 M€	74,970 M€

100 MWh – 2 hours	100	500	19,992 M€	29,988 M€	49, 980 M€
50 MWh – 1 hour	50	250	9,996 M€	14,994 M€	24,990 M€
150 MWh – 3 hours Seville	150	750	29,988 M€	44,982 M€	74,970 M€

Table 28. TES investment costs

7.5.8 RESULTS

In order to compare the economical viability of the different scenarios for TES, the following approach has been followed. For each CAPEX value, the four scenarios, TES of 3, 2 and 1 hours and the TES of 3 hours of Seville, have been compared. The aim is to see how the cost of different sizes varies and analyze up to what extent, including a TES does not increase the costs of the data centers.

It can be expected that including thermal energy storage may increase the total costs of data centers. However, it must be considered that, even though there is an investment required, the electrical bill can decrease due to lowering the demand required from the grid in times in which the electricity costs are higher.

Therefore, in order to compare all the scenarios, the total cost of the data centers, which are the electricity costs and the annualized investment cost, are compared amongst all scenarios by means of the average cost. This means that the total costs for each scenario is divided by the total energy consumption to obtain the average cost and be able to compare between them in absolute terms.

It must be said that for each CAPEX value, the total investment costs are divided by the useful life, which was 40 years, to obtain the annualized costs of the investment.

All the following scenarios are compared with Table 29 results from the baseline scenario.

Energy	
Total energy cost (€)	77.128.983 €
Total energy (MWh)	1129722
Average cost (€/MWh)	68,3

Emissions	
Total emissions (tCO_2)	122534
Average emissions (tCO_2/MWh)	0,108

Table 29. Baseline scenario reference values

7.5.8.1 Results for low CAPEX of 40 €/kWh$_t$

Table 30 shows the total energy costs, the total energy costs including the annualized investment costs, the total energy and the average cost for each TES size for a low CAPEX value of 40 €/kWht.

Outputs	*150 MWh- 3 hours*	*100 MWh – 2 hours*	*50 MWh – 1 hour*
Total energy cost (€)	75.979.910	76.208.738	76.599.494
Total energy and annualized investment cost (€)	76.729.610	76.708.538	76.849.394
Total energy (MWh)	1129722	1129722	1129722
Average cost (€/MWh)	67,9	67,9	68

Table 30. Average costs for low CAPEX 40 eur/kWht

7.5.8.2 Results for medium CAPEX of 60 €/kWh$_t$

Table 31 shows the total energy costs, the total energy costs including the annualized investment costs, the total energy and the average cost for each TES size for a medium CAPEX value of 60 €/kWht.

Outputs	*150 MWh- 3 hours*	*100 MWh – 2 hours*	*50 MWh – 1 hour*
Total energy cost (€)	75.979.910	76.208.738	76.599.494
Total energy and annualized investment cost (€)	77.104.460	76.958.438	76.974.344
Total energy (MWh)	1129722	1129722	1129722
Average cost (€/MWh)	68,3	68,1	68,1

Table 31. Average costs for medium CAPEX 60 eur/kWht

7.5.8.3 Results for high CAPEX of 100 €/kWh$_t$

Table 32 shows the total energy costs, the total energy costs including the annualized investment costs, the total energy and the average cost for each TES size for a high CAPEX value of 100 €/kWht.

Outputs	*150 MWh- 3 hours*	*100 MWh – 2 hours*	*50 MWh – 1 hour*
Total energy cost (€)	75.979.910	76.208.738	76.599.494

Total energy and annualized investment cost (€)	77.854.160	77.458.238	77.224.244
Total energy (MWh)	1129722	1129722	1129722
Average cost (€/MWh)	68,9	68,6	68,4

Table 32. Average costs for high CAPEX 100 eur/kWht

7.5.8.4 Average emissions results

Table 33 shows the average emissions for each of the TES sizes

Outputs	*150 MWh- 3 hours*	*100 MWh – 2 hours*	*50 MWh – 1 hour*
Total emissions (tCO2)	121.642	121.823	122.127
Average emissions (tCO2/MWh)	0,108	0,108	0,108

Table 33. Average emissions for different TES sizes

7.5.8.5 Results for the case of Seville

Table 34 shows the average costs for the case of the TES of 150 MWh in Seville for the different CAPEX values.

Outputs	*Low CAPEX - 40 €/kWht*	*Medium CAPEX - 60 €/kWht*	*High CAPEX - 100 €/kWht*
Total energy cost (€)	77.575.730	77.575.730	77.575.730
Total energy and annualized investment cost (€)	78.325.430	78.700.280	79.449.980
Total energy (MWh)	1158436	1158436	1158436
Average cost (€/MWh)	67,6	67,9	68,6

Table 34. Average costs for Seville case

The average emissions for the case of TES of 3 hours in Seville are 0.109 tCO2/MWh.

7.5.9 Comparison

Figure 14 shows the results graphed. Each series represents the different average costs for each TES size for each CAPEX value. There is also a series belonging to the average emissions for each TES size.

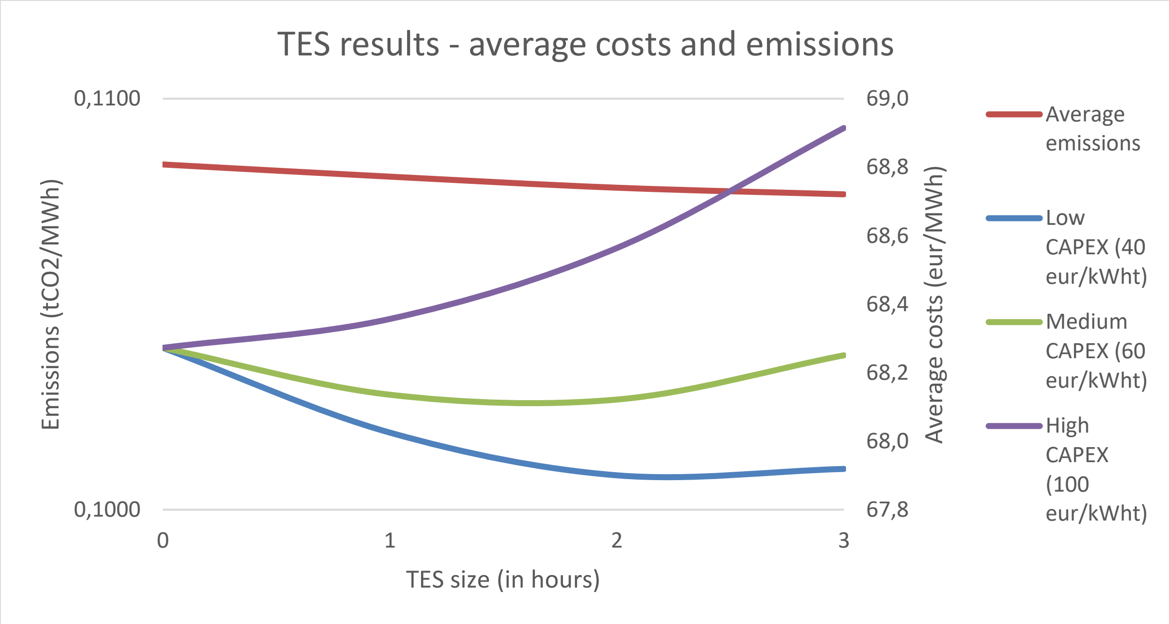


Figure 14. TES results - average costs and emissions

The comparison between the different TES scenarios shows that thermal storage provides a limited reduction in induced emissions. The values represented at TES size zero correspond to the baseline scenario, which is used as the reference case for the comparison. As the TES size increases, average emissions decrease slightly, because a larger amount of cooling consumption is shifted from higher-emission hours to lower-emission hours. However, the slope of the emissions curve is very moderate, which confirms that the environmental impact of TES is constrained by the fact that it only acts on the cooling component of the data center demand.

From an economic perspective, the result depends strongly on the assumed CAPEX. For the low and medium CAPEX cases, the introduction of TES reduces the average cost compared with the baseline scenario. This occurs because cooling production is shifted towards hours with lower electricity prices, while consumption during more expensive hours is partially avoided. Therefore, under relatively low investment cost assumptions, the TES can provide a modest economic benefit in addition to the emissions reduction.

However, the high CAPEX case shows the opposite effect. When the investment cost of the thermal storage system is high, the savings obtained from shifting cooling consumption are not sufficient to compensate for the additional annualized investment cost. As a result, the average cost increases as TES size grows. This indicates that, although TES can contribute to reducing electricity costs and emissions, its attractiveness is highly sensitive to investment costs. In this sense, the 3-hour TES provides the largest emissions reduction, but not necessarily the best economic balance once investment costs are included. The 1-hour and 2-hour configurations may offer a more moderate but more efficient compromise, since they capture part of the most valuable shifting opportunities with lower investment requirements. This indicates that the marginal value of additional TES capacity decreases once the most emitting and economically favorable hours have already been covered.

Overall, Figure 14 suggests that TES should not be interpreted as a main decarbonization solution for data centers. Its contribution is positive but limited. Therefore, TES is better understood as a complementary flexibility measure, it can improve the operation of the cooling system and slightly reduce induced emissions, but its economic justification depends on achieving sufficiently low CAPEX values and on the existence of adequate price differences between charging and discharging hours. This result is consistent with the Pareto-oriented approach of the model, since the objective is not to identify a single optimal TES size, but to understand which configurations provide a reasonable balance between emissions reduction and economic impact.

7.5.9.1 Comparison between Madrid and Seville

Due to the limited viability of a TES in Madrid, it is interesting to analyze the case of Seville as a sensitivity case under warmer climatic conditions. The comparison between Madrid and Seville confirms that the performance of TES is strongly influenced by climatic conditions. In Seville, higher ambient temperatures reduce the availability of free cooling and increase the number of hours in which mechanical cooling is required. As a result, a larger share of the cooling demand becomes potentially shiftable through thermal storage.

In terms of induced emissions, the situation is similar to the Madrid case. The reduction of the emissions is limited, therefore, if the TES were installed only for reducing the induced emissions, it would not achieve a significant reduction. Although the absolute emissions reduction is higher in Seville, the reduction remains limited when compared with the total annual emissions of the data center. Therefore, a warmer location improves the utilization of TES, but it does not fundamentally change its role as a decarbonization measure.

In terms of costs, a TES in Seville would have lower average costs than a TES in Madrid. This is because, as temperatures are higher in Seville, less free cooling can be used and therefore there are more hours in which the TES can be used. This increased use of the TES reduces the electricity consumption costs as it can be charged during more months at times where the electricity prices are lower, or even zero or negative, and discharged when the electricity prices are higher. Therefore, the avoided costs are higher and the average costs lower, as it can be seen in Figure 15.

Consequently, the Seville case shows that warmer locations can increase the economic value of TES because the storage system can operate during more hours and shift a larger amount of cooling consumption. However, this does not modify the main conclusion of the TES analysis. Thermal storage can contribute to reducing induced emissions and electricity costs, especially in warmer locations, but its potential is limited because it only acts on the cooling demand and not on the total electricity consumption of the data center. For this reason, TES should be interpreted as a complementary flexibility resource rather than as the main solution for reducing the carbon impact of data centers.

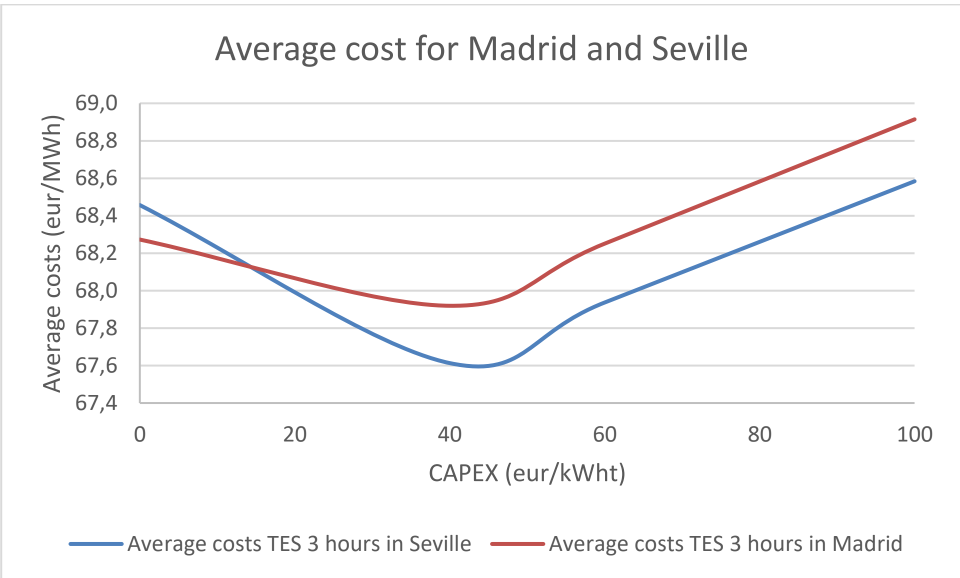


Figure 15. TES results - average cost comparison between Madrid and Seville

7.6 SCENARIO WITH BATTERY ENERGY STORAGE SYSTEM (BESS)

The second flexibility strategy analysed in the model is the implementation of a Battery Energy Storage System (BESS). Unlike the thermal storage system, which only modifies the cooling electricity consumption, the BESS acts on the electrical side of the data center and can therefore modify the total electricity demand profile.

The purpose of the BESS scenario is not to minimize the electricity supply cost of the data center directly, but to analyze the potential of the battery as a flexibility resource for reducing emissions. The battery, like the TES, is operated using a carbon-aware criterion: it charges during hours with lower emissions intensity and discharges during hours with higher emissions intensity. In this way, part of the electricity consumption of the data center is shifted away from the most carbon-intensive periods.

This distinction is important because the battery is not modelled as a pure economic arbitrage asset. The objective is not to identify the cheapest possible charging and discharging schedule, but to evaluate how much emissions reduction can be achieved when a large data center adapts part of its electricity consumption to the hourly carbon intensity of the Spanish electricity system.

The electricity cost is calculated afterwards as an output of the model. This allows the analysis to quantify the economic impact of the emissions-oriented operation of the battery. Therefore, the BESS results are interpreted in terms of both environmental performance and associated cost, rather than as a conventional cost-minimization problem.

7.6.1 BESS SCENARIOS, SIZING AND TECHNICAL ASSUMPTIONS

Several BESS scenarios are analysed in the model in order to evaluate how the size of the battery affects the emissions reduction potential, the electricity cost and the economic performance of the data center. The objective is not to define a single optimal battery size, but to compare different storage configurations under the same methodology and assess the trade-off between avoided emissions and cost.

The BESS is defined by two main technical parameters: power and energy capacity. The power rating determines the maximum amount of electricity that the battery can charge or discharge in one hour, while the energy capacity determines the total amount of electricity that can be stored and later be supplied to the data center.

In this model, all BESS scenarios are assumed to have a maximum charge and discharge power of 120 MW. This value was selected as a representative battery power for a large data center with an IT load of 100 MW. Since the total electricity demand of the data center is higher than the IT load once cooling and auxiliary consumption are included, a 120 MW battery is large enough to significantly modify the hourly demand profile, while remaining consistent with the scale of the facility.

The power capacity is kept constant across all scenarios in order to isolate the effect of storage duration. In this way, the comparison does not evaluate increasingly larger power blocks, but rather how many hours of demand shifting are useful once the same maximum hourly modulation capability is available. This distinction is important because the environmental and economic value of the BESS depends not only on the maximum power that can be shifted in one hour, but also on the number of hours during which that shift can be sustained.

Based on this approach, the energy capacity is progressively increased while maintaining the same power capacity. The BESS configurations considered are shown in Table 35:

BESS scenario	*Power (MW)*	*Energy capacity (MWh)*	*Storage duration (h)*
BESS 120 MW / 360 MWh	120	360	3
BESS 120 MW / 480 MWh	120	480	4

BESS 120 MW / 600 MWh	120	600	5
BESS 120 MW / 720 MWh	120	720	6
BESS 120 MW / 840 MWh	120	840	7
BESS 120 MW / 960 MWh	120	960	8
BESS 120 MW / 1,080 MWh	120	1,080	9

Table 35. BESS scenarios and sizes

Some of the battery sizes considered in the model are very large. However, they are intentionally included in the analysis in order to test a wide range of flexibility possibilities. The smaller and medium-sized batteries represent more moderate configurations, while the largest cases act as extreme scenarios that allow the model to observe how emissions reduction, electricity costs and investment requirements evolve when storage capacity increases significantly.

This approach is useful because the relationship between battery size and benefits is not necessarily linear. Therefore, comparing several storage durations makes it possible to identify whether the additional capacity provides proportional benefits or whether the average value decreases beyond a certain size.

For the BESS case, battery losses are represented through charging and discharging efficiencies. In the model, both charging and discharging efficiency are assumed to be 95%, resulting in a round-trip efficiency of:

$$\eta_{BESS} = 0.95 \times 0.95 = 0.9025$$

Equation 20. BESS efficiency factor

This means that the electricity discharged by the battery is lower than the electricity initially charged from the grid. In order to discharge 120 MWh, the battery needs to charge 133 MWh. Therefore, the BESS slightly increases the total amount of electricity withdrawn from the grid due to storage losses.

Finally, the model does not include battery degradation, replacement cycles, ancillary service revenues or detailed grid constraints. These factors may be relevant in a real investment decision, but they are outside the scope of this thesis.

7.6.2 CHARGE AND DISCHARGE HOURS

The BESS follows the same emissions logic as the TES scenario as it charges during the least-emitting hours and discharges during the most-emitting hours. However, the BESS operation is simpler because it acts on the total electricity demand of the data center, not only on the cooling load which was also limited by the minimum cooling consumption that had to remain in operation. In contrast, the BESS is not constrained by the cooling profile therefore charge and discharge are performed according to the available battery capacity and the selected hourly emissions ranking.

In addition, the BESS is modelled as a behind-the-meter flexibility asset for the data center and not as an electricity-exporting resource. For this reason, the discharge in each hour cannot exceed the total electricity demand of the data center in that same hour. This prevents the battery from creating a negative net load or injecting electricity into the grid. When the selected discharge hour has a data center demand lower than the BESS discharge power, the discharge is limited to the hourly demand and the remaining discharge energy is reallocated to the next available hours with the highest emissions factor.

The colder months when the cooling consumption is lower, the overall consumption may be lower than 120 MW. When this happens, instead of discharging at full capacity during certain hours, the discharge is done throughout more hours until the battery is fully discharged. The same happens during warmer months, when the total consumption is over 120 MW. The battery discharges up to 120 MW, leaving a little bit of consumption in certain hours uncovered by the BESS supply.

Table 36 shows the discharge and charge of a BESS of 360 MWh of 3 hours. The cells in red are when the BESS is discharging and the cells in green is when it is charging.

(MW)	***January***	***February***	***March***	***April***	***May***	***June***	***July***	***August***	***September***	***October***	***November***	***December***
h0	-18	-13	-8	0	0	0	0	0	0	0	-8	-18
h1	0	0	0	0	0	0	0	0	0	0	0	0
h2	0	0	0	0	0	0	0	0	0	0	0	0
h3	0	0	0	0	-120	0	0	0	0	0	0	0
h4	0	0	0	0	-120	-120	0	0	0	-120	0	0
h5	0	0	0	-120	-120	-120	-120	-120	0	-120	0	0
h6	-114	0	0	-120	0	-120	-120	-120	0	-120	0	0
h7	0	0	0	-120	0	0	-120	-120	-120	0	0	0
h8	0	0	0	0	0	0	0	0	0	0	0	0
h9	0	0	0	0	133	0	0	0	0	0	0	0
h10	0	0	0	0	133	0	0	0	0	0	0	0
h11	133	0	0	133	133	0	0	0	133	0	133	0
h12	133	133	133	133	0	133	0	133	133	133	133	133
h13	133	133	133	133	0	133	133	133	133	133	133	133
h14	0	133	133	0	0	133	133	133	0	133	0	133
h15	0	0	0	0	0	0	133	0	0	0	0	0
h16	0	0	0	0	0	0	0	0	0	0	0	0
h17	0	0	0	0	0	0	0	0	0	0	0	-114
h18	-114	-116	0	0	0	0	0	0	0	0	-117	-114
h19	0	-116	-117	0	0	0	0	0	0	0	-117	-114
h20	-114	-116	-117	0	0	0	0	0	-120	0	-117	0
h21	0	0	-117	0	0	0	0	0	-120	0	0	0
h22	0	0	0	0	0	0	0	0	0	0	0	0
h23	0	0	0	0	0	0	0	0	0	0	0	0

Table 36. BESS discharge and charge for BESS of 3 hours - 360 MWh

7.6.3 BESS INTEGRATION INTO TOTAL DATA CENTER CONSUMPTION

Once the charging and discharging hours have been defined, the hourly electricity consumption of the data center is recalculated. With the BESS, this profile changes because the battery modifies the timing of grid electricity consumption.

During charging hours, the electricity withdrawn from the grid increases. This is because the data center continues consuming its normal electricity demand while the battery also absorbs electricity from the grid. During discharging hours, the opposite effect occurs: the electricity withdrawn from the grid decreases, since part of the data center demand is supplied by the battery.

This increase in grid withdrawal during charging hours should be interpreted together with the emissions-based operation of the battery. In the model, charging is concentrated in lower-emission hours, which frequently correspond to central hours of the day with higher renewable availability. Therefore, the battery does not simply increase the data center peak randomly, but shifts part of the demand towards hours that are more favorable from the perspective of the electricity mix.

Therefore, the net electricity consumption from the grid with BESS is calculated as:

$$E_{grid,h}^{BESS} = E_{total,h}^{baseline} + E_{charge,h} - E_{discharge,h}$$

Equation 21. Total consumption calculation with BESS discharge and charge

Where $E_{grid,h}^{BESS}$ is the electricity withdrawn from the grid in hour h, $E_{total,h}^{baseline}$ is the original electricity demand of the data center, $E_{charge,h}$ is the electricity used to charge the battery, and $E_{discharge,h}$ is the electricity supplied by the battery during discharge.

This results in a new table of 288 representative hourly values for each BESS scenario, which can be directly compared with the baseline scenario.

Figure 16 shows the daily electricity consumption profiles of the data center after implementing the 360 MWh BESS. The BESS shifts part of the demand towards the central hours of the day, increasing consumption during charging periods while reducing it during the hours selected for discharge. Depending on the season of the year, the most carbon emitting hours occur at different times of the day. During the cooler and warmer months, the most carbon emitting hours occur during the night, when the heats or air conditioners are on because people are back home from work and due to the lack of solar photovoltaic generation, more CCGTs technologies are generating. Durind the mild temperature months, since no air conditioners or heat is needed, the most emitting hours shift from the night to the early morning.

In contrast with the TES, BESS is used all year round, therefore, there are no flat profiles like in the TES profiles.

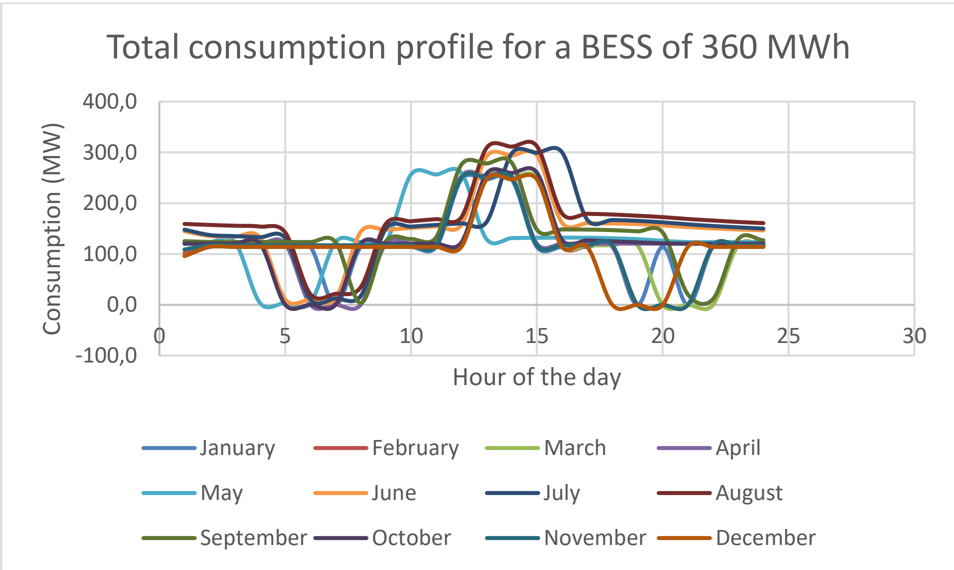


Figure 16. Total consumption profile for a BESS of 360 MWh

7.6.4 COST CALCULATIONS IN BESS SCENARIO

The electricity costs of the BESS scenario are calculated using the same cost structure as in the baseline and TES scenarios. For each representative hour, the total electricity consumption with BESS is multiplied by the sum of the spot price, network tariffs and regulated charges:

$$Cost_h^{BESS} = E_{total,h}^{BESS} \times (P_{spot,h} + NT_h + RC_h)$$

Equation 22. BESS costs calculation

where $Cost_h^{BESS}$ is the electricity cost in hour h, $E_{total,h}^{BESS}$ is the total electricity consumption with BESS, $P_{spot,h}$ is the hourly spot price, NT_h represents network tariffs, and RC_h represents regulated charges.

The annual cost is then obtained by multiplying each representative day by the number of days in the corresponding month and adding the twelve monthly results.

7.6.4.1 Price differential sensitivity

At this stage of the model, the cost variation is calculated using the original hourly spot prices, network tariffs and regulated charges. Therefore, the results show the direct effect of applying the BESS operation to the current price profile. However, this cost impact is also analysed under an additional sensitivity assumption. As battery storage becomes more widespread in the electricity system, the price differential between low-price and high-price hours may progressively decrease. If many batteries charge during low-price hours, demand in those hours increases and prices tend to rise; conversely, if batteries discharge during high-price hours, demand from the grid decreases and prices tend to fall. As a result, the hourly price curve may become flatter, reducing the economic value of arbitrage.

For this reason, an additional price differential sensitivity has been carried out. The objective of this sensitivity is not to forecast future electricity prices, but to test how robust the economic results are if the spread between low-price and high-price hours decreases over the useful life of the BESS, which is 12 years. Two scenarios are considered:

- A conservative scenario, where the price differential is reduced by 25% over 12 years. In this case, the differential in year 12 is 75% of the initial value. This scenario will be referred to as the 25% price-differential reduction scenario.
- A more aggressive scenario, where the price differential is reduced by 45% over 12 years. In this case, the differential in year 12 is 55% of the initial value. This scenario will be referred to as the 50% price-differential reduction scenario.

The reduction of the price differential is modelled through an exponential decay function rather than a linear reduction. For each month, the initial price differential is calculated from the representative daily spot price profile of 2025. More specifically, the model calculates the difference between the highest and lowest hourly prices, the second highest and second lowest hourly prices, and the third highest and third lowest hourly prices. The average of these three differences is used as the monthly reference price differential.

	Difference between highest and lowest hourly price	*Difference between second highest and lowest hourly price*	*Difference between third highest and lowest hourly price*	*Average*
January	64,4	58,3	55,4	59,4
February	112,0	105,8	81,7	99,8
March	89,4	88,3	68,4	82,0
April	82,3	63,1	61,9	69,1
May	68,4	61,3	43,9	57,9
June	119,3	116,8	94,3	110,1
July	95,3	92,2	76,5	88,0
August	106,1	97,5	88,6	97,4
September	115,8	103,7	88,9	102,8
October	103,8	94,7	82,7	93,7
November	82,1	81,2	73,4	78,9
December	46,0	43,0	40,0	43,0

Table 37. Price differential from spot prices 2025

The reduction of the price differential is modelled as an exponential decay rather than as a linear decrease. This means that the model does not assume that the price spread is reduced by the same absolute amount every year. Instead, it assumes that each year the remaining differential is a fixed proportion of the differential of the previous year. This approach is useful because the expected flattening of the electricity price curve is not necessarily linear.

The exponential decay is represented through the following expression:

$$Price_{y,m} = Price_{average,m} * e^{(-k*(year_y-1))}$$

Equation 23. Price differential reduction exponential calculation

Where $Price_{y,m}$ is the differential price in year y and in month m, $Price_{average,m}$ is the average differential price calculated for each month from the spot prices, k is the exponential decay parameter and $year_y$ is the year.

The term (y − 1) is used because year 1 represents the initial situation. Therefore, in year 1, the exponent is zero and the differential is still equal to 100% of the initial value. The reduction is then applied progressively from year 2 onwards.

The parameter k is calculated by imposing the condition that, in year 12, the differential reaches the assumed final value. Since the useful life of the BESS is 12 years, the model imposes that the differential in year 12 is equal to 75% of the initial differential in the conservative scenario, and 55% of the initial differential in the aggressive scenario.

$$k = -\ln\frac{price\ differential\ fall}{11}$$

Equation 24. Exponential decay function

Where k is the decay parameter and the final remaining price-differential factor is 75% in the conservative scenario and 50% in the aggressive scenario. Equivalently, these values correspond to a 25% and a 50% reduction in the initial price differential, respectively.

Therefore, k is 0,026 for the 25% price-differential reduction scenario and k should be recalculated consistently for the 50% price-differential reduction scenario.

Once k is calculated, the model obtains the remaining differential factor for each year of the BESS useful life. The relation is lineal with a slight exponential decrease. Therefore, it has been chosen to do the average between values in years 6 and 7, to obtain the mean value. This gives an average remaining differential of 87% in the conservative scenario and 71% in the aggressive scenario. Therefore, the corresponding loss of arbitrage value is 13% in the conservative case and 29% in the aggressive case. These percentages represent the average value over the BESS lifetime, while the scenario definition refers to the final reduction reached in year 12.

This loss of arbitrage value is applied to the energy charged by the battery. The logic is that each MWh cycled by the BESS obtains part of its economic value from the difference between the price at which it charges and the price avoided during discharge. If this price differential becomes smaller in the future, the economic saving associated with each MWh cycled is also reduced.

For all of the BESS size scenarios the total cost and the variation respect to the baseline costs are shown in Table 38. The electricity cost of the baseline scenario is 77.128.983 €

BESS scenario	***Total costs with BESS for 25% price differential reduction (€)***	***Total costs with BESS for 50% price differential reduction (€)***
120 MW / 360 MWh	71.795.883	73.680.793
120 MW / 480 MWh	70.217.175	72.730.389
120 MW / 600 MWh	68.989.030	72.130.547
120 MW / 720 MWh	68.594.188	72.364.009
120 MW / 840 MWh	67.304.296	71.702.420
120 MW / 960 MWh	66.718.192	71.744.619
120 MW / 1080 MWh	66.518.876	72.173.607

Table 38. BESS total costs under price differential sentivity scenarios

The results show that the economic performance of the BESS is strongly affected by the assumed evolution of the price differential. For all cases, the total costs are always lower than the total costs of the baseline scenario. This was expected due to the cost savings due to the charging patterns. Also, for all the cases, the total costs for the price differential fall of 25% are lower than the ones for 50%. This was also expected, as the first case implied lower costs and more savings due to the price profile not being flat.

This is because, in the conservative scenario, the price spread between charging and discharging hours remains larger. Therefore, the BESS charges during relatively cheaper hours and reduces grid consumption during relatively more expensive hours, which increases the operational saving associated with each MWh shifted.

By contrast, when the price differential decreases more strongly, the electricity price curve becomes flatter. In this case, the operational electricity saving provided by the BESS is reduced, because the economic difference between the charging hours and the discharging hours becomes smaller. As a result, each MWh shifted by the battery provides a lower cost benefit, even though the emissions reduction remains unchanged.

However, these results only represent the operational electricity cost savings. They do not yet determine whether the BESS is economically profitable. To assess the final attractiveness of each option, these savings must later be compared with the annualized investment cost of each BESS size. In particular, the analysis should evaluate whether the additional cost of installing more storage capacity is justified by the additional savings and emissions reductions obtained.

7.6.5 EMISSIONS CALCULATION IN BESS SCENARIO

The emissions of the BESS scenario are calculated by multiplying the total hourly electricity consumption with BESS by the hourly emissions factor:

$$Emissions_h^{BESS} = E_{total,h}^{BESS} \times EF_h$$

Equation 25. BESS emissions calculation

where $Emissions_h^{BESS}$ represents the emissions in hour h, $E_{total,h}^{BESS}$ is the total electricity consumption with BESS, and EF_h is the estimated hourly emissions factor.

The total emissions of the baseline scenario were 122.534 tCO_2.

For each of the four scenarios considered, the total emissions and the variation respect to the baseline emissions is shown in Table 39:

BESS scenario	*Total emissions with BESS (tons CO2)*	*Avoided emissions (tons CO2)*
120 MW / 360 MWh	116.329	6.205
120 MW / 480 MWh	113.981	8.616
120 MW / 600 MWh	112.224	10.310
120 MW / 720 MWh	111.320	11.214
120 MW / 840 MWh	109.531	13.004
120 MW / 960 MWh	108.547	13.987
120 MW / 1080 MWh	107.904	14.630

Table 39. Total emissions for BESS scenarios

The table presents the total annual emissions obtained for each BESS scenario and their variation with respect to the baseline case. This confirms that the carbon-aware operation of the battery is effective: by charging during lower-emission hours and discharging during higher-emission hours, part of the electricity consumption is shifted towards cleaner periods of the day.

As expected, avoided emissions increase as the size of the BESS increases. Larger batteries are able to shift a greater amount of electricity consumption, which leads to a larger reduction in total annual emissions.

However, the increase in avoided emissions is not perfectly proportional to the increase in battery capacity. The additional emissions reduction becomes progressively smaller as the BESS size increases. This suggests that smaller and medium-sized batteries are able to target the most carbon-intensive hours, while larger batteries start shifting consumption from hours with a lower emissions differential.

This result is important for the later economic assessment. Although larger batteries reduce more emissions in absolute terms, they also require a higher investment cost. Therefore, the best option should not be selected only according to total avoided emissions, but also considering the cost per ton of CO_2 avoided and the marginal benefit of adding more storage capacity.

Overall, the table shows that BESS can reduce the emissions associated with the electricity consumption of the data center, but the value of increasing battery capacity must be evaluated carefully. The following analysis will therefore compare these environmental benefits with the corresponding cost impact and investment requirements.

7.6.6 Investment costs

The CAPEX values selected for the BESS scenarios were defined as a sensitivity range rather than as a single fixed investment cost, in order to reflect the current uncertainty in battery project costs and the differences between global and European markets.

The selected range is based on recent market references. According to internal meetings, the actual costs range from 200 to 250 €/kWh. It is expected that in the upcoming future these values can decrease to 150 €/kWh due to the deployment of batteries and the improvement in the development of technologies. In the long-term future, it is expected that the prices can fall down to 75 €/kW, however, the market is still far from these values

For this reason, the model applies different CAPEX assumptions to evaluate the economic sensitivity of the results. The lower value represents a favorable cost case aligned with recent global turnkey benchmarks, the central value reflects a realistic reference case, and the upper value captures a more conservative assumption closer to the European market context. This approach is appropriate because the objective of the analysis is not to forecast the exact future cost of BESS, but to assess how different investment cost assumptions affect the total cost of implementing battery storage in data centers.

Table 40 shows the required investments for each BESS size and each CAPEX value.

BESS scenario	*Electrical energy (MWh)*	*Low CAPEX – 75 €/kWh*	*Medium CAPEX - 150 €/kWh*	*High CAPEX- 225 €/kWh*
120 MW / 360 MWh	360	27 M€	54 M€	81 M€
120 MW / 480 MWh	480	36 M€	72 M€	108 M€
120 MW / 600 MWh	600	45 M€	90 M€	135 M€
120 MW / 720 MWh	720	54 M€	108 M€	162 M€
120 MW / 840 MWh	840	63 M€	126 M€	189 M€
120 MW / 960 MWh	960	72 M€	144 M€	216 M€
120 MW / 1080 MWh	1080	81 M€	162 M€	243 M€

Table 40. BESS investment costs

7.6.7 RESULTS

In order to compare the economic viability of the different scenarios for the BESS, the following approach has been followed. For each CAPEX value, all the BESS sizes results have been compared. The aim is to see how the cost of different sizes varies and analyze up to what extent, including a BESS does not increase the costs of the data centers.

