Norwegian University of Science and Technology

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Bachelor thesis

Analysis of the April 28th Blackout in Spain

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Abstract

As the future of electric energy takes shape, many countries are accelerating the energy transition by promoting renewable technologies and pursuing ambitious targets that seek to combine economic competitiveness, rapid deployment, and deep decarbonization.

The frequently questioned, yet inevitable, energy transition is being propelled by the rapid expansion of renewable energy sources, introducing operational challenges that are reshaping both, the technical, and economic foundations of modern power systems. As inverter-based renewable generation becomes increasingly predominant, system operators face a dual challenge: integrating large shares of intermittent, non-dispatchable resources into existing grids while ensuring security of supply in a context where cost-effective ancillary services still depend heavily on conventional synchronous generation.

Historically, technologies such as gas, nuclear, and large hydropower plants have provided not only active power, but also essential non-energy services, which include inertia, frequency response, and dynamic voltage control, services that are now progressively diminishing as these units retreat from the generation mix.

As Spain aims at a net-zero energy system by 2050, the potential role of traditional energy sources as nuclear energy and combined cycles remains highly debated. Many studies generally focus on the technologies themselves, e.g. carbon footprint, construction time, commissioning or payback period or individual wholesale prices, often aiming to demonstrate the advantages of fast and low-cost installation of renewable technologies. The share of renewable energy in the generation mix has grown continuously, delivering significant benefits such as lower prices, increased competitiveness, and progress in electrification. However, renewable deployment has been regionally uneven, leading to imbalances between regions. Moreover, because this growth has largely relied on replacing conventional generation, some areas now lack crucial synchronous generation, which has historically provided the services necessary to maintain system stability.

Although the European grid expansion targets to address this problems, there are scenarios where the physical expansion of interconnections is constrained, problem usually found on the periphery of the Continental Europe Synchronous Area. This is worsened in the case of the Iberian Peninsula, due to the French reluctance to expand interconnection capacity aiming at shielding its centralized electricity market from the competitive pressure of the Iberian market.

In this cases, ensuring a stable power output and a reliable contribution to overall system performance becomes a critical concern. Renewable technologies, while essential to decarbonization, present intrinsic limitations due to the mismatch between their nominal capacity and their effective system contribution. Furthermore, their limited inertia and controllability exacerbate the complexity of solving frequency and voltage events, incurring into higher ancillary services costs and renewables market share reduction.

To address these challenges, technological innovation is indispensable. Advances such as synthetic inertia, grid-forming converters, reactive power control and dynamic, agile grid operation to enable renewable and storage technologies to participate more actively in system stability and ancillary service provision. However, technological progress alone is insufficient without corresponding regulatory and market progression. The evolution toward high-renewable electricity systems demands a reframing of market design, from a primarily focused on energy transactions to one that systematically integrates resilience, flexibility, and the secure delivery of system services [1, 2] . These attributes must be recognized as fundamental components of cost-effective and sustainable decarbonization, as the electric system is the cornerstone of the energy transition and the electrification of industry and transport.

The analysis of unprecedented events, as Spain's April 28$^{\text{th}}$ blackout illustrates the critical importance of resilient system, highlighting vulnerabilities linked to the reliance on emergency balancing actions unable to compete with power electronics effects, and the need to still rely on intrinsically secure generation technologies, whose stability is based on physical principles, such as nuclear [3, 4], combined-cycle, and large hydro power.

Acknowledgement

I would like to express my sincere gratitude to all those who have supported me throughout the completion of this work. First and foremost, I am deeply thankful to my supervisor, Jonas Kristiansen Nøland, for his guidance, encouragement, and valuable insights during the research process. This thesis would not have been possible without him, and I am truly grateful for his unwavering support. He accepted the proposal of a thesis from an Erasmus student he did not know at the time, and it is because of that that this thesis exists.

I also wish to thank my friend Aaron and my brother Mario for their helpful discussions, support, revisions, and experience, all of which greatly enriched my work. Special thanks go to NTNU for providing the necessary resources and facilities to carry out this project.

Finally, I would like to express my heartfelt appreciation to my parents Luis Miguel and María José, and especially to my girlfriend Ana, for their continuous encouragement and understanding throughout this journey.

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Nomenclature

Abbreviations

AC	Alternating Current
AVR	Automatic Voltage Regulator
DC	Direct Current
DVC	Dynamic Voltage Control
FCR	Frequency Containment Reserve
GDP	Gross Domestic Product
IBR	Inverter-Based Resources
ICE	Internal Combustion Engine
KE	Kinetic Energy
PFC	Primary Frequency Control
PSS	Power System Stabilizer
REE	Red Eléctrica de España
REN	Redes Energéticas Nacionais
RoCoF	Rate of Change of Frequency
ROI	Return On Investment
SFC	Secondary Frequency Control
SO	System Operator
SVC	Static Var Compensator
TSO	Transmission System Operator
UFLS	Under Frequency Load Shedding

Mathematical Variables

E	Excitation voltage (V)
f	Frequency (Hz)
H	Inertia constant (s)
J	Moment of inertia (kg/m
m	Mass (kg)
P	Active power (W)
Q	Reactive power (VAr
S	Rated power (VA)
V	Terminal voltage (V)
v	Speed (m/s)
w	Angular speed (rad/s)
X	Reactance (Ω)

1 Introduction

1.1 Scope and Structure of the Thesis

Chapter 1 - *Introduction*:

1. Scope and Structure of the Thesis
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1.2 Historical Background and Evolution of the Spanish Power System

Throughout this chapter, the historical evolution of electricity in Spain is examined, including the development of all technologies in the system. The chapter concludes by addressing recent changes and challenges, as well as the technological and regulatory framework. In short, the context of the situation that ultimately led to the April 28$^{\text{th}}$ blackout.

It is commonly stated in media that the European power system is the biggest and most complex machine ever made. Energy has become crucial among developed societies, and electric energy is gaining importance not only as an efficient and flexible option for industries, but as a promising decarbonized energy vector.

The history of electricity generation in Spain began in the late 19th century, with the first public lighting appearing in cities such as Barcelona and Madrid, initially powered by small hydroelectric or thermal plants. It soon spread through industries, driven by its technical versatility, economic efficiency, and capacity to transform production processes. Unlike steam power, electric energy could be transmitted over long distances, allowing factories to be located closer to cities and markets rather than near coal or water sources.

During the first decades of the 20th century, hydroelectric power plants became increasingly common as the country entered the Second Industrial Revolution, and private and public companies developed the first small power networks. By the 1960s, electricity generation was dominated by hydro (Figure 1.1), oil, and coal, but nuclear power made its appearance in 1968 with Spain's first three nuclear reactors *José Cabrera* (1968), *Santa María de Garoña* (1971) and *Vandellós I* (1972). The oil crisis reinforced Spain's commitment to nuclear energy as a way to secure and diversify the electricity mix, with the nowadays 7 nuclear reactors being built between 1981 and 1988, and Figure 1.3 shows that little variation happened after them.

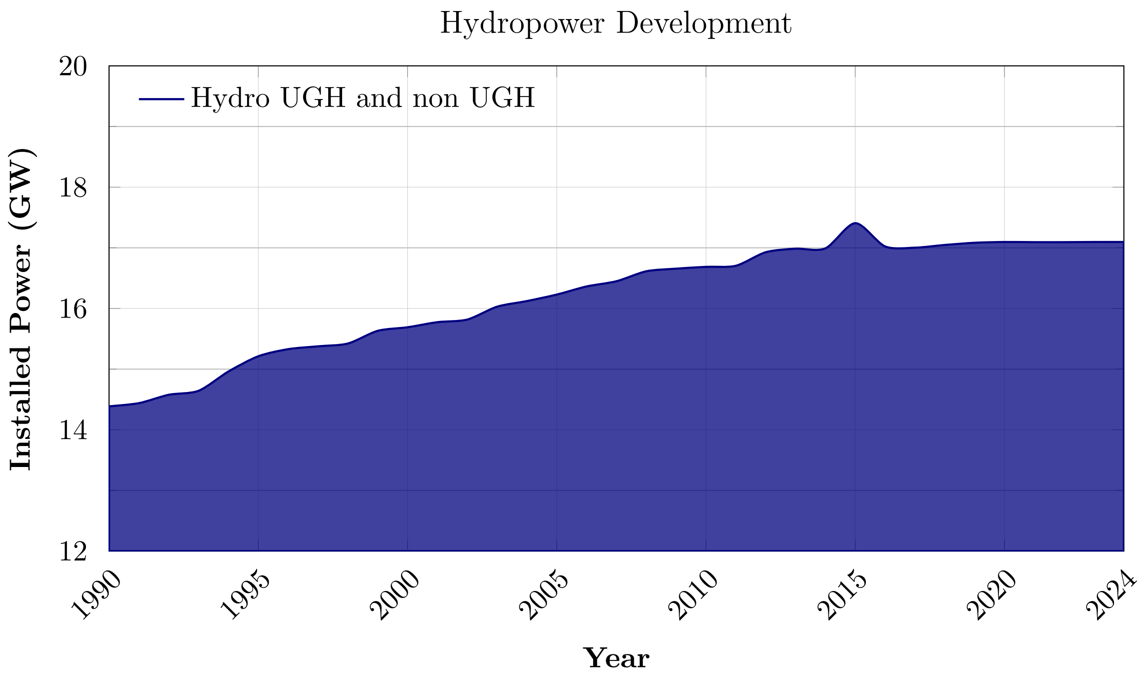


Figure 1.1: *Progression of Hydropower Installed Capacity in Peninsular Spain from 1990 to 2024 (REE [5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15], see appendix A)*

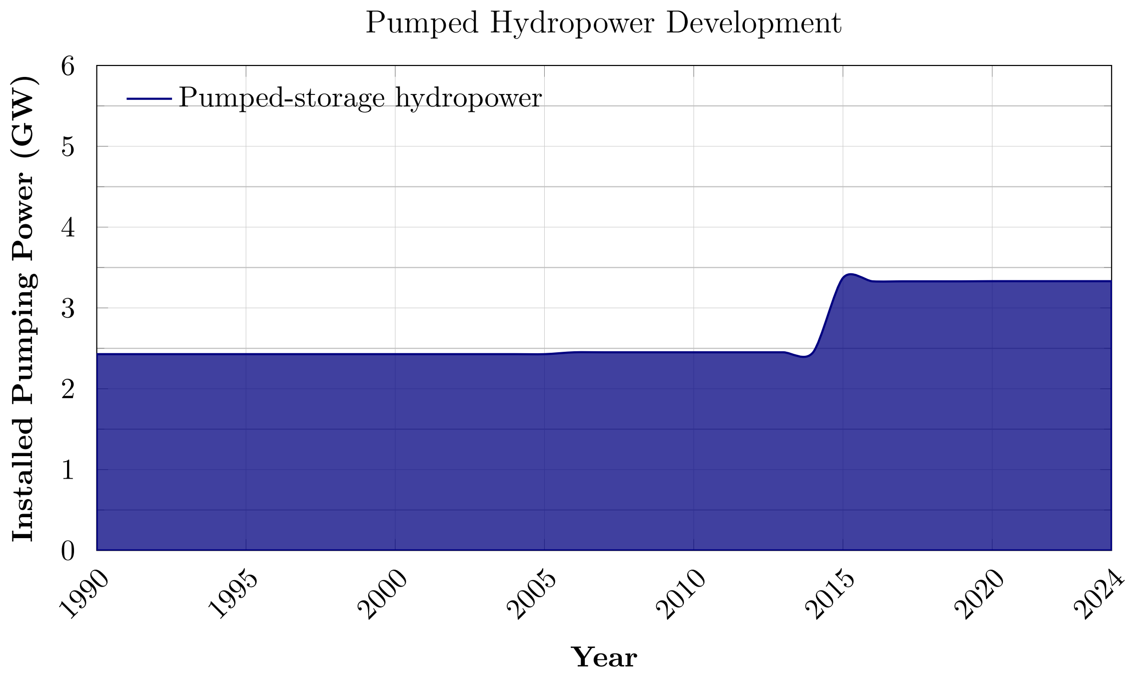


Figure 1.2: *Progression of Pumped Hydropower Installed Capacity in Peninsular Spain from 1990 to 2024 (REE [5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15], see appendix A)*

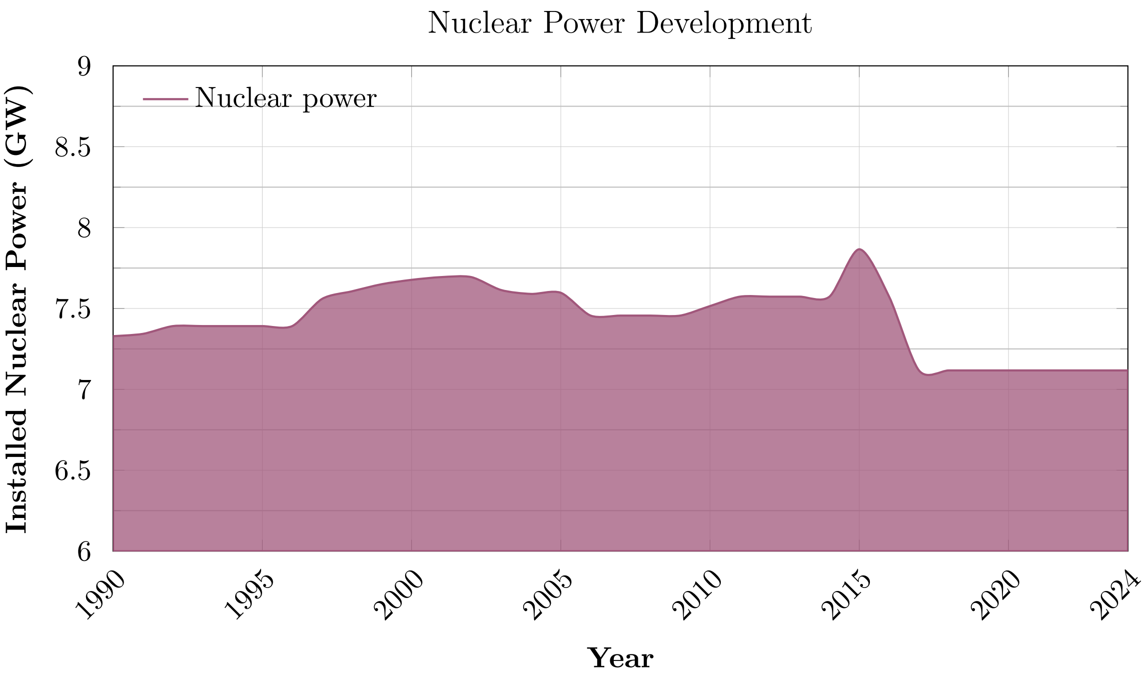


Figure 1.3: *Progression of Nuclear Installed Capacity in Peninsular Spain from 1990 to 2024 (REE [5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15], see appendix A)*

Combined Cycles came onto the scene on the early 90s as the technology was developed. The entrance of Spain in the European Union required the liberalization of the electric markets, and the situation as one of the most efficient fossil fuels generation sources made it profitable and allowed heavy private investments in the field to take advantage of the new market situation. This led to a massive proliferation of combined cycle plants between 2002 and 2011, thanks to their short construction time (less than 3 years) and the need to compensate the fluctuancy of wind generation. At the same time, more contaminant and less efficient technologies as fuel, natural gas and coal started to decrease their presence, not entirely by economic but to environmental reasons, as ahown in Figures 1.5, 1.4 and 1.6. Cogeneration has remained significant despite its recent decline in popularity, as it is closely associated with industrial activities rather than electricity production. Figure 1.7 shows its development in the last decades [16].

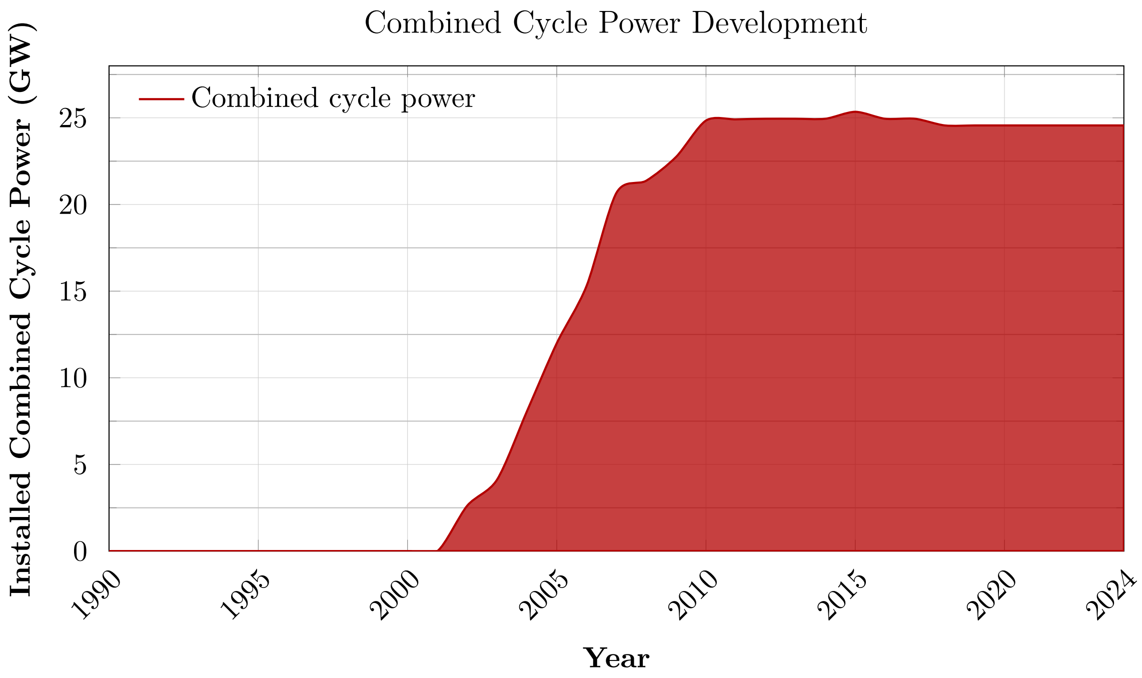


Figure 1.4: *Progression of Combined Cycle Installed Capacity in Peninsular Spain from 1990 to 2024 (REE [5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15], see appendix A)*

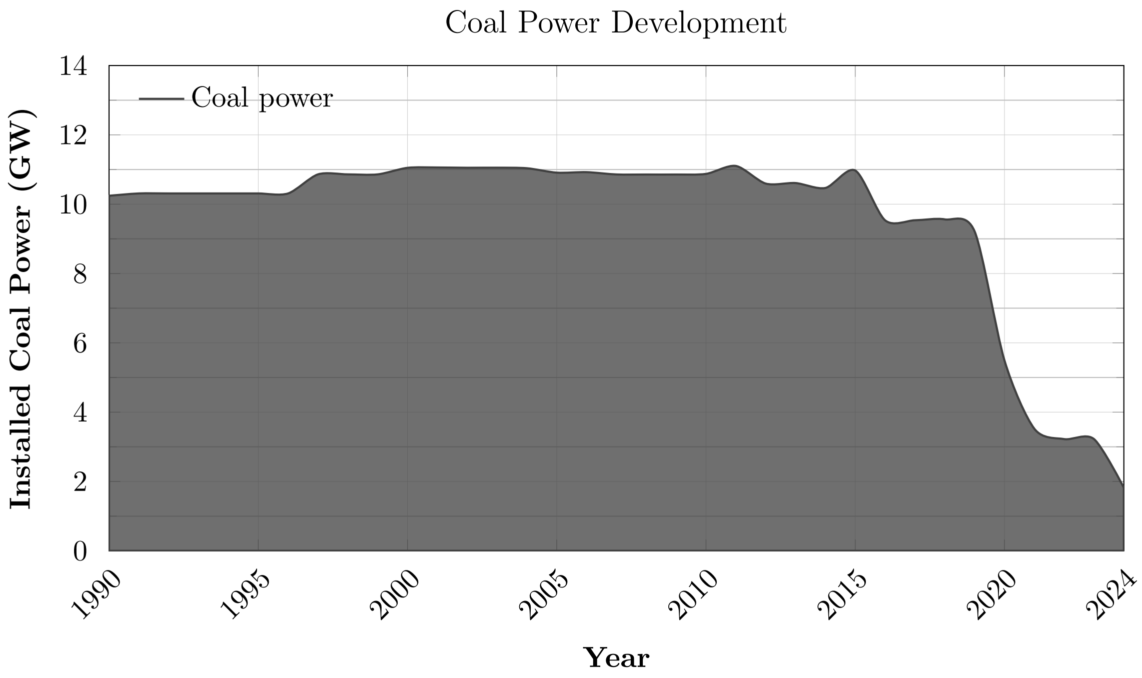


Figure 1.5: *Progression of Coal Installed Capacity in Peninsular Spain from 1990 to 2024 (REE [5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15], see appendix A)*