It can be expected that including BESS may increase the total costs of data centers. However, it must be considered that, even though there is an investment required, the electrical bill can decrease due to lowering the demand required from the grid in times in which the electricity costs are higher.

This reduction in the electricity bill should not be interpreted as final profitability. It only reflects the operational saving obtained from the BESS dispatch. The economic assessment must also include the annualized investment cost, because larger batteries may reduce the electricity bill more, but they also require a much higher capital investment. Therefore, the relevant comparison is not only the reduction in the electricity bill, but the balance between operational savings, annualized CAPEX and avoided emissions.

Therefore, in order to compare all the scenarios, the total cost of the data centers, which are the electricity costs and the annualized investment cost, are compared amongst all scenarios by means of the average cost. This means that the total costs for each scenario are divided by the total energy consumption to obtain the average cost and be able to compare between them in absolute terms.

It must be said that for each CAPEX value, the total investment costs are divided by the useful life, which was 12 years, to obtain the annualized costs of the investment.

All the following scenarios are compared with Table 41 results from the baseline scenario.

Energy	
Total energy cost (€)	77.128.983 €
Total energy (MWh)	1129722
Average cost (€/MWh)	68,3

Emissions	
Total emissions (tCO_2)	122534
Average emissions (tCO_2/MWh)	0,108

Table 41. Baseline scenario reference values

There are two different scenarios, one for each price differential sensitivity analysis.

7.6.7.1 Results for price differential reduction of 25%

The following tables present the results obtained for each BESS size for each CAPEX scenario.

7.6.7.1.1 Results for low CAPEX of 75 €/kWh

Table 42 shows the total energy costs, the total energy costs including the annualized investment costs, the total energy and the average cost for each BESS size for a low CAPEX value of 75 €/kWh.

BESS scenario	*Total energy cost (€)*	*Total energy and annualized investment cost (€)*	*Total energy (MWh)*	*Average cost (€/MWh)*
120 MW / 360 MWh	71.795.883	74.045.883	1.143.917	64,7
120 MW / 480 MWh	70.217.175	73.217.175	1.144.099	64
120 MW / 600 MWh	68.989.030	72.739.030	1.148.831	63,3
120 MW / 720 MWh	68.594.188	73.094.188	1.158.113	63,1

120 MW / 840 MWh	67.304.296	72.554.296	1.158.295	62,6
120 MW / 960 MWh	66.718.192	72.718.192	1.163.027	62,5

Table 42. Average costs for low CAPEX 75 eur/kWh for price differential reduction of 25%

7.6.7.1.2 Results for medium CAPEX of 150 €/kWh

Table 43 shows the total energy costs, the total energy costs including the annualized investment costs, the total energy and the average cost for each BESS size for a medium CAPEX value of 150 €/kWh.

BESS scenario	*Total energy cost (€)*	*Total energy and annualized investment cost (€)*	*Total energy (MWh)*	*Average cost (€/MWh)*
120 MW / 360 MWh	71.795.883	76.295.883	1.143.917	66,7
120 MW / 480 MWh	70.217.175	76.217.175	1.144.099	66,6
120 MW / 600 MWh	68.989.030	76.489.030	1.148.831	66,6
120 MW / 720 MWh	68.594.188	77.594.188	1.158.113	67

120 MW / 840 MWh	67.304.296	77.804.296	1.158.295	67,2
120 MW / 960 MWh	66.718.192	78.718.192	1.163.027	67,7
120 MW / 1080 MWh	66.518.876	80.018.876	1.167.759	68,5

Table 43. Average costs for medium CAPEX 150 eur/kWh for price differential reduction of 25%

7.6.7.1.3 Results for high CAPEX of 225 €/kWh

Table 44 shows the total energy costs, the total energy costs including the annualized investment costs, the total energy and the average cost for each BESS size for a high CAPEX value of 225 €/kWh.

BESS scenario	*Total energy cost (€)*	*Total energy and annualized investment cost (€)*	*Total energy (MWh)*	*Average cost (€/MWh)*
120 MW / 360 MWh	71.795.883	78.545.883	1.143.917	68.7
120 MW / 480 MWh	70.217.175	79.217.175	1.144.099	69,2
120 MW / 600 MWh	68.989.030	80.239.030	1.148.831	69,8

120 MW / 720 MWh	68.594.188	82.094.188	1.158.113	70,9
120 MW / 840 MWh	67.304.296	83.054.296	1.158.295	71,7
120 MW / 960 MWh	66.718.192	84.718.192	1.163.027	72,8

Table 44. Average costs for high CAPEX 225 eur/kWh for price differential reduction of 25%

7.6.7.2 Results for price differential reduction of 50%

The following tables present the results obtained for each BESS size for each CAPEX scenario.

7.6.7.2.1 Results for low CAPEX of 75 €/kWh

Table 45 shows the total energy costs, the total energy costs including the annualized investment costs, the total energy and the average cost for each BESS size for a low CAPEX value of 75 €/kWh.

BESS scenario	***Total energy cost (€)***	***Total energy and annualized investment cost (€)***	***Total energy (MWh)***	***Average cost (€/MWh)***
120 MW / 360 MWh	73.680.793	75.930.793	1.143.917	66,4
120 MW / 480 MWh	72.730.389	75.730.389	1.144.099	66,2

120 MW / 600 MWh	72.130.547	75.880.547	1.148.831	66,1
120 MW / 720 MWh	72.364.009	76.864.009	1.158.113	66,4
120 MW / 840 MWh	71.702.420	76.952.420	1.158.295	66,4
120 MW / 960 MWh	71.744.619	77.744.619	1.163.027	66,8

Table 45. Average costs for low CAPEX 75 eur/kWh for price differential reduction of 50%

7.6.7.2.2 Results for medium CAPEX of 150 €/kWh

Table 46 shows the total energy costs, the total energy costs including the annualized investment costs, the total energy and the average cost for each BESS size for a medium CAPEX value of 150 €/kWh.

BESS scenario	***Total energy cost (€)***	***Total energy and annualized investment cost (€)***	***Total energy (MWh)***	***Average cost (€/MWh)***
120 MW / 360 MWh	73.680.793	78.180.793	1.143.917	68,3
120 MW / 480 MWh	72.730.389	78.730.389	1.144.099	68,8

120 MW / 600 MWh	72.130.547	79.630.547	1.148.831	69,3
120 MW / 720 MWh	72.364.009	81.864.009	1.158.113	70,3
120 MW / 840 MWh	71.702.420	82.202.420	1.158.295	71
120 MW / 960 MWh	71.744.619	83.744.619	1.163.027	72
120 MW / 1080 MWh	72.173.607	85.673.607	1.167.759	73,4

Table 46. Average costs for medium CAPEX 150 eur/kWh for price differential reduction of 50%

7.6.7.2.3 Results for high CAPEX of 225 €/kWh

Table 47 shows the total energy costs, the total energy costs including the annualized investment costs, the total energy and the average cost for each BESS size for a high CAPEX value of 225 €/kWh.

BESS scenario	***Total energy cost (€)***	***Total energy and annualized investment cost (€)***	***Total energy (MWh)***	***Average cost (€/MWh)***
120 MW / 360 MWh	73.680.793	80.430.793	1.143.917	70,3

120 MW / 480 MWh	72.730.389	81.730.389	1.144.099	71,4
120 MW / 600 MWh	72.130.547	83.380.547	1.148.831	72,6
120 MW / 720 MWh	72.364.009	85.864.009	1.158.113	74,1
120 MW / 840 MWh	71.702.420	87.452.420	1.158.295	75,5
120 MW / 960 MWh	71.744.619	89.744.619	1.163.027	77,2

Table 47. Average costs for high CAPEX 225 eur/kWh for price differential reduction of 50%

7.6.7.3 Average emissions results

Table 48 shows the average emissions for each of the BESS sizes

BESS scenario	*Total emissions (tCO2)*	*Average emissions (tCO2/MWh)*
120 MW / 360 MWh	116.329	0,102
120 MW / 480 MWh	113.981	0,1
120 MW / 600 MWh	112.224	0,098
120 MW / 720 MWh	111.320	0,096
120 MW / 840 MWh	109.531	0,095
120 MW / 960 MWh	108.547	0,093

120 MW / 1080 MWh	107.904	0,092

Table 48. Average emission results

7.6.8 Comparison

Figure 17 and Figure 18 show the comparison between the different BESS scenarios under the two price-spread sensitivity assumptions: a conservative case with a 25% reduction in the price differential over 12 years, and an aggressive case with a 50 % reduction in the price differential over 12 years. The comparisons include both the average cost and the average induced emissions for each battery size. As in the TES comparison, the value represented at 0 MWh corresponds to the baseline scenario, which is used as the reference case. Therefore, the results show how the average emissions and average cost evolve when the data center incorporates progressively larger battery storage capacity.

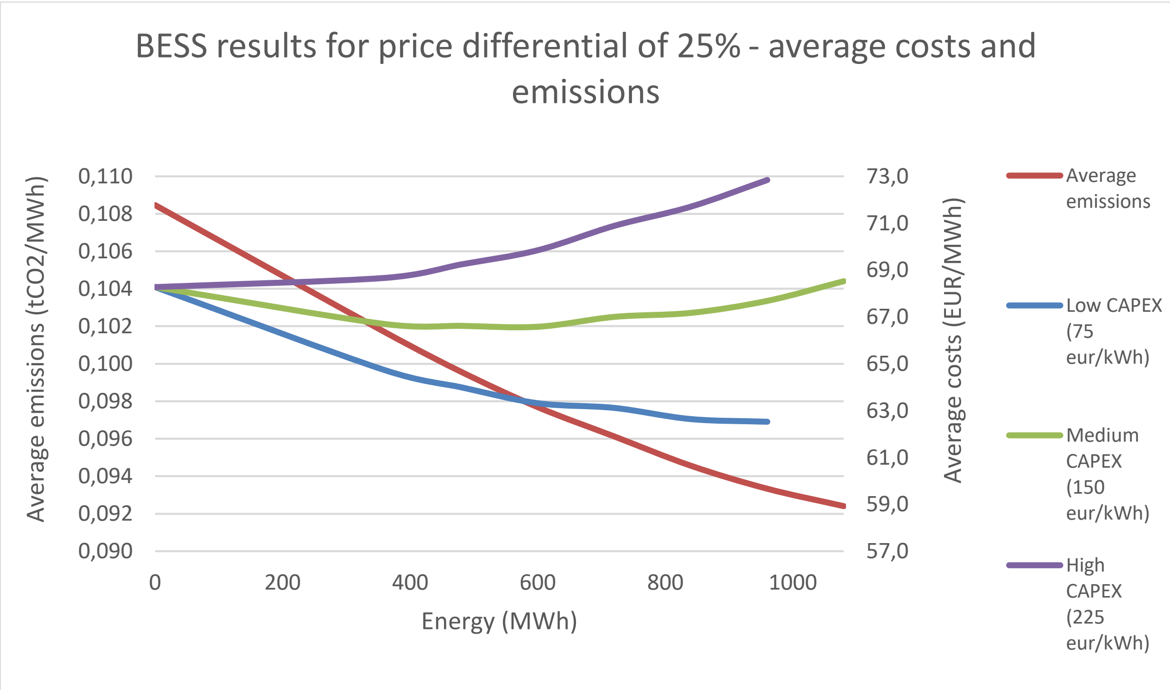


Figure 17. BESS results for price differential reduction of 25% - average costs and emissions

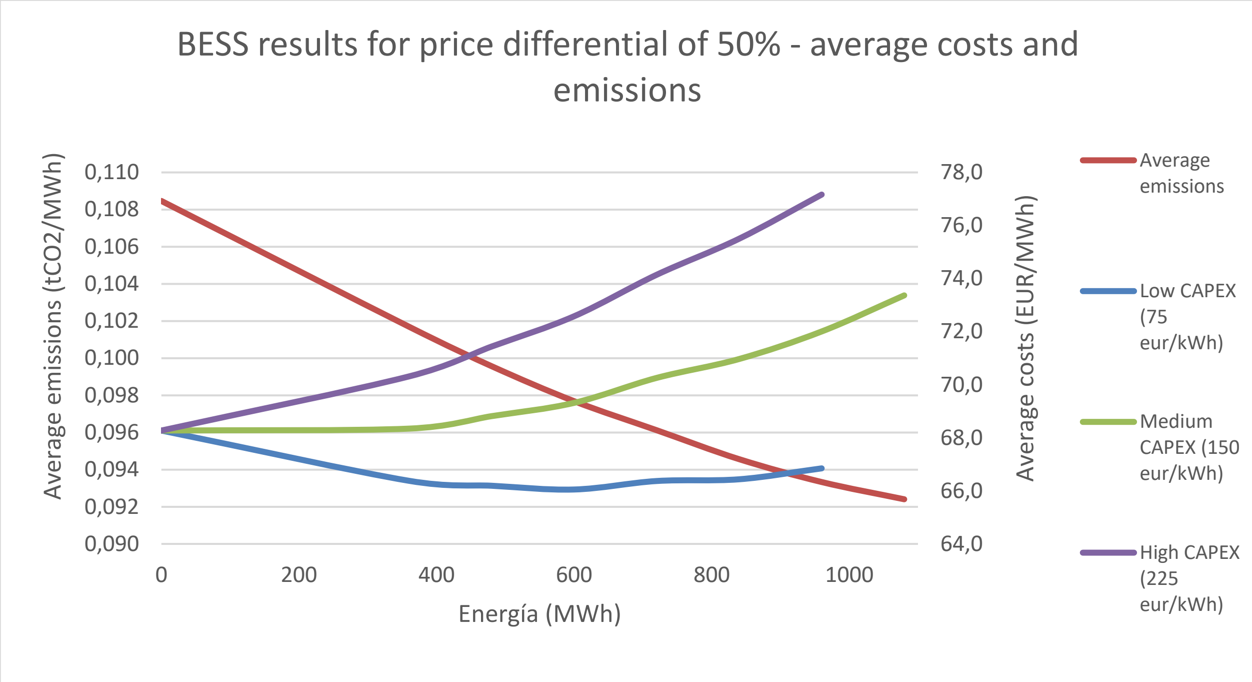


Figure 18. BESS results for price differential reduction of 50% - average costs and emissions

The first relevant result is that the BESS provides a much clearer emissions reduction than the TES. This is because the battery does not act only on the cooling demand, but on the total electricity consumption of the data center. While thermal storage can only shift part of the cooling-related electricity consumption, the BESS can reduce grid withdrawal during high-emission hours across the whole facility demand, including IT load, cooling and auxiliary consumption. As a result, the average emissions decrease from approximately 0.108 tCO_2/MWh in the baseline scenario to around 0.102 tCO_2/MWh for the 360 MWh BESS, and continue decreasing as battery size increases. In the largest scenario, the average emissions fall to around 0.092 tCO_2/MWh.

This confirms that the carbon-aware operation of the BESS is effective. By charging during hours with lower emissions intensity and discharging during hours with higher emissions intensity, the data center is able to reduce its induced emissions without reducing its useful electricity consumption. However, the emissions curve also shows that the reduction is not perfectly proportional to the increase in storage capacity. The first battery sizes capture the most valuable emissions-shifting opportunities, because they discharge during the most carbon-intensive hours of the representative days. As the BESS size increases, the additional stored energy has to be used in hours with a lower emissions differential. Therefore, the marginal emissions reduction per additional MWh of storage becomes progressively smaller.

This result is important because it shows that the largest battery is not necessarily the most reasonable solution, even if it achieves the highest absolute emissions reduction. From an environmental perspective, larger BESS capacities reduce more emissions, but the slope of the emissions curve becomes flatter. This indicates that there is a point beyond which additional storage still improves the result, but with decreasing marginal benefit. Therefore, the comparison should not be based only on total avoided emissions, but also on the economic cost required to achieve each additional reduction.

From an economic perspective, the interpretation depends strongly on the CAPEX assumption and on the expected evolution of the price differential. Figure 17 represents the conservative sensitivity case, in which the price differential decreases by 25% over the lifetime of the battery. In this case, the low CAPEX scenario shows a clear reduction in average cost for all battery sizes. This occurs because the operational savings obtained by charging during cheaper hours and discharging during more expensive hours are large enough to compensate for the annualized investment cost. Under this assumption, the BESS provides both environmental and economic benefits.

The medium CAPEX case in Figure 17 also remains relatively favorable, especially for the smaller and medium battery sizes. The average cost is below the baseline for the 360 MWh, 480 MWh and 600 MWh scenarios. However, as the battery becomes larger, the cost curve starts increasing. This means that, although larger batteries continue reducing emissions, the additional investment cost begins to offset the operational savings. The high CAPEX case shows the opposite result as the average cost is above the baseline from the first BESS size and increases as storage capacity grows. Therefore, under high investment cost assumptions, the BESS can still reduce emissions, but it would represent an additional cost for the data center.

Figure 18 shows the same comparison under a stronger reduction of the price differential. The emissions curve remains the same, since the dispatch of the battery is based on emissions and not on prices. However, the cost curves change significantly. When the price differential between charging and discharging hours becomes smaller, the operational saving from the BESS is reduced. This is because the battery charges and discharges with a lower economic spread, so each MWh shifted provides less cost benefit. As a result, the total economic attractiveness of the BESS decreases.

In this second sensitivity scenario, the low CAPEX case still remains below the baseline average cost for the smaller and medium BESS sizes, although the margin is much smaller than in the first sensitivity scenario. This suggests that, if battery investment costs fall sufficiently, BESS could still be economically acceptable even in a future electricity system with flatter price curves. However, the medium and high CAPEX cases become clearly less attractive. For medium CAPEX, the average cost is close to the baseline for the 360 MWh case but increases progressively for larger sizes. For high CAPEX, all battery sizes imply a significant increase in average cost compared with the baseline.

The comparison between Figure 17 and Figure 18 therefore highlights a key conclusion.The environmental value of the BESS is robust, but its economic value is highly sensitive to market conditions. The battery always reduces induced emissions because the model operates it according to hourly carbon intensity. However, whether this emissions reduction can be achieved without increasing the average cost of the data center depends on two factors: the investment cost of the battery and the persistence of sufficient price differences between low-price and high-price hours.

Overall, the BESS appears as a more powerful flexibility solution than TES from an emissions perspective, because it can act on the full electricity profile of the data center. Nevertheless, it also requires a much larger investment and its economic performance is more exposed to CAPEX assumptions and future price flattening. The most balanced configurations appear to be the smaller and medium-sized batteries, especially around 360–600 MWh, since they achieve a significant share of the emissions reduction while keeping the average cost close to or below the baseline under favorable or moderate CAPEX assumptions. Larger BESS capacities provide additional emissions reductions, but with lower marginal benefit and higher economic risk.

Therefore, the BESS should not be interpreted as a universally profitable solution for all data center configurations. Its value depends on the regulatory, economic and technical context in which it is deployed. If future regulation requires data centers to demonstrate flexibility or emissions reduction capability, BESS could be an effective option. However, imposing very large battery capacities could create disproportionate economic impacts unless battery costs decrease, price spreads remain sufficiently high, or additional value streams such as flexibility services, grid support or capacity-related benefits are considered. In this sense, the BESS results support the Pareto-oriented approach of the model. The objective is not to identify a single optimal battery size, but to understand which combinations of emissions reduction and economic impact are reasonable for a large data center.

Chapter 8. DISCUSSION OF RESULTS

This chapter discusses the modelling results from a technical, economic and regulatory perspective. The analysis is not intended to identify a single optimal configuration for a data center, but to interpret the results through a Pareto-oriented approach. This means assessing which flexibility options provide relevant emissions reductions and whether those reductions are achieved with an economic impact that could be considered reasonable for the data center operator. This interpretation is especially relevant if future regulation were to require data centers to incorporate flexibility, storage or emissions-reduction capabilities as part of their access or sustainability obligations.

8.1 DOES FLEXIBILITY ACTUALLY REDUCE EMISSIONS?

The results obtained in the modelling chapter show that including energy storage systems can reduce the induced emissions of a data center, but only under specific operating conditions. The reduction is not achieved because the data center consumes less electricity in annual terms, but because part of its consumption is shifted from hours with higher emissions intensity to hours with lower emissions intensity. Therefore, the incorporation of energy storage can provide environmental value by shifting electricity consumption towards lower-emission hours. The relevant question is not whether this benefit exists, but under which capacity ranges, operating strategies and system scenarios storage remains an efficient and proportionate measure in relation to the environmental objective pursued.

The magnitude of the reduction depends strongly on the type of flexibility considered. Thermal energy storage provides a limited reduction because it can only act on the cooling component of the data center demand and the IT load and the remaining auxiliary consumption remain unchanged. As a result, TES can improve the emissions profile of the facility, but its effect is bounded by the amount of cooling demand that can be shifted and by the thermal constraints of the system.

By contrast, the BESS achieves a larger reduction because it acts on the total net electricity demand of the data center. The battery can charge during lower-emission hours and discharge during higher-emission hours, reducing grid consumption when the electricity mix is more carbon intensive. Even though the battery introduces additional consumption due to round-trip efficiency losses, the results show that the emissions benefit of shifting electricity to cleaner hours compensates for these losses and slight increase in energy consumption.

The results also suggest that the emissions reduction follows a pattern of decreasing marginal returns. The first storage capacities are able to capture the most favorable hourly differences between high-emission and low-emission periods. However, as storage capacity increases, the additional energy shifted tends to involve hours with a lower emissions differential. For this reason, larger storage sizes still reduce emissions, but the additional benefit obtained from each extra unit of capacity becomes progressively smaller. This is particularly relevant for interpreting the largest BESS scenarios, which should be understood as sensitivity cases rather than direct design recommendations.

Therefore, the results show that battery storage can be one of the main tools available to data centers to respond to potential regulatory obligations related to emissions reduction and to increasing the temporal correlation between their electricity consumption and renewable generation. The data center does not become a fully decarbonized consumer, but storage allows part of its net demand to be shifted towards hours with lower carbon intensity or greater renewable availability without requiring an equivalent modification of the underlying IT workload.

This distinction is particularly relevant because the natural flexibility of data center operations is relatively limited. Data centers rely on IT equipment, particularly processors and servers, that becomes technologically obsolete within relatively short periods. To recover this investment efficiently, operators seek to maintain high utilization rates throughout the useful life of the equipment. Energy storage provides an external source of flexibility that can reconcile this relatively rigid operating profile with the needs of an electricity system characterized by a high penetration of variable renewable generation.

From a regulatory perspective, the relevant uncertainty is not whether storage can provide environmental and system benefits, but whether the available solutions remain economically competitive under different battery cost trajectories and regulatory requirements. The future evolution of battery investment costs remains uncertain, while larger or more demanding storage obligations may impose significant additional costs on data center projects. Consequently, the intensity of any regulatory requirement concerning emissions reduction or renewable matching should take into account the economic competitiveness of the technologies available to comply with it. Such requirements should therefore be designed according to a proportionate balance between the environmental or system benefits pursued and the cost of the storage capacity required from the data center.

8.2 WHICH SOLUTION PROVIDES MORE VALUE: BESS, THERMAL STORAGE, OR LOAD MANAGEMENT?

The comparison between BESS, thermal storage and load management shows that the value of flexibility depends on the criterion used to assess it. If the objective is to maximize emissions reduction, the BESS provides the highest value among the options analysed in the model. This is because it can act on the total net electricity demand of the data center, instead of being limited to one specific subsystem. By charging during lower-emission hours and discharging during higher-emission hours, the battery modifies the overall load profile of the facility and achieves a larger reduction in induced emissions than thermal storage.

However, this higher environmental value comes with a higher economic and technical burden. BESS requires a significant investment and its economic performance depends strongly on battery CAPEX and on the price differences between charging and discharging hours. If price spreads decrease over time, the operational savings obtained from the battery are reduced, while the annualized investment cost remains. Therefore, BESS can be considered the most effective flexibility option from an emissions perspective, but not necessarily the most robust option from an economic perspective.

Thermal energy storage provides a more limited but also more targeted form of flexibility. Its main advantage is that it acts on the cooling system without directly modifying the IT load, which makes it less intrusive from an operational point of view. This is relevant for data centers, where service continuity remains the main priority. However, its impact is necessarily bounded because cooling represents only one part of total electricity consumption. In addition, the amount of cooling that can be shifted depends on outdoor temperature, free cooling availability, storage size and minimum cooling requirements.

This explains why the value of TES is strongly dependent on the climatic conditions of the location. In warmer climates, such as Sevilla, cooling demand is higher and free cooling availability is lower, which increases the amount of cooling consumption that can potentially be shifted. As a result, thermal storage becomes more useful in high-temperature locations than in milder locations such as Madrid. Even so, its contribution remains limited to the cooling subsystem and cannot modify the full electricity profile of the data center.

For this reason, TES should not be interpreted as the main decarbonization solution for data centers, but as a complementary measure that can reduce part of the emissions impact with lower operational interference. Its value is therefore more specific and context-dependent than that of BESS. It can be useful when cooling demand is high and when investment costs remain within a reasonable range, but its overall impact is structurally lower because it cannot act on the IT load or on the full facility demand.

Load management represents a different type of flexibility. Unlike BESS or TES, it does not require shifting energy through a physical storage system, but through the rescheduling or relocation of computational tasks. In principle, this could provide significant value, especially for delay-tolerant workloads such as batch processing, backups, data analytics or certain AI training tasks. However, its practical implementation is highly dependent on the type of data center, the workload mix, latency requirements, contractual obligations and the degree of control that the operator has over the IT load. For this reason, workload shifting is conceptually relevant but more difficult to generalize and quantify.

Overall, the results suggest that there is no single flexibility solution that provides the highest value under all criteria. Nevertheless, for the objective of this thesis, BESS appears as the most attractive option in general terms. It provides the greatest measurable emissions reduction, it can operate throughout the year and it acts on the total net demand of the data center rather than on a specific subsystem. Its main drawback is the higher investment cost and its sensitivity to future electricity price spreads.

Thermal storage provides a smaller but more operationally conservative contribution, especially useful as a complementary solution linked to cooling demand and more valuable in warmer locations. Load management could offer an additional source of flexibility, but its value depends on operational information that is not publicly available and has not been modelled in this thesis.

Therefore, the most reasonable interpretation is that BESS is the most relevant flexibility option among those assessed, while TES and load management should be understood as complementary mechanisms that could increase the flexibility potential of the facility under specific conditions.

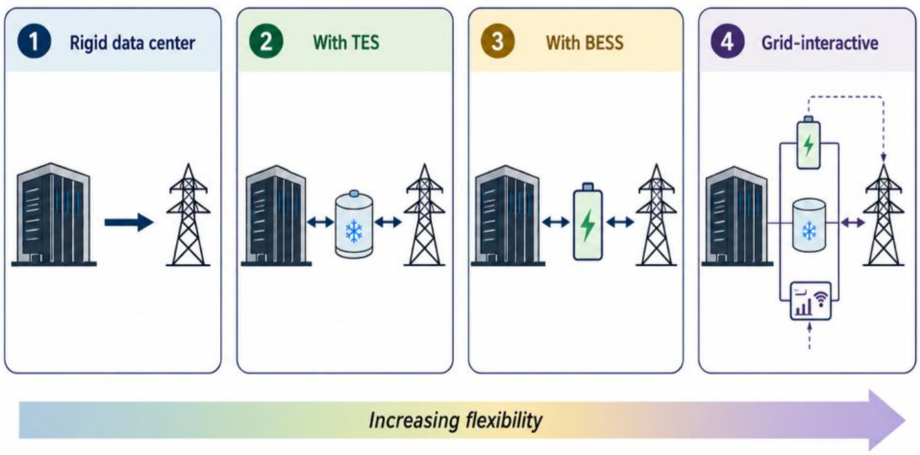


Figure 19. Types of flexible configurations (Source: generated with AI)

From a regulatory perspective, this means that flexibility obligations should not necessarily prescribe a single technology. BESS provides the highest measurable emissions reduction in the model, but it also creates the highest economic exposure. TES provides a smaller but less intrusive contribution, while load management may be relevant only for certain workload types. Therefore, a future regulatory framework should focus on the flexibility outcome that the data center can provide, rather than imposing the same technical solution on all projects. The Pareto approach helps identify which combinations of technology, size and cost can provide a reasonable balance between system benefit and economic burden.

8.3 CAN FLEXIBILITY IMPROVE THE INTEGRATION OF DATA CENTERS IN THE ELECTRIC POWER SYSTEM?

The integration of data centers into the electricity system is not only a question of accommodating their annual electricity consumption. Their system impact also depends on the amount of capacity requested, the location of the connection, the timing of consumption and the ability of the facility to adapt part of its demand to changing system conditions. In Spain, these aspects are particularly relevant because the rapid growth of large electricity demand is taking place in a context of increasing pressure on grid access capacity, renewable deployment and emerging sustainability requirements. For this reason, data centers are not assessed only as digital infrastructure, but also as large electricity consumers whose connection and operation must be compatible with the objectives and constraints of the electricity system.

The results of the model show that flexibility can improve this integration, although only partially. A data center with flexible resources remains a large electricity consumer and continues to require significant access capacity. However, if part of its demand can be shifted from higher-emission hours to lower-emission hours or higher renewable availability, the facility can adapt part of its net grid withdrawal to the time-varying conditions of the electricity system. In this sense, flexibility does not eliminate the energy impact of the data center, but it can reduce part of the negative impact associated with the timing of its consumption.

This is relevant because flexibility changes the way data centers can be interpreted from a system perspective. Instead of being seen only as rigid loads that increase electricity demand continuously, they can be presented as consumers capable of adapting part of their operation to system conditions.

The contribution of flexibility can be observed in different ways. First, it can reduce the hourly impact of the data center on the electricity mix by avoiding consumption during more carbon-intensive hours. Second, it can support a more efficient integration of renewable generation by shifting demand towards hours with higher renewable availability or lower emissions intensity. Third, if combined with flexible access schemes or demand response mechanisms, it could help reduce grid withdrawal during selected critical periods. Therefore, flexibility does not make the data center neutral from an energy perspective, but it can make its operation more compatible with the needs of the power system.

An important implication of the results concerns the temporal granularity required to obtain these benefits. The objective of flexibility should not necessarily be interpreted as requiring a data center to match its electricity consumption with renewable generation on a strict hour-by-hour basis. The BESS analysis shows that relevant improvements are already obtained with storage durations that shift electricity over periods of several hours, while progressively larger storage capacities provide diminishing additional benefits. This is particularly relevant in a power system with substantial solar generation, where periods of high photovoltaic availability and potential surplus generation are often concentrated within windows of approximately four to six hours per day, depending on the season. Therefore, a significant share of the system benefit may already be captured by allowing flexible consumption to be concentrated within these multi-hour periods, rather than requiring perfect matching in every individual hour.

The increase in grid withdrawal during storage charging should also be interpreted in relation to when that additional demand occurs. In the scenarios analysed, BESS and TES shift part of the consumption towards central hours of the day, when solar generation is generally more abundant and the share of emitting generation is lower. Therefore, the charging peak created by storage is not equivalent, from a system perspective, to an identical increase in demand during more critical periods. However, this does not imply that charging during solar hours is always beneficial, since the local impact still depends on the conditions of the connection point and any existing network constraints.

The different flexibility options contribute to this objective in different ways. BESS provides the most direct contribution because it can act on the total net electricity demand of the facility and reduce grid withdrawal during selected high-emission hours. Thermal storage offers a more limited contribution because it only affects cooling demand, but it can still improve integration by shifting part of the refrigeration load. Load management could provide an additional layer of flexibility if delay-tolerant workloads can be rescheduled or relocated, although this depends strongly on the type of data center and its operational constraints.

This discussion is also connected with the regulatory direction introduced by RDL 7/2026. If future data center requirements include sustainability criteria, renewable additionality, hourly matching, efficient use of resources or compatibility with the grid, flexibility may become a useful tool to improve both regulatory acceptability and system integration. In that context, the value of TES, BESS or workload management is not only that they reduce emissions or costs, but that they help demonstrate that the data center can contribute to a more responsible use of the electricity system.

Therefore, flexibility should not be interpreted as a complete solution to the concerns associated with data center deployment. It does not remove the need for grid capacity, network reinforcement, renewable procurement or environmental requirements. However, the results suggest that the integration of data centers should not be approached as a binary choice between completely rigid demand and strict hour-by-hour adaptation. Intermediate levels of temporal flexibility may already capture a significant part of the potential system benefit. The relevant question for future regulation is therefore not only whether data centers should be flexible, but how much temporal flexibility is necessary to achieve meaningful renewable integration and emissions benefits without imposing disproportionate technical or economic requirements on the operator.

8.4 TECHNICAL, ECONOMIC AND REGULATORY CONSIDERATIONS

The results should be interpreted within the technical, economic and regulatory assumptions of the model. However, these limitations do not change the main contribution of the analysis. The results show that BESS and, to a lesser extent, TES can be used not only to reduce induced emissions, but also to modify the temporal profile of data center electricity demand. This capability may become particularly relevant if future regulation requires large data centers to demonstrate emissions reductions, sustainability performance or a greater temporal correlation between electricity consumption and renewable generation.

8.4.1 TECHNICAL LIMITATIONS

The model includes several technical simplifications that define the scope of the results. The IT load has been considered constant and non-flexible, meaning that the potential contribution of workload shifting is not quantified. TES is limited to the cooling component of the data center demand and is constrained by minimum cooling requirements and thermal operating conditions. BESS can act on the total net electricity demand, but the model does not include detailed battery degradation, replacement requirements, cycling constraints or operational strategies that preserve part of the battery capacity for backup and resilience purposes.

The model is also designed to assess hourly energy shifting rather than to reproduce all operational conditions of a real data center or electricity network. It is based on twelve representative days instead of the full 8,760 hours of the year and does not include nodal congestion or specific local constraints at the connection point. Similarly, it does not reproduce fast dynamic phenomena such as voltage dips, UPS switching or reconnection behaviour. Therefore, the results quantify the potential for temporal load adaptation, emissions reduction and cost variation, but they should not be interpreted as a complete operational or grid-stability assessment of a specific data center.

8.4.2 Economic limitations

The economic results should be interpreted as scenario-dependent rather than as a complete business case. The value of BESS depends strongly on both investment costs and the difference between charging and discharging prices. If storage deployment increases across the electricity system, price spreads may decrease as the electricity price curve becomes flatter, reducing the future value of arbitrage even if the technical capability of the battery to shift demand remains unchanged. Similarly, the results show that the configuration achieving the highest emissions reduction is not necessarily the most economically efficient, particularly when larger storage capacities produce diminishing marginal benefits while requiring substantially higher investment.

The cost assessment also excludes several elements that may affect the actual economic performance of a data center, including bilateral electricity contracts, hedging strategies, guarantees of origin, taxes, supplier margins, imbalance costs and potential revenues from ancillary services or other flexibility mechanisms. The economic results should therefore be understood as a comparative assessment of the different flexibility scenarios under common assumptions, rather than as a final investment decision.

8.4.3 Regulatory implications and limitations

The regulatory limitations are also relevant, especially in the regulatory evolution initiated by RDL 7/2026. At the time of this thesis, the future requirements for data centers under RDL 7/2026 have not yet been fully defined, and it is still uncertain how flexibility will be valued in access permits, demand capacity tenders or sustainability requirements.

In future sustainability requirements, flexibility could be assessed as a way to improve hourly renewable matching, reduce induced emissions or demonstrate a more efficient use of electricity system resources.

However, none of these applications is yet fully defined. It is not clear whether future regulation will reward the mere installation of flexible assets, such as BESS or TES, or whether it will require actual operational commitments, hourly matching evidence or participation in specific flexibility mechanisms. This distinction is relevant because a data center may include storage capacity in its design, but this does not necessarily mean that the storage will be operated in a way that supports the electricity system. For flexibility to have regulatory value, it must therefore be measurable, controllable and verifiable. A theoretical ability to shift demand is not sufficient if the system operator or the administration cannot rely on that flexibility under real operating conditions.

An especially relevant question is the temporal granularity of any future requirement intended to improve the correlation between data center consumption and renewable generation. A strict hourly matching requirement would provide a high level of temporal correlation, but it could also require greater storage capacity and impose additional operational and economic constraints on data center operators. The results of this thesis suggest that meaningful benefits can already be obtained with flexibility durations of several consecutive hours and that progressively larger storage capacities provide diminishing additional benefits. This is particularly relevant because periods of high solar availability and potential surplus generation are typically concentrated within multi-hour windows of approximately four to six hours per day, depending on the season.

Therefore, improving temporal correlation with renewable generation does not necessarily imply that every unit of electricity consumed by the data center must be matched with renewable generation in every individual hour. Broader multi-hour matching windows could provide an intermediate approach, allowing flexible demand to be concentrated during periods of high renewable availability while reducing the operational burden associated with strict hour-by-hour compliance. The model does not directly optimize the duration of a future regulatory matching window and therefore cannot identify a single optimal level of temporal granularity. Nevertheless, the results suggest that the regulatory discussion should consider whether part of the intended system benefit can be achieved with a less restrictive temporal requirement.

Overall, these limitations do not invalidate the results, but they define how they should be interpreted. The model shows that flexibility has potential to reduce induced emissions and to improve the system compatibility of data centers. However, this potential should not be understood as a universal guarantee of profitability, regulatory acceptance or technical feasibility. Its value depends on the specific technology, location, cost assumptions, operational constraints and future regulatory framework.

These limitations are important when interpreting the results as a possible basis for future regulation. The model shows that flexibility can reduce emissions, but it also shows that the economic impact depends strongly on CAPEX assumptions, electricity price spreads and the size of the storage system. For this reason, regulatory obligations should avoid imposing very large flexibility requirements without considering proportionality. A more appropriate approach would be to define ranges or performance-based requirements, allowing data centers to demonstrate that they can provide a certain level of emissions reduction, demand shifting or flexible capacity without compromising service continuity or creating excessive costs.

Chapter 9. CONCLUSIONS

9.1 ROLE OF DATA CENTERS IN THE SPANISH ELECTRICITY SYSTEM

Data centers are becoming strategic infrastructures for digitalization, cloud services, artificial intelligence and digital sovereignty. However, their deployment also introduces a relevant challenge for the electricity system, since they represent large and concentrated electricity demand. One of the main conclusions of this thesis is that the concern associated with data center consumption cannot be understood only through annual electricity demand or maximum power, but also through when that electricity is consumed and how the resulting demand profile interacts with the conditions of the electricity system.

The modelling results show that this temporal dimension is particularly important. Although the IT load remains constant, the total electricity consumption of the data center is not completely flat throughout the year, since cooling demand increases with temperature. As a result, the highest consumption levels occur during the warmer months and particularly during the central hours of the day. However, these hours currently coincide in Spain with periods of high photovoltaic production. Therefore, the maximum electricity demand of the data center is not necessarily the period of greatest concern from the perspective analysed in this thesis.

The main concern is associated with the persistence of a high electricity demand of the data center outside these solar-rich periods. During morning and especially evening peak periods, this large demand may coincide with more demanding conditions and stress for the electricity system. During purely night-time hours, the concern is different. Although they do not necessarily represent the most critical periods for the grid, renewable availability is lower and the average emissions intensity is higher. Therefore, the impact of data center consumption depends not only on how much electricity is consumed, but also on when it is consumed and on its potential effect on emissions and electricity prices during specific periods.

The results show that flexibility can mitigate part of this temporal mismatch as flexibility can reduce induced emissions when the operation is based on hourly emissions signals. The reduction in induced emissions does not come mainly from lowering the total annual electricity consumption of the facility, but from shifting part of that consumption from higher-emission periods towards hours with greater renewable availability. Therefore, the model shows that the temporal profile of consumption is itself a relevant variable as the same amount of electricity can have a different emissions impact depending on when it is withdrawn from the grid.

Thermal energy storage and BESS have shown to provide different levels of flexibility. TES is a complementary solution because it only affects the cooling component of the load and its impact is limited by cooling demand, ambient temperature, free cooling availability and storage size. BESS has a broader effect because it can act on the total net electricity demand of the data center, which explains its higher emissions reduction potential. In particular, the BESS results show that electrochemical storage can shift part of the persistent electricity demand of the data center away from higher-emission periods and towards the central hours of the day, when renewable generation is generally more abundant. However, increasing storage capacity produces diminishing marginal benefits: larger batteries continue to reduce emissions, but the additional improvement becomes progressively smaller.

An additional conclusion concerns the temporal granularity required to obtain these benefits. The results suggest that improving the correlation between data center consumption and renewable generation does not necessarily require strict hour-by-hour matching. Periods of high solar availability in Spain are generally concentrated within relatively limited windows, typically around four to six hours per day depending on the season. Therefore, a significant part of the intended benefit could potentially be achieved by shifting flexible consumption towards these multi-hour periods, rather than by requiring perfect matching in every individual hour. This distinction may become particularly relevant if future sustainability requirements for data centers include criteria related to emissions reduction, renewable additionality or temporal correlation between consumption and renewable generation.

The economic viability of these strategies depends strongly on the cost of storage. The model demonstrates the technical capability of BESS to shift demand and reduce induced emissions, but its economic attractiveness remains highly dependent on CAPEX and on the future evolution of electricity price differentials. Moreover, the economic balance becomes less favorable as storage capacity increases and the additional emissions reductions become progressively smaller. Therefore, if future regulation were to require data centers to meet specific sustainability or temporal-flexibility objectives, the level of the requirement should consider the trade-off between the additional environmental benefit obtained and the economic cost of the technology required to achieve it. The objective should not necessarily be to impose the maximum technically achievable level of flexibility, but to identify requirements that provide meaningful sustainability benefits without creating a disproportionate economic burden for the data center operator.

This trade-off is one of the main contributions of the Pareto-oriented approach adopted in this thesis. The results do not identify a single optimal BESS size or define the appropriate level of a future regulatory obligation. However, they show that the proportionality of any potential requirement would depend strongly on the evolution of storage costs. As BESS CAPEX decreases, higher levels of flexibility may become economically more accessible, whereas requirements that could be reasonable under future technology costs may still be disproportionate under current conditions. Therefore, the evolution of the cost of the available technologies should be considered together with the sustainability benefit pursued.

In addition to emissions-based shifting, the technical characteristics of BESS have shown to be more eligible to support flexible access schemes. A data center with battery capacity can temporarily reduce its withdrawal from the grid during restrictions, contingencies or critical operating conditions, while maintaining part of its internal supply for a limited period. This can make flexible access more technically feasible, especially in constrained areas where full firm capacity is not immediately available. Once installed, the same battery could also potentially participate in demand-management mechanisms or provide other flexibility services, subject to the applicable technical and regulatory conditions. These additional capabilities are relevant because the value of the investment should not be assessed only through the emissions reduction quantified in the model. These additional applications have not been directly quantified in the model, but they reinforce the broader value of storage as a flexibility resource.

This is particularly relevant for future regulation. If data centers are required to contribute to decarbonization, renewable integration or flexible grid access, the requirements should be designed with proportionality. A flexibility obligation should be high enough to provide measurable system value, but not so high that it creates an excessive burden for the data center operator. The results of this thesis suggest that smaller and medium flexibility configurations may provide a more balanced solution than very large storage capacities, because they capture a significant part of the emissions reduction while limiting the increase in average cost.

More generally, future sustainability requirements should be assessed together with the technical capabilities and costs of the solutions available to comply with them. The relevant trade-off is therefore not simply between flexibility and no flexibility, but between the additional sustainability benefit obtained, the temporal requirement imposed and the economic cost required to achieve it.

Overall, data centers will continue to be large electricity consumers and will still require grid capacity and connection infrastructure Flexibility does not eliminate these needs, but it changes the way data centers can be integrated into the electricity system. A data center with verifiable flexibility can reduce induced emissions, adapt part of its demand to more favorable system hours and potentially support flexible access schemes. Therefore, the main conclusion is not simply that data centers can be flexible or that batteries can reduce emissions. The analysis shows that the concern associated with data center demand depends strongly on its temporal profile and that storage can partially correct the mismatch between persistent electricity consumption and renewable availability. From a future regulatory perspective, this implies that any sustainability or flexibility requirement should consider not only the environmental objective pursued, but also the temporal granularity required to achieve it, the technical means available for compliance and their economic cost. For this reason, the future integration of data centers in Spain should not be based only on how much electricity they consume, but on when that demand occurs, how much of it can be shifted and at what cost.

9.2 FUTURE RESEARCH LINES

This thesis provides a simplified but useful framework to assess the flexibility potential of data centers. However, several aspects could be developed in future research.

First, the model could be extended to the full 8,760 hours of the year instead of using twelve representative days. This would allow a more accurate representation of extreme events, heat waves, very low or very high renewable generation periods, and short-term price and emissions variability.

Second, future work could include real grid constraints and nodal congestion signals. This would make it possible to assess not only whether flexibility reduces emissions at system level, but also whether it helps relieve constraints in specific connection points. In this context, it would also be relevant to compare different Spanish locations, such as Madrid, Aragón, Sevilla or areas with high solar photovoltaic generation. This geographical comparison would allow the analysis to capture differences in cooling demand, renewable availability, grid congestion and the value of shifting consumption towards solar hours.

Third, the economic analysis of BESS could be further developed. Future studies could include battery degradation, equivalent cycles, real electricity contracts, hedging strategies and potential revenues from flexibility services. This would provide a more complete view of whether BESS can be economically justified beyond the reduction of induced emissions.

Fourth, future research should analyse concrete regulatory schemes for flexible access applied to data centers. This would require defining how much of the requested capacity should be firm or flexible, how reductions would be activated, how compliance would be verified, and how batteries or other internal flexibility resources could support these obligations.

Also, future research should further develop this Pareto-oriented approach by analysing more detailed regulatory thresholds for data center flexibility. This would include assessing different definitions of mandatory flexible capacity, minimum storage requirements, emissions-reduction obligations or performance-based indicators. Future work should also evaluate whether these requirements should depend on the size of the data center, its location, the level of grid congestion, the availability of renewable generation and the type of workloads hosted by the facility. This would make it possible to move from a general discussion on data center flexibility towards more specific regulatory ranges that are technically feasible, economically proportionate and useful for the electricity system.

Finally, a further research line would be the dynamic modelling of data centers as large power-electronics-based loads to analyze the behavior of data centers during voltage dips, UPS disconnection and reconnection, fast load ramps, harmonic distortion and forced oscillations. This would make it possible to connect the emissions-oriented flexibility analysis with a complete grid- stability assessment.

Future research could also study whether BESS, UPS systems or workload-management strategies can be used to smooth AI-driven power fluctuations without compromising the reliability of the data center. This would be especially relevant for AI-oriented hyperscale campuses, where synchronized GPU workloads may create fast and structured variations in electricity demand.

Overall, these future research lines would allow the analysis to move from a simplified emissions-oriented model towards a more complete assessment of data center flexibility, combining hourly operation, territorial differences, grid constraints, economic feasibility and regulatory implementation.

Chapter 10. BIBLIOGRAPHY

[1] SpainDC and Pb7 Research, *Informe Anual 2025 sobre el Sector de los Centros de Datos en España: Situación Actual y Perspectivas para 2030*. SpainDC, 2026.

[2] European Data Centre Association, *State of European Data Centres 2026*. EUDCA, 2026.

[3] O. Lobera Segurado, *Centros de Datos en Aragón: Impacto Socioeconómico*. Fundación Basilio Paraíso, 2025.

[4] Jefatura del Estado, "Real Decreto-ley 7/2026, de 20 de marzo, por el que se aprueba el Plan Integral de Respuesta a la Crisis en Oriente Medio," *Boletín Oficial del Estado*, no. 71, Mar. 2026.

[5] ENTSO-E, *Data Centres and the Power System: Expected Trends, Challenges and Opportunities*. ENTSO-E, 2026

[6] E. Ginzburg-Ganz, P. Lifshits, R. Machlev, J. Belikov, Z. Krieger, and Y. Levron, 'Technical Challenges of AI Data Center Integration into Power Grids—A Survey', *Energies*, vol. 19, no. 1, p. 137, Dec. 2025, doi: 10.3390/en19010137.

[7] Ministerio para la Transición Ecológica y el Reto Demográfico, "Real Decreto 1183/2020, de 29 de diciembre, de acceso y conexión a las redes de transporte y distribución de energía eléctrica," *Boletín Oficial del Estado*, no. 340, Dec. 2020.

[8] Colliers, *Data Center Snapshot: Iberian Region, October 2025–March 2026*. Colliers, 2026. Accessed: Jun. 23, 2026. [Online]. Available: https://www.colliers.com/-/media/files/emea/spain/2026/colliers_dc_snapshot_oct25_mar26_.ashx

[9] European Commission, "Commission Regulation (EU) 2016/1388 of 17 August 2016 establishing a Network Code on Demand Connection," *Official Journal of the European Union*, 2016.

[10] International Energy Agency, "Energy demand from AI," in *Energy and AI*. IEA, 2025. Accessed: Jun. 04, 2026. [Online]. Available: https://www.iea.org/reports/energy-and-ai/energy-demand-from-ai

[11] Central Statistics Office, *Data Centres Metered Electricity Consumption 2024*. CSO, 2025. Accessed: Jun. 04, 2026. [Online]. Available: https://www.cso.ie/en/releasesandpublications/ep/p-dcmec/datacentresmeteredelectricityconsumption2024

[12] Central Statistics Office, "Key findings," *Data Centres Metered Electricity Consumption 2024*. CSO, 2025. Accessed: Jun. 04, 2026. [Online]. Available: https://www.cso.ie/en/releasesandpublications/ep/p-dcmec/datacentresmeteredelectricityconsumption2024/keyfindings

[13] Commission for Regulation of Utilities, *Large Energy User Connection Policy: Decision Paper*, CRU/2025/236. CRU, 2025. Accessed: Jun. 04, 2026. [Online]. Available: https://cruie-live-96ca64acab2247eca8a850a7e54b-5b34f62.divio-media.com/documents/CRU2025236_Large_Energy_User_connection_policy_decision_paper.pdf

[14] European Commission, "Commission Delegated Regulation (EU) 2024/1364 of 14 March 2024 on the first phase of the establishment of a common Union rating scheme for data centres," *Official Journal of the European Union*, 2024.

[15] European Commission, "Energy performance of data centres," *European Commission*, 2026. Accessed: Jun. 04, 2026. [Online]. Available: https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficiency-targets-directive-and-rules/energy-efficiency-directive/energy-performance-data-centres_en

[16] Monitor Deloitte, *La contribución de la energía nuclear a la competitividad industrial en España*. Monitor Deloitte, 2026.

[17] Comisión Nacional de los Mercados y la Competencia, *Memoria justificativa de la Circular por la que se establece la metodología y condiciones del acceso y de la conexión a las redes de transporte y distribución de las instalaciones de demanda de energía eléctrica*. CNMC, 2024.

[18] K.-B. Kwon, S. Mukherjee, and V. Adetola, 'Operational Risks in Grid Integration of Large Data Center Loads: Characteristics, Stability Assessments, and Sensitivity Studies', Oct. 28, 2025, *arXiv*: arXiv:2510.05437. doi: 10.48550/arXiv.2510.05437.

[19] M.-S. Ko and H. Zhu, 'Wide-Area Power System Oscillations from Large-Scale AI Workloads', Apr. 20, 2026, *arXiv*: arXiv:2508.16457. doi: 10.48550/arXiv.2508.16457.

[20] A. Jimenez-Ruiz and F. Milano, 'Data Center Model for Transient Stability Analysis of Power Systems', May 22, 2025, *arXiv*: arXiv:2505.16575. doi: 10.48550/arXiv.2505.16575.

[21] Jefatura del Estado, "Ley 24/2013, de 26 de diciembre, del Sector Eléctrico," *Boletín Oficial del Estado*, no. 310, Dec. 2013.

[22] Comisión Nacional de los Mercados y la Competencia, "Circular 1/2024, de 27 de septiembre, por la que se establece la metodología y condiciones del acceso y de la conexión a las redes de transporte y distribución de las instalaciones de demanda de energía eléctrica," *Boletín Oficial del Estado*, 2024.

[23] Comisión Nacional de los Mercados y la Competencia, "Resolución de 1 de diciembre de 2025 por la que se establecen las especificaciones de detalle para la determinación de la capacidad de acceso de la demanda a las redes de transporte de electricidad," *Boletín Oficial del Estado*, no. 296, Dec. 2025.

[24] Comisión Nacional de los Mercados y la Competencia, *Trámite de audiencia sobre la propuesta de Resolución por la que se modifica la Resolución de 1 de diciembre de 2025 relativa a las especificaciones de detalle para la determinación de la capacidad de acceso de la demanda a las redes de transporte de electricidad*, RDC/DE/008/25. CNMC, 2026.

[25] Y. Sheng *et al.*, 'Power for AI Data Centers: Energy Demand, Grid Impacts, Challenges and Perspectives', *Energies*, vol. 19, no. 3, p. 722, Jan. 2026, doi: 10.3390/en19030722.

[26] Secretaría de Estado de Energía, "Resolución de 11 de julio de 2025 por la que se convocan los concursos de capacidad de acceso de demanda en determinados nudos de la red de transporte," *Boletín Oficial del Estado*, no. 171, Jul. 2025.

[27] European Parliament and Council of the European Union, "Directive (EU) 2023/1791 of 13 September 2023 on energy efficiency and amending Regulation (EU) 2023/955," *Official Journal of the European Union*, 2023.

[28] European Commission. Directorate General for Energy., EY., AIT., and Borderstep., *Assessment of the energy performance and sustainability of data centres in EU: first technical report.* LU: Publications Office, 2025. doi: 10.2833/3168794.

[29] V. D. Reddy, B. Setz, G. S. V. R. K. Rao, G. R. Gangadharan, and M. Aiello, 'Metrics for Sustainable Data Centers', *IEEE Trans. Sustain. Comput.*, vol. 2, no. 3, pp. 290–303, Jul. 2017, doi: 10.1109/TSUSC.2017.2701883.

[30] European Commission. Joint Research Centre., *Energy consumption in data centres and broadband communication networks in the EU.* LU: Publications Office, 2024. doi: 10.2760/706491.

[31] F. Brocklehurst, *International Review of Energy Efficiency in Data Centres*. IEA EBC Building Energy Codes Working Group, 2022.

[32] BloombergNEF, Eaton, and Statkraft, *Data Centers and Decarbonization: Unlocking Flexibility in Europe's Data Centers*. BloombergNEF, Eaton, and Statkraft, 2021.

[33] Electric Power Research Institute, *Powering Intelligence: Analyzing Artificial Intelligence and Data Center Energy Consumption*. EPRI, 2024.

[34] M. Dayarathna, Y. Wen, and R. Fan, 'Data Center Energy Consumption Modeling: A Survey', *IEEE Commun. Surv. Tutor.*, vol. 18, no. 1, pp. 732–794, 2016, doi: 10.1109/COMST.2015.2481183.

[35] C. Crozier and M. Liska, 'The Potential of Data Center Energy Demand To Provide Grid Flexibility', *Curr. Sustain. Energy Rep.*, vol. 12, no. 1, p. 12, Apr. 2025, doi: 10.1007/s40518-025-00258-9.

[36] Z. G. M. Setyo, H. B. Rijal, N. Aqilah, and N. Abdullah, 'Energy Efficiency Measurement Method and Thermal Environment in Data Centers—A Literature Review', *Energies*, vol. 18, no. 14, p. 3689, Jul. 2025, doi: 10.3390/en18143689.

[37] J. H. Kim, D. U. Shin, and H. Kim, 'Data Center Energy Evaluation Tool Development and Analysis of Power Usage Effectiveness with Different Economizer Types in Various Climate Zones', *Buildings*, vol. 14, no. 1, p. 299, Jan. 2024, doi: 10.3390/buildings14010299.

[38] O. Van Geet and D. Sickinger, 'Best Practices Guide for Energy-Efficient Data Center Design', NREL/TP--5R00-89843, DOE/GO--102024-6283, 2417618, Jul. 2024. doi: 10.2172/2417618.

[39] C. R. Knittel, J. R. L. Senga, and S. Wang, "Flexible Data Centers and the Grid: Lower Costs, Higher Emissions?," *NBER Working Paper Series*, no. 34065, 2025, doi: 10.3386/w34065.

[40] M. Zhao and X. Wang, 'A Synthetic Approach for Datacenter Power Consumption Regulation towards Specific Targets in Smart Grid Environment', *Energies*, vol. 14, no. 9, p. 2602, May 2021, doi: 10.3390/en14092602.

[41] C. Nadjahi, H. Louahlia, and S. Lemasson, 'A review of thermal management and innovative cooling strategies for data center', *Sustain. Comput. Inform. Syst.*, vol. 19, pp. 14–28, Sep. 2018, doi: 10.1016/j.suscom.2018.05.002.

[42] Q. Zhang *et al.*, 'A survey on data center cooling systems: Technology, power consumption modeling and control strategy optimization', *J. Syst. Archit.*, vol. 119, p. 102253, Oct. 2021, doi: 10.1016/j.sysarc.2021.102253.

[43] D. Quirk, 'ASHRAE's Data Center Thermal Guidelines— Air-Cooled Evolution', 2004.

[44] S. Xu, H. Zhang, and Z. Wang, 'Thermal Management and Energy Consumption in Air, Liquid, and Free Cooling Systems for Data Centers: A Review', *Energies*, vol. 16, no. 3, p. 1279, Jan. 2023, doi: 10.3390/en16031279.

[45] Y. Wang, X. Wang, and Y. Zhang, 'Leveraging thermal storage to cut the electricity bill for datacenter cooling', in *Proceedings of the 4th Workshop on Power-Aware Computing and Systems*, Cascais Portugal: ACM, Oct. 2011, pp. 1–5. doi: 10.1145/2039252.2039260.

[46] I. Sarbu and C. Sebarchievici, 'A Comprehensive Review of Thermal Energy Storage', *Sustainability*, vol. 10, no. 1, p. 191, Jan. 2018, doi: 10.3390/su10010191.

[47] W. Zheng, K. Ma, and X. Wang, 'Exploiting thermal energy storage to reduce data center capital and operating expenses', in *2014 IEEE 20th International Symposium on High Performance Computer Architecture (HPCA)*, Orlando, FL, USA: IEEE, Feb. 2014, pp. 132–141. doi: 10.1109/HPCA.2014.6835924.

[48] D. Garday, *Thermal Storage System Provides Emergency Data Center Cooling*. Intel IT, 2007.

[49] J. Winick, G. Zhu, K. Kitz, and A. Adams, 'Reducing Data Center Peak Cooling Demand and Energy Costs with Underground Thermal Energy Storage (UTES)'.

[50] B. W. Nkwawir, M. O. Kayalica, D. Guven, A. C. Duman, and H. S. Erden, 'Carbon-Aware Workload Management in Data Centers: A Multi-Energy Integration Approach', in *Proceedings of the 16th ACM International Conference on Future and Sustainable Energy Systems*, Rotterdam Netherlands: ACM, Jun. 2025, pp. 907–914. doi: 10.1145/3679240.3735104.

[51] S. Sarkar *et al.*, 'Carbon Footprint Reduction for Sustainable Data Centers in Real-Time', *Proc. AAAI Conf. Artif. Intell.*, vol. 38, no. 20, pp. 22322–22330, Mar. 2024, doi: 10.1609/aaai.v38i20.30238.

[52] Y. Chen, K. Shi, M. Chen, and D. Xu, 'Data Center Power Supply Systems: From Grid Edge to Point-of-Load', *IEEE J. Emerg. Sel. Top. Power Electron.*, vol. 11, no. 3, pp. 2441–2456, Jun. 2023, doi: 10.1109/JESTPE.2022.3229063.

[53] D. Wang, C. Ren, A. Sivasubramaniam, B. Urgaonkar, and H. Fathy, 'Energy Storage in Datacenters: What, Where, and How much?'.

[54] I. Narayanan, D. Wang, A. Mamun, A. Sivasubramaniam, H. K. Fathy, and S. James, 'Evaluating energy storage for a multitude of uses in the datacenter', in *2017 IEEE International Symposium on Workload Characterization (IISWC)*, Seattle, WA: IEEE, Oct. 2017, pp. 12–21. doi: 10.1109/IISWC.2017.8167752.

[55] European Commission. Joint Research Centre., *2025 best practice guidelines for the EU code of conduct on data centre energy efficiency.* LU: Publications Office, 2025. doi: 10.2760/9449356.

[56] Arthur D. Little, *Green Data Centers: Opportunities for Decarbonization*. Arthur D. Little, 2023.

[57] Redeia, 'Red Eléctrica publica las capacidades de acceso de la demanda a la red de transporte', Red Eléctrica. Accessed: Jun. 18, 2026. [Online]. Available: https://www.ree.es/es/sala-de-prensa/actualidad/nota-de-prensa/2026/02/red-electrica-publica-las-capacidades-de-acceso-de-la-demanda-a-la-red-de-transporte

[58] M. T. Takci, M. Qadrdan, J. Summers, and J. Gustafsson, 'Data centres as a source of flexibility for power systems', *Energy Rep.*, vol. 13, pp. 3661–3671, Jun. 2025, doi: 10.1016/j.egyr.2025.03.020.

[59] Y. Guo, Y. Gong, Y. Fang, P. P. Khargonekar, and X. Geng, 'Energy and Network Aware Workload Management for Sustainable Data Centers with Thermal Storage',

IEEE Trans. Parallel Distrib. Syst., vol. 25, no. 8, pp. 2030–2042, Aug. 2014, doi: 10.1109/TPDS.2013.278.

[60] M. M. MacCracken, *The Role of Energy Storage for Data Centers*. Trane, 2025.

[61] K. Zhang, Y. Zhang, J. Liu, and X. Niu, 'Recent advancements on thermal management and evaluation for data centers', *Appl. Therm. Eng.*, vol. 142, pp. 215–231, Sep. 2018, doi: 10.1016/j.applthermaleng.2018.07.004.

[62] J. J. Monsalves, C. Bergaentzlé, and D. Keles, 'Impacts of flexible-cooling and waste-heat recovery from data centres on energy systems: a Danish case study'.

[63] K. Simou and C. Bolintineanu, *Data Centre Flexibility in Germany and China: Status Quo and Best Practices*. Berlin, Germany: Deutsche Energie-Agentur GmbH (dena), 2022.

[64] Comisión Nacional de los Mercados y la Competencia, *Memoria justificativa de la propuesta de resolución por la que se aprueban los permisos de acceso flexibles a las redes de transporte y distribución de energía eléctrica*, RDC/DE/003/25. CNMC, 2026. Accessed: Jun. 18, 2026. [Online]. Available: https://www.cnmc.es/sites/default/files/editor_contenidos/Energia/Consulta%20Publica/2_RDC_DE_003_25_%20Memoria.pdf

[65] Redeia, 'Procedimientos de operación', Red Eléctrica. Accessed: Jun. 29, 2026. [Online]. Available: https://www.ree.es/es/conocenos/marco-regulatorio/procedimientos-de-operacion

[66] Comisión Nacional de los Mercados y la Competencia, "Resolución de 6 de marzo de 2024 por la que se aprueba el procedimiento de operación P.O. 3.11, Sistema de reducción automática de potencia," *Boletín Oficial del Estado*, no. 76, Mar. 2024.

[67] Comisión Nacional de los Mercados y la Competencia, *P.O. 7.5. Servicio de respuesta activa de la demanda*, DCOOR/DE/003/23. CNMC, 2023. Accessed: Jun. 29, 2026. [Online]. Available: https://www.cnmc.es/sites/default/files/editor_contenidos/Energia/Consulta%20Publica/3_DCOOR_DE_003_23_PO7.5_SRAD_CNMC_CC.pdf

[68] Redeia, 'El servicio de respuesta activa de la demanda (SRAD) contará con 1.775 MW para el segundo semestre del año', Red Eléctrica. Accessed: Jun. 29, 2026. [Online]. Available: https://www.ree.es/es/sala-de-prensa/actualidad/nota-de-prensa/2026/05/el-

servicio-de-respuesta-activa-de-la-demanda-srad-contara-con-1775-mw-para-el-segundo-semestre-del-ano

[69] Ministerio para la Transición Ecológica y el Reto Demográfico, *Proyecto de Real Decreto por el que se regula el procedimiento de publicidad de la información de los centros de datos en relación con su eficiencia energética y sostenibilidad*. MITECO, 2025. Accessed: Jun. 29, 2026. [Online]. Available: https://www.miteco.gob.es/content/dam/miteco/es/energia/files-1/es-ES/Participacion/Documents/anexos/aeip-rd-cpds/20250807_RD-CD.pdf

[70] R. B. P. Prieto *et al.*, 'Sustentabilidade energética e ambiental em datacenters de inteligência artificial: estudo de caso Google Data Centers (2024–2025)', *Rev. DELOS*, vol. 18, no. 75, p. e7760, Dec. 2025, doi: 10.55905/rdelosv18.n75-008.

[71] Endesa, "Nuevos períodos horarios en la Península," *Endesa*, 2026. Accessed: Jul. 02, 2026. [Online]. Available:https://www.endesa.com/es/comunicacion/cartera/peajes-empresas-asesoramiento/periodos-horarios/peninsula

ANNEX I. GLOSSARY

AI	Artificial Intelligence
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
AWS	Amazon Web Services
BESS	Battery Energy Storage System
CAD1	*Capacidad de Acceso de Demanda 1*: demand access capacity applicable to power-electronics-connected installations that declare voltage-dip ride-through and active-power recovery capability
CAD2	*Capacidad de Acceso de Demanda 2*: demand access capacity applicable to power-electronics-connected installations that do not declare those capabilities
CAPEX	Capital Expenditure
CEP	*Conectados con Electrónica de Potencia*: demand connected through power electronics
CH	*Con Huecos*: classification for demand capable of remaining connected during voltage dips
CNAE	*Clasificación Nacional de Actividades Económicas*: Spanish National Classification of Economic Activities
CNMC	*Comisión Nacional de los Mercados y la Competencia*: Spanish National Commission on Markets and Competition

COP	Coefficient of Performance
CRU	Commission for Regulation of Utilities
CUE	Carbon Usage Effectiveness
ENTSO-E	European Network of Transmission System Operators for Electricity
ERF	Energy Reuse Factor
EU	European Union
FLAP-D	Frankfurt, London, Amsterdam, Paris and Dublin
GdO	Guarantees of Origin
GPU	Graphics Processing Unit
HVAC	Heating, Ventilation and Air Conditioning
IEA	International Energy Agency
IoT	Internet of Things
IT	Information Technology
Li-ion	Lithium-ion
MITECO	*Ministerio para la Transición Ecológica y el Reto Demográfico*: Spanish Ministry for the Ecological Transition and the Demographic Challenge
MPE	*Módulo de Parque Eléctrico*: Power Park Module

N-1	Security criterion requiring the system to withstand the loss of one network element
OPEX	Operating Expenditure
PIGA	*Planes y Proyectos de Interés General de Aragón*: Plans and Projects of General Interest of Aragón
PLC	Programmable Logic Controller
P.O.	*Procedimiento de Operación*: Operating Procedure
PPA	Power Purchase Agreement
PQ	Active-power and reactive-power load model
PUE	Power Usage Effectiveness
PV	Photovoltaic
RD	*Real Decreto*: Royal Decree
RDL	*Real Decreto-ley*: Royal Decree-Law
REE	Red Eléctrica de España, the Spanish Transmission System Operator
REF	Renewable Energy Factor
SLA	Service-Level Agreement
SRAD	*Servicio de Respuesta Activa de la Demanda*: Active Demand Response Service

SRAP	*Sistema de Reducción Automática de Potencia*: Automatic Power Reduction System
TES	Thermal Energy Storage
TSO	Transmission System Operator
UPS	Uninterruptible Power Supply
WUE	Water Usage Effectiveness

ANNEX II. INPUT DATA

This annex shows the input data that has been used. As it was mentioned, the input data is not the raw data obtained from official resources. As the model was based on twelve representative days, the raw data had to be modified in order to obtain the average of the disaggregated hours for each representative day.

Therefore, the following tables show the modified data that was used as input data for the model.

Temperature

	January	*February*	*March*	*April*	*May*	*June*	*July*	*August*	*September*	*October*	*November*	*December*
h0	5,6	6,4	6,7	11,1	14,1	22,7	22,6	24,6	18,8	14,9	7,7	6,4
h1	5,3	5,9	6,3	10,4	13,4	22,0	21,7	23,8	18,1	14,4	7,3	6,1
h2	5,0	5,3	6,1	10,0	12,9	21,4	21,0	23,1	17,5	13,8	7,1	5,9
h3	4,7	4,9	5,9	9,6	12,4	20,7	20,2	22,4	16,8	13,4	6,9	5,6
h4	4,4	4,6	5,6	9,2	11,9	20,1	19,6	21,8	16,3	13,0	6,5	5,5
h5	4,2	4,3	5,5	8,9	11,9	20,0	19,4	21,4	15,7	12,7	6,2	5,5
h6	4,0	4,0	5,4	9,3	12,9	20,8	20,1	21,5	15,8	12,6	6,2	5,4
h7	3,9	4,1	6,0	10,6	14,2	22,2	21,7	22,7	17,0	13,4	6,3	5,3
h8	4,6	5,4	6,9	12,0	15,6	24,1	23,6	24,7	18,6	14,8	7,6	5,8
h9	5,6	6,8	7,6	13,3	17,0	26,0	25,5	26,7	20,5	16,4	8,8	6,4
h10	6,7	8,5	8,5	14,4	18,1	27,7	27,1	28,4	22,0	17,9	10,1	7,3
h11	7,9	9,9	9,3	15,5	19,2	29,0	28,5	30,0	23,5	19,2	11,3	8,3
h12	8,9	11,3	10,0	16,3	20,3	30,1	29,7	31,4	24,8	20,3	12,2	9,1
h13	9,7	12,2	10,8	16,6	21,2	31,0	30,7	32,4	25,7	21,1	12,8	9,6
h14	10,1	12,9	11,1	16,9	21,5	31,2	31,4	32,8	26,4	21,6	13,0	9,8
h15	10,2	13,3	11,1	17,1	21,6	31,3	31,8	33,1	26,5	21,8	13,0	9,7
h16	9,8	13,2	11,0	17,0	21,5	30,8	31,9	32,8	26,4	21,3	12,3	9,2

h17	8,9	12,3	10,5	16,6	21,1	30,6	31,7	32,2	25,8	20,4	11,1	8,6
h18	8,1	11,3	9,8	15,7	20,4	29,9	30,9	31,2	24,5	19,4	10,4	8,0
h19	7,6	10,4	9,1	14,6	19,0	28,6	29,5	30,1	23,2	18,3	9,8	7,6
h20	7,1	9,5	8,4	13,7	17,9	26,9	27,6	28,6	22,1	17,5	9,3	7,3
h21	6,7	8,7	8,0	12,9	16,9	25,6	26,1	27,3	21,2	16,8	8,8	7,0
h22	6,2	8,1	7,5	12,3	16,0	24,5	24,8	26,2	20,3	16,0	8,3	6,8
h23	5,9	7,3	7,1	11,8	15,2	23,6	23,7	25,2	19,5	15,3	7,8	6,5

Table 49. Temperature input data – Madrid

The following figure shows the hourly temperature for a whole year for the years from 2020 to 2025. As it is seen, all the years are similar, since none of them present abrupt increases or decreases in temperature. For the year 2022, there are three outliers due to the lack of data from the raw data.