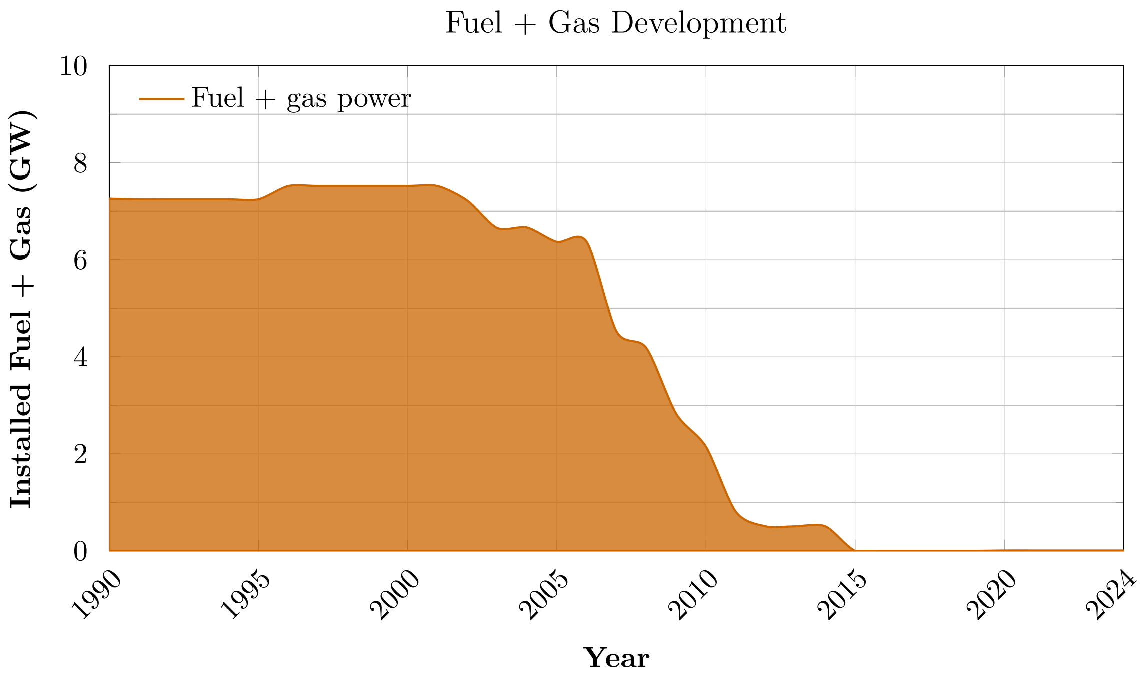


Figure 1.6: *Progression of Fuel + Gas Installed Capacity in Peninsular Spain from 1990 to 2024 (REE [5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15], see appendix A)*

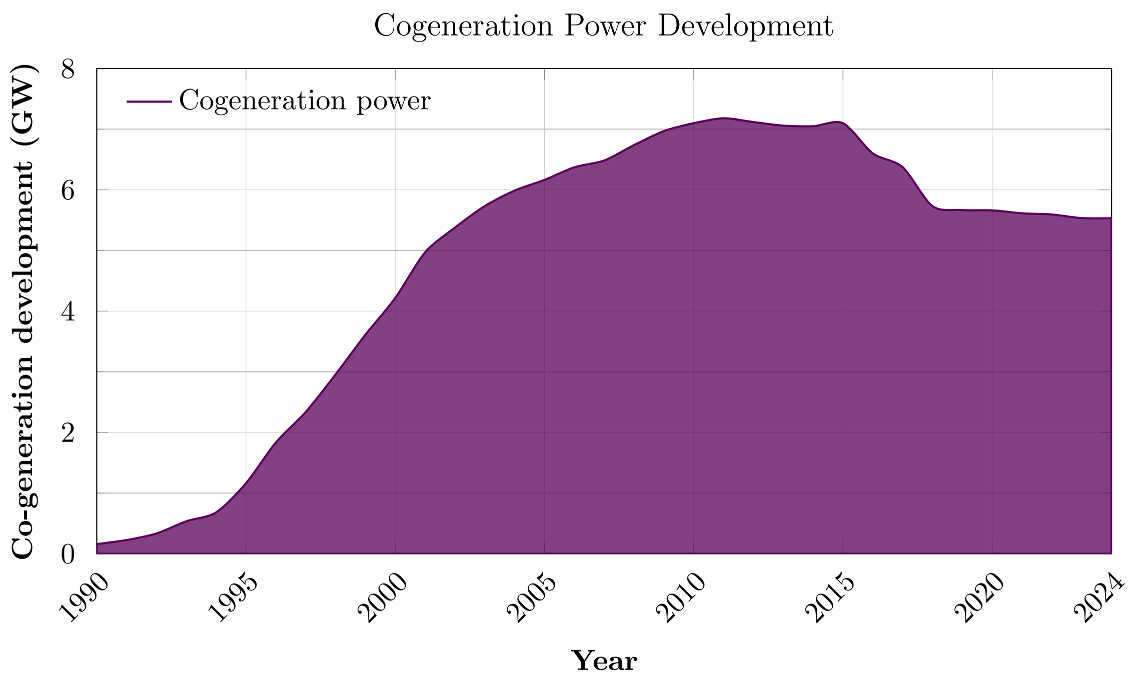


Figure 1.7: *Progression of Cogeneration Installed Capacity in Peninsular Spain from 1990 to 2024 (REE [5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15], see appendix A)*

As Figure 1.8 shows, wind energy made its debut in the early 2000s and soon became the largest renewable energy source after hydropower. Larger and more efficient turbines, and high wind resource areas with stables production, has made it a reliable and competitive technology.

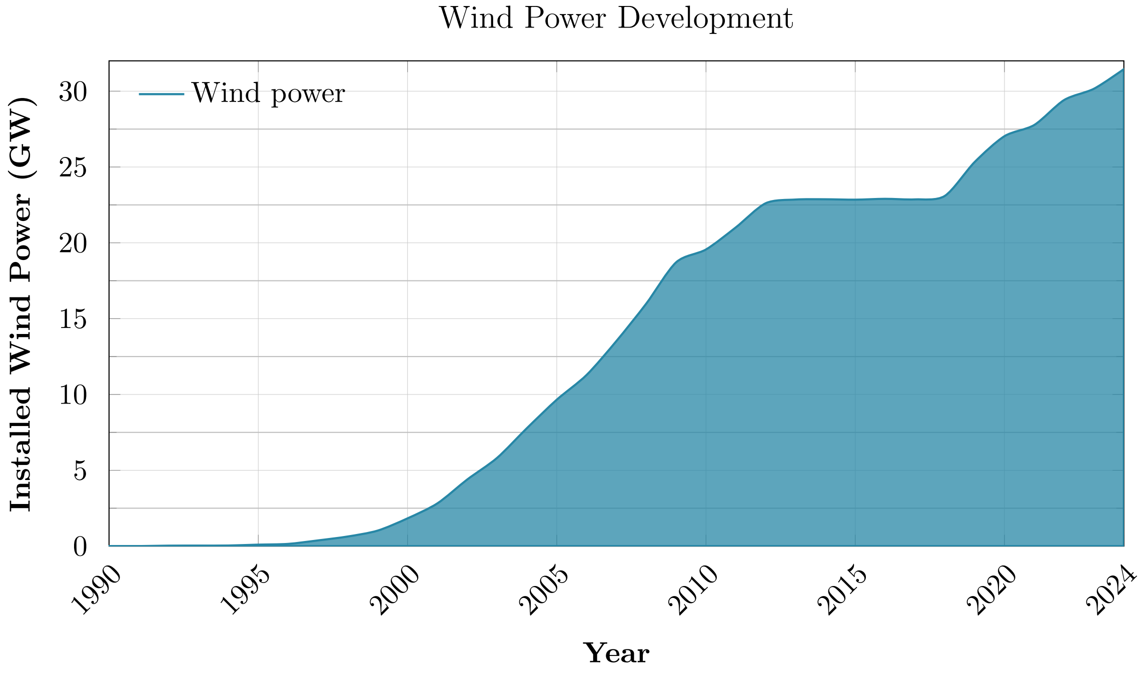


Figure 1.8: *Progression of Wind Power Installed Capacity in Peninsular Spain from 1990 to 2024 (REE [5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15], see appendix A)*

Other minor technologies that have started to take part on the electric mix are based on waste, renewable or non renewable, and on the utilization of renewable thermal energy sources, as shown in Figure 1.9.

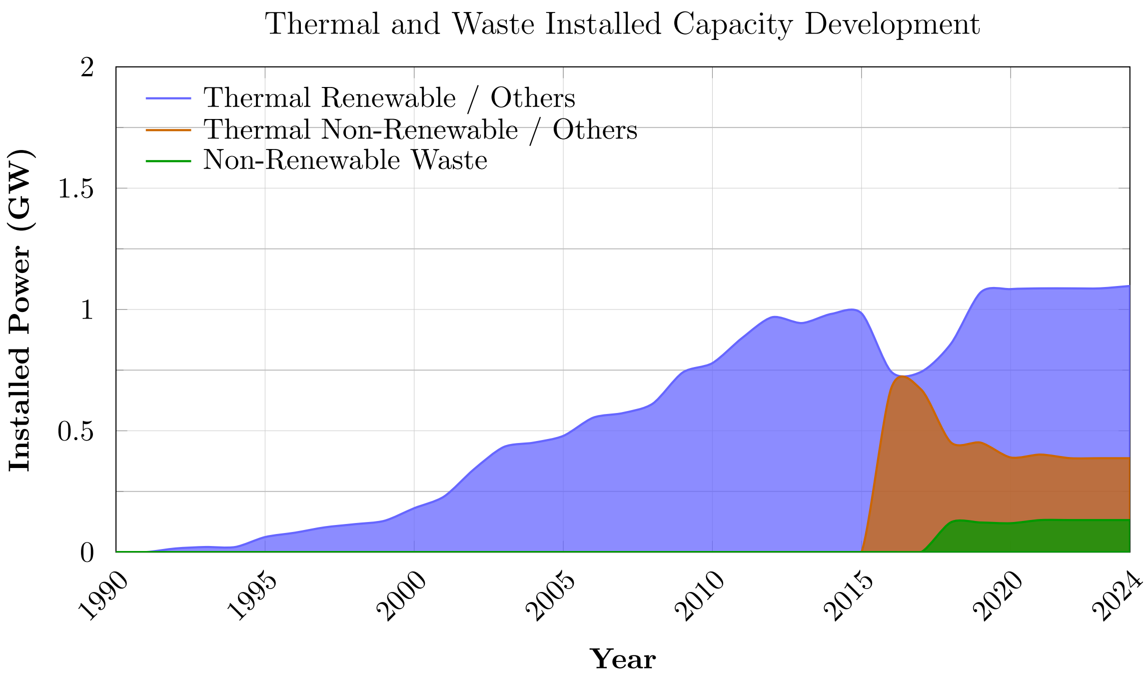
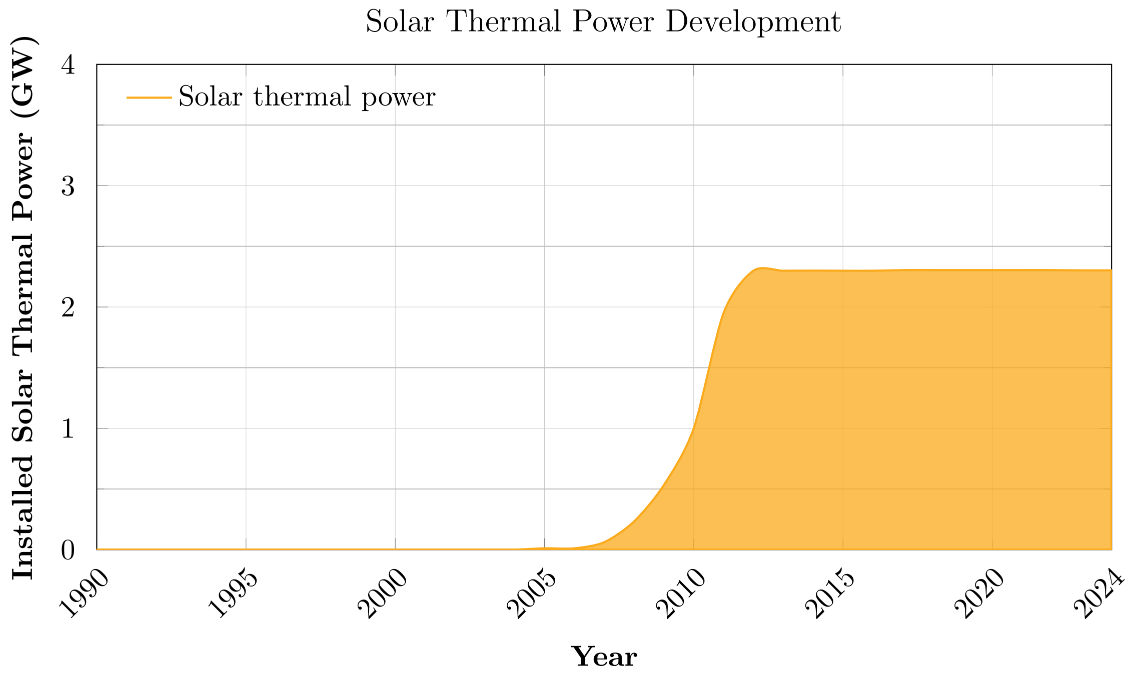


Figure 1.9: *Installed capacity of thermal and waste technologies in Peninsular Spain from 1990 to 2024 (REE [5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15], see appendix A)*

Solar technologies started developing later than wind power, but their development happened fast and soon it became one of the the biggest technology installed in Spain, as shown in Figures 1.10 and 1.11. The "sorpasso" occurred on 2024.



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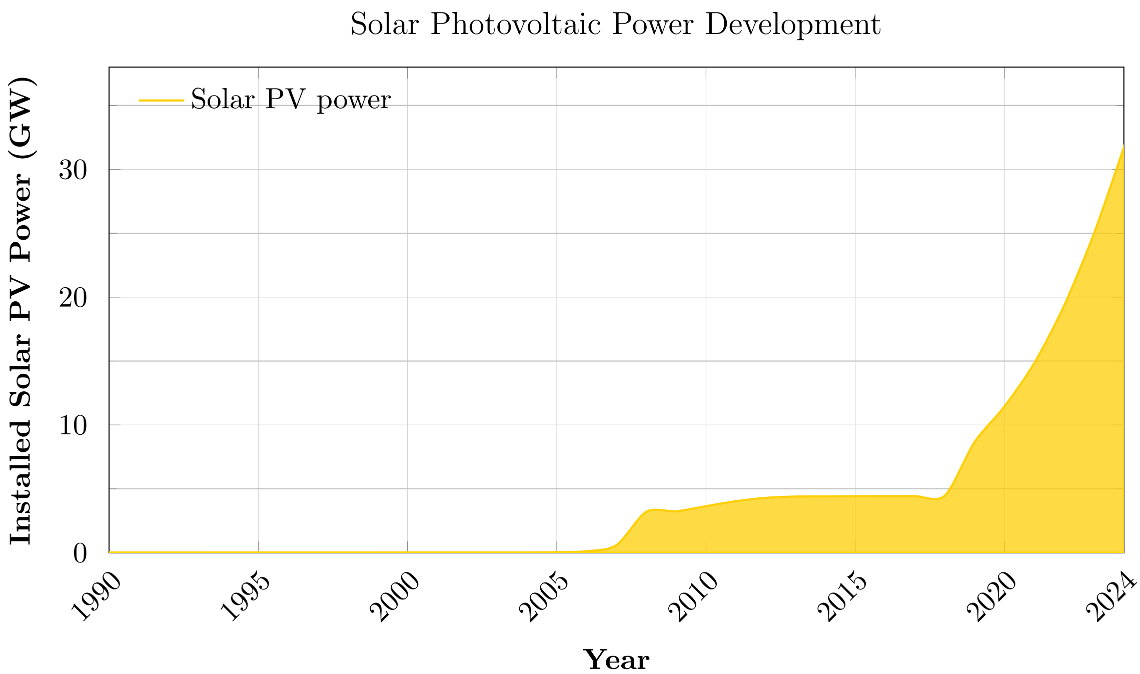

Figure 1.11: *Progression of Solar Photovoltaic Installed Capacity in Peninsular Spain from 1990 to 2024 (REE [5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15], see appendix A)*

The skyrocketing growth of solar technologies is clearly understandable, as Spain is one of the sunniest countries in Europe, reaching irradiation values above 2000 kWh/m^2 [17]. Solar thermal energy was promising at the beginning, as it aimed to address some of the issues associated with IBRs by using rotating machinery and synchronous generators. This made Spanish electric companies among the most advanced in the world in the thermal field. However, the development of photovoltaic technology has drop in prices of solar panels, as Figure 1.12 shows. This has made solar thermal relatively expensive, and the ambitious projects combining it with thermal storage, although still operational today, were ultimately replaced by the massive deployment of PV installations across the country. Solar has grown unabated over the last decade, thanks to its declining cost, market competitiveness, and a favourable contractual framework dominated by Power Purchase Agreements (PPAs), which transformed the variability of solar output into steady revenues, ensuring a reliable return on investment.

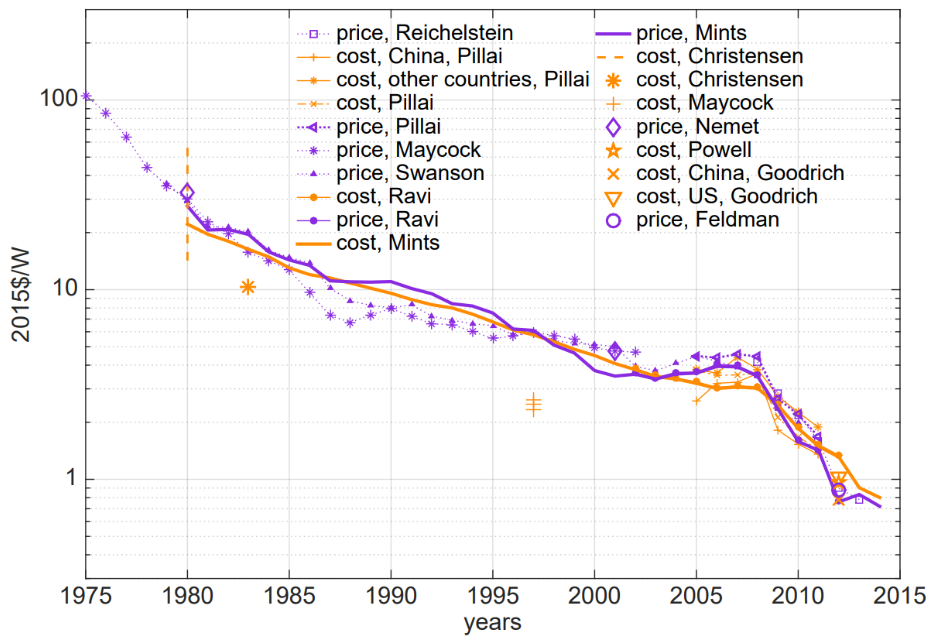

Figure 1.12: *Drop in solar panel prices [18].*

In table 1.1 it can be appreciated hoy the energy production is dominated by renewable technologies as wind and PV, but other traditional sources as nuclear still remains one of the largest energy producers, while having almost 5 times less installed capacity.

Table 1.1: *Electricity Generation by Technology (GWh) – Peninsular System [19]*

Technology	**Peninsular System (GWh)**
Hydropower	34,908
Wind Power	59,512
Photovoltaic Solar	43,609
Solar Thermal	4,127
Other Renewables	3,679
Renewable Waste	654
Nuclear	52,391
Combined Cycle	29,107
Coal	2,972
Cogeneration	16,324
Non-renewable Waste	1,195
	Total Generation: 248,478

Although solar production was expected to surpass nuclear in 2025, but the blackout has delayed this milestone until 2026.