With this figure, it is justified to use the temperatures of year 2025 since it can be considered a regular year in terms of temperature.

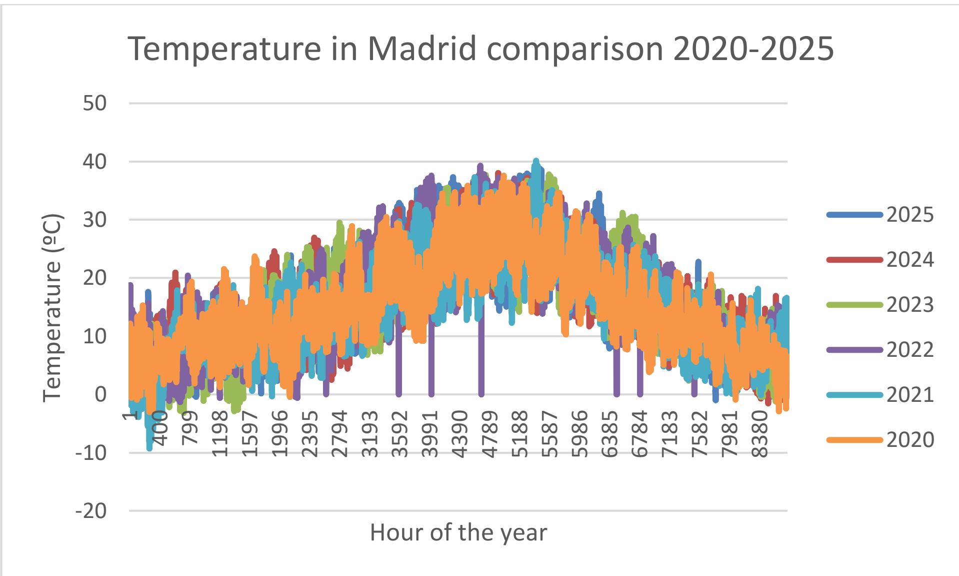


Figure 20. Temperature in Madrid comparison 2020-2025

	January	*February*	*March*	*April*	*May*	*June*	*July*	*August*	*September*	*October*	*November*	*December*
h0	10,4	11,5	12,2	16,0	20,2	27,2	27,9	28,7	25,6	22,0	13,4	10,6
h1	10,0	10,8	11,7	15,4	19,4	26,3	26,9	27,7	24,6	21,4	12,8	10,1
h2	9,6	10,2	11,4	14,8	18,7	25,4	26,0	27,0	23,7	20,8	12,7	10,2
h3	9,5	9,9	11,5	14,7	18,2	24,4	24,9	26,0	22,8	20,2	12,2	9,9
h4	9,2	9,4	11,2	14,2	17,5	23,8	24,2	25,4	22,1	19,7	11,8	9,4
h5	9,0	9,0	10,9	13,7	16,9	23,2	23,7	24,8	21,6	19,3	11,5	8,9
h6	8,8	8,7	10,6	13,3	16,4	22,6	23,3	24,2	21,0	18,8	11,1	8,6
h7	8,6	8,4	10,4	13,1	16,0	22,2	22,8	23,7	20,6	18,5	10,7	8,3
h8	8,4	8,1	10,2	13,1	16,1	22,3	22,9	23,3	20,1	18,2	10,8	8,3
h9	8,3	7,8	10,2	13,7	17,4	23,6	24,0	24,2	20,4	18,1	10,5	8,1
h10	8,3	8,2	11,1	15,0	19,3	25,5	26,0	26,2	22,1	19,3	11,1	8,1
h11	9,3	9,6	12,6	16,7	21,4	27,7	28,2	28,6	24,4	21,3	12,6	9,1
h12	10,7	11,6	14,1	18,4	23,4	29,9	30,4	31,1	26,7	23,3	14,4	10,6
h13	12,4	13,6	15,3	19,8	25,1	31,9	32,5	33,3	28,8	25,2	16,0	12,1
h14	13,9	15,3	16,3	20,8	26,3	33,6	34,1	35,1	30,4	26,2	17,4	13,3
h15	14,9	16,4	16,7	21,8	27,1	34,4	35,0	36,0	31,5	27,6	18,1	14,2
h16	15,4	17,1	17,0	22,2	27,6	35,1	35,9	36,7	32,2	28,1	18,3	14,6
h17	15,5	17,4	17,2	22,2	27,8	35,2	36,3	37,0	32,6	28,1	18,3	14,8
h18	15,2	17,2	16,8	21,8	27,7	34,9	36,3	36,9	32,5	27,9	17,8	14,4
h19	14,1	16,5	16,3	21,2	27,3	34,5	35,6	36,3	32,1	27,1	16,4	13,2
h20	12,9	14,9	15,3	20,2	26,1	33,6	34,2	35,1	31,0	25,8	15,7	12,5
h21	12,3	13,8	14,2	18,7	24,5	31,8	32,2	33,2	29,3	24,6	15,0	12,1
h22	11,6	13,1	13,6	17,6	22,8	29,6	30,1	31,3	27,8	23,5	14,3	11,5
h23	11,0	12,3	12,9	16,8	21,6	28,3	28,9	29,8	26,6	22,6	13,7	11,0

Table 50. Temperature input data – Seville

Spot price

	January	February	March	April	May	June	July	August	September	October	November	December
h0	92,8	112,0	57,3	29,7	22,9	100,8	93,1	95,4	77,3	84,8	65,4	78,8
h1	84,3	104,6	48,1	27,6	20,2	97,6	88,8	90,9	75,0	78,5	56,9	70,9
h2	78,8	100,2	44,3	25,0	17,6	95,9	85,5	87,2	72,3	75,9	51,7	65,9
h3	74,0	96,7	42,4	24,0	17,6	95,7	82,6	86,1	71,6	76,1	48,4	61,5
h4	71,7	94,3	41,6	26,6	20,5	97,1	86,4	87,9	73,3	77,6	46,2	59,3
h5	75,8	98,0	44,3	35,5	26,5	102,3	92,8	92,6	78,8	84,6	50,2	62,5
h6	88,9	108,5	54,7	57,3	34,2	103,0	98,0	97,8	92,6	97,6	61,8	71,2
h7	105,6	132,5	73,3	53,4	22,9	86,6	83,6	87,8	89,7	110,1	76,1	81,6
h8	123,1	145,4	60,0	26,0	7,7	55,9	55,5	58,0	64,2	90,6	76,4	89,0
h9	109,3	119,2	43,5	11,0	-0,9	37,2	37,4	35,1	31,4	63,0	49,8	82,9
h10	92,5	92,8	35,3	3,2	-2,2	26,5	31,7	23,1	16,6	42,4	30,2	73,7
h11	83,4	77,5	29,1	1,2	-3,0	21,7	30,8	18,7	12,6	33,1	22,6	65,4
h12	78,9	66,9	26,1	0,3	-3,8	18,0	29,7	15,5	10,8	28,8	21,4	62,9
h13	74,6	64,0	23,6	-0,2	-4,3	16,2	28,3	15,8	8,5	26,3	20,5	59,8
h14	72,9	60,2	22,5	-0,4	-4,5	16,0	27,9	16,7	9,7	27,1	21,8	60,6
h15	74,9	62,4	25,0	-0,1	-4,0	18,9	29,7	23,2	13,0	33,4	29,5	67,2
h16	88,0	76,1	30,8	1,4	-2,2	29,8	36,5	33,4	23,2	52,3	48,8	78,4
h17	109,5	105,4	40,3	6,6	2,7	50,5	45,1	51,5	47,2	81,5	78,2	91,9
h18	129,4	144,1	65,8	25,5	12,2	79,1	68,4	82,4	86,5	111,5	94,2	100,3
h19	136,1	168,2	112,0	61,8	35,3	105,6	96,9	105,3	113,4	130,1	102,5	102,8
h20	131,3	172,2	111,9	81,9	63,9	135,3	120,6	121,6	124,3	121,8	102,6	105,2
h21	124,6	145,7	93,5	62,9	57,0	133,0	123,2	113,2	99,6	105,6	95,2	100,7
h22	115,9	131,8	82,1	44,9	39,9	112,3	106,2	100,7	89,5	93,7	83,9	92,8
h23	104,2	120,6	68,0	36,2	30,9	110,0	100,6	100,8	86,3	90,8	73,4	84,4

Table 51. Spot price 2025 input data

The spot price for 2025 is similar to the spot prices in 2024 and 2023, shown in Z>>>, therefore, since it does not present several outliers, 2025 has been taken as a regular year. However, if comparing it for the years 2022, 2021 and 2020, it does present a complete different profile. Since the years 2023, 2024 and 2025 all show similar profiles, the differences between these years and years 2022, 2021 and 2020 have been rejected, because these last three years do not show similarities between them, therefore, it can be assumed that there we anomalous events in those years that varied the spot price.

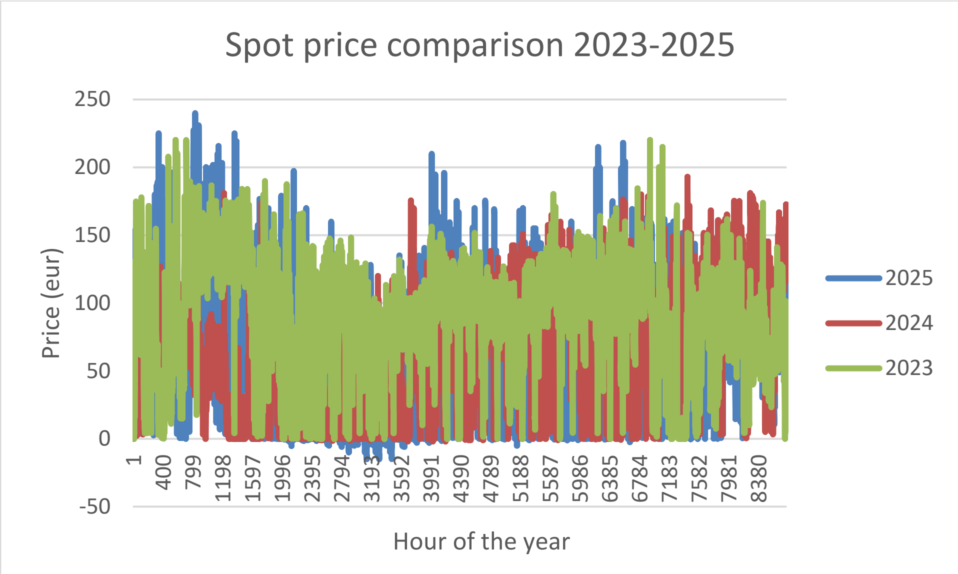


Figure 21. Spot price comparison 2023-2025

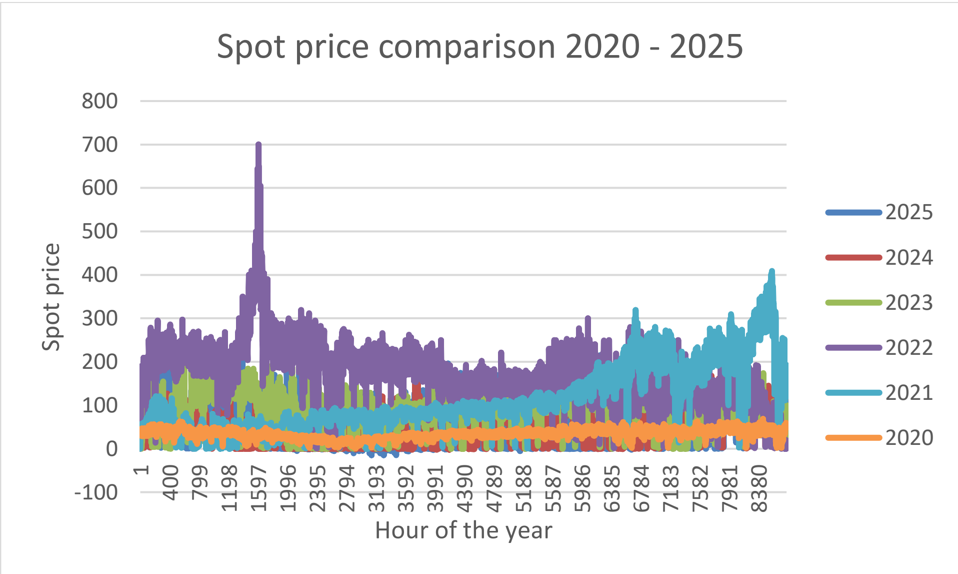


Figure 22. Spot price comparison 2020-2025

Network tariffs and regulated charges

In Spain, the network tariffs and regulated charges are regulated by the CNMC and are classified according to the following voltage levels.

Características del suministro	Peaje T&D	Segmentos tarifarios de cargos
Baja tensión ≤ 15kW	2.0 TD	1
Baja tensión > 15kW	3.0 TD	2
Alta tensión entre 1kV y 30kV	6.1 TD	3
Alta tensión entre 30kV y 72,5kV	6.2 TD	4
Alta tensión entre 72,5kV y 145kV	6.3 TD	5
Alta tensión > 145kV	6.4 TD	6

Table 52. Tariffs and charges classification according to voltage level (Source: MITECO)

Since data centers are connected to high voltage network, the applied tariff is 6.4 TD and the charge segment is 6.

Network tariffs and regulated charges distinguish between power term (€/kWh year) and energy term (€/kWh). Since in this thesis focuses on calculating the energy costs, only the energy term has been considered.

Table 53 shows the energy term for the network tariffs. For data centers, the tariff group that applies is 6.4 TD.

Grupo tarifario	Término de energía del peaje de transporte y distribución (€/kWh)					
	Periodo 1	Periodo 2	Periodo 3	Periodo 4	Periodo 5	Periodo 6
2.0 TD	0,033261	0,016409	0,000077			
3.0 TD	0,027511	0,012376	0,004943	0,002627	0,000111	0,000031
6.1 TD	0,026785	0,012281	0,005133	0,002780	0,000120	0,000029
6.2 TD	0,014736	0,007202	0,002542	0,001254	0,000062	0,000020
6.3 TD	0,011279	0,005324	0,001994	0,000995	0,000048	0,000014
6.4 TD	0,008427	0,003946	0,001458	0,000716	0,000038	0,000004

Table 53. Energy term for network tariffs (Source: MITECO)

Table 54 shows the energy term for the regulated charges. For data centers, the tariff segment that applies is 6.

b) Términos de energía:

Segmento tarifario	Término de energía de los cargos (€/kWh)					
	Periodo 1	Periodo 2	Periodo 3	Periodo 4	Periodo 5	Periodo 6
1	0,064292	0,012858	0,003215			
2	0,035841	0,026538	0,014336	0,007168	0,004595	0,002867
3	0,019489	0,014436	0,007795	0,003898	0,002499	0,001559
4	0,009144	0,006773	0,003658	0,001829	0,001172	0,000732
5	0,007496	0,005552	0,002998	0,001499	0,000961	0,000600
6	0,002848	0,002109	0,001139	0,000570	0,000365	0,000228

Table 54. Energy term for regulated charges (Source: MITECO)

For the network tariffs 3.0 TD, 6.1 TD, 6.2 TD, 6.3 TD and 6.4 TD, there are 6 hourly periods P1, P2, P3, P4, P5 and P6 as it can be seen on the previous tables. Each of these periods are assigned to different hours of the day depending on the season and the expected level of electricity demand. P1 corresponds to the hours with the highest pressure on the electricity network and therefore has the highest regulated cost, whereas P6 represents the off-peak period with the lowest cost. The remaining periods reflect intermediate demand levels. The hourly allocation changes throughout the year because electricity consumption patterns and network congestion vary between seasons, while weekends and public holidays are generally classified as P6. Table 55 shows the distribution of these periods throughout the year.

Table 55. Electricity hourly periods for the Iberian Peninsula (Source: Endesa)

Since the model works with 12 representative days and does not distinguish between weekdays and weekends or holidays, the disaggregated hourly average approach was carried out.

Table 56 shows the average period of each hour.

	January	*February*	*March*	*April*	*May*	*June*	*July*	*August*	*September*	*October*	*November*	*December*
h0	6,0	6,0	6,0	6,0	6,0	6,0	6,0	6,0	6,0	6,0	6,0	6,0
h1	6,0	6,0	6,0	6,0	6,0	6,0	6,0	6,0	6,0	6,0	6,0	6,0
h2	6,0	6,0	6,0	6,0	6,0	6,0	6,0	6,0	6,0	6,0	6,0	6,0
h3	6,0	6,0	6,0	6,0	6,0	6,0	6,0	6,0	6,0	6,0	6,0	6,0
h4	6,0	6,0	6,0	6,0	6,0	6,0	6,0	6,0	6,0	6,0	6,0	6,0
h5	6,0	6,0	6,0	6,0	6,0	6,0	6,0	6,0	6,0	6,0	6,0	6,0
h6	6,0	6,0	6,0	6,0	6,0	6,0	6,0	6,0	6,0	6,0	6,0	6,0
h7	6,0	6,0	6,0	6,0	6,0	6,0	6,0	6,0	6,0	6,0	6,0	6,0
h8	3,0	3,1	4,0	5,3	5,3	4,6	3,0	4,6	4,5	5,3	4,0	3,0
h9	2,3	2,4	2,6	2,3	2,5	2,5	2,3	2,6	2,3	2,3	2,7	2,3
h10	2,3	2,4	2,6	2,3	2,5	2,5	2,3	2,6	2,3	2,3	2,7	2,3
h11	2,3	2,4	2,6	2,3	2,5	2,5	2,3	2,6	2,3	2,3	2,7	2,3
h12	2,3	2,4	2,6	2,3	2,5	2,5	2,3	2,6	2,3	2,3	2,7	2,3
h13	2,3	2,4	2,6	2,3	2,5	2,5	2,3	2,6	2,3	2,3	2,7	2,3
h14	3,0	3,1	4,0	5,3	5,3	4,6	3,0	4,6	4,5	5,3	4,0	3,0
h15	3,0	3,1	4,0	5,3	5,3	4,6	3,0	4,6	4,5	5,3	4,0	3,0
h16	3,0	3,1	4,0	5,3	5,3	4,6	3,0	4,6	4,5	5,3	4,0	3,0
h17	3,0	3,1	4,0	5,3	5,3	4,6	3,0	4,6	4,5	5,3	4,0	3,0
h18	2,3	2,4	2,6	2,3	2,5	2,5	2,3	2,6	2,3	2,3	2,7	2,3
h19	2,3	2,4	2,6	2,3	2,5	2,5	2,3	2,6	2,3	2,3	2,7	2,3
h20	2,3	2,4	2,6	2,3	2,5	2,5	2,3	2,6	2,3	2,3	2,7	2,3
h21	2,3	2,4	2,6	2,3	2,5	2,5	2,3	2,6	2,3	2,3	2,7	2,3
h22	3,0	3,1	4,0	5,3	5,3	4,6	3,0	4,6	4,5	5,3	4,0	3,0
h23	3,0	3,1	4,0	5,3	5,3	4,6	3,0	4,6	4,5	5,3	4,0	3,0

Table 56. Average period

Table 57 and Table 58 show the average network tariffs and regulated charges according to the average time periods.

€/kWh	*January*	*February*	*March*	*April*	*May*	*June*	*July*	*August*	*September*	*October*	*November*	*December*
h0	0,000004	0,000004	0,000004	0,000004	0,000004	0,000004	0,000004	0,000004	0,000004	0,000004	0,000004	0,000004
h1	0,000004	0,000004	0,000004	0,000004	0,000004	0,000004	0,000004	0,000004	0,000004	0,000004	0,000004	0,000004
h2	0,000004	0,000004	0,000004	0,000004	0,000004	0,000004	0,000004	0,000004	0,000004	0,000004	0,000004	0,000004
h3	0,000004	0,000004	0,000004	0,000004	0,000004	0,000004	0,000004	0,000004	0,000004	0,000004	0,000004	0,000004
h4	0,000004	0,000004	0,000004	0,000004	0,000004	0,000004	0,000004	0,000004	0,000004	0,000004	0,000004	0,000004
h5	0,000004	0,000004	0,000004	0,000004	0,000004	0,000004	0,000004	0,000004	0,000004	0,000004	0,000004	0,000004
h6	0,000004	0,000004	0,000004	0,000004	0,000004	0,000004	0,000004	0,000004	0,000004	0,000004	0,000004	0,000004
h7	0,000004	0,000004	0,000004	0,000004	0,000004	0,000004	0,000004	0,000004	0,000004	0,000004	0,000004	0,000004
h8	0,002929	0,002820	0,000989	0,000029	0,000028	0,000502	0,002929	0,000486	0,000526	0,000029	0,000973	0,002929
h9	0,006253	0,006020	0,005710	0,006181	0,005982	0,005900	0,006253	0,005710	0,006181	0,006253	0,005619	0,006253
h10	0,006253	0,006020	0,005710	0,006181	0,005982	0,005900	0,006253	0,005710	0,006181	0,006253	0,005619	0,006253
h11	0,006253	0,006020	0,005710	0,006181	0,005982	0,005900	0,006253	0,005710	0,006181	0,006253	0,005619	0,006253
h12	0,006253	0,006020	0,005710	0,006181	0,005982	0,005900	0,006253	0,005710	0,006181	0,006253	0,005619	0,006253
h13	0,006253	0,006020	0,005710	0,006181	0,005982	0,005900	0,006253	0,005710	0,006181	0,006253	0,005619	0,006253
h14	0,002929	0,002820	0,000989	0,000029	0,000028	0,000502	0,002929	0,000486	0,000526	0,000029	0,000973	0,002929
h15	0,002929	0,002820	0,000989	0,000029	0,000028	0,000502	0,002929	0,000486	0,000526	0,000029	0,000973	0,002929
h16	0,002929	0,002820	0,000989	0,000029	0,000028	0,000502	0,002929	0,000486	0,000526	0,000029	0,000973	0,002929
h17	0,002929	0,002820	0,000989	0,000029	0,000028	0,000502	0,002929	0,000486	0,000526	0,000029	0,000973	0,002929
h18	0,006253	0,006020	0,005710	0,006181	0,005982	0,005900	0,006253	0,005710	0,006181	0,006253	0,005619	0,006253
h19	0,006253	0,006020	0,005710	0,006181	0,005982	0,005900	0,006253	0,005710	0,006181	0,006253	0,005619	0,006253
h20	0,006253	0,006020	0,005710	0,006181	0,005982	0,005900	0,006253	0,005710	0,006181	0,006253	0,005619	0,006253
h21	0,006253	0,006020	0,005710	0,006181	0,005982	0,005900	0,006253	0,005710	0,006181	0,006253	0,005619	0,006253
h22	0,002929	0,002820	0,000989	0,000029	0,000028	0,000502	0,002929	0,000486	0,000526	0,000029	0,000973	0,002929
h23	0,002929	0,002820	0,000989	0,000029	0,000028	0,000502	0,002929	0,000486	0,000526	0,000029	0,000973	0,002929

Table 57. Average network tariff (eur/kWh)

€/kWh	January	February	March	April	May	June	July	August	September	October	November	December
h0	0,000228	0,000228	0,000228	0,000228	0,000228	0,000228	0,000228	0,000228	0,000228	0,000228	0,000228	0,000228
h1	0,000228	0,000228	0,000228	0,000228	0,000228	0,000228	0,000228	0,000228	0,000228	0,000228	0,000228	0,000228
h2	0,000228	0,000228	0,000228	0,000228	0,000228	0,000228	0,000228	0,000228	0,000228	0,000228	0,000228	0,000228
h3	0,000228	0,000228	0,000228	0,000228	0,000228	0,000228	0,000228	0,000228	0,000228	0,000228	0,000228	0,000228
h4	0,000228	0,000228	0,000228	0,000228	0,000228	0,000228	0,000228	0,000228	0,000228	0,000228	0,000228	0,000228
h5	0,000228	0,000228	0,000228	0,000228	0,000228	0,000228	0,000228	0,000228	0,000228	0,000228	0,000228	0,000228
h6	0,000228	0,000228	0,000228	0,000228	0,000228	0,000228	0,000228	0,000228	0,000228	0,000228	0,000228	0,000228
h7	0,000228	0,000228	0,000228	0,000228	0,000228	0,000228	0,000228	0,000228	0,000228	0,000228	0,000228	0,000228
h8	0,001624	0,001572	0,000845	0,000328	0,000325	0,000467	0,001624	0,000460	0,000479	0,000330	0,000835	0,001624
h9	0,002172	0,002099	0,002003	0,002149	0,002087	0,002062	0,002172	0,002003	0,002149	0,002172	0,001975	0,002172
h10	0,002172	0,002099	0,002003	0,002149	0,002087	0,002062	0,002172	0,002003	0,002149	0,002172	0,001975	0,002172
h11	0,002172	0,002099	0,002003	0,002149	0,002087	0,002062	0,002172	0,002003	0,002149	0,002172	0,001975	0,002172
h12	0,002172	0,002099	0,002003	0,002149	0,002087	0,002062	0,002172	0,002003	0,002149	0,002172	0,001975	0,002172
h13	0,002172	0,002099	0,002003	0,002149	0,002087	0,002062	0,002172	0,002003	0,002149	0,002172	0,001975	0,002172
h14	0,001624	0,001572	0,000845	0,000328	0,000325	0,000467	0,001624	0,000460	0,000479	0,000330	0,000835	0,001624
h15	0,001624	0,001572	0,000845	0,000328	0,000325	0,000467	0,001624	0,000460	0,000479	0,000330	0,000835	0,001624
h16	0,001624	0,001572	0,000845	0,000328	0,000325	0,000467	0,001624	0,000460	0,000479	0,000330	0,000835	0,001624
h17	0,001624	0,001572	0,000845	0,000328	0,000325	0,000467	0,001624	0,000460	0,000479	0,000330	0,000835	0,001624
h18	0,002172	0,002099	0,002003	0,002149	0,002087	0,002062	0,002172	0,002003	0,002149	0,002172	0,001975	0,002172
h19	0,002172	0,002099	0,002003	0,002149	0,002087	0,002062	0,002172	0,002003	0,002149	0,002172	0,001975	0,002172
h20	0,002172	0,002099	0,002003	0,002149	0,002087	0,002062	0,002172	0,002003	0,002149	0,002172	0,001975	0,002172
h21	0,002172	0,002099	0,002003	0,002149	0,002087	0,002062	0,002172	0,002003	0,002149	0,002172	0,001975	0,002172
h22	0,001624	0,001572	0,000845	0,000328	0,000325	0,000467	0,001624	0,000460	0,000479	0,000330	0,000835	0,001624
h23	0,001624	0,001572	0,000845	0,000328	0,000325	0,000467	0,001624	0,000460	0,000479	0,000330	0,000835	0,001624

Table 58. Average regulated charge (eur/kWh)

Price differential sensitivity

Table 37 shows the price differential from spot prices for the three highest price hours and lowest three price hours.

	1	*2*	*3*	*Average*
January	64,4	58,3	55,4	59,4
February	112,0	105,8	81,7	99,8
March	89,4	88,3	68,4	82,0
April	82,3	63,1	61,9	69,1
May	68,4	61,3	43,9	57,9
June	119,3	116,8	94,3	110,1
July	95,3	92,2	76,5	88,0
August	106,1	97,5	88,6	97,4
September	115,8	103,7	88,9	102,8
October	103,8	94,7	82,7	93,7
November	82,1	81,2	73,4	78,9
December	46,0	43,0	40,0	43,0

Table 37. Price differential from spot prices 2025

For both sensibility scenarios, price differential reduction of 25% and 50%, the average final price differential for the twelve years are shown in the following tables.

Moderate scenario: price differential reduction of 25%

€/MWh	*January*	*February*	*March*	*April*	*May*	*June*	*July*	*August*	*September*	*October*	*November*	*December*
Year 1	59,4	99,8	82,0	69,1	57,9	110,1	88,0	97,4	102,8	93,7	78,9	43,0
Year 2	57,8	97,2	79,9	67,3	56,4	107,3	85,7	94,9	100,2	91,3	76,8	41,9
Year 3	56,4	94,7	77,9	65,6	54,9	104,5	83,5	92,4	97,6	88,9	74,9	40,8
Year 4	54,9	92,3	75,8	63,9	53,5	101,8	81,4	90,0	95,0	86,7	72,9	39,8
Year 5	53,5	89,9	73,9	62,2	52,1	99,2	79,3	87,7	92,6	84,4	71,0	38,7
Year 6	52,1	87,6	72,0	60,6	50,8	96,6	77,2	85,5	90,2	82,2	69,2	37,7
Year 7	50,8	85,3	70,1	59,1	49,5	94,2	75,2	83,2	87,9	80,1	67,4	36,8

Year 8	49,4	83,1	68,3	57,5	48,2	91,7	73,3	81,1	85,6	78,0	65,7	35,8
Year 9	48,2	81,0	66,5	56,0	47,0	89,4	71,4	79,0	83,4	76,0	64,0	34,9
Year 10	46,9	78,9	64,8	54,6	45,7	87,0	69,6	77,0	81,2	74,1	62,3	34,0
Year 11	45,7	76,8	63,2	53,2	44,6	84,8	67,8	75,0	79,1	72,2	60,7	33,1
Year 12	44,5	74,9	61,5	51,8	43,4	82,6	66,0	73,0	77,1	70,3	59,2	32,2

Table 59. Final yearly average price reduction for the price differential reduction case of 25%

Figure 23 shows the decay. As it can be seen, it is more lineal than exponential. For the reason, the approach followed was obtaining the average between the mean years, year 6 and year 7.

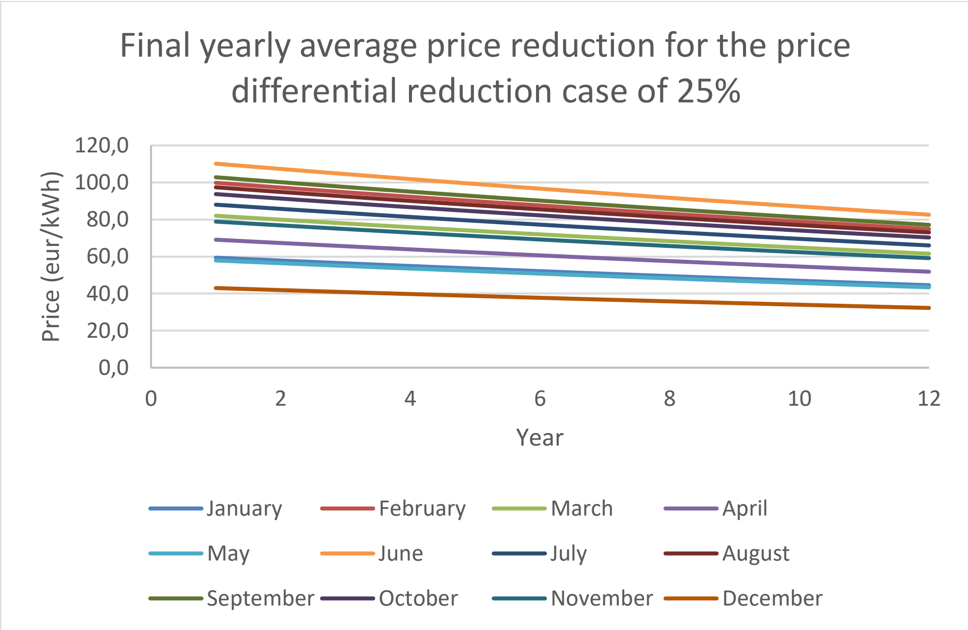


Figure 23. Final yearly average price reduction for the price differential reduction case of 25%

The price in years 6 and 7 was 12,3% and 14,5% lower respectively, than the price in year 1. Therefore, the mean decay taken for calculating the price increase per MWh due to the deployment of BESS and therefore flattening of the price curve is 13,4%.

Table 60 shows the yearly price increase that has been used in the model for the case of the price differential reduction of 25%.

	Average price differential (€/MWh)	*Average price reduction (%)*	*Yearly increase (€/MWh)*
January	59,4	13,4	8,0
February	99,8	13,4	13,4
March	82,0	13,4	11,0
April	69,1	13,4	9,3
May	57,9	13,4	7,8
June	110,1	13,4	14,7
July	88,0	13,4	11,8
August	97,4	13,4	13,0
September	102,8	13,4	13,8
October	93,7	13,4	12,5
November	78,9	13,4	10,6
December	43,0	13,4	5,8

Table 60. Yearly price increase for the price differential reduction of 25%

Aggresive scenario: price differential reduction of 50%

€/MWh	*January*	*February*	*March*	*April*	*May*	*June*	*July*	*August*	*September*	*October*	*November*	*December*
Year 1	59,4	99,8	82,0	69,1	57,9	110,1	88,0	97,4	102,8	93,7	78,9	43,0
Year 2	55,8	93,7	77,0	64,9	54,3	103,4	82,6	91,4	96,5	88,0	74,1	40,4
Year 3	52,3	88,0	72,3	60,9	51,0	97,1	77,6	85,9	90,6	82,6	69,5	37,9
Year 4	49,2	82,6	67,9	57,2	47,9	91,2	72,9	80,6	85,1	77,6	65,3	35,6
Year 5	46,1	77,6	63,8	53,7	45,0	85,6	68,4	75,7	79,9	72,8	61,3	33,4
Year 6	43,3	72,8	59,9	50,4	42,2	80,4	64,2	71,1	75,0	68,4	57,6	31,4
Year 7	40,7	68,4	56,2	47,3	39,7	75,5	60,3	66,7	70,4	64,2	54,0	29,5
Year 8	38,2	64,2	52,8	44,4	37,2	70,9	56,6	62,7	66,1	60,3	50,7	27,7
Year 9	35,9	60,3	49,6	41,7	35,0	66,5	53,2	58,8	62,1	56,6	47,6	26,0
Year 10	33,7	56,6	46,5	39,2	32,8	62,5	49,9	55,2	58,3	53,2	44,7	24,4
Year 11	31,6	53,2	43,7	36,8	30,8	58,7	46,9	51,9	54,7	49,9	42,0	22,9
Year 12	29,7	49,9	41,0	34,5	28,9	55,1	44,0	48,7	51,4	46,9	39,4	21,5

Table 61. Final yearly average price reduction for the price differential reduction case of 50%

Figure 24 shows the decay. As it can be seen, it is a slight exponential. For the reason, the approach followed was obtaining the average between the mean years, year 6 and year 7.

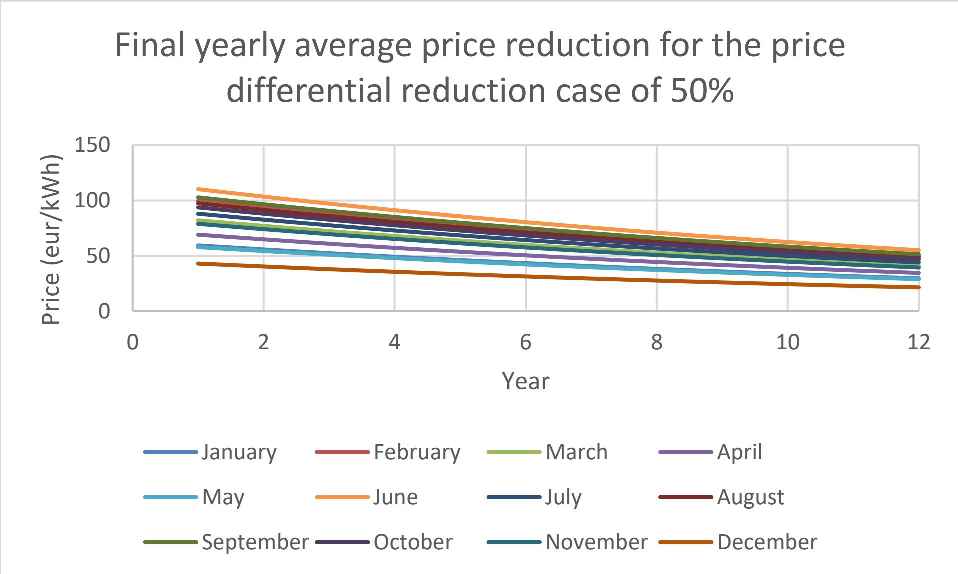


Figure 24. Final yearly average price reduction for the price differential reduction case of 50%

The price in years 6 and 7 was 27% and 31,5 % lower respectively, than the price in year 1. Therefore, the mean decay taken for calculating the price increase per MWh due to the deployment of BESS and therefore flattening of the price curve is 29,3%.

Table 62 shows the yearly price increase that has been used in the model for the case of the price differential reduction of 50%.

	Average price differential (€/MWh)	***Average price reduction (%)***	***Yearly increase (€/MWh)***
January	59,4	29,3	17,4
February	99,8	29,3	70,6
March	82,0	29,3	58,0
April	69,1	29,3	48,9
May	57,9	29,3	40,9
June	110,1	29,3	77,9
July	88,0	29,3	62,3
August	97,4	29,3	68,9
September	102,8	29,3	72,7

October	93,7	29,3	66,3
November	78,9	29,3	55,8
December	43,0	29,3	30,4

Table 62. Yearly price increase for the price differential reduction of 25%

Emissions

The induced emissions were calculated using an hourly emission factor that reflects the variation in the Spanish generation mix throughout the year.

First, the daily emissions from coal and fuel, combined-cycle gas turbines, natural gas cogeneration and biomass technologies was obtained from the Spanish TSO REE 2025 data webpage. The data provided the total emissions of each technology and provided a daily average factor of tCO_2e/MWh. Therefore, an average factor for the 365 days was calculated. This emission factor is 0.1085 tCO_2e/MWh.

After, using the 2025 electricity generation mix, the percentage of generation associated with emitting technologies was calculated for each hour of every representative day, as shown on Table 63.

	January	*February*	*March*	*April*	*May*	*June*	*July*	*August*	*September*	*October*	*November*	*December*
h0	19,7%	19,4%	14,3%	17,3%	19,4%	29,4%	26,2%	27,9%	25,2%	33,4%	23,5%	25,2%
h1	19,6%	18,6%	13,7%	17,6%	19,9%	29,8%	26,4%	27,7%	25,6%	34,0%	23,5%	25,0%
h2	19,8%	18,2%	13,9%	18,2%	20,5%	30,2%	26,5%	28,2%	26,2%	34,7%	24,0%	25,3%
h3	20,0%	18,3%	14,2%	18,8%	20,9%	30,7%	26,6%	28,5%	26,6%	35,2%	24,3%	25,7%
h4	20,4%	18,4%	14,4%	19,2%	21,2%	31,3%	26,8%	29,0%	26,9%	35,7%	24,5%	26,0%
h5	20,6%	19,4%	14,9%	19,3%	21,0%	31,8%	27,5%	29,4%	26,8%	35,9%	24,4%	26,0%
h6	21,2%	21,5%	16,1%	19,6%	20,7%	32,4%	28,5%	29,8%	27,8%	35,8%	24,7%	26,4%
h7	21,2%	22,4%	16,4%	19,7%	20,0%	31,1%	27,7%	29,1%	28,1%	34,8%	25,2%	26,7%
h8	20,8%	22,0%	15,2%	18,7%	17,8%	25,9%	23,2%	25,8%	27,6%	34,3%	25,7%	27,8%
h9	19,1%	19,4%	12,6%	14,9%	16,3%	20,6%	17,4%	19,0%	21,1%	29,0%	20,7%	26,0%
h10	15,9%	14,9%	10,8%	12,4%	16,4%	18,4%	15,6%	15,3%	16,1%	22,4%	18,0%	22,2%
h11	14,1%	12,5%	9,9%	12,0%	16,9%	17,5%	15,2%	14,7%	15,1%	20,2%	17,9%	20,5%
h12	13,8%	11,6%	9,3%	12,0%	17,0%	17,1%	15,2%	14,4%	14,8%	19,7%	17,4%	19,7%
h13	13,9%	11,3%	9,2%	12,2%	17,2%	17,0%	15,0%	14,5%	14,9%	19,5%	17,6%	19,8%
h14	14,2%	11,5%	9,4%	12,3%	17,4%	16,9%	14,8%	14,3%	15,1%	19,7%	18,1%	20,3%

h15	15,1%	12,3%	9,9%	12,5%	17,6%	17,3%	14,9%	14,6%	15,4%	20,4%	19,0%	21,6%
h16	17,5%	15,1%	11,2%	12,8%	17,8%	18,1%	15,3%	15,0%	15,6%	21,2%	21,1%	24,6%
h17	20,7%	20,3%	13,4%	12,8%	17,4%	18,9%	15,4%	15,7%	16,1%	23,7%	26,5%	28,8%
h18	21,5%	24,4%	15,8%	12,8%	16,9%	19,7%	16,0%	17,2%	18,4%	29,0%	27,7%	29,0%
h19	21,2%	24,8%	17,2%	14,6%	17,1%	22,2%	18,3%	21,0%	24,5%	34,2%	27,0%	28,5%
h20	21,2%	24,4%	17,3%	16,8%	18,5%	27,1%	22,8%	26,2%	28,7%	34,4%	26,6%	27,6%
h21	21,1%	24,1%	17,2%	17,4%	19,7%	29,5%	26,4%	28,6%	28,7%	32,6%	25,5%	27,3%
h22	20,7%	23,1%	16,6%	17,0%	19,3%	29,4%	26,5%	28,3%	27,3%	32,1%	25,0%	26,7%
h23	19,8%	21,3%	15,8%	17,1%	18,8%	29,4%	26,5%	28,4%	26,7%	32,8%	24,6%	25,8%

Table 63. Average share of emitting generation in the 2025 generation mix

The average emitting share across all the representative hours is 21,19 %.

An hourly adjustment was then applied through a proportional calculation, in which the reference emission factor was multiplied by the emitting share of each hour and divided by the average emitting share:

$$Hourly\ emission\ factor = 0{,}1085 * \frac{hourly\ emitting\ share}{21{,}19\%}\ [tCO_2]$$

Equation 26. Hourly emission factor calculation

Therefore, an hour with an emitting share equal to 21.9% retains the reference factor of 0.1085 tCO_2e/MWh. When the hourly emitting share is below the average, the resulting emission factor is lower, whereas hours with a higher emitting share receive a proportionally higher emission factor. This methodology preserves the average reference value while introducing the hourly variability of the electricity generation mix.

Table 64 shows the calculated factors.

tCO_2e/MWh	*January*	*February*	*March*	*April*	*May*	*June*	*July*	*August*	*September*	*October*	*November*	*December*
h0	0,101	0,099	0,073	0,089	0,099	0,150	0,134	0,143	0,129	0,171	0,120	0,129
h1	0,100	0,095	0,070	0,090	0,102	0,153	0,135	0,142	0,131	0,174	0,120	0,128
h2	0,101	0,093	0,071	0,093	0,105	0,154	0,136	0,145	0,134	0,177	0,123	0,130
h3	0,102	0,094	0,072	0,096	0,107	0,157	0,136	0,146	0,136	0,180	0,124	0,132
h4	0,104	0,094	0,074	0,098	0,108	0,160	0,137	0,148	0,138	0,183	0,126	0,133
h5	0,106	0,099	0,076	0,099	0,108	0,163	0,141	0,151	0,137	0,184	0,125	0,133
h6	0,109	0,110	0,082	0,101	0,106	0,166	0,146	0,153	0,142	0,183	0,127	0,135
h7	0,108	0,115	0,084	0,101	0,103	0,159	0,142	0,149	0,144	0,178	0,129	0,137
h8	0,107	0,113	0,078	0,096	0,091	0,133	0,119	0,132	0,141	0,176	0,132	0,142
h9	0,098	0,099	0,064	0,076	0,084	0,106	0,089	0,097	0,108	0,148	0,106	0,133
h10	0,081	0,076	0,055	0,064	0,084	0,094	0,080	0,078	0,083	0,115	0,092	0,114
h11	0,072	0,064	0,051	0,061	0,087	0,090	0,078	0,075	0,077	0,103	0,092	0,105
h12	0,071	0,059	0,048	0,062	0,087	0,088	0,078	0,074	0,076	0,101	0,089	0,101
h13	0,071	0,058	0,047	0,062	0,088	0,087	0,077	0,074	0,076	0,100	0,090	0,101
h14	0,073	0,059	0,048	0,063	0,089	0,087	0,076	0,073	0,077	0,101	0,093	0,104
h15	0,077	0,063	0,051	0,064	0,090	0,089	0,076	0,075	0,079	0,104	0,097	0,111
h16	0,090	0,077	0,057	0,065	0,091	0,093	0,078	0,077	0,080	0,109	0,108	0,126
h17	0,106	0,104	0,069	0,066	0,089	0,097	0,079	0,080	0,082	0,121	0,136	0,148
h18	0,110	0,125	0,081	0,066	0,087	0,101	0,082	0,088	0,094	0,149	0,142	0,148
h19	0,108	0,127	0,088	0,075	0,088	0,114	0,094	0,108	0,125	0,175	0,138	0,146
h20	0,109	0,125	0,088	0,086	0,095	0,139	0,117	0,134	0,147	0,176	0,136	0,142
h21	0,108	0,123	0,088	0,089	0,101	0,151	0,135	0,147	0,147	0,167	0,131	0,140
h22	0,106	0,118	0,085	0,087	0,099	0,151	0,136	0,145	0,140	0,164	0,128	0,137
h23	0,101	0,109	0,081	0,088	0,096	0,151	0,135	0,145	0,137	0,168	0,126	0,132

Table 64. Emissions factors

Table 65 shows the daily ranking from the lowest to the highest emitting hours. This table was used to choose the charging and discharging hours.

tCO_{2e}/MWh	***January***	***February***	***March***	***April***	***May***	***June***	***July***	***August***	***September***	***October***	***November***	***December***
h0	10	14	13	15	16	14	14	15	12	14	10	9
h1	9	11	10	17	18	18	15	14	13	15	9	8
h2	11	8	11	18	20	19	19	16	14	19	11	10
h3	13	9	12	20	22	20	20	19	15	21	12	11
h4	14	10	14	21	24	22	21	21	18	22	14	14
h5	15	12	15	22	23	23	22	23	17	24	13	15
h6	22	17	19	23	21	24	24	24	21	23	16	16
h7	20	19	20	24	19	21	23	22	22	20	18	17
h8	18	18	16	19	11	12	13	12	20	17	20	21
h9	8	13	8	11	1	10	10	10	10	9	7	13
h10	6	6	6	5	2	7	8	7	8	7	4	6
h11	3	5	4	1	3	5	5	5	3	4	3	4
h12	1	3	2	2	5	3	4	2	1	3	1	1
h13	2	1	1	3	7	2	3	3	2	1	2	2
h14	4	2	3	4	8	1	1	1	4	2	5	3
h15	5	4	5	6	10	4	2	4	5	5	6	5
h16	7	7	7	7	12	6	6	6	6	6	8	7
h17	17	15	9	9	9	8	7	8	7	8	21	23
h18	24	22	18	8	4	9	9	9	9	10	24	24
h19	21	24	23	10	6	11	11	11	11	16	23	22
h20	23	23	24	12	13	13	12	13	24	18	22	20
h21	19	21	22	16	17	17	16	20	23	12	19	19
h22	16	20	21	13	15	16	18	17	19	11	17	18
h23	12	16	17	14	14	15	17	18	16	13	15	12

Table 65. Ranking from lowest to highest emitting hours

ANNEX III. MODEL BASELINE SCENARIO OUTPUTS

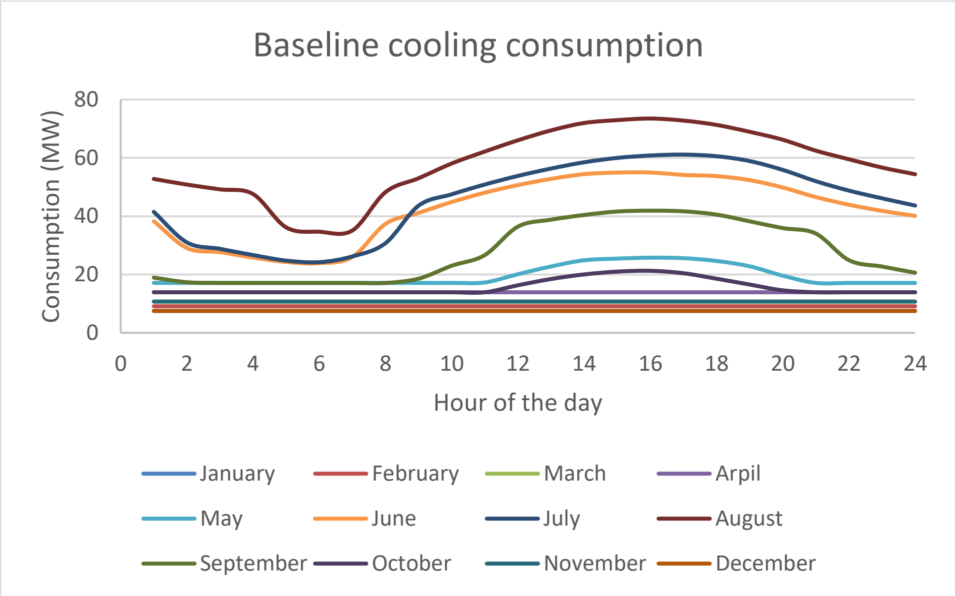


Figure 25. Baseline cooling consumption

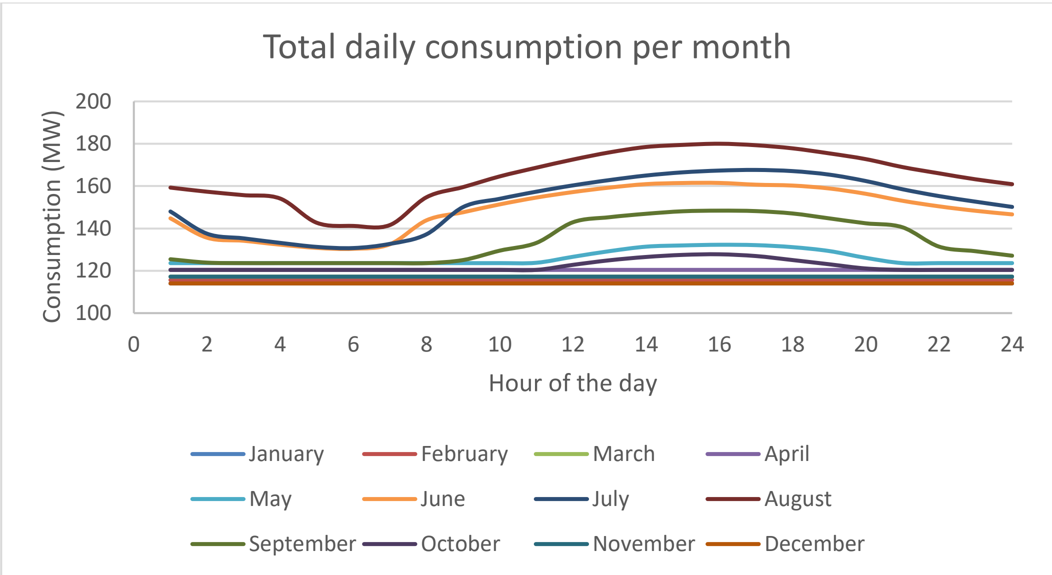


Figure 26. Baseline total daily consumption per month

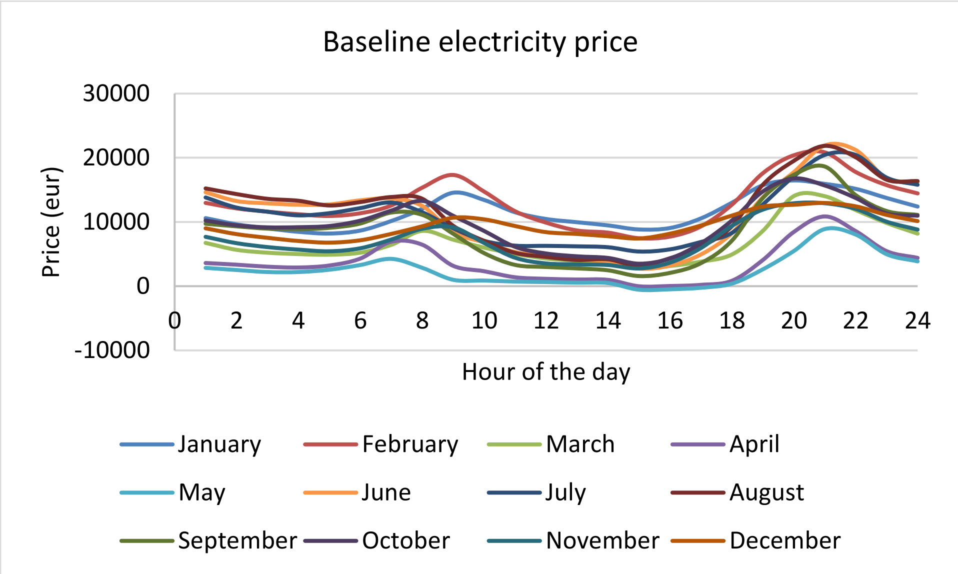


Figure 27. Baseline electricity price

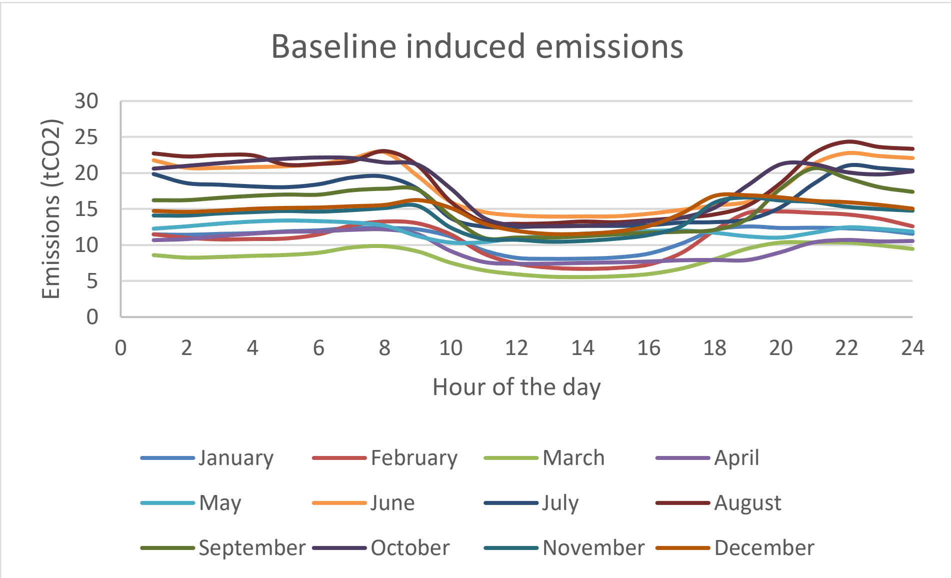


Figure 28. Baseline induced emissions

Seville

	January	*February*	*March*	*April*	*May*	*June*	*July*	*August*	*September*	*October*	*November*	*December*
h0	1	1	1	1	0,46	0	0	0	0	0	1	1
h1	1	1	1	1	0,65	0	0	0	0	0,16	1	1
h2	1	1	1	1	0,83	0	0	0	0	0,31	1	1
h3	1	1	1	1	0,96	0	0	0	0	0,46	1	1
h4	1	1	1	1	1	0	0	0	0	0,58	1	1
h5	1	1	1	1	1	0	0	0	0,11	0,69	1	1
h6	1	1	1	1	1	0	0	0	0,24	0,80	1	1
h7	1	1	1	1	1	0	0	0	0,35	0,88	1	1
h8	1	1	1	1	1	0	0	0	0,47	0,95	1	1
h9	1	1	1	1	1	0	0	0	0,39	0,98	1	1
h10	1	1	1	1	0,67	0	0	0	0	0,69	1	1
h11	1	1	1	1	0,15	0	0	0	0	0,18	1	1
h12	1	1	1	0,90	0	0	0	0	0	0	1	1
h13	1	1	1	0,55	0	0	0	0	0	0	1	1
h14	1	1	1	0,31	0	0	0	0	0	0	1	1
h15	1	1	1	0,04	0	0	0	0	0	0	0,97	1
h16	1	1	1	0	0	0	0	0	0	0	0,92	1
h17	1	1	1	0	0	0	0	0	0	0	0,92	1
h18	1	1	1	0,04	0	0	0	0	0	0	1	1
h19	1	1	1	0,20	0	0	0	0	0	0	1	1
h20	1	1	1	0,45	0	0	0	0	0	0	1	1
h21	1	1	1	0,83	0	0	0	0	0	0	1	1
h22	1	1	1	1	0	0	0	0	0	0	1	1
h23	1	1	1	1	0,09	0	0	0	0	0	1	1

Table 66 Free cooling factor – Seville

	January	*February*	*March*	*April*	*May*	*June*	*July*	*August*	*September*	*October*	*November*	*December*
h0	0	0	0	0	0	0,35	0,40	0,45	0,24	0,00	0	0
h1	0	0	0	0	0	0,29	0,32	0,38	0,17	0	0	0
h2	0	0	0	0	0	0,23	0,26	0,33	0,12	0	0	0
h3	0	0	0	0	0	0,16	0,19	0,27	0,05	0	0	0
h4	0	0	0	0	0	0,12	0,15	0,22	0,01	0	0	0
h5	0	0	0	0	0	0,08	0,11	0,18	0	0	0	0
h6	0	0	0	0	0	0,04	0,08	0,15	0	0	0	0
h7	0	0	0	0	0	0,01	0,06	0,12	0	0	0	0
h8	0	0	0	0	0	0,02	0,06	0,09	0	0	0	0
h9	0	0	0	0	0	0,11	0,14	0,15	0	0	0	0
h10	0	0	0	0	0	0,23	0,27	0,28	0,00	0	0	0
h11	0	0	0	0	0	0,38	0,41	0,44	0,16	0	0	0
h12	0	0	0	0	0,09	0,53	0,56	0,60	0,31	0,09	0	0
h13	0	0	0	0	0,21	0,66	0,70	0,75	0,46	0,21	0	0
h14	0	0	0	0	0,29	0,77	0,81	0,87	0,56	0,28	0	0
h15	0	0	0	0	0,34	0,82	0,87	0,93	0,63	0,37	0	0
h16	0	0	0	0,01	0,37	0,87	0,93	0,98	0,68	0,41	0	0
h17	0	0	0	0,01	0,39	0,88	0,95	1,00	0,70	0,41	0	0
h18	0	0	0	0	0,38	0,86	0,95	0,99	0,70	0,39	0	0
h19	0	0	0	0	0,35	0,84	0,91	0,95	0,67	0,34	0	0
h20	0	0	0	0	0,27	0,77	0,81	0,87	0,60	0,25	0	0
h21	0	0	0	0	0,17	0,65	0,68	0,74	0,48	0,17	0	0
h22	0	0	0	0	0,06	0,50	0,54	0,62	0,39	0,10	0	0
h23	0	0	0	0	0	0,42	0,46	0,52	0,30	0,04	0	0

Table 67. Cooling load factor

	January	*February*	*March*	*April*	*May*	*June*	*July*	*August*	*September*	*October*	*November*	*December*
h0	7,5	9,1	10,7	13,9	17,1	39,4	44,3	53,1	33,1	21,8	10,7	7,5
h1	7,5	9,1	10,7	13,9	17,1	37,6	42,1	50,8	31,3	13,9	10,7	7,5
h2	7,5	9,1	10,7	13,9	17,1	35,9	40,1	48,9	29,8	13,9	10,7	7,5
h3	7,5	9,1	10,7	13,9	17,1	33,9	37,9	46,6	28,2	13,9	10,7	7,5
h4	7,5	9,1	10,7	13,9	17,1	32,7	36,4	45,0	27,0	13,9	10,7	7,5
h5	7,5	9,1	10,7	13,9	17,1	31,5	35,4	43,5	17,1	13,9	10,7	7,5
h6	7,5	9,1	10,7	13,9	17,1	30,5	34,4	42,2	17,1	13,9	10,7	7,5
h7	7,5	9,1	10,7	13,9	17,1	29,5	33,5	41,0	17,1	13,9	10,7	7,5
h8	7,5	9,1	10,7	13,9	17,1	29,8	33,6	40,0	17,1	13,9	10,7	7,5
h9	7,5	9,1	10,7	13,9	17,1	32,4	36,1	42,2	17,1	13,9	10,7	7,5
h10	7,5	9,1	10,7	13,9	17,1	36,1	40,2	47,1	26,9	13,9	10,7	7,5
h11	7,5	9,1	10,7	13,9	17,1	40,4	44,8	53,0	30,9	13,9	10,7	7,5
h12	7,5	9,1	10,7	13,9	29,2	44,7	49,6	59,0	35,2	23,7	10,7	7,5
h13	7,5	9,1	10,7	13,9	32,3	48,6	53,9	64,4	38,9	26,4	10,7	7,5
h14	7,5	9,1	10,7	13,9	34,5	51,9	57,4	68,8	41,7	27,8	10,7	7,5
h15	7,5	9,1	10,7	13,9	35,8	53,3	59,3	70,9	43,6	29,8	10,7	7,5
h16	7,5	9,1	10,7	22,0	36,8	54,8	61,1	72,8	44,9	30,6	10,7	7,5
h17	7,5	9,1	10,7	22,0	37,1	55,0	62,0	73,5	45,6	30,6	10,7	7,5
h18	7,5	9,1	10,7	13,9	36,9	54,3	62,1	73,2	45,5	30,3	10,7	7,5
h19	7,5	9,1	10,7	13,9	36,1	53,7	60,5	71,7	44,7	29,2	10,7	7,5
h20	7,5	9,1	10,7	13,9	34,1	51,9	57,6	68,7	42,8	27,3	10,7	7,5
h21	7,5	9,1	10,7	13,9	31,3	48,4	53,4	64,1	39,7	25,5	10,7	7,5
h22	7,5	9,1	10,7	13,9	28,2	43,9	49,0	59,4	37,1	23,9	10,7	7,5
h23	7,5	9,1	10,7	13,9	17,1	41,4	46,4	55,8	34,9	22,6	10,7	7,5

Table 68. Cooling consumption – Seville

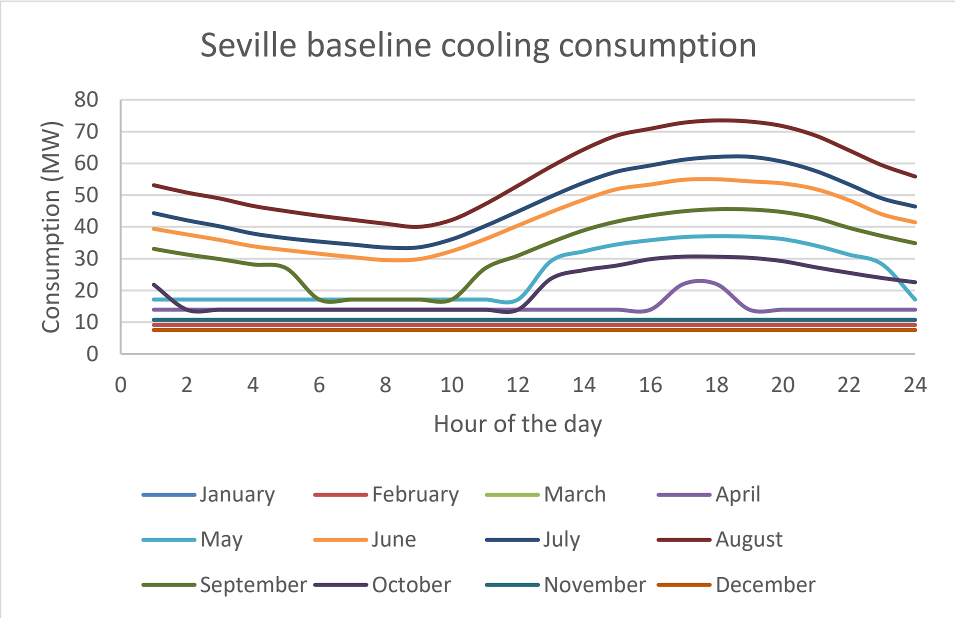


Figure 29. Seville baseline cooling consumption

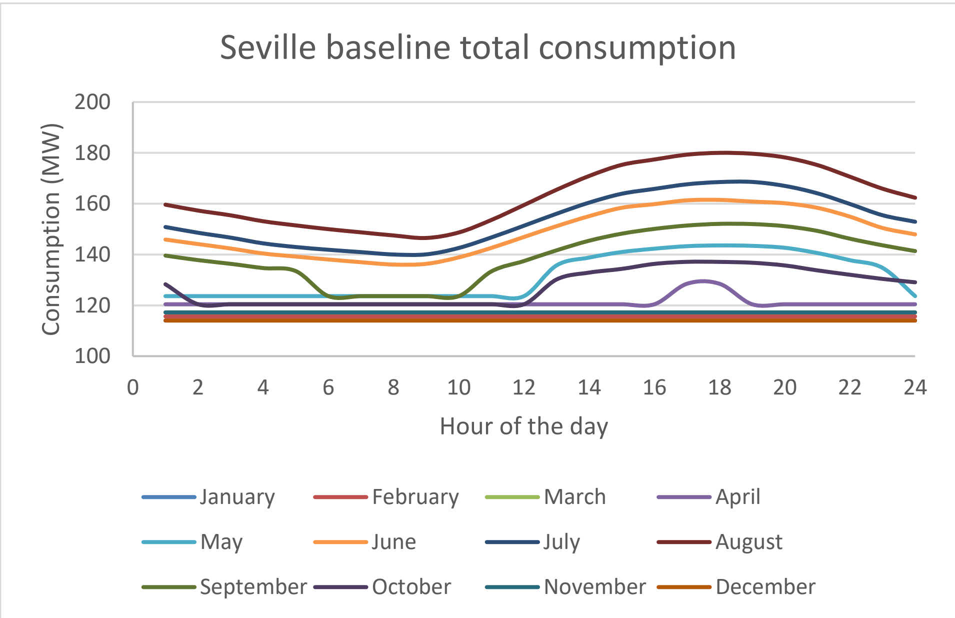


Figure 30. Seville baseline total consumption

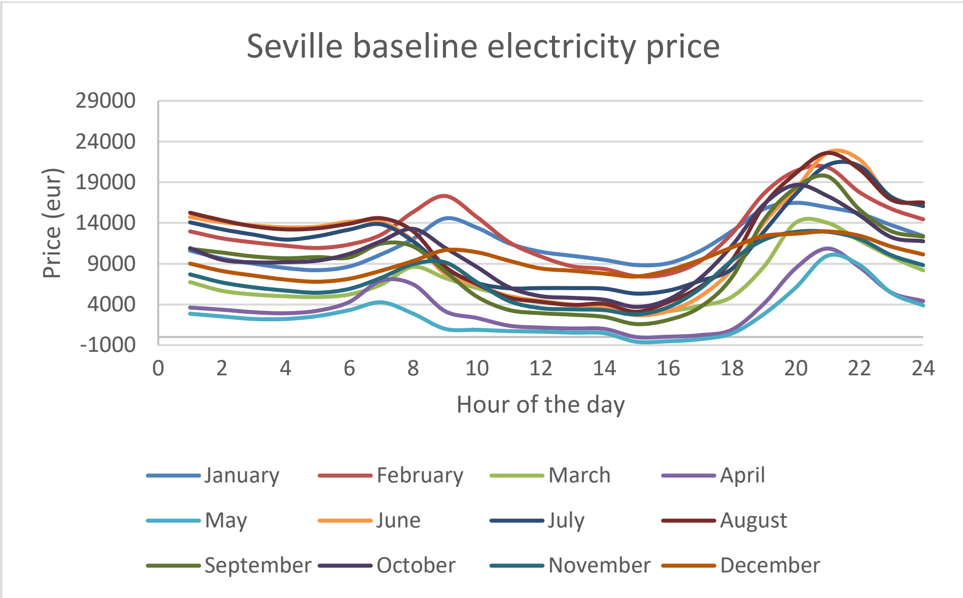


Figure 31. Seville baseline electricity price

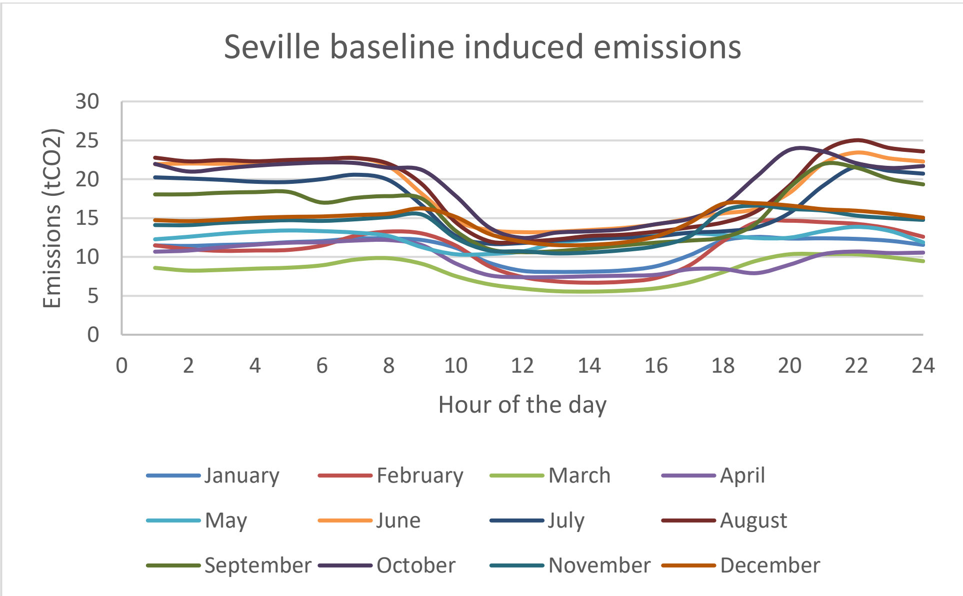


Figure 32. Seville baseline induced emissions

ANNEX IV. MODEL TES SCENARIOS OUTPUTS

3 hour TES – 150 MWh

MW	*January*	*February*	*March*	*April*	*May*	*June*	*July*	*August*	*September*	*October*	*November*	*December*
h0	0	0	0	0	0	-14	-17	-17	-1	0	0	0
h1	0	0	0	0	0	-5	-7	-15	0	0	0	0
h2	0	0	0	0	0	-3	-4	-14	0	0	0	0
h3	0	0	0	0	0	-1	-2	-12	0	0	0	0
h4	0	0	0	0	0	0	0	-1	0	0	0	0
h5	0	0	0	0	0	0	0	0	0	0	0	0
h6	0	0	0	0	0	-2	-2	0	0	0	0	0
h7	0	0	0	0	0	-13	-6	-13	0	0	0	0
h8	0	0	0	0	0	-17	-19	-18	-1	0	0	0
h9	0	0	0	0	0	0	0	0	0	0	0	0
h10	0	0	0	0	0	0	0	0	0	0	0	0
h11	0	0	0	0	0	0	0	0	0	0	0	0
h12	0	0	0	0	0	30	0	50	50	0	0	0
h13	0	0	0	0	0	50	47	50	1	0	0	0
h14	0	0	0	0	0	50	50	50	0	0	0	0
h15	0	0	0	0	0	0	50	0	0	0	0	0
h16	0	0	0	0	0	0	0	0	0	0	0	0
h17	0	0	0	0	0	0	0	0	0	0	0	0
h18	0	0	0	0	0	0	0	0	0	0	0	0
h19	0	0	0	0	0	0	0	0	-18	0	0	0
h20	0	0	0	0	0	-22	-28	-27	-17	0	0	0
h21	0	0	0	0	0	-19	-24	-24	-7	0	0	0
h22	0	0	0	0	0	-17	-22	-6	-5	0	0	0
h23	0	0	0	0	0	-16	-19	0	-3	0	0	0