1.3 Current Scenario of the Spanish Power System

The electrical development detailed above shows the radical change that the Spanish power system has gone through in the last decade. This demonstrates a tremendous capacity to integrate renewable technologies, transforming a traditional carbon-based energy importer into an ultra-competitive market dominated by some of the largest electrical companies in Europe. At the same time, it also includes small yet competitive companies, mainly focused on renewable energies, which make the market highly dynamic and attractive to both large-scale and small investors. A symptom of this is that, since 2022, Spain has been a net energy exporter, breaking the historical trend of importing electricity, mainly from France.

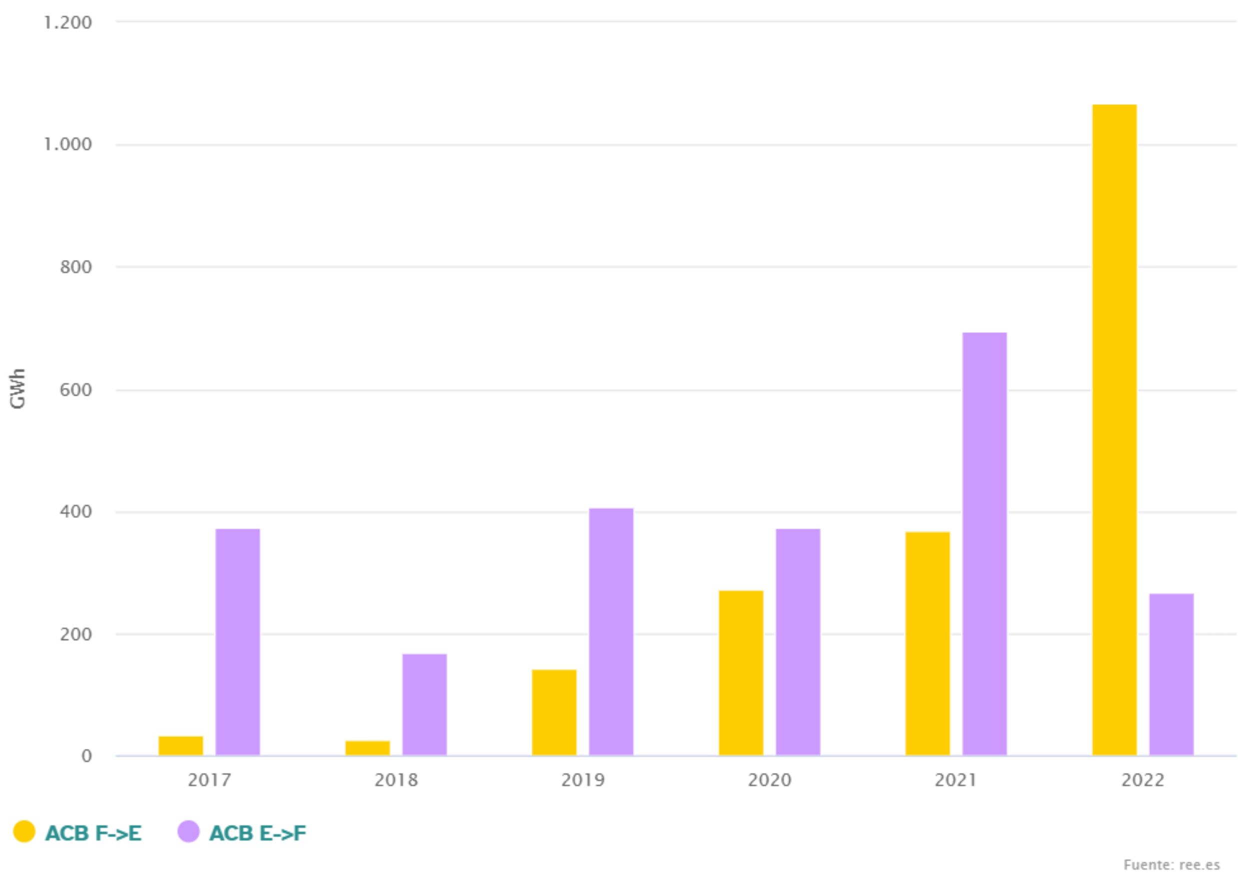

Figure 1.13: *Energy exchange between France and Spain [20].*

Following the perspective presented by Dr. Manuel Fernández Ordóñez — Doctor in Nuclear Physics and specialist in Electric Power Generation — during his appearance before the Spanish Senate's Commission of Investigation on the Interruption of Electricity Supply and Communications on April 28$^{\text{th}}$, 2025 [21].

The year 2024 ended with 41.5% of electricity being produced by solar and wind, achieving the lowest emissions ever recorded and clearly positioning Spain at the forefront of the European energy transition.

As a consequence, wholesale prices have dropped significantly, sometimes even reaching zero or negative values. While this creates an attractive environment for industrial competitiveness, these low prices often do not translate into lower energy bills. Moreover, this compromises new investments, as the expected return on investment is decreasing and uncertain [22].

Most of these achievements have been accomplished thanks to the flexibility of the system. The three pillars of the system are the diversification of the electricity mix, interconnections with surrounding countries, and available storage, which allow for the compensation of imbalances between generation and consumption.

All of this could not have been achieved without a reliable network. The rate of Energy Not Supplied (ENS) was exceptionally low, decreasing from 159 MWh in 2023 to 32 MWh in 2024, and the System Average Interruption Duration Index (SAIDI) reached 0.07 minutes (0.34 minutes in 2023) [23]. Red Eléctrica de España (REE) is the first TSO in the world, fundedç

in 1985, creating an operational framework that was later adopted by almost the entire European continent.

On the other hand, while the European Council established a 15% target for interconnection between countries and the rest of the European Union, France and Spain maintain only a 2% interconnection of approximately 3 GW. Moreover, the level of congestion on the Spain–France interconnection reached 67.6% in 2024, compared with just 6.8% with Portugal [24].

At the same time, the incredibly fast development of land-intensive generation has resulted in 83% of the nodes being saturated [25]. Speculation is occurring with the available capacity, and the combination of this with the long time required for processing procedures is causing the country to lose important opportunities for development. Grid development in Spain is limited to 0.2% of GDP, lower than similar European countries such as the Netherlands, Germany or Italy (0.34%), resulting in a 23% inferior ROI (Return On Investment) than Europe average.

Since the blackout, Spain has incurred into significant economic losses. The “reinforced” operation mode aplicated by REE, with more sincronous and conventional technologies share, has incremented the operative and final costs of electricity on final energy energy prices. Technical restrictions made up to around 450 M€/year in 2020, 2021 and 2022, but in 2025 it is estimated to incur in around 2000 M€, with the extra costs affecting the final consumers and the renewable investors, as their power gets out of the market as more conventional power is required.

Turning to the system itself, it reveals a clear hypertrophy of generation: 132 GW of installed capacity in a context where the historical 45 GW peak of consumption occurred in 2007. Since then, installed capacity has grown by 51.4%, while national demand has done nothing but decline, driven by energy efficiency and self-consumption, even as both industrial and residential sectors move toward electrification. This is shown in Figure 1.14:

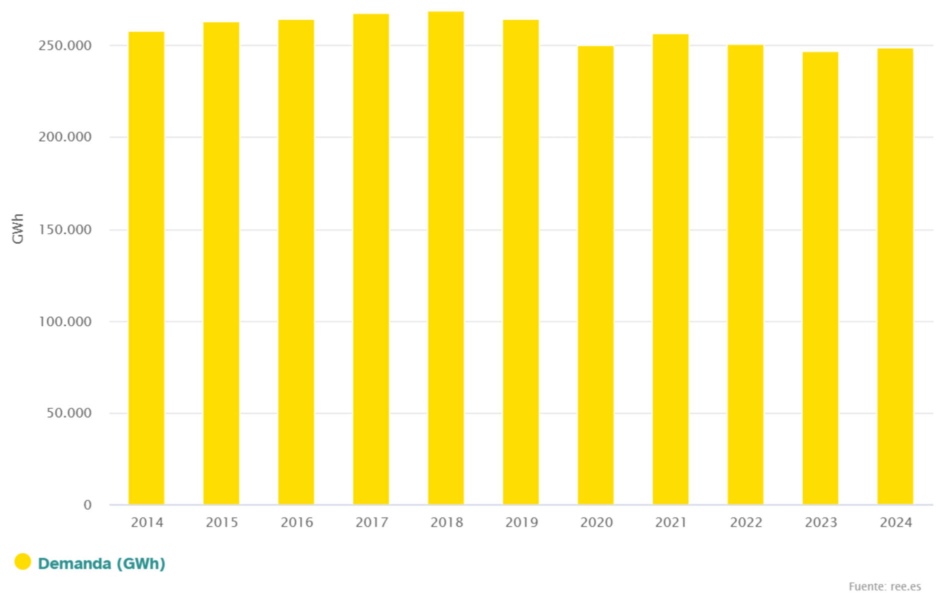

Figure 1.14: *Spanish electric demand in the last 10 years [26].*

Moreover, the annual consumption peak has shifted from the traditional heating-related winter period to the summer months, mainly due to the increasing use of air conditioning. The large penetration of renewable energies is adding complexity and instability to an already challenging context, forcing the system beyond its limits.

2 Conceptual Background

Throughout this chapter, the technical characteristics of the Spanish power system will be described. The purpose of the information presented is to enhance the conceptual understanding of the methodology, the results, and the conclusions exposed through the thesis. Physic principles and theoretical background is explained, state-of-the-art of technical solutions and the regulatory framework is described, in order to demonstrate how the calculations are performed, enabling their replication, and allowing to follow the reasoning under the analysis developed. These concepts form the basis for the subsequent chapters, providing the necessary background knowledge for understanding what is presented in this thesis.

2.1 Power System

The electric system is built under the fundamental principle that the power delivered to the final consumer has a consistent, predictable set of characteristics. The power system lives up to its name: it is an infrastructure intended to transport energy from one point to another. It was invented to be able to use electric energy in a different place than where is produced, and also to use the right amount one needs. That exploits the advantages of allowing producers and consumers to specialize in one job, with the efficiency benefits that this implies. The working principles of transmitting electric energy from one point to the other are relatively simple. Some technical problems were solved on the way, usually with the prize of putting your name to a measuring unit or a law, but eventually we figured out how to handle voltage and how AC and DC worked.

The problem is that as size of the network is scaled, the electric grid starts becoming a system itself. Transmitting energy through a wire works like a pipe, what enters one side is transmitted to the other, and a modern power system still follows energy conservation laws, but many other variables become part of the equation. Modern devices usually have installed protections against deviations from the normal grid conditions, but in general, the grid must always ensure that the energy is being delivered within a very narrow tolerance band. Outside that band, equipment can fail since it is designed to operate within a narrow frequency and voltage range. As a result, in order to ensure overall efficiency, reliability, and security, the operation and planning of a system must not only take into account the normal cases, but also need to be designed to withstand uncertainties and disturbances in potentially hazardous circumstances. When events occur within a system, such as line faults or the loss of generating units, the critical concern is whether the system can remain within its stability limits. Such an approach is known as the N-1 criterion.

Moreover, guaranteeing the conditions of the grid become tremendously complex. System operators need to run a load flow model with immense amounts of data to assess the impact and power flows in the power system. Due to the non-convex nature of the load flow equations, it proves troublesome to find global optimal solutions, and no efficient approach is guaranteed in such a problem. In addition, the power systems are typically large in size. This leads to difficulties in constructing and solving full-scale mathematical models. Furthermore, as the technology mix is changing, grid operators are having to develop new ways of managing their networks, creating new markets for ancillary services such as fast and dynamic frequency response, reserve and reactive power products, short circuit levels and inertia support. New technologies such as chemical batteries are being used for some of these services, and old technologies like synchronous condensers are being used in new ways to support changing grid needs.

The energy transition has seen a major deployment of renewable generation across the world. A generation that is not only intermittent but also is connected via power electronics to the grid, as they produce DC current. Although wind turbines rotate, they do not do so at a constant rate, so are unable to generate AC electricity with a stable waveform, and it is imperative the use of power electronics to produce an AC wave and inject energy into the grid. They also tend to be "distributed", particularly in the case of solar. This means instead of grids based around large units of generation connected to high voltage networks, we have many smaller generation sources connected to distribution networks.

This presents both physical and economic challenges. Physical challenges relate to how the stable electricity expected by end users can be maintained when the means of generation no longer supports that to the same degree. Economic challenges are focused on the growth of self-generation, which challenges the economic assumptions behind the way in which networks are built and paid for. The main problems occasioned by the described changes in the power system are listed below. They will be further discussed and mentioned throughout the rest of the text.

1. Reduced system inertia – Due to the replacement of conventional synchronous generators with inverter-based renewable sources, the natural damping of voltage oscillations is diminished.

2. Limited reactive power capability of inverter-based resources – Unlike synchronous machines, most renewable generators cannot inherently supply or absorb large amounts of reactive power, which is crucial for voltage support.

3. Fast and stochastic variations in generation – Wind and solar power introduce rapid fluctuations, requiring faster voltage control actions to maintain stability.

4. Spatial distribution of generation – Renewable plants are often located far from load centers, increasing the complexity of maintaining voltage profiles across the network.

5. Interactions with existing control devices – Coordination between traditional voltage control equipment (OLTCs, SVCs, STATCOMs) and distributed renewable resources becomes critical to prevent instability or voltage collapse.

2.2 Technical Requirements and Regulations of Spanish system

Spanish Power System consists of two parts: the Distribution Network and the Transmission Network (RdT). The limit between them is not geographical but functional, located on the transformers that make the voltage change between different tension levels. Transmission Network encompasses all the lines of 400 kV and 220 kV, with the exception of some 66 kV lines on the Canary and Balearic Islands. The Distribution Network is the rest of the grid, where most of the generation under 50 MW is connected, and where the vast majority of the load is linked.

In Spanish grid codes, the Power Generating Modules (PGM) are divided in 3 general types.

I Synchronous PGMs: Those having an inherent capability to resist or slow down frequency deviations.

II Power park modules: Those generating units that are either connected to the network through power electronics or non-synchronously connected. Renewable energy falls into this category.

III Offshore power park modules: Uncommon in Spain.

Although this distinction exists, no differentiation will be made in the rest of the text between synchronous PGMs and power park modules, as the grid codes on which this chapter is focused impose the same requirements on both.

The classification of the generators is made depending on the voltage level of their connection points, or Point of Common Coupling (PCC), and their maximum capacity.

Type	**Voltage Requirement**	**Power Range**
A	< 110 kV	0.8 kW – 100 kW
B	< 110 kV	100 kW – 5 MW
C	< 110 kV	5 MW – 50 MW
D	≥ 110 kV	> 50 MW

Table 2.1: *Generator type as per PCC voltage and power requirements [1].*

Given this classification, the grid code establishes a series of requirements for the generating units connected to the grid regarding frequency, active and reactive power management, voltage, and the events that can disturb these magnitudes.

Most of these technical requirements are designed to protect equipment, machines, and ultimately, human lives, but also to withstand abnormal events while continuing to operate, allowing protections and the grid operator to intervene. This matter will be relevant through the rest of this thesis, as it is a crucial property that the elements that form a grid network must possess.

To properly understand the codes presented below is that, in terms of number, renewable energy plants and self-consumption installations usually fall under types A or B. Although their individual rated power may be small, their widespread adoption has increased the total installed capacity to significant levels, yet the technical requirements remain the ones who apply for PCCs of less than 5 or 0.1 MW.

The voltage deviations tolerated without disconnecting for PCCs is $\pm 10\%$ of the nominal value.

Voltage requirements for nodes and generation are shown in the tables below:

	Normal Operating Conditions (P.O. 1.4)		Coordination Measures		Exceptional Measures	
	Lower	**Upper**	**Lower**	**Upper**	**Lower**	**Upper**
220 kV nodes	205	245	205	235	198	246
400 kV nodes	390	420	380	420	375	435

Table 2.2: *Voltage limits established by regulation for transmission network nodes [27].*

	Lower limit	**Upper limit**
Generation facilities connected to 220 kV	187	225
Generation facilities connected to 400 kV	340	440

Table 2.3: *Order TED/749/2020. Voltage limits established by regulation for generation plants with installed capacity above 50 MW [27].*

The nominal frequency in the Spanish system is 50 Hz, but it is considered normal to operate between 49,85 and 50,15 Hz [28]. Aditionally, certain deviations must be tolerated during normal system operation, showed in table 2.4. Moreover, since frequency is the primary indicator of the load–generation balance, the system may have to withstand out-of-range conditions in order for operational responses to be carried out. This matter will be further discussed in Section 2.3.

Type	Frequency Range	Time of Operation in Frequency Ranges	RoCoF	Frequency Sensitive Modes
A	47.5–51.5 Hz	47.5–48.5 Hz →30 min 48.5–49.0 Hz →unlimited 49.0–51.0 Hz →unlimited 51.0–51.5 Hz →30 min	$\leq$ 2 Hz/s	Not required
B	47.5–51.5 Hz	47.5–48.5 Hz →30 min 48.5–49.0 Hz →unlimited 49.0–51.0 Hz →unlimited 51.0–51.5 Hz →30 min	$\leq$ 2 Hz/s	Optional
C	47.5–51.5 Hz	47.5–48.5 Hz →30 min 48.5–49.0 Hz →unlimited 49.0–51.0 Hz →unlimited 51.0–51.5 Hz →30 min	$\leq$ 2 Hz/s	LFSM-O & LFSM-U optional
D	47.5–51.5 Hz	47.5–48.5 Hz →30 min 48.5–49.0 Hz →unlimited 49.0–51.0 Hz →unlimited 51.0–51.5 Hz →30 min	$\leq$ 2 Hz/s	LFSM-O, LFSM-U, FSM required

Table 2.4: *Frequency ranges, time of operation, RoCoF, and frequency sensitive modes by generator type [1].*

RoCoF is measured over a 500 ms interval.

LFSM-O = Limited Frequency Sensitive Mode – Overfrequency.

LFSM-U = Limited Frequency Sensitive Mode – Underfrequency.

FSM = Frequency Sensitive Mode.

The frequency-response related features that are required for generating units are listed below:

Feature	Active Power Frequency Response	Maximum Power Reduction with Falling Frequency	Maximum Active Power Change (%Pmax)
Type A	Not required	Not required	Not required
Type B	Optional	Limited	Optional
Type C	Required	Limited	8%
Type D	Required	Required	8%

Table 2.5: *Active power frequency response, power reduction, and maximum active power change by generator type [1].*

A certain percentage of active power reduction rates related to frequency are required to be followed in the frequency response. Frequency response is not only designed to restore the system to within-range frequency values, but also to protect synchronous machinery from overloading or pole slipping. Moreover, in systems with high penetration of non-synchronous renewable sources, frequency response acts as a protective measure. If IBRs are kept producing at their maximum output, the system risks saturating the PLL (phase-locked loop), losing synchronism, or even causing sudden disconnections, which could lead to an uncontrolled mass-tripping event.

Table 2.6 shows reactive power control requirements, as it is a critical feature:

Feature	**Reactive Power Capability**
Type A	Optional / Limited
Type B	Required
Type C	Required
Type D	Required

Table 2.6: *Reactive power capability requirements by generator type [1].*

Reactive power may be absorbed or injected to regulate voltage. Although is required for type B, C and D, the capability to do the task in real time is not required. Type B and C units typically operate under a fixed power factor and cannot follow real-time set-points, which means that they do not contribute effectively to voltage control. Furthermore, in the event of a generation trip, like a disconnection of a power plant due to overvoltage or undervoltage, the reactive power that was being absorbed or injected disappears instantaneously, potentially causing cascading trips as the reactive power imbalance that led to the voltage rise will do nothing but exacerbate.

Feature	Fault-Ride-Through (FRT)	Automatic Connection	Initial Delay to Full Response (t1)	Time to Full Activation (t2)
Type A	Not required	Optional	500 ms for non-inertial PGMs	30 s
Type B	Required for symmetrical faults	Required*	500 ms–2 s	30 s
Type C	Required for symmetrical faults	Required	500 ms–2 s	30 s
Type D	Required for symmetrical & asymmetrical faults	Required	500 ms–2 s	30 s

Table 2.7: *Fault-ride-through, automatic connection, and response timing requirements by generator type [1].*

*Required if PGM capable
FRT refers to the capability to remain connected during faults.
Symmetrical or asymmetrical faults refer to failures occurring simultaneously on all three phases or only on some of them. It is a vital requirement for IBRs to remain connected during voltage-related events, enabling them to absorb or inject reactive power to support voltage regulation.
The automatic capability to connect is defined for the 47.5–51.5 Hz range, although additional requirements may be imposed by the DSO.
t1 = Delay before full activation of the active power response.
t2 = Time for the PGM to reach its full active power frequency response.