Table 69. 3 hour TES charged and discharged energy

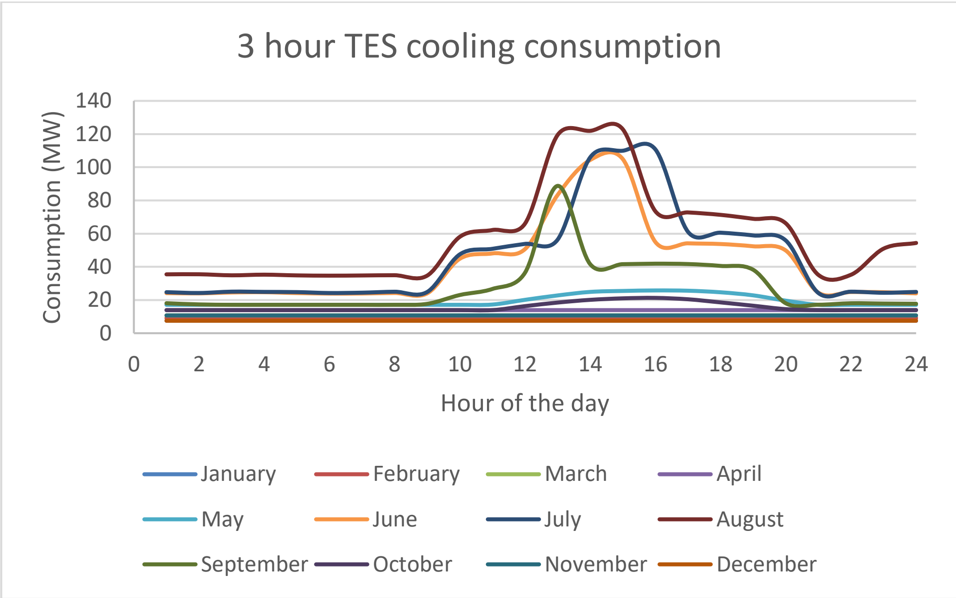


Figure 33. 3 hour TES cooling consumption

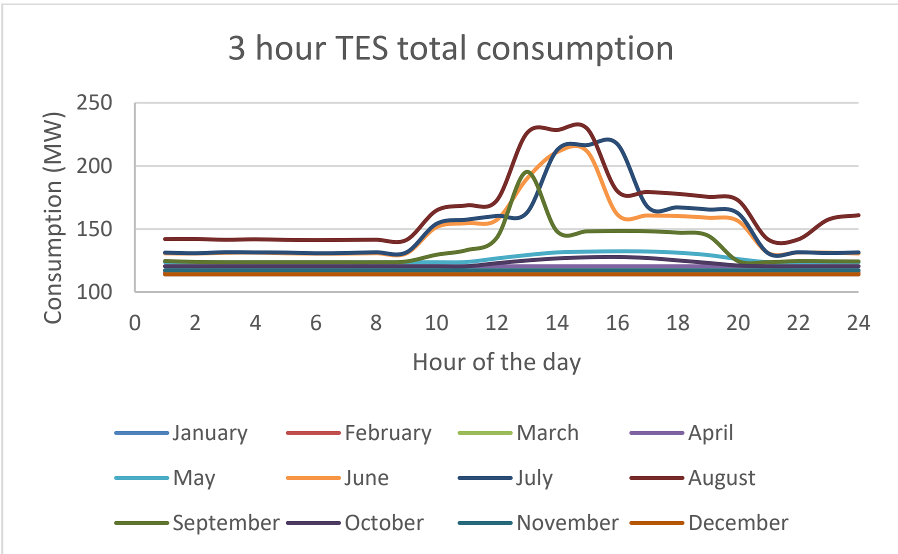


Figure 34. 3 hour TES total consumption

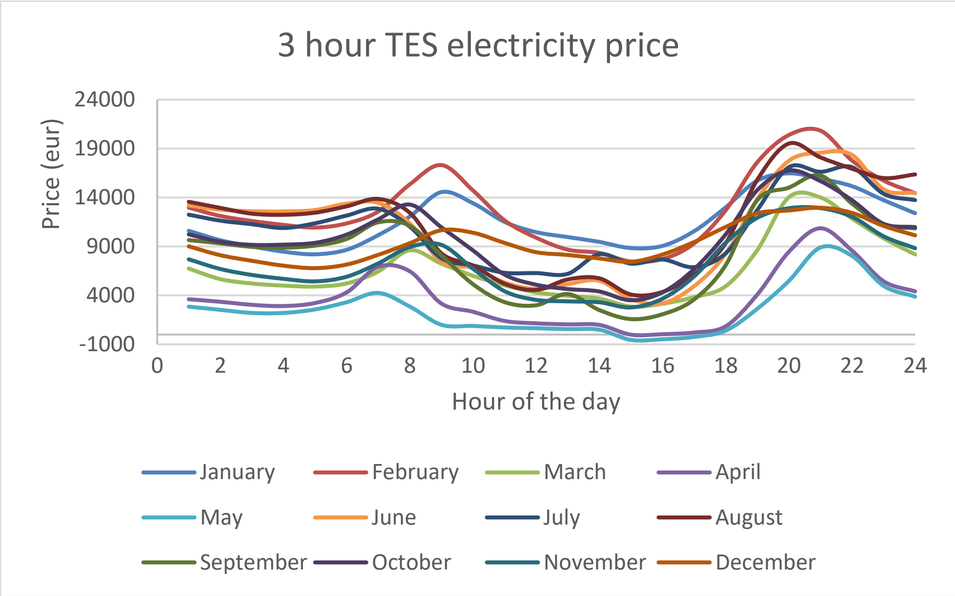


Figure 35. 3 hour TES electricity price

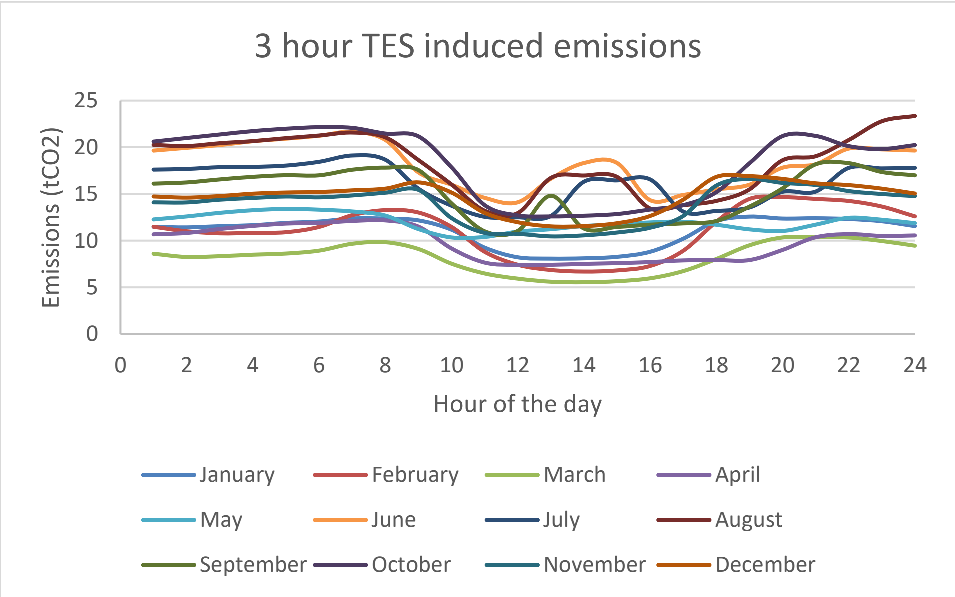


Figure 36. 3 hour TES induced emissions

2 hour TES – 100 MWh

MW	*January*	*February*	*March*	*April*	*May*	*June*	*July*	*August*	*September*	*October*	*November*	*December*
h0	0	0	0	0	0	-14	-11	0	-2	0	0	0
h1	0	0	0	0	0	-5	-7	0	0	0	0	0
h2	0	0	0	0	0	-4	-5	-5	0	0	0	0
h3	0	0	0	0	0	-2	-2	-13	0	0	0	0
h4	0	0	0	0	0	0	-1	-1	0	0	0	0
h5	0	0	0	0	0	0	0	0	0	0	0	0
h6	0	0	0	0	0	-2	-2	0	0	0	0	0
h7	0	0	0	0	0	-13	-7	-14	0	0	0	0
h8	0	0	0	0	0	0	0	0	-1	0	0	0
h9	0	0	0	0	0	0	0	0	0	0	0	0
h10	0	0	0	0	0	0	0	0	0	0	0	0
h11	0	0	0	0	0	0	0	0	0	0	0	0
h12	0	0	0	0	0	0	0	50	50	0	0	0
h13	0	0	0	0	0	50	0	0	6	1	0	0
h14	0	0	0	0	0	50	50	50	0	0	0	0
h15	0	0	0	0	0	0	50	0	0	0	0	0
h16	0	0	0	0	0	0	0	0	0	0	0	0
h17	0	0	0	0	0	0	0	0	0	0	0	0
h18	0	0	0	0	0	0	0	0	0	0	0	0
h19	0	0	0	0	0	0	0	0	-19	-1	0	0
h20	0	0	0	0	0	-4	0	0	-17	0	0	0
h21	0	0	0	0	0	-20	-25	-25	-8	0	0	0
h22	0	0	0	0	0	-18	-22	-22	-6	0	0	0
h23	0	0	0	0	0	-16	-19	-20	-3	0	0	0

Table 70. 2 hour TES charged and discharged energy

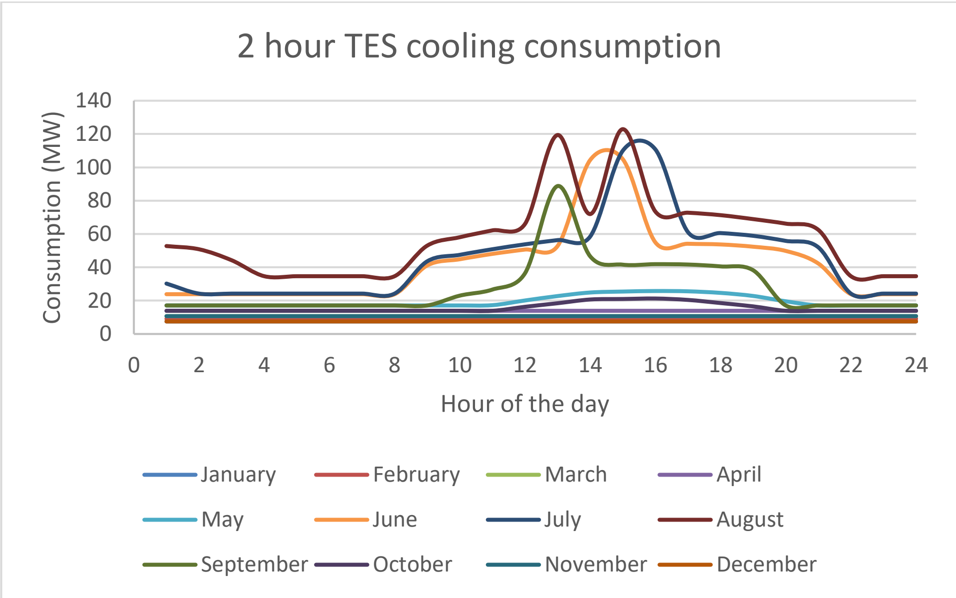


Figure 37. 2 hour TES cooling consumption

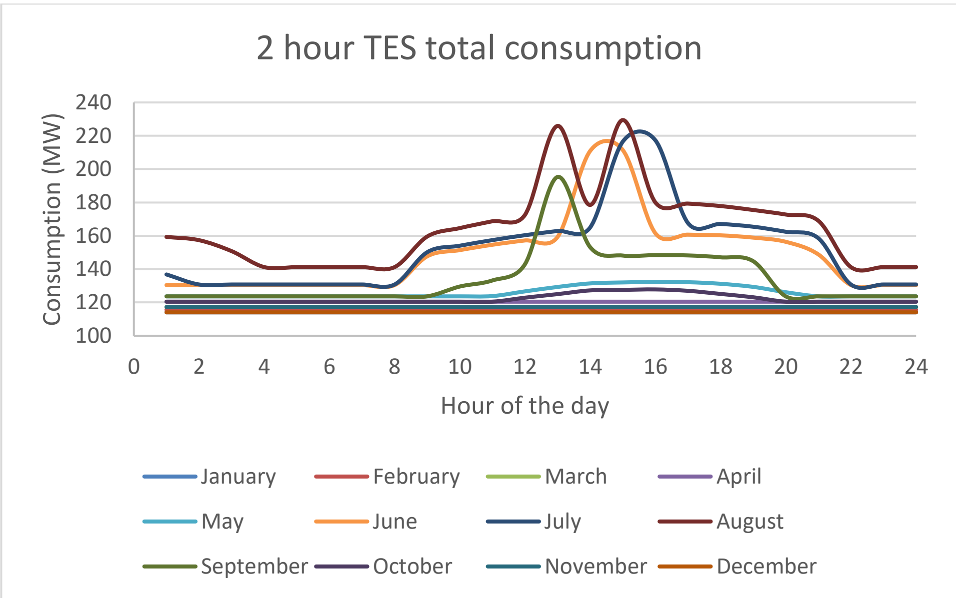


Figure 38. 2 hour TES total consumption

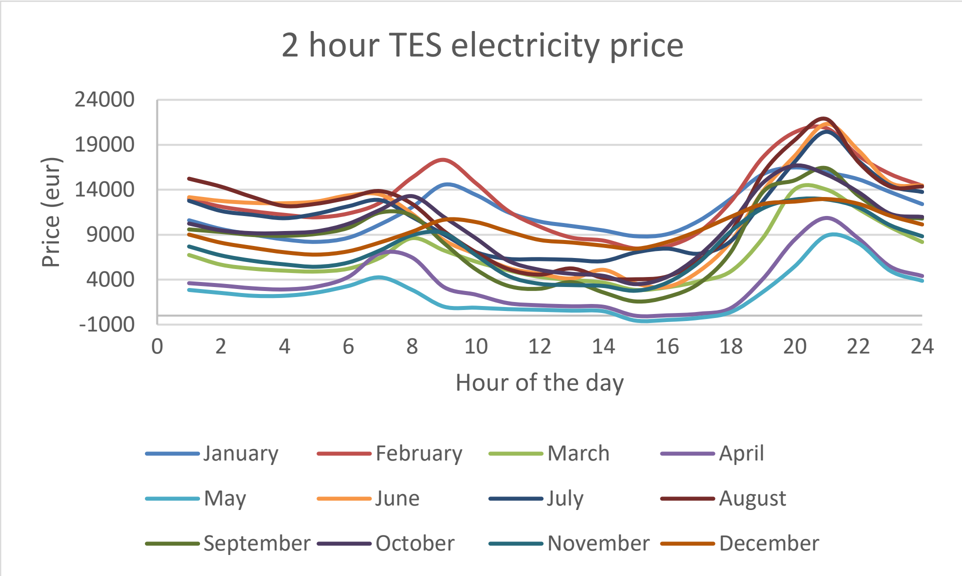


Figure 39. 2 hour TES electricity price

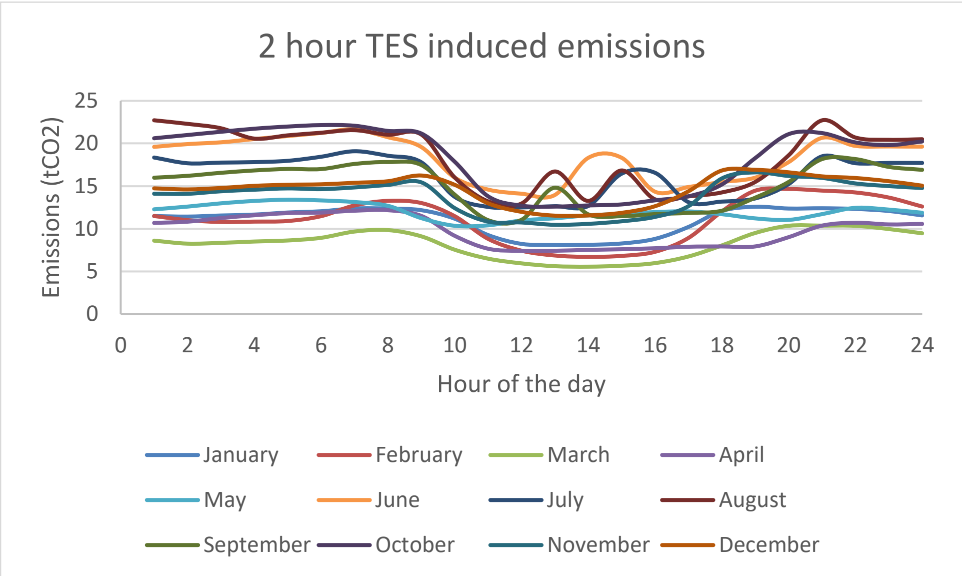


Figure 40. 2 hour TES induced emissions

1 hour TES – 50 MWh

MW	***January***	***February***	***March***	***April***	***May***	***June***	***July***	***August***	***September***	***October***	***November***	***December***
h0	0	0	0	0	0	0	0	0	-2	0	0	0
h1	0	0	0	0	0	-5	0	0	0	0	0	0
h2	0	0	0	0	0	-4	-5	0	0	0	0	0
h3	0	0	0	0	0	-2	-2	-10	0	0	0	0
h4	0	0	0	0	0	0	-1	-1	0	0	0	0
h5	0	0	0	0	0	0	0	0	0	0	0	0
h6	0	0	0	0	0	-2	-2	0	0	0	0	0
h7	0	0	0	0	0	-13	-7	-14	0	0	0	0
h8	0	0	0	0	0	0	0	0	-1	0	0	0
h9	0	0	0	0	0	0	0	0	0	0	0	0
h10	0	0	0	0	0	0	0	0	0	0	0	0
h11	0	0	0	0	0	0	0	0	0	0	0	0
h12	0	0	0	0	0	0	0	0	50	0	0	0
h13	0	0	0	0	0	0	0	0	0	1	0	0
h14	0	0	0	0	0	50	50	50	0	0	0	0
h15	0	0	0	0	0	0	0	0	0	0	0	0
h16	0	0	0	0	0	0	0	0	0	0	0	0
h17	0	0	0	0	0	0	0	0	0	0	0	0
h18	0	0	0	0	0	0	0	0	0	0	0	0
h19	0	0	0	0	0	0	0	0	-13	-1	0	0
h20	0	0	0	0	0	0	0	0	-17	0	0	0
h21	0	0	0	0	0	-20	0	-25	-8	0	0	0
h22	0	0	0	0	0	-3	-22	0	-6	0	0	0
h23	0	0	0	0	0	0	-12	0	-3	0	0	0

Table 71. 1 hour TES charged and discharged energy

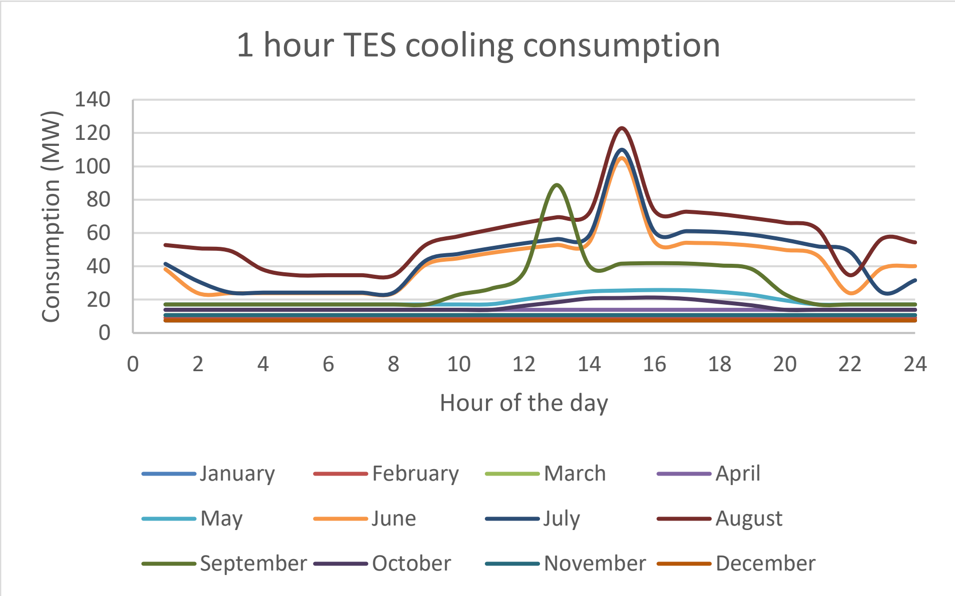


Figure 41. 1 hour TES cooling consumption

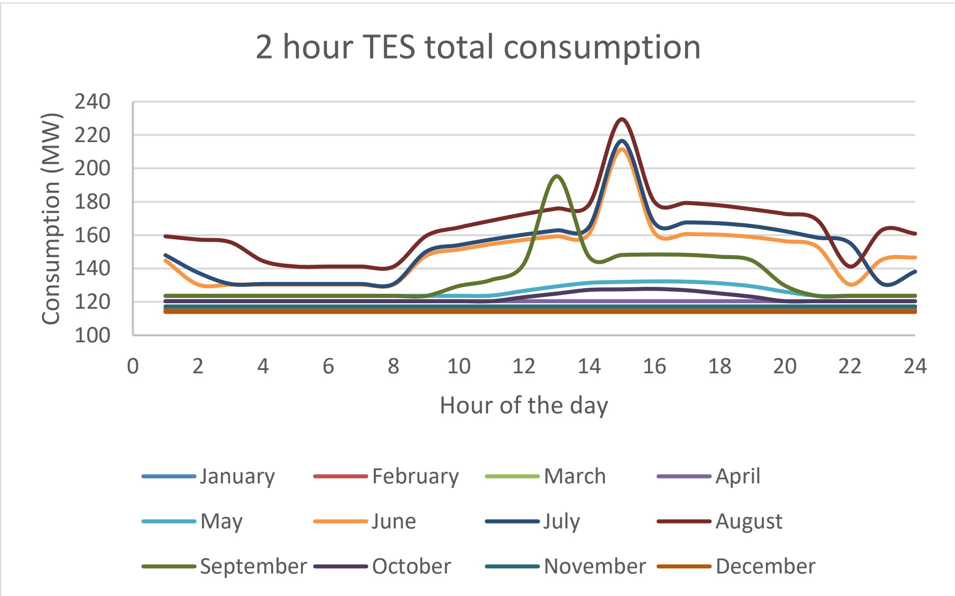


Figure 42. 1 hour TES total consumption

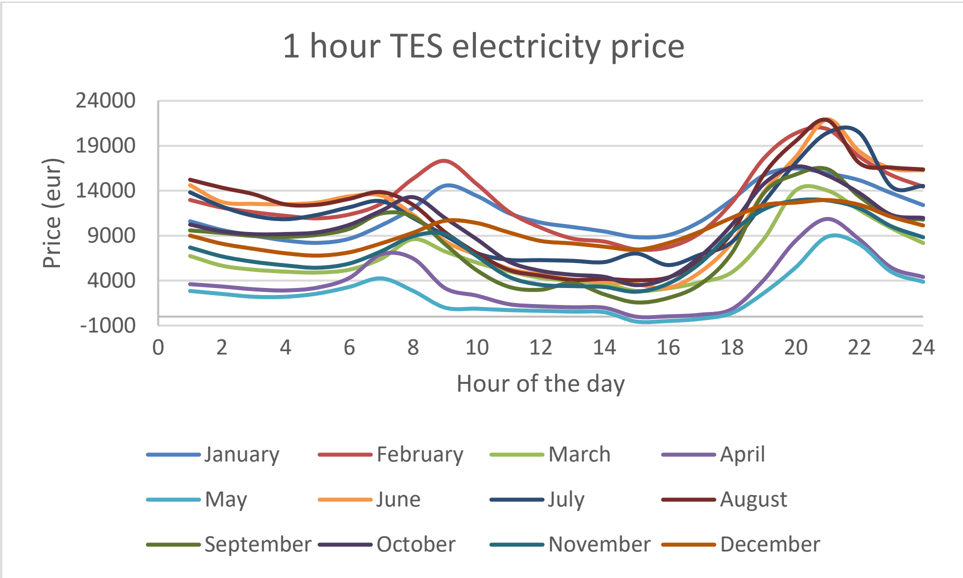


Figure 43. 1 hour TES electricity price

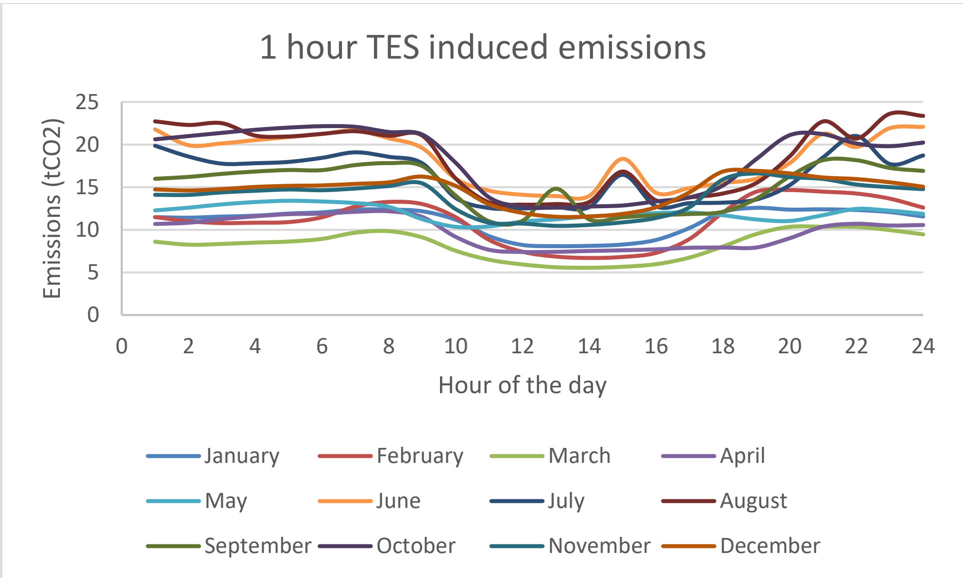


Figure 44. 1 hour TES induced emissions

3 hour TES Seville – 150 MWh

MW	*January*	*February*	*March*	*April*	*May*	*June*	*July*	*August*	*September*	*October*	*November*	*December*
h0	0	0	0	0	-5	-8	-9	-10	-15	-12	0	0
h1	0	0	0	0	-3	-6	-7	-9	-14	-6	0	0
h2	0	0	0	0	-2	-5	-5	-7	-13	-5	0	0
h3	0	0	0	0	0	-3	-3	-5	-11	-4	0	0
h4	0	0	0	0	0	-2	-2	-4	-10	-3	0	0
h5	0	0	0	0	0	-2	-1	-3	-3	-2	0	0
h6	0	0	0	0	0	-1	-1	-2	-2	-1	0	0
h7	0	0	0	0	0	0	0	-1	-1	-1	0	0
h8	0	0	0	0	0	0	0	0	0	0	0	0
h9	0	0	0	0	50	-2	-2	-2	0	0	0	0
h10	0	0	0	0	50	-5	-5	0	0	0	0	0
h11	0	0	0	50	50	0	0	0	50	0	0	0
h12	0	0	0	11	0	50	0	50	50	50	1	0
h13	0	0	0	-4	0	50	50	50	50	50	0	0
h14	0	0	0	-5	-5	50	50	50	0	50	0	0
h15	0	0	0	-8	-22	0	50	0	0	0	0	0
h16	0	0	0	-13	-23	-3	0	0	0	0	-1	0
h17	0	0	0	-13	-23	-20	-13	0	0	-18	0	0
h18	0	0	0	-7	0	-20	-23	-13	0	-19	0	0
h19	0	0	0	-6	0	-19	-21	-25	-2	-18	0	0
h20	0	0	0	-4	-21	-18	-19	-23	-23	-17	0	0
h21	0	0	0	-1	-19	-15	-16	-19	-20	-15	0	0
h22	0	0	0	0	-16	-11	-12	-15	-18	-14	0	0
h23	0	0	0	0	-9	-9	-10	-13	-17	-13	0	0

Table 72. 3 hour TES Seville charged and discharged energy

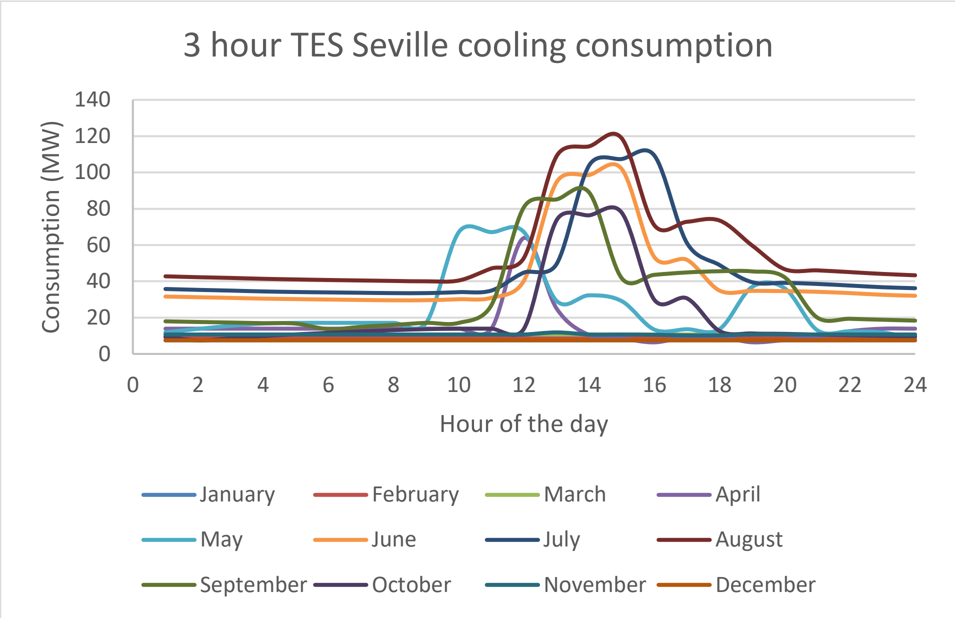


Figure 45. 3 hour TES Seville cooling consumption

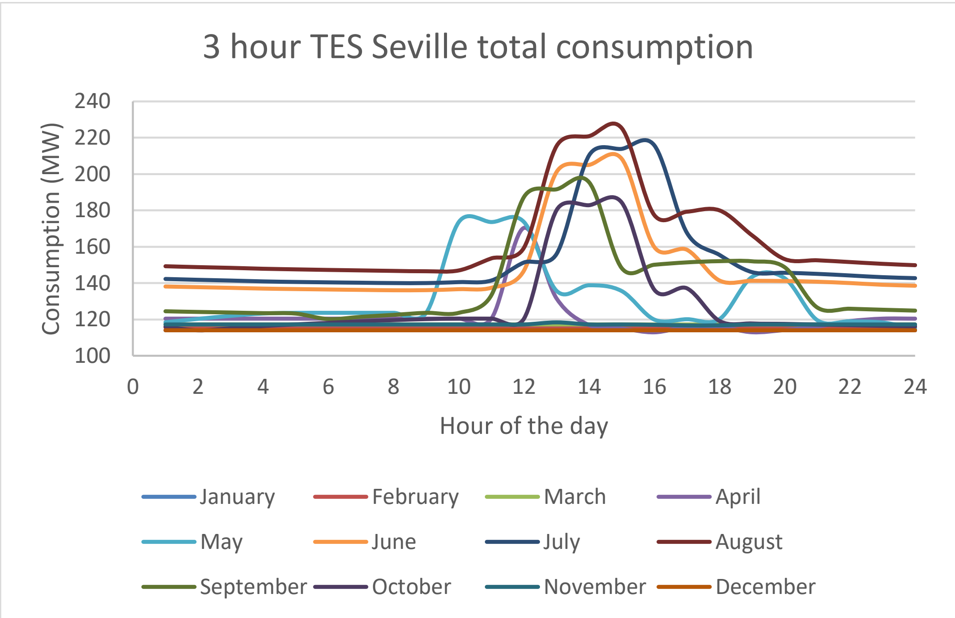


Figure 46. 3 hour TES Seville total consumption

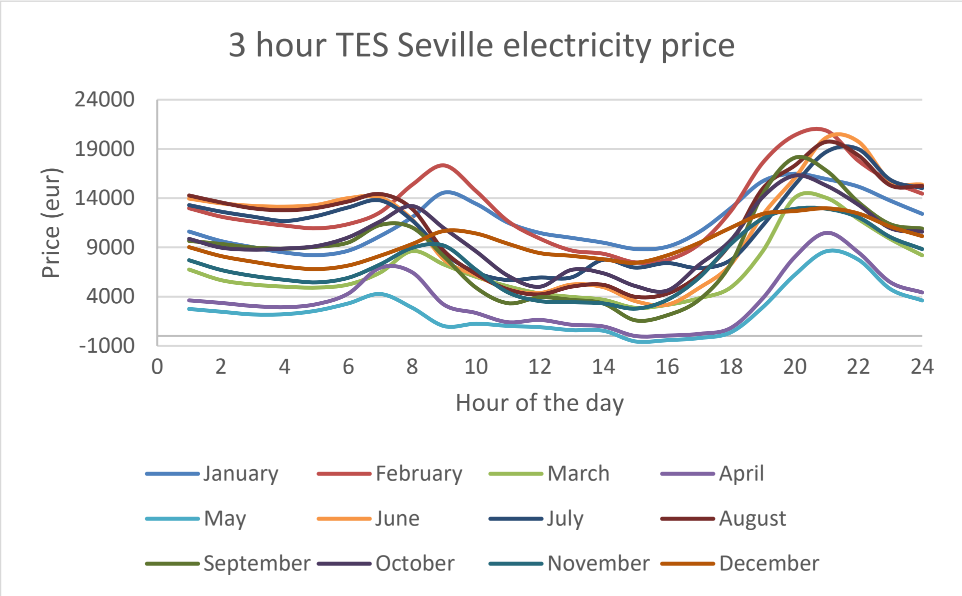


Figure 47. 3 hour TES Seville electricity price

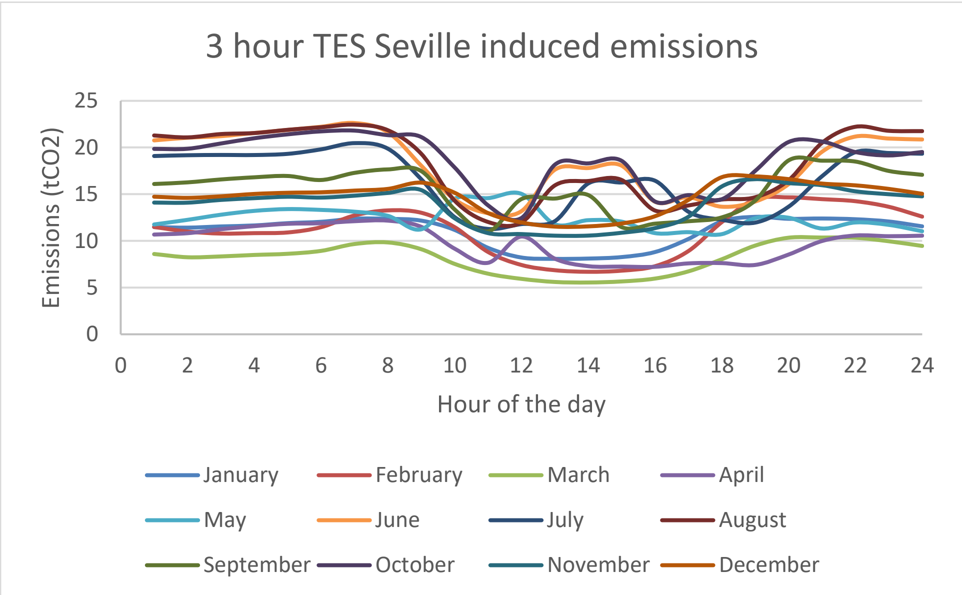


Figure 48. 3 hour TES Seville induced emissions

ANNEX V. MODEL BESS SCENARIOS OUTPUTS

In the graphs representing the total consumption it can seem like the graph goes below cero. However, this is just due to the graph format, the minimum consumption from the grid is cero.

BESS 120 MW – 360 MWh

MW	***January***	***February***	***March***	***April***	***May***	***June***	***July***	***August***	***September***	***October***	***November***	***December***
h0	-18	-13	-8	0	0	0	0	0	0	0	-8	-18
h1	0	0	0	0	0	0	0	0	0	0	0	0
h2	0	0	0	0	0	0	0	0	0	0	0	0
h3	0	0	0	0	-120	0	0	0	0	0	0	0
h4	0	0	0	0	-120	-120	0	0	0	-120	0	0
h5	0	0	0	-120	-120	-120	-120	-120	0	-120	0	0
h6	-114	0	0	-120	0	-120	-120	-120	0	-120	0	0
h7	0	0	0	-120	0	0	-120	-120	-120	0	0	0
h8	0	0	0	0	0	0	0	0	0	0	0	0
h9	0	0	0	0	133	0	0	0	0	0	0	0
h10	0	0	0	0	133	0	0	0	0	0	0	0
h11	133	0	0	133	133	0	0	0	133	0	133	0
h12	133	133	133	133	0	133	0	133	133	133	133	133
h13	133	133	133	133	0	133	133	133	133	133	133	133
h14	0	133	133	0	0	133	133	133	0	133	0	133
h15	0	0	0	0	0	0	133	0	0	0	0	0
h16	0	0	0	0	0	0	0	0	0	0	0	0
h17	0	0	0	0	0	0	0	0	0	0	0	-114
h18	-114	-116	0	0	0	0	0	0	0	0	-117	-114
h19	0	-116	-117	0	0	0	0	0	0	0	-117	-114
h20	-114	-116	-117	0	0	0	0	0	-120	0	-117	0

h21	0	0	-117	0	0	0	0	0	-120	0	0	0
h22	0	0	0	0	0	0	0	0	0	0	0	0
h23	0	0	0	0	0	0	0	0	0	0	0	0

Table 73. BESS 120 MW - 360 MWh charged and discharged energy

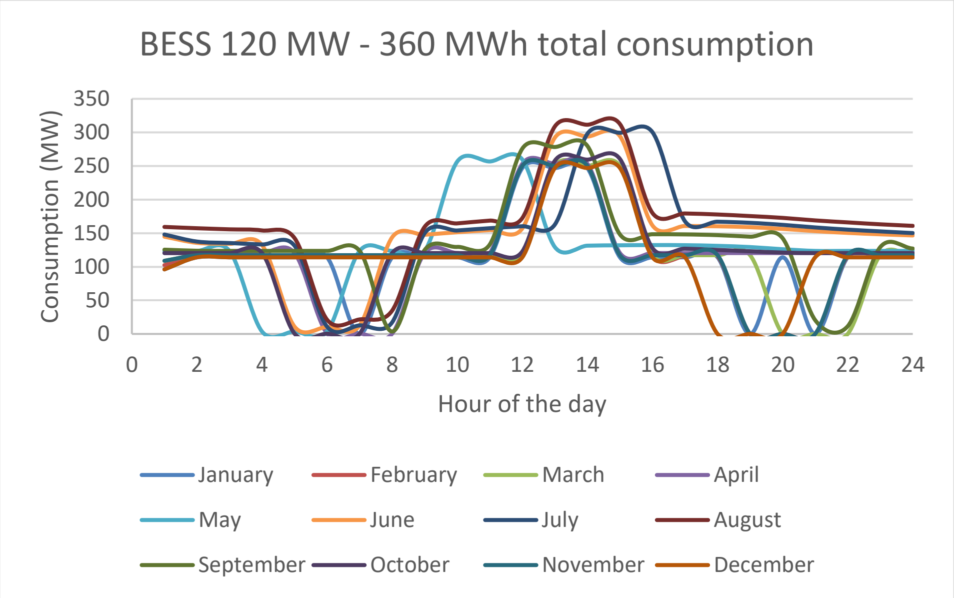


Figure 49. BESS 120 MW - 360 MWh total consumption

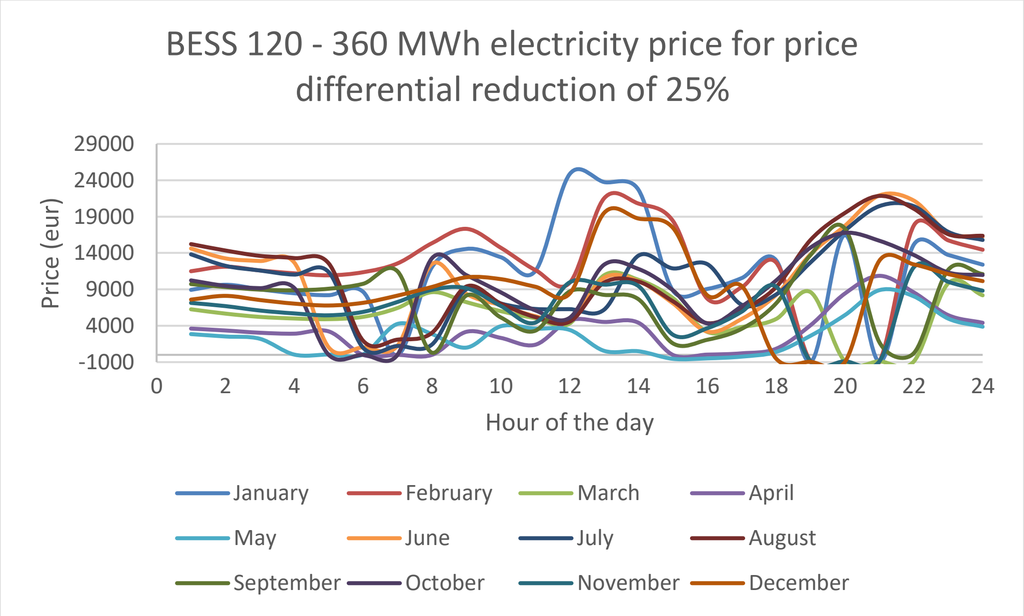


Figure 50. BESS 120 MW - 360 MWh electricity price for price differential reduction of 25%

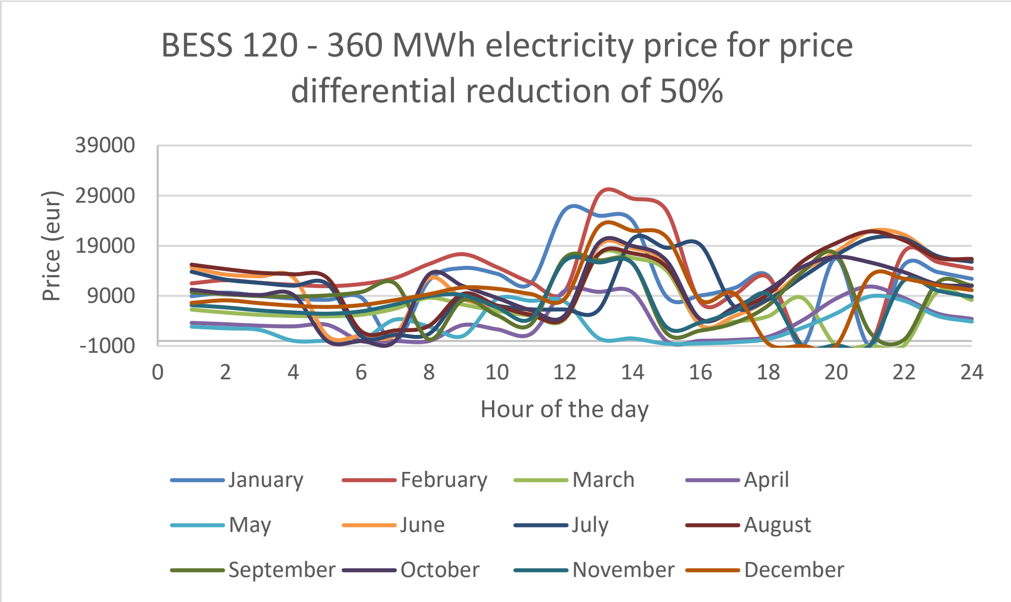


Figure 51. BESS 120 MW - 360 MWh electricity price for price differential reduction of 50%

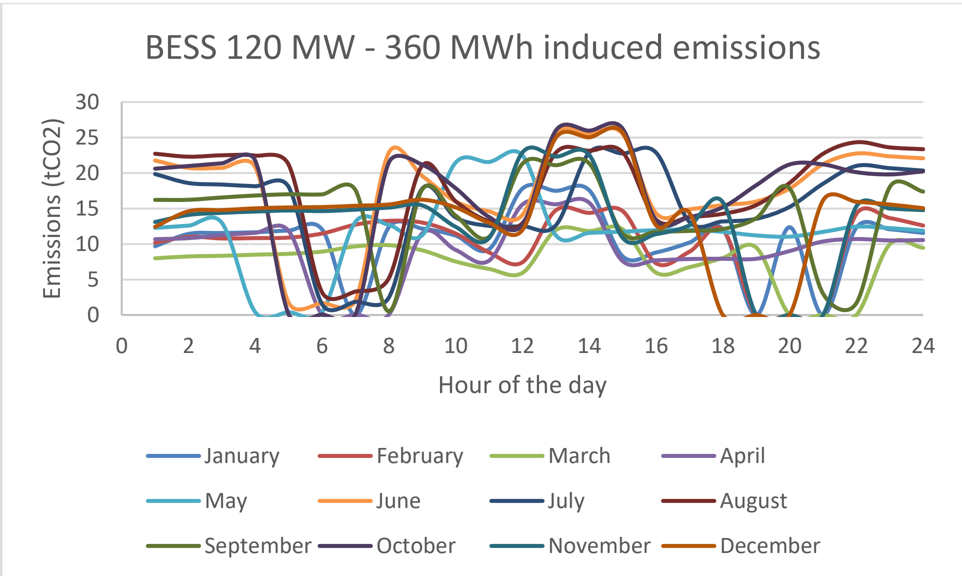


Figure 52. BESS 120 MW - 360 MWh induced emissions

BESS 120 MW – 480 MWh

MW	***January***	***February***	***March***	***April***	***May***	***June***	***July***	***August***	***September***	***October***	***November***	***December***
h0	-24	-18	-11	0	0	0	0	0	0	0	-11	-24
h1	0	0	0	0	0	0	0	0	0	0	0	0
h2	0	0	0	0	0	0	0	0	0	0	0	0
h3	0	0	0	0	-120	0	0	0	0	-120	0	0
h4	0	0	0	-120	-120	-120	-120	-120	0	-120	0	0
h5	0	0	0	-120	-120	-120	-120	-120	0	-120	0	0
h6	-114	0	0	-120	-120	-120	-120	-120	-120	-120	0	0
h7	0	0	0	-120	0	-120	-120	-120	-120	0	0	0
h8	0	0	0	0	0	0	0	0	0	0	0	-114
h9	0	0	0	0	133	0	0	0	0	0	0	0
h10	0	0	0	0	133	0	0	0	0	0	133	0
h11	133	0	133	133	133	0	0	0	133	133	133	133
h12	133	133	133	133	0	133	133	133	133	133	133	133
h13	133	133	133	133	0	133	133	133	133	133	133	133
h14	133	133	133	133	0	133	133	133	133	133	0	133
h15	0	133	0	0	0	133	133	133	0	0	0	0
h16	0	0	0	0	0	0	0	0	0	0	0	0
h17	0	0	0	0	0	0	0	0	0	0	-117	-114
h18	-114	-116	0	0	133	0	0	0	0	0	-117	-114
h19	-114	-116	-117	0	0	0	0	0	0	0	-117	-114
h20	-114	-116	-117	0	0	0	0	0	-120	0	-117	0
h21	0	-116	-117	0	0	0	0	0	-120	0	0	0
h22	0	0	-117	0	0	0	0	0	0	0	0	0
h23	0	0	0	0	0	0	0	0	0	0	0	0

Table 74. BESS 120 MW - 480 MWh charged and discharged energy

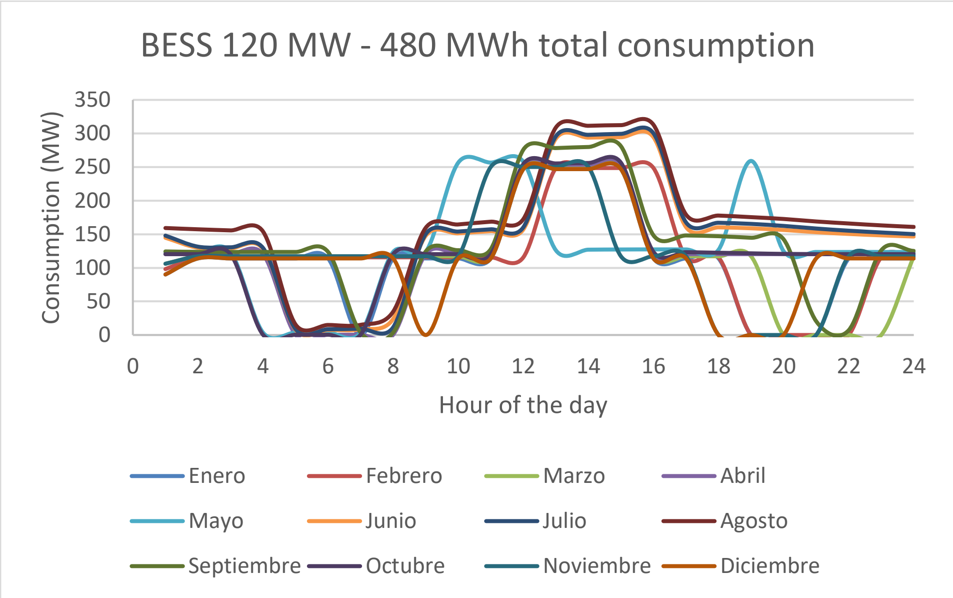


Figure 53. BESS 120 MW - 480 MWh total consumption

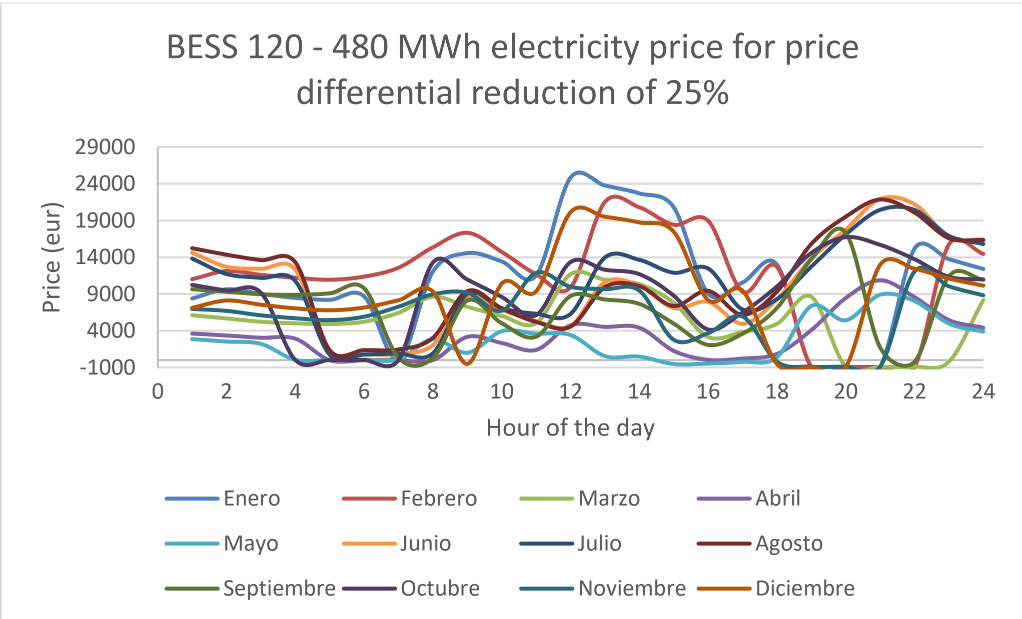


Figure 54. BESS 120 MW - 480 MWh electricity price for price reduction differential of 25%

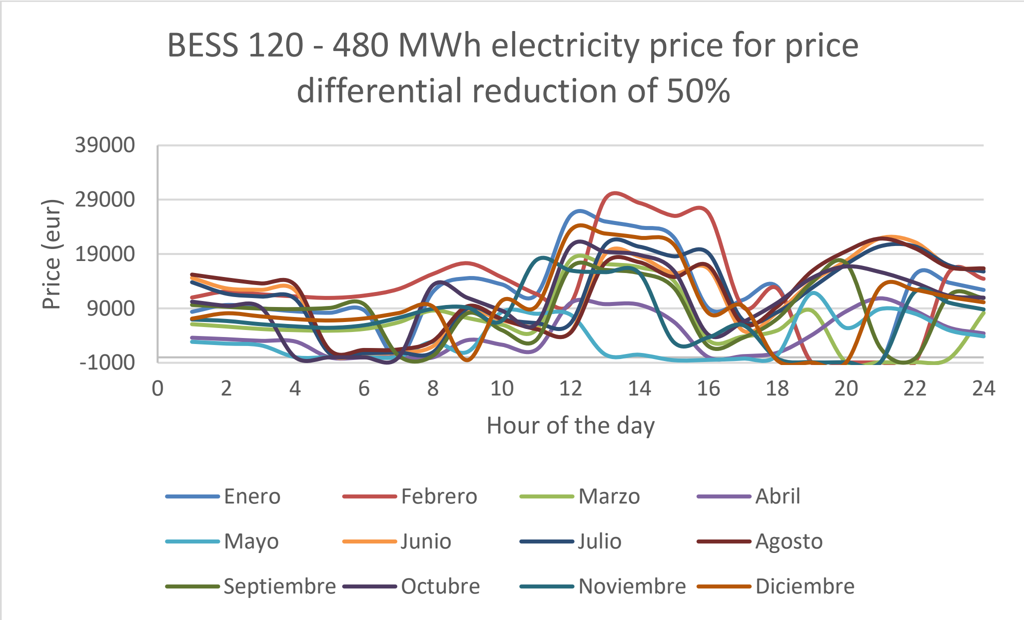


Figure 55. BESS 120 MW - 480 MWh electricity price for price reduction differential of 50%

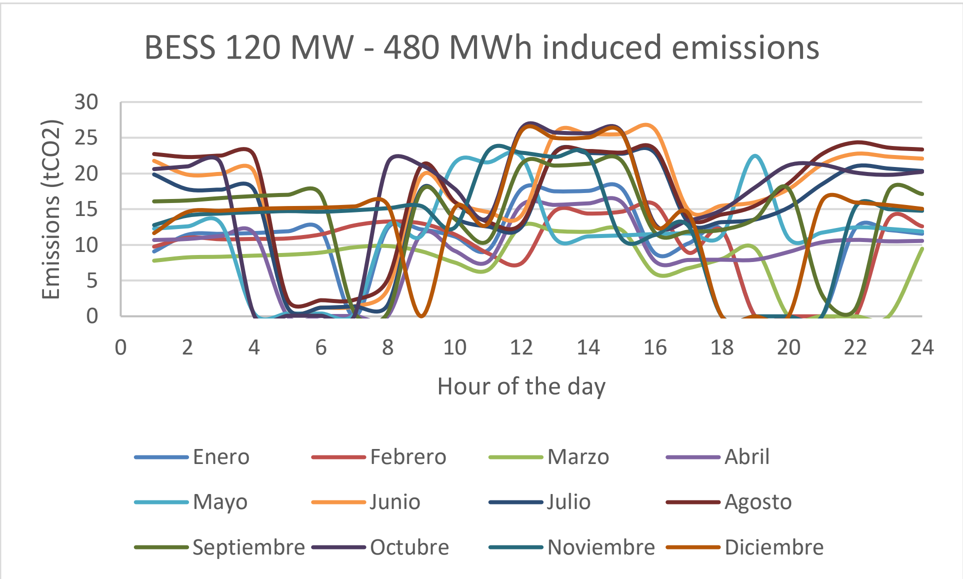


Figure 56. BESS 120 MW - 480 MWh induced emissions

BESS 120 MW – 600 MWh

MW	***January***	***February***	***March***	***April***	***May***	***June***	***July***	***August***	***September***	***October***	***November***	***December***
h0	-30	-22	-14	0	0	0	0	0	0	0	-14	-30
h1	0	0	0	0	0	0	0	0	0	0	0	0
h2	0	0	0	0	-120	0	0	0	0	0	0	0
h3	0	0	0	-120	-120	-120	-120	0	0	-120	0	0
h4	0	0	0	-120	-120	-120	-120	-120	0	-120	0	0
h5	0	0	0	-120	-120	-120	-120	-120	0	-120	0	0
h6	-114	0	0	-120	-120	-120	-120	-120	-120	-120	0	0
h7	-114	0	-117	-120	0	-120	-120	-120	-120	-120	0	0
h8	0	0	0	0	0	0	0	0	-120	0	-117	-114
h9	0	0	0	0	133	0	0	0	0	0	0	0
h10	0	0	0	133	133	0	0	0	0	0	133	0
h11	133	133	133	133	133	133	133	133	133	133	133	133
h12	133	133	133	133	133	133	133	133	133	133	133	133
h13	133	133	133	133	0	133	133	133	133	133	133	133
h14	133	133	133	133	0	133	133	133	133	133	133	133
h15	133	133	133	0	0	133	133	133	133	133	0	133
h16	0	0	0	0	0	0	0	0	0	0	0	0
h17	0	0	0	0	0	0	0	0	0	0	-117	-114
h18	-114	-116	0	0	133	0	0	0	0	0	-117	-114
h19	-114	-116	-117	0	0	0	0	0	0	0	-117	-114
h20	-114	-116	-117	0	0	0	0	0	-120	0	-117	-114
h21	0	-116	-117	0	0	0	0	-120	-120	0	0	0
h22	0	-116	-117	0	0	0	0	0	0	0	0	0
h23	0	0	0	0	0	0	0	0	0	0	0	0

Table 75. BESS 120 MW - 600 MWh charged and discharged energy

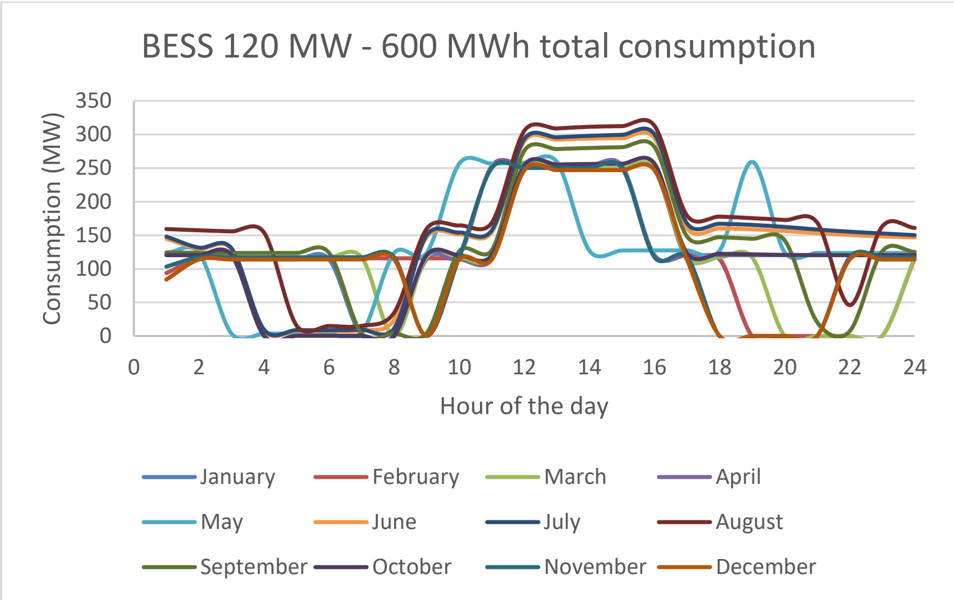


Figure 57. BESS 120 MW - 600 MWh total consumption

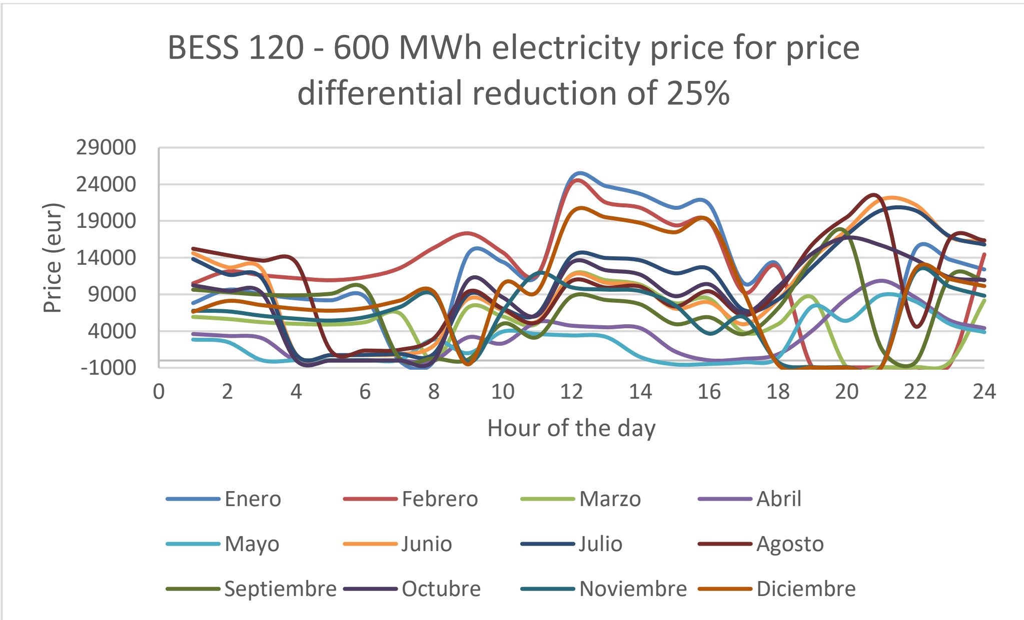


Figure 58. BESS 120 MW - 600 MWh electricity price for price differential reduction of 25%

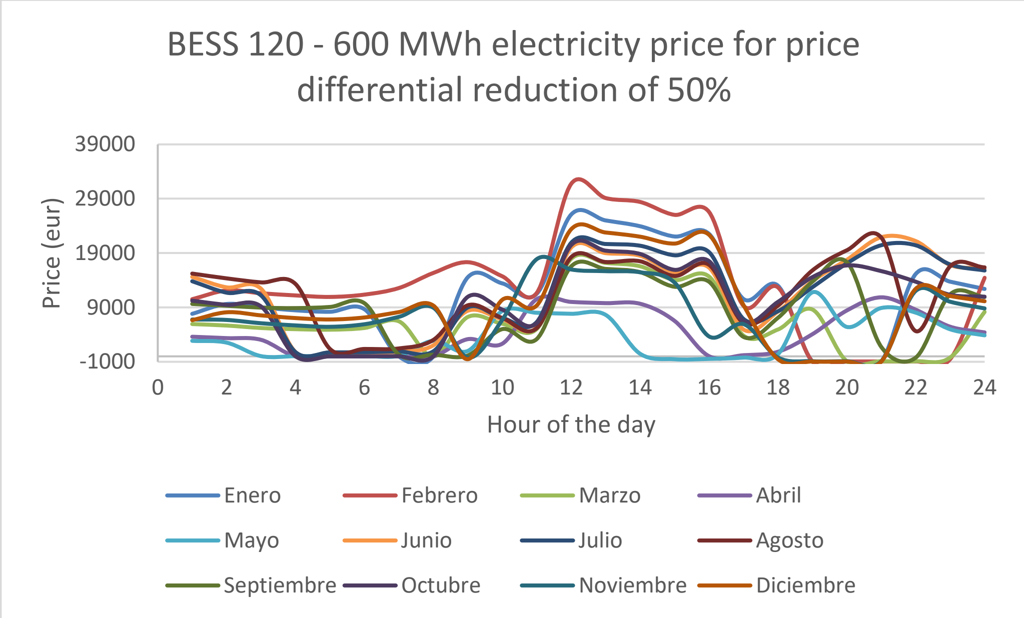


Figure 59. BESS 120 MW - 600 MWh electricity price for price differential reduction of 50%

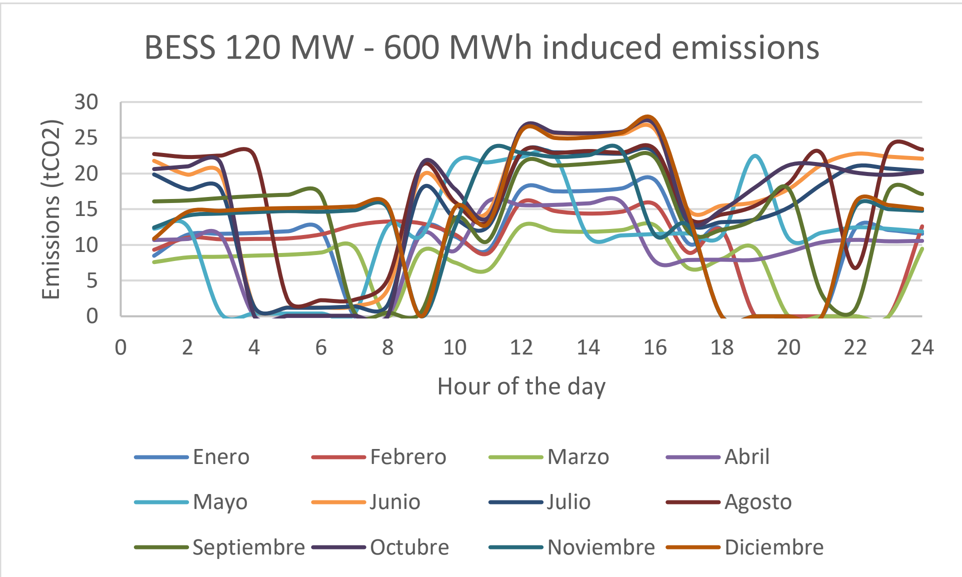


Figure 60. BESS 120 MW - 600 MWh induced emissions

BESS 120 MW – 720 MWh

MW	*January*	*February*	*March*	*April*	*May*	*June*	*July*	*August*	*September*	*October*	*November*	*December*
h0	-36	-26	-17	0	0	0	0	0	0	0	-17	-36
h1	0	0	0	0	0	0	0	0	0	0	0	0
h2	0	0	0	0	-120	-120	-120	0	0	-120	0	0
h3	0	0	0	-120	-120	-120	-120	-120	0	-120	0	0
h4	0	0	0	-120	-120	-120	-120	-120	0	-120	0	0
h5	0	0	0	-120	-120	-120	-120	-120	0	-120	0	0
h6	-114	0	-117	-120	-120	-120	-120	-120	-120	-120	0	0
h7	-114	-116	-117	-120	-120	-120	-120	-120	-120	-120	0	0
h8	0	0	0	-120	0	0	0	0	-120	0	-117	-114
h9	0	0	0	0	133	0	0	0	0	0	0	0
h10	133	133	133	133	133	0	0	0	0	0	133	133
h11	133	133	133	133	133	133	133	133	133	133	133	133
h12	133	133	133	133	133	133	133	133	133	133	133	133
h13	133	133	133	133	0	133	133	133	133	133	133	133
h14	133	133	133	133	0	133	133	133	133	133	133	133
h15	133	133	133	133	0	133	133	133	133	133	133	133
h16	0	0	0	0	0	133	133	133	133	133	0	0
h17	0	0	0	0	0	0	0	0	0	0	-117	-114
h18	-114	-116	0	0	133	0	0	0	0	0	-117	-114
h19	-114	-116	-117	0	133	0	0	0	0	0	-117	-114
h20	-114	-116	-117	0	0	0	0	0	-120	0	-117	-114
h21	-114	-116	-117	0	0	0	0	-120	-120	0	-117	-114
h22	0	-116	-117	0	0	0	0	0	-120	0	0	0
h23	0	0	0	0	0	0	0	0	0	0	0	0

Table 76. BESS 120 MW - 720 MWh charged and discharged energy

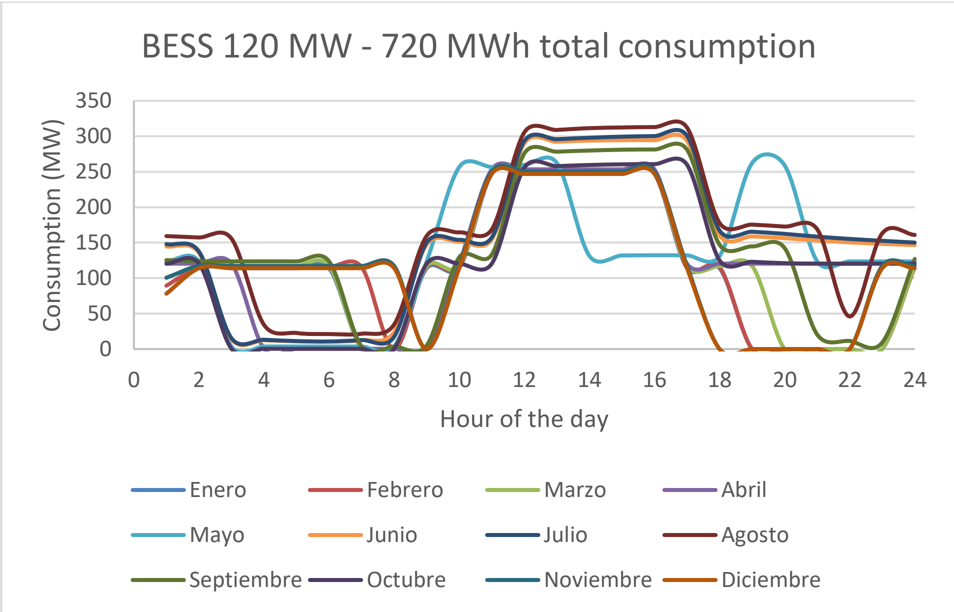


Figure 61. BESS 120 MW - 720 MWh total consumption

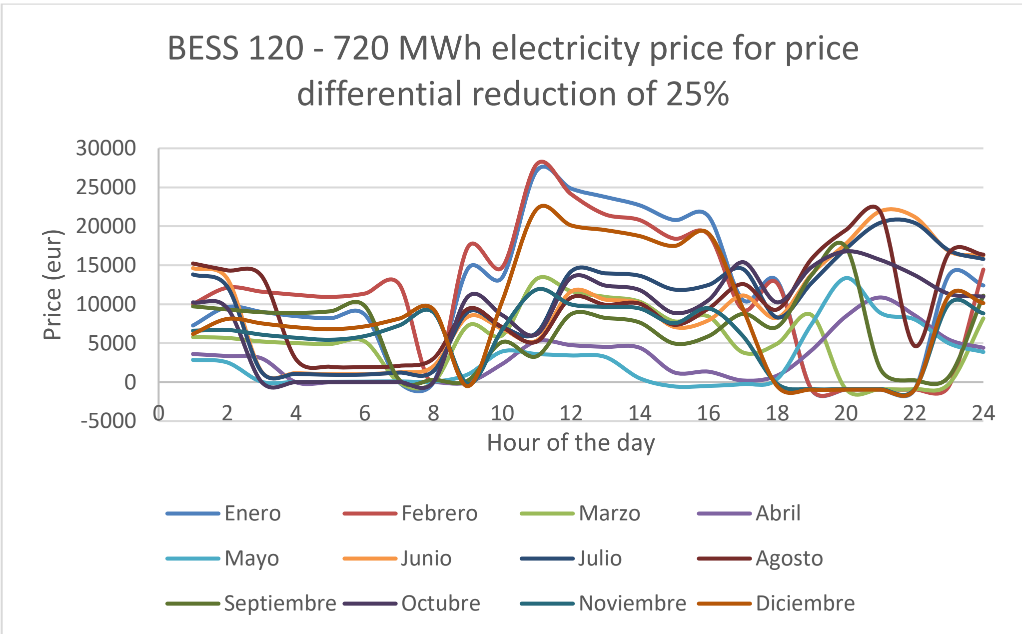


Figure 62. BESS 120 MW - 720 MWh electricity price for price differential reduction of 25%