This section offers a brief overview of a broad and technically demanding topic. Still, a few clear conclusions emerge. Current grid code requirements are mainly designed for generating units above 50 MW. Most IBR installations fall well below this threshold, meaning that a significant share of today's renewable capacity operates under comparatively light technical obligations despite its growing influence on system behaviour.

In practice, this creates a mismatch: the normative framework still reflects a system dominated by synchronous plants, while the actual generation mix no longer does. As a result, many small IBR units provide limited services, their aggregated impact is becoming increasingly relevant, and they are not fully reliable for the TSO.

Overall, these observations point to a simple conclusion: Grid codes must evolve so that technical responsibilities scale with the real contribution and impact of each technology on system stability.

2.3 Introduction to Inertia and its Role in the Power System

Inertia is the property of matter by which it continues in its existing state of rest or uniform motion in a straight line, unless that state is changed by an external force. This includes changes in the speed, direction, or resting state of the object. Inertia is also defined as the tendency of objects to keep moving in a straight line at a constant speed [29]. When applied to rotating machines, this means that they keep rotating unless external forces, such as friction or the electromagnetic torque of a generator, slow them down.

A well-known example to understand this concept is to think of frequency as the revolutions per minute (RPM) of an ICE (Internal Combustion Engine), similar to the one we all have in our cars. When power is added by pressing the gas pedal, the engine overcomes the friction of the air and the road and begins to increase its revolutions (frequency rises), and therefore its speed. However, if the car is going uphill and the elevation change starts to exceed the effort of the engine, the car will slow down as the engine loses RPM (frequency decays). In this case, inertia is represented by the total weight of the car moving at a certain speed, which keeps the car in motion when the gas pedal is not pressed and tends to keep the engine revolutions from rapid changes, even when the gas pedal or the brake are pressed.

In electrical systems, traditional inertia is provided by the set of heavy components present in many synchronous power generation facilities, such as turbines, generators, alternators, and shafts that remain in motion within the electrical system in technologies such as combined cycles, nuclear reactors and large hydroelectric power plants.

Figure 2.1: *Gas Turbine size*

These components rotate at a speed proportional to 50 Hz, which is the grid frequency in Europe. When an external factor affects the grid frequency, it must force these rotating elements to adjust their speed, decreasing it if the frequency falls, or increasing it if the frequency rises. As a result, the system as a whole 'resists' changes in frequency. During abnormal events in electric systems, frequency acts as a measure of the generation and consumption equilibrium, and it rises if generation is greater than the load, and it decreases if consumption exceeds generation.

Many industrial and pumping loads are inductive; their disconnection reduces reactive demand and mitigates voltage depression following a frequency event. In pumped-storage plants, ceasing pumping or switching to generation mode allows synchronous machines to provide reactive support.When generation loss occurs during normal functioning of a power system, KE is extracted from the spinning components and supplied into the grid, with the side effect of slowing them down and eventually triggering protections. This relation between KE and angular speed is showed below:

$$\Delta KE = \frac{1}{2}m(\Delta v)^2 \tag{2.1}$$

The inertia of a power plant usually requires a complex calculation that is individual and unique for each plant or at least each technology. As such calculation is impossible to do on each plant, both in terms of time and specific information about the plant itself, the inertia of a power plant usually is quantified using its inertia constant, commonly denoted as H, which represents the stored kinetic energy in the rotating components per unit of rated power. As shown in Eq. (2.2) [30], for synchronous generators, the kinetic energy is given by:

$$KE = \frac{1}{2} J\omega^2 \tag{2.2}$$

Where J is the moment of inertia of the rotor and ω is the angular speed. The inertia constant H is then calculated as the ratio of this kinetic energy at nominal speed to the rated apparent power of the machine:

$$H = \frac{KE}{S_{\text{rated}}} \tag{2.3}$$

This value, usually expressed in seconds, indicates how long the generator can supply energy to the grid before the speed drops significantly, and get out of the ranges explained in Table 2.4. In practice, the inertia constant depends on the type of generator, the turbine design, and the size of the rotating mass. Therefore, generation technologies exhibit significantly different inertia characteristics due to the nature of their prime movers, the design of their machines, and the way energy is converted into electricity. For complex plants, such as combined cycles or hybrid systems, the total inertia is obtained by summing the contributions of all synchronous machines operating in parallel.

2.4 Automatic Load-Shedding Mechanisms in Modern Power Systems

Automatic load-shedding (LS) constitutes one of the most essential emergency control mechanisms in modern power systems and represents REE's ace up its sleeve when it comes to preventing frequency collapse and cascading outages following severe generation–demand imbalances. Its main function is to rapidly disconnect selected portions of electrical load, such as industrial facilities, pumping stations, or auxiliary systems within power plants, in order to stabilize system frequency and maintain network integrity when inertial and primary reserves are insufficient to counteract sudden disturbances. While primarily a frequency-control measure, load-shedding plays a significant role in the management of both inertia and dynamic voltage stability. By reducing the instantaneous load, UFLS (Under Frecuency Load Shedding) alleviates the need for synchronous machines to supply additional KE during transient disturbances. This effectively “buys time” for primary frequency control or governor action to stabilize the system. In low-inertia systems dominated by renewable generation, this fast-acting mechanism becomes increasingly critical.

Continuing with the engine analogy introduced in Section 2.3, load-shedding deballasting, is to the power system what throwing weight out is to the car when it starts losing speed when the vehicle begins to go uphill.

As the share of non-synchronous renewable generation increases, the effective inertia of the system decreases, accelerating the frequency decline and reducing the time available for corrective actions. In such circumstances UFLS schemes are automatically activated to disconnect preselected loads, rebalancing supply and demand and halting the frequency decay. Controlled disconnection of geographically distributed loads prevents voltage collapse and limits the overloading of transmission corridors, thereby maintaining system stability during transient and post-fault conditions.

Industrial and pumped-storage loads are particularly valuable for UFLS participation due to their controllability and significant power ratings. In pumped-storage plants, transitioning from pumping (consuming) to generating mode provides a dual stabilizing effect: the reduction of system demand and, when turbines are switched to generation, the injection of active power and reactive and voltage support. Industrial consumers participating in demand response schemes typically employ frequency-sensitive relays or receive control signals from the system operator through SCADA or WAMS systems. In the Spanish peninsular system the UFLS is carried out by large pumped-storage facilities such as La Muela, Aguayo, and Duero that represents a significant fraction of the pumping installed capacity and before 2021 by the *"Servicio de Interrumpibilidad"* or "Interruptibility Service" what implied signing up for taking part in the service and receiving an economic compensation. It was closed in 2022 and replaced by SRAD (*Servicio de Respuesta Activa de la Demanda*, or Active Demand Response Service), which operates based on an auction structure, in a more competitive and transparent way than the previous one. This measure was a complete exit, since its creation, an increasingly number of industries have joined the system, from 490 MW in 2023, 609 MW in 2024, 1148 MW in 2025 and 2339 MW in 2026 [31] [32] [33] [34]. Their participation in automatic load-shedding and dynamic voltage control is crucial for avoiding frequency collapse during major disturbances.

UFLS schemes are organized in staged frequency thresholds, each corresponding to a progressively larger proportion of load to be shed. The Spanish grid applies the activation thresholds summarized in Table 2.8.

Table 2.8: *Spanish UFLS activation thresholds*

Stage	Frequency (Hz)	Load shed	Response time (s)
Stage 1	49.5	Pumping facilities	<1
Stage 2	49	1º demand load-shedding	<1
Stage 3	48.8	2º demand load-shedding	<1
Stage 4	48.6	3º demand load-shedding	<1
Stage 5	48.4	4º demand load-shedding	<1
Stage 6	48.2	5º demand load-shedding	<1
Stage 7	48	6º and last demand load-shedding	<1

Once frequency recovery begins, previously disconnected loads are reconnected in controlled steps to avoid secondary oscillations or voltage instability. These thresholds are continuously reviewed by the TSO, REE in the case of Spain and REN in the case of Portugal.

2.5 Introduction to Voltage Control

The frequency and power angle problems essentially result from the imbalance of active power, which is heavily determined by the frequency support and the response of both traditional and renewable energies. However, many of the voltage related events that occurred during the Spanish blackout are related to reactive power control, with special mention to the relevant role of synchronous generation. This chapter will try to address the dynamic voltage problems in large-scale renewable-penetrated power systems, explaining concepts and technologies that will result useful to understand the rest of the document.

These dynamic voltage phenomena may be caused by fluctuations in loads and power resources during the normal operation of the grid, or due to a concrete event, like a fault. As a result, there are mainly two types of voltage control: Static and Dynamic.

Static Voltage Control is designed to maintain system requirements, typically in response to gradual changes in load. It reacts to steady-state conditions, not transient events. It relays on On-load tap changers (OLTC) in transformers, capacitor and reactor banks and regulation at substations. As a consequence, it cannot respond to rapid disturbances or sudden voltage fluctuations.

Those fluctuations is what Dynamic voltage control is designed for, using devices as SVC, SVG, synchronous generators with fast excitation control and inverters in non-synchronous renewable sources with dynamic voltage support. It aims to reduce them and maintain a stable voltage level by providing “timely” and “appropriate” dynamic reactive power. It is the most critic and the most demanded service on modern energy systems. After the renewable energy generation is connected to the grid through the converters, the nonlinear behavior of the converter leads to harmonics in the voltage dynamics. Thus, the renewable energy plants and the power grid is prone to oscillation, the frequency of which ranges in tens to thousands of Hertz, bringing about voltage fluctuations and stability problems [35]. As the transmission and consumption of large scale renewable generations are usually based on inverter-based devices, renewable plants disconnections implies the loose of both, the active power and the reactive power provided, aggravating dynamic voltage issues. With increasing renewable penetration, the grid strength dominated by conventional synchronous generators weakens, making the system more prone to dynamic voltage fluctuations. In practice, voltage problems caused by high-renewable-penetration grids have occurred in events such as the South Australia blackout in 2016 and the United Kingdom blackout in 2019, apart from the Spanish blackout.