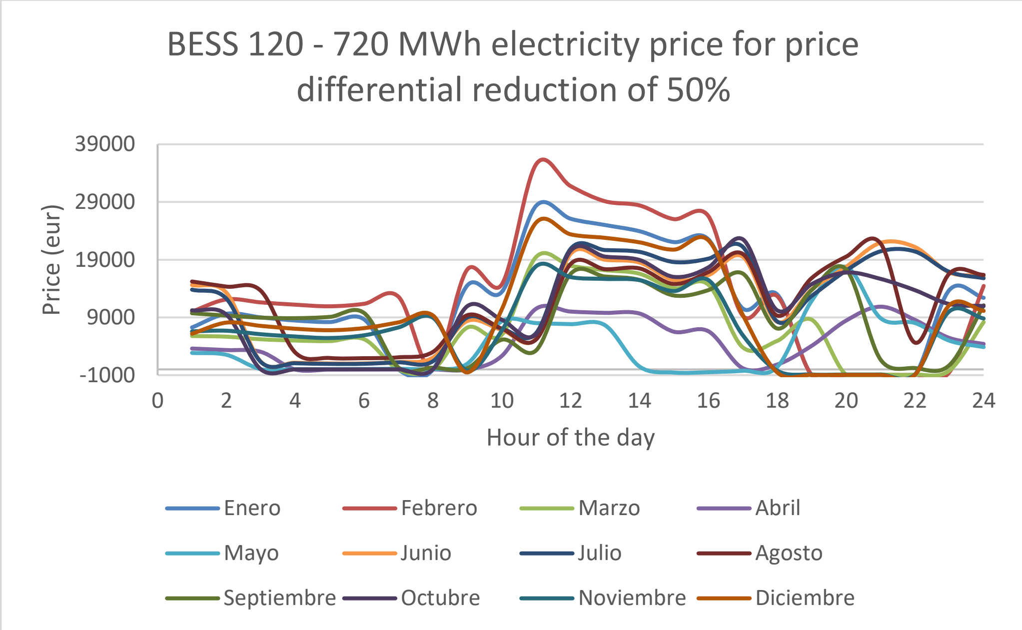


Figure 63. BESS 120 MW - 720 MWh electricity price for price differential reduction of 50%

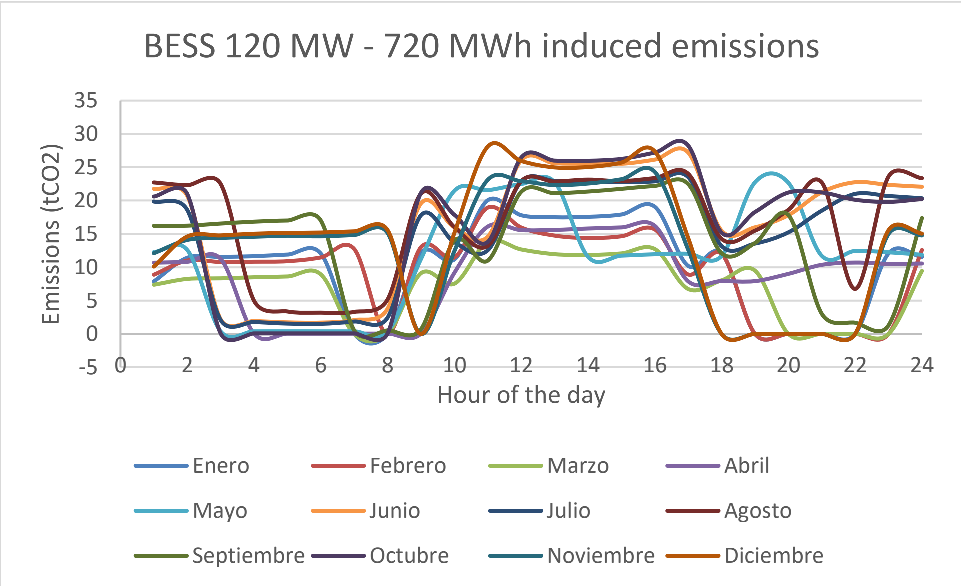


Figure 64. BESS 120 MW - 720 MWh induced emissions

BESS 120 MW – 840 MWh

MW	*January*	*February*	*March*	*April*	*May*	*June*	*July*	*August*	*September*	*October*	*November*	*December*
h0	-42	-31	-19	0	0	0	0	0	0	0	-19	-42
h1	0	0	0	0	-120	-120	0	0	0	0	0	0
h2	0	0	0	-120	-120	-120	-120	0	0	-120	0	0
h3	0	0	0	-120	-120	-120	-120	-120	0	-120	0	0
h4	0	0	0	-120	-120	-120	-120	-120	-120	-120	0	0
h5	0	0	0	-120	-120	-120	-120	-120	0	-120	0	0
h6	-114	0	-117	-120	-120	-120	-120	-120	-120	-120	0	0
h7	-114	-116	-117	-120	-120	-120	-120	-120	-120	-120	-117	0
h8	-114	-116	0	-120	0	0	0	0	-120	0	-117	-114
h9	0	0	0	0	133	0	0	0	0	0	133	0
h10	133	133	133	133	133	133	0	133	0	133	133	133
h11	133	133	133	133	133	133	133	133	133	133	133	133
h12	133	133	133	133	133	133	133	133	133	133	133	133
h13	133	133	133	133	133	133	133	133	133	133	133	133
h14	133	133	133	133	0	133	133	133	133	133	133	133
h15	133	133	133	133	0	133	133	133	133	133	133	133
h16	133	133	133	133	0	133	133	133	133	133	0	133
h17	0	0	0	0	0	0	133	0	133	0	-117	-114
h18	-114	-116	-117	0	133	0	0	0	0	0	-117	-114
h19	-114	-116	-117	0	133	0	0	0	0	0	-117	-114
h20	-114	-116	-117	0	0	0	0	0	-120	-120	-117	-114
h21	-114	-116	-117	0	0	0	0	-120	-120	0	-117	-114
h22	0	-116	-117	0	0	0	-120	0	-120	0	0	-114
h23	0	0	0	0	0	0	0	-120	0	0	0	0

Table 77. BESS 120 MW - 840 MWh charged and discharged energy

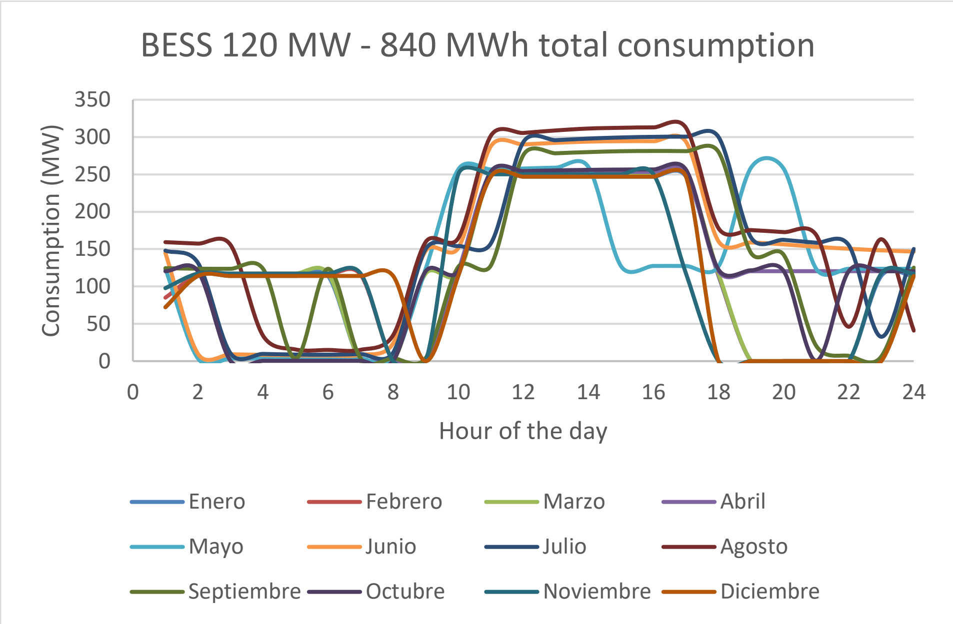


Figure 65. BESS 120 MW - 840 MWh total consumption

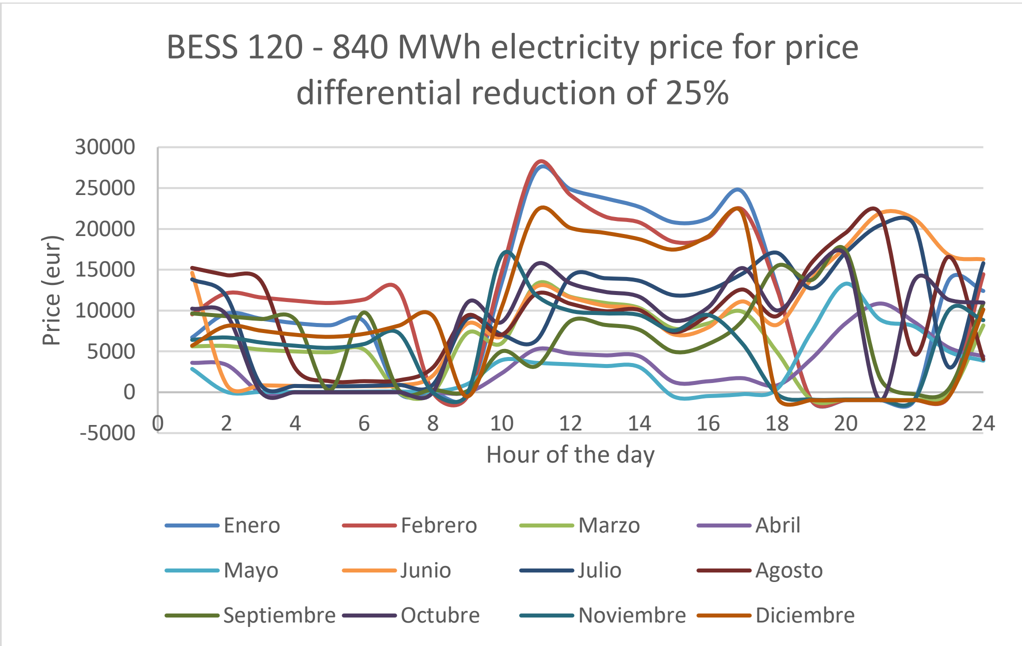


Figure 66. BESS 120 MW - 840 MWh electricity price for price differential reduction of 25%

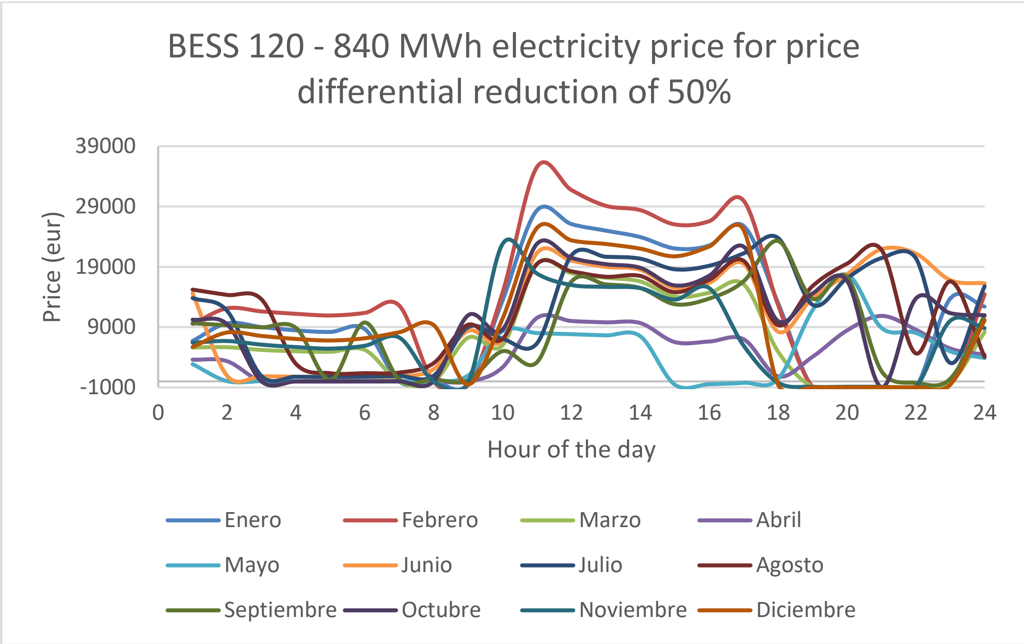


Figure 67. BESS 120 MW - 840 MWh electricity price for price differential reduction of 50%

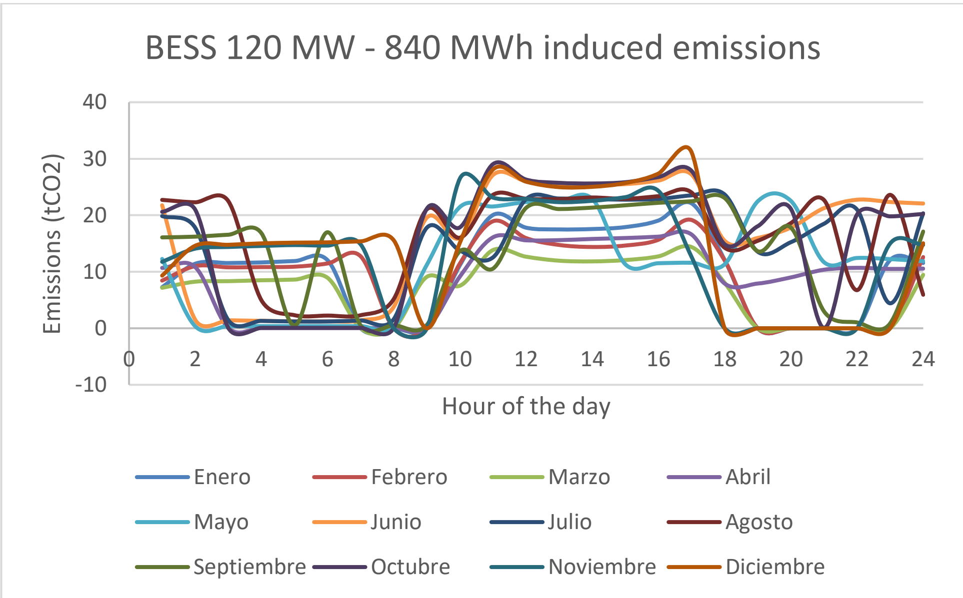


Figure 68. BESS 120 MW - 840 MWh induced emissions

BESS 120 MW – 960 MWh

MW	***January***	***February***	***March***	***April***	***May***	***June***	***July***	***August***	***September***	***October***	***November***	***December***
h0	-48	-35	-22	0	0	0	0	0	0	0	-22	-48
h1	0	0	0	-120	-120	-120	0	0	0	0	0	133
h2	0	133	0	-120	-120	-120	-120	0	0	-120	0	0
h3	0	0	0	-120	-120	-120	-120	-120	0	-120	0	0
h4	0	0	0	-120	-120	-120	-120	-120	-120	-120	0	0
h5	0	0	0	-120	-120	-120	-120	-120	-120	-120	0	0
h6	-114	-116	-117	-120	-120	-120	-120	-120	-120	-120	0	0
h7	-114	-116	-117	-120	-120	-120	-120	-120	-120	-120	-117	-114
h8	-114	-116	0	-120	0	0	0	0	-120	-120	-117	-114
h9	133	0	133	0	133	0	0	0	0	0	133	0
h10	133	133	133	133	133	133	133	133	133	133	133	133
h11	133	133	133	133	133	133	133	133	133	133	133	133
h12	133	133	133	133	133	133	133	133	133	133	133	133
h13	133	133	133	133	133	133	133	133	133	133	133	133
h14	133	133	133	133	133	133	133	133	133	133	133	133
h15	133	133	133	133	0	133	133	133	133	133	133	133
h16	133	133	133	133	0	133	133	133	133	133	133	133
h17	-114	0	0	0	0	133	133	133	133	133	-117	-114
h18	-114	-116	-117	133	133	0	0	0	0	0	-117	-114
h19	-114	-116	-117	0	133	0	0	0	0	0	-117	-114
h20	-114	-116	-117	0	0	0	0	0	-120	-120	-117	-114
h21	-114	-116	-117	0	-120	-120	0	-120	-120	0	-117	-114
h22	0	-116	-117	0	0	0	-120	-120	-120	0	-117	-114
h23	0	0	-117	0	0	0	-120	-120	0	0	0	0

Table 78. BESS 120 MW - 960 MWh charged and discharged energy

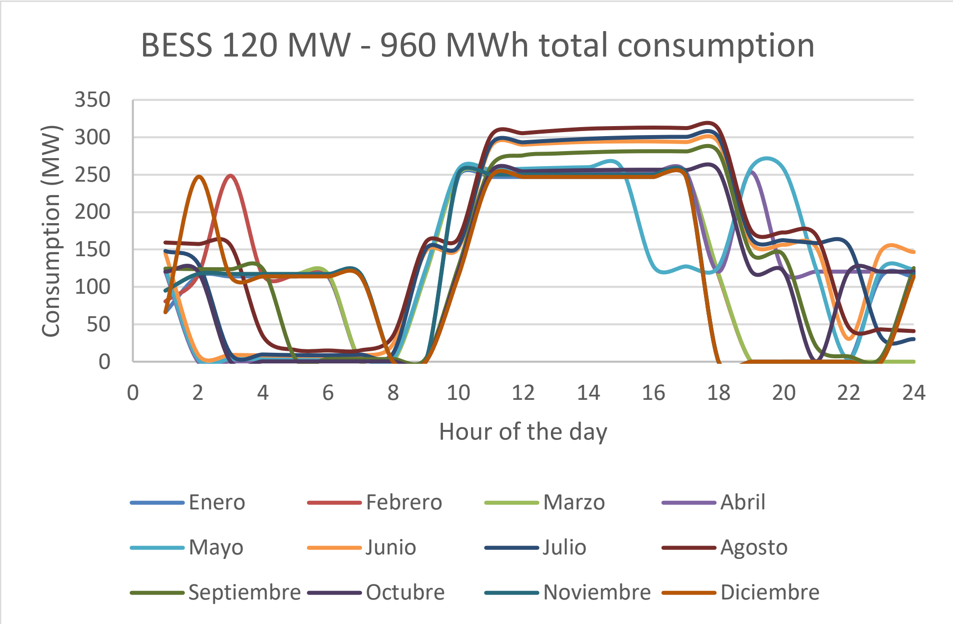


Figure 69. BESS 120 MW - 960 MWh total consumption

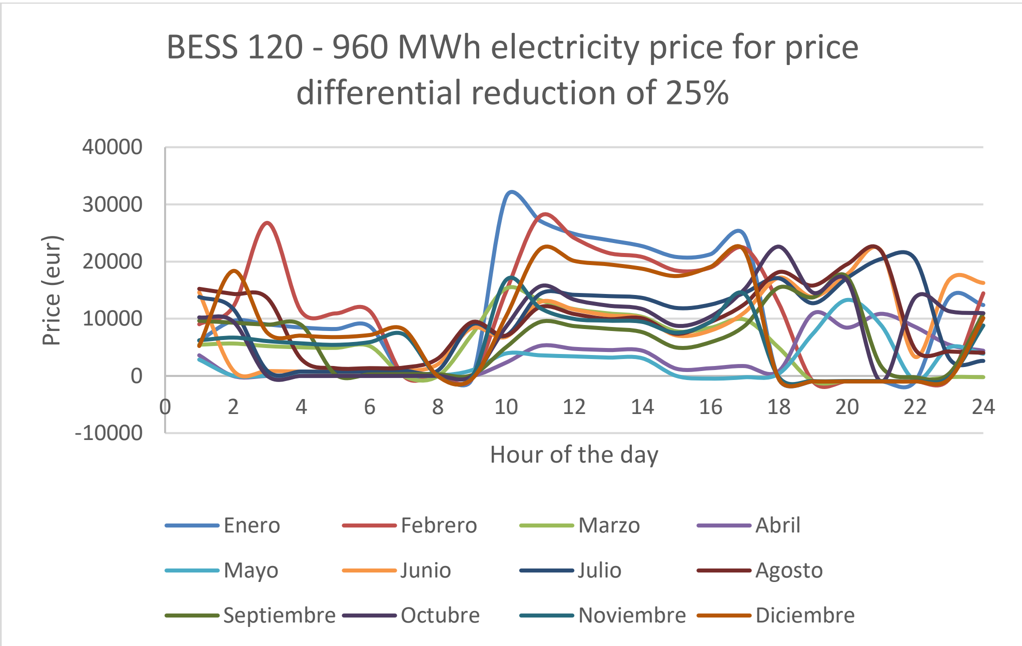


Figure 70. BESS 120 MW - 960 MWh electricity price for price differential reduction of 25%

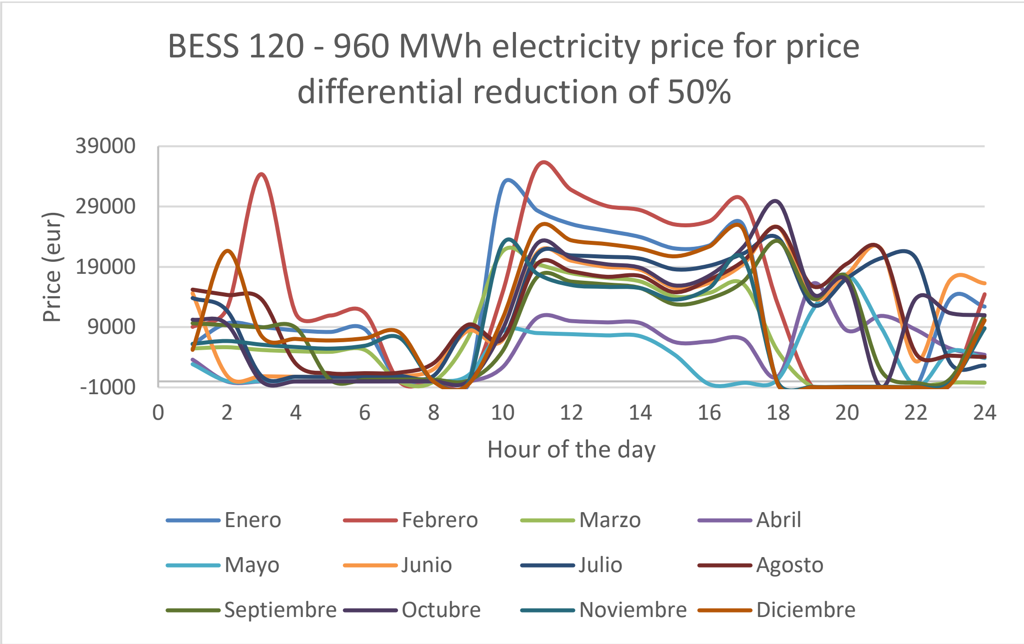


Figure 71. BESS 120 MW - 960 MWh electricity price for price differential reduction of 50%

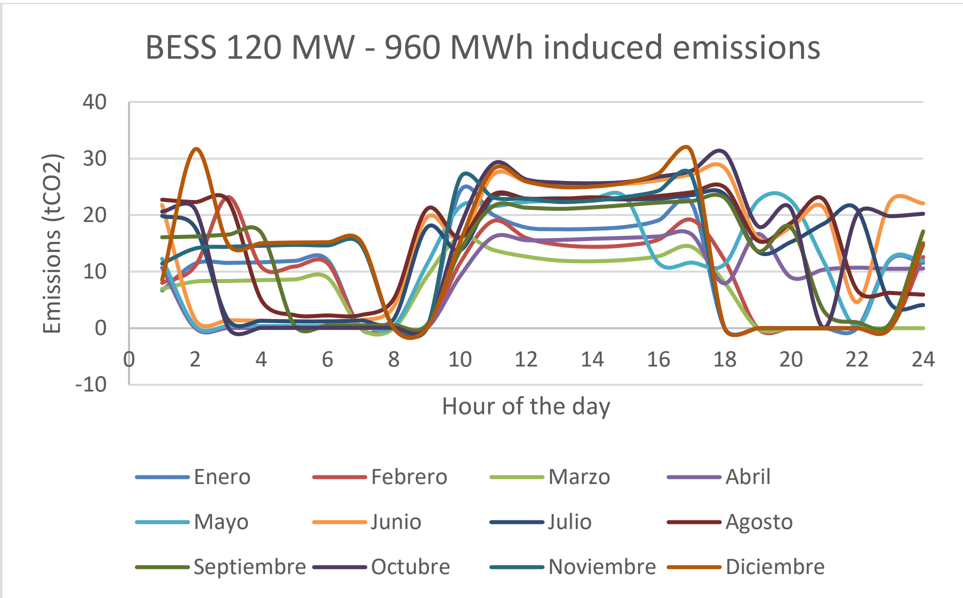


Figure 72. BESS 120 MW - 960 MWh induced emissions

BESS 120 MW – 1080 MWH

MW	***January***	***February***	***March***	***April***	***May***	***June***	***July***	***August***	***September***	***October***	***November***	***December***
h0	-54	-39	-25	0	-120	0	0	0	0	0	-25	133
h1	133	0	0	-120	-120	-120	0	0	0	0	133	133
h2	0	133	0	-120	-120	-120	-120	-120	0	-120	0	-54
h3	0	133	0	-120	-120	-120	-120	-120	0	-120	0	0
h4	0	0	0	-120	-120	-120	-120	-120	-120	-120	0	0
h5	0	0	0	-120	-120	-120	-120	-120	-120	-120	0	0
h6	-114	-116	-117	-120	-120	-120	-120	-120	-120	-120	-117	-114
h7	-114	-116	-117	-120	-120	-120	-120	-120	-120	-120	-117	-114
h8	-114	-116	-117	-120	0	0	0	0	-120	-120	-117	-114
h9	133	0	133	0	133	0	0	0	0	133	133	0
h10	133	133	133	133	133	133	133	133	133	133	133	133
h11	133	133	133	133	133	133	133	133	133	133	133	133
h12	133	133	133	133	133	133	133	133	133	133	133	133
h13	133	133	133	133	133	133	133	133	133	133	133	133
h14	133	133	133	133	133	133	133	133	133	133	133	133
h15	133	133	133	133	0	133	133	133	133	133	133	133
h16	133	133	133	133	0	133	133	133	133	133	133	133
h17	-114	0	133	133	133	133	133	133	133	133	-117	-114
h18	-114	-116	-117	133	133	133	133	133	133	0	-117	-114
h19	-114	-116	-117	0	133	0	0	0	0	-120	-117	-114
h20	-114	-116	-117	0	0	0	0	0	-120	-120	-117	-114
h21	-114	-116	-117	-120	-120	-120	-120	-120	-120	0	-117	-114
h22	-114	-116	-117	0	0	-120	-120	-120	-120	0	-117	-114
h23	0	-116	-117	0	0	0	-120	-120	-120	0	0	0

Table 79. BESS 120 MW - 1080 MWh charged and discharged energy

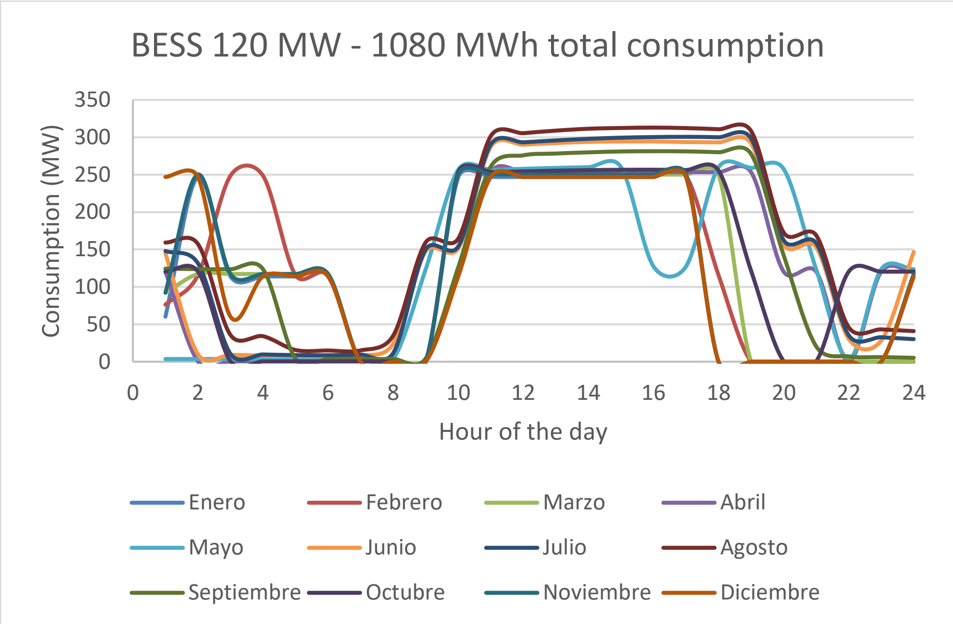


Figure 73. BESS 120 MW - 1080 MWh total consumption

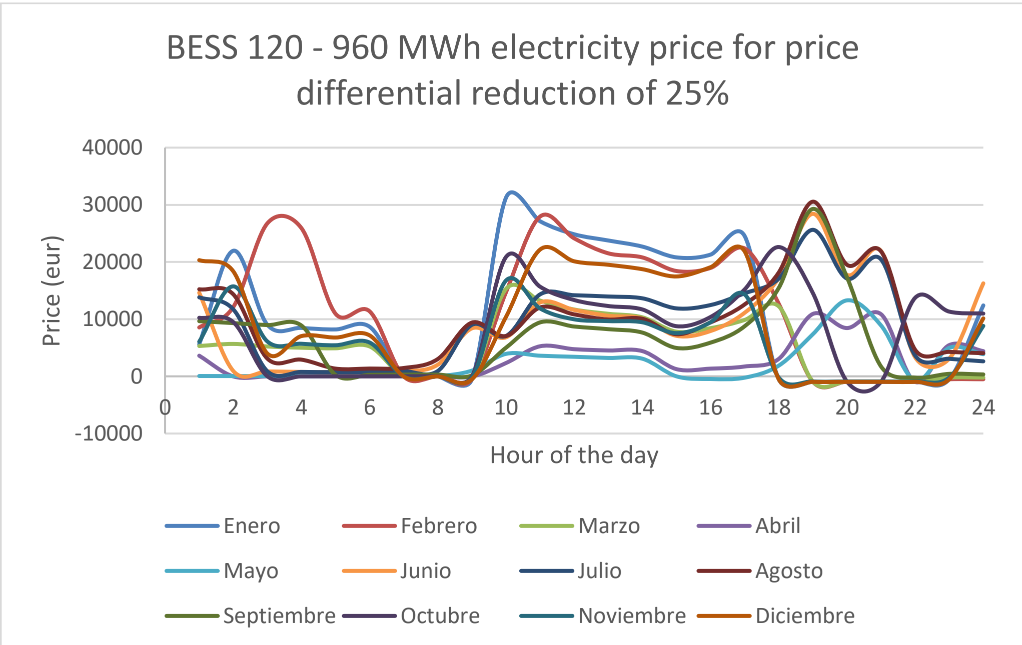


Figure 74. BESS 120 MW - 1080 MWh electricity price for price differential reduction of 25%

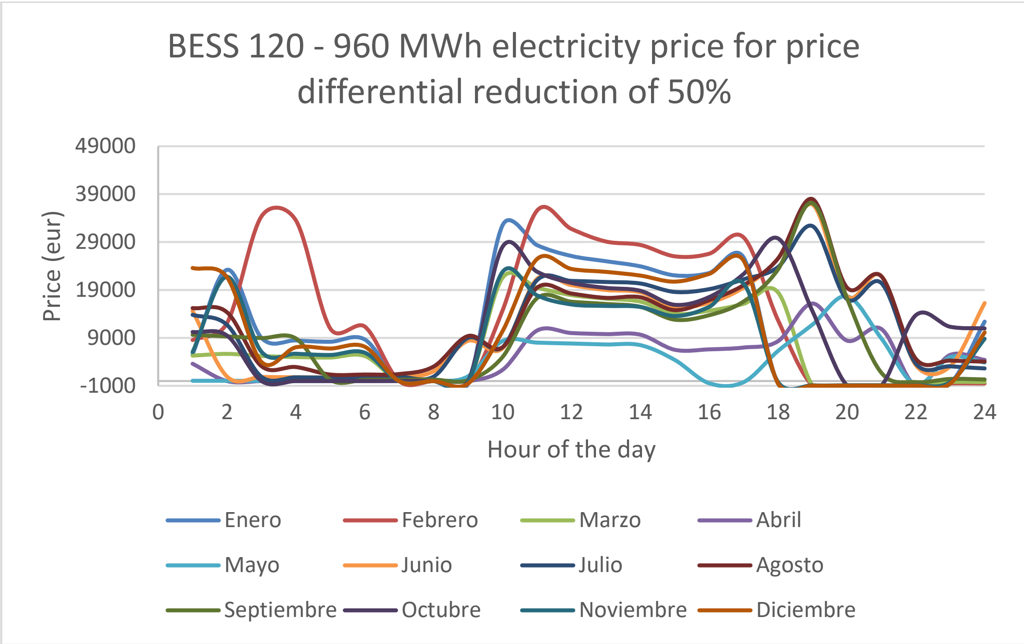


Figure 75. BESS 120 MW - 1080 MWh electricity price for price differential reduction of 50%

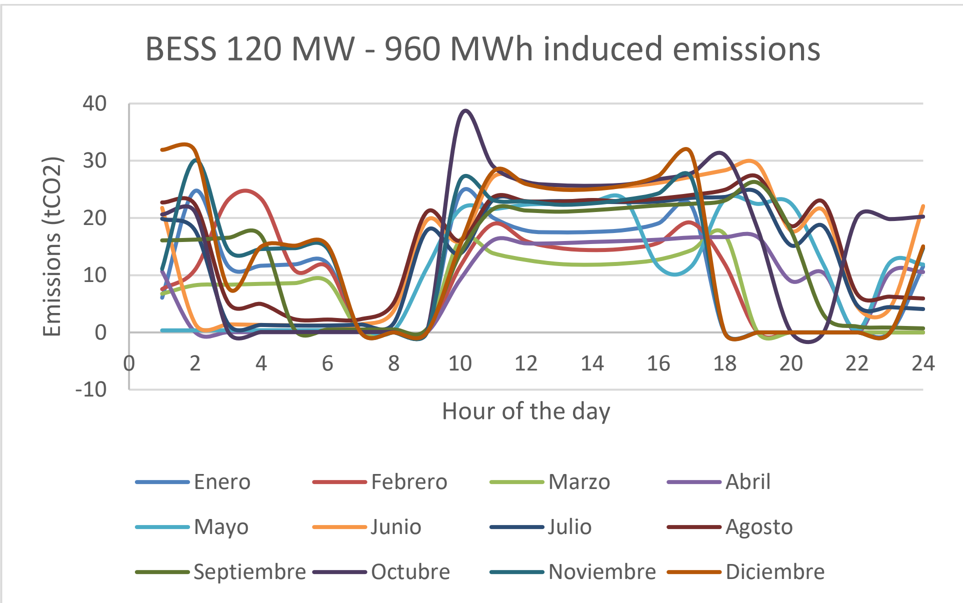


Figure 76. BESS 120 MW - 1080 MWh induced emissions