Different technologies and their analysis are provided below:

- **Synchronous condenser**

  A synchronous condenser is a synchronous generator operating without a mechanical load, connected to an electrical power system to provide dynamic voltage support and reactive power compensation, helping to stabilize system voltage, improve power factor, and enhance overall network stability. Unlike static devices, it contributes rotational inertia, which also aids in damping frequency and voltage oscillations.

  By adjusting its excitation, it can either generate or absorb reactive power, as explained below. The stator current can be expressed as:

$$I = \frac{V_t - E_f}{jX_s} \tag{2.4}$$

  Where:

- I = stator current
- V_t = terminal voltage of the grid
- E_f = excitation voltage of the rotor
- X_s = synchronous reactance

The reactive power Q delivered or absorbed by the condenser is:

$$Q = \frac{V_t E_f}{X_s} \cos \delta - \frac{V_t^2}{X_s} \tag{2.5}$$

Where δ is the angle between the rotor-induced voltage and the grid voltage. For operation at no active power ($\delta \approx 0$), this simplifies to:

$$Q \approx \frac{E_f^2 - V_t^2}{X_s} \tag{2.6}$$

- *Advantages:*
  1. Overloaded capacity
  2. Rotational inertia
  3. Dynamic reactive power supply
  4. Suitable for variable scenarios
- *Disadvantages:*
  1. Rotating device
  2. High cost

- **HVDC**

  Voltage Source Converter HVDC is used to transmit power over long distances, interconnect asynchronous AC networks, or integrate renewable generation. It played a role during the Spanish blackout, as one of the interconnections between France and Spain was switched to HVDC mode in an attempt to reduce oscillations while preventing the French system from accelerating the desynchronization of the Iberian system [28].

  - *Advantages:*
    1. Control AC node voltage and active power injection, and provide dynamic voltage support by controlling reactive power (especially in VSC-HVDC)
    2. Faster response than a Synchronous Condenser
    3. Current injection depends on IGBTs

4. Can help integrate distant renewable generation

– *Disadvantages:*

1. Complex structure
2. Limited to specific scenarios
3. High cost

There is a HVDC link on the border between France and Spain, named INELFE-1. It has a rated power of 2 × 1,000 MW and is a VSC-type HVDC. Station A of the HVDC is connected to Santa Llogaia 400 kV substation (Spain) and Station B is connected to Baixas 400 kV substation (France) [36].

- **SVC: Static Var Compensator**

  A SVC is a shunt-connected device based on thyristor-controlled components that provides fast-acting reactive power compensation to maintain or control the voltage at a specific point in the power system. It is one of the technologies expected to help DVC power systems with a large penetration of renewables, as it could play a crucial role in stabilizing network voltage and improving power quality. However, it is not common on the Spanish grid, nor is the regulatory framework fully adapted to them.

  – *Advantages:*

  1. Lower cost than a Synchronous Condenser
  2. Maintains system voltage within acceptable limits by dynamically compensating reactive power
  3. Large capacitor capacity
  4. Can be used across the grid: at generation, consumption facilities, or grid nodes

  – *Disadvantages:*

  1. Limited by voltage profile
  2. Resonance risk
  3. Provides no inertia

- **SVG: Static Synchronous Generator**

  A SVG, commonly referred to as a STATCOM (Static Synchronous Compensator), is a shunt-connected power-electronic device based on a voltage-source converter (VSC) that provides high-speed reactive power compensation to maintain or control voltage at a point of connection. Unlike thyristor-switched SVCs, SVG/STATCOMs synthesize an AC voltage waveform through IGBT/IGCT switching and can supply or absorb reactive power by controlling the converter output voltage and current.

– *Advantages:*

1. Low cost
2. Flexible control mode: can both inject and absorb reactive power instantly; maintains reactive capability even at low AC voltages, often better than SVCs
3. Very fast response speed

– *Disadvantages:*

1. Failure under unbalanced faults
2. Small capacitor capacity
3. No rotational inertia

The only STATCOM that was in service in the Spanish grid on 28 April is Vitoria 220kV. The nominal reactive power of this STATCOM is ±150 Mvar (inductive and capacitive), for V=1pu in the point of connection. Another 150 Mvar STATCOM has been commissioned in Tabernas 220kV after 28 April 2025 and two additional 150Mvar STATCOMs are planned to be commissioned in 2025 (Lousame 220kV and Moraleja 400kV). The steady-state voltage control modes available at STATCOM Vitoria are Q-mode and V-mode. The V-mode was active during the incident and means that STATCOM injects a current proportional to the voltage deviation from a reference value. The reference voltage set by the RE Control Centre at the time of the incident was 222kV [36].

2.6 Introduction to Frecuency Control

As inertia is a crucial factor regarding frecuency control, it is not the only one. Frequency control in power systems is organized in a hierarchical structure defined by ENTSO-E [37], composed of four main stages: inertial response, primary control, secondary control, and tertiary control. Each stage operates on a different timescale and involves distinct physical mechanisms and control objectives. Together, they ensure that the system frequency remains within acceptable limits after disturbances, while maintaining power balance and reserve availability.

The Inertial Response has already been covered in this thesis. Immediately after a sudden imbalance between generation and demand, the KE stored in the rotating masses of synchronous machines provides the first line of defense. This inertial response temporarily compensates for the active power deficit by converting mechanical energy into electrical power, thereby limiting the RoCoF. The relationship between frequency deviation and power imbalance is given by:

$$\frac{df}{dt} = \frac{\Delta P}{2HS_{\text{base}}} \tag{2.7}$$

where:

- $\Delta P = P_{\text{gen}} - P_{\text{load}}$ is the instantaneous active power imbalance,
- H is the inertia constant (in seconds),
- S_{base} is the system base apparent power.

Systems with higher inertia exhibit slower frequency changes, providing more time for active control measures to take effect. However, with the increasing integration of converter-based renewable generation (e.g., wind and solar), system inertia is decreasing, making the frequency more sensitive to power disturbances. To compensate for this, new control strategies have been developed, including:

- *Virtual inertia* and *synthetic inertia*, where power electronic converters emulate the inertial response of rotating machines.
- *Fast Frequency Response* (FFR), where renewable sources or energy storage systems rapidly inject or absorb active power to stabilize the frequency.
- *Droop control in converters*, allowing distributed renewable units to participate in frequency regulation.

Once the inertial response has slowed the frequency deviation, the Primary Frequency Control or PFC takes over. It is an automatic, decentralized action performed by the governors of synchronous generators, which adjust the mechanical input power according to the frequency deviation. This action follows the so-called droop characteristic:

$$\Delta P = -\frac{1}{R}\Delta f \tag{2.8}$$

where R is the droop constant (typically 4–5%) and $\Delta f = f - f_0$ is the deviation from nominal frequency. The PFC arrests the frequency decline by rebalancing the generation–demand mismatch and establishing a new quasi-steady-state frequency slightly below nominal. It does not restore the nominal frequency, which instead is achieved by the secondary control stage.

The Secondary Frequency Control or SFC, acts after the PFC has stabilized the system. Its goal is to restore the frequency to its nominal value, 50Hz in Europe and to re-establish the power interchange schedules between control areas. The SFC operates via centralized control signals sent from the system operator, REE in the studied case, to selected generators participating in AGC. These generators adjust their setpoints in a coordinated manner based on the measured frequency deviation and tie-line power errors. The control action is slower than PFC but precise, typically acting within tens of seconds to several minutes.

Finally, the Tertiary Frequency Control provides manual or semi-automatic re-dispatch actions to optimize system operation after the secondary control has stabilized the frequency. This includes:

- Reallocation of generation and reserve resources.
- Activation or deactivation of slower reserve units.
- Preparation for subsequent contingencies.

Table 2.9: *Summary of frequency control layers in modern power systems.*

Control Type	**Time Scale**	**Mechanism**	**Objective**
Inertial response	0–1 s	Rotational kinetic energy	Limit RoCoF
Primary control	1–30 s	Governor droop control	Arrest frequency deviation
Secondary control	30 s–15 min	AGC / centralized feedback	Restore nominal frequency
Tertiary control	>15 min	Manual or optimized redispatch	Rebalance reserves

The Primary Frequency Control thus represents the first automatic and decentralized mechanism to stabilize the system frequency immediately after a disturbance, acting as a bridge between the inertial response and the slower secondary control layers that restore nominal operating conditions.

2.7 Introduction to Reactive Power control

Reactive power plays a fundamental role in the secure and stable operation of AC power systems. It is generated or absorbed by the electromagnetic fields associated with connected equipment, but it is not transported over long distances through the network. As a result, reactive power is continuously produced and consumed locally, depending on the characteristics of the devices and their operating conditions. Although it does not contribute to net energy transfer, reactive power is essential for enabling the transmission of active power across the grid. It also serves as an indicator of the electrical quality and efficiency of power delivery within the network.

Reactive power is intrinsically related to the voltage of the system. For a simplified two-bus system, the reactive power flow is given by:

$$Q_1 = \frac{V_1^2}{X} - \frac{V_1 V_2}{X} \cos(\theta_1 - \theta_2) \tag{2.9}$$

where:

- V_1, V_2 are the voltages at bus 1 and bus 2,
- X is the line reactance,
- $\delta = \theta_1 - \theta_2$ is the power angle.

In typical transmission scenarios, where δ tends to be small, $\cos(\delta)$ may be approximated as 1. Thus, we can approximate:

$$Q_1 \approx \frac{V_1^2}{X} - \frac{V_1 V_2}{X} = \frac{V_1^2 - V_1 V_2}{X} \tag{2.10}$$

If the voltages are close, $V_1 \approx V_2$, then $V_1 V_2 \approx V_2^2$. By convention, taking reactive power injected into the system as positive, so that:

$$Q \approx -\frac{V_1^2 - V_2^2}{X} \tag{2.11}$$

From this:

- If $V_1 > V_2$, the node injects reactive power Q into the system.
- If $V_1 < V_2$, the node absorbs reactive power Q from the system.

The relation between reactive power and voltage implies:

- Adding reactive power increases voltage.
- Removing reactive power decreases voltage.

As demonstrated above, voltage levels are strongly coupled to the reactive power balance, and even small mismatches between local reactive power demand and supply can drive voltages away from their nominal values. When such imbalances persist, the system may enter unstable regimes in which voltage oscillations are amplified rather than damped, potentially leading to voltage collapse or widespread disconnections. Effective reactive power management—dynamic, distributed, and responsive to varying operating conditions—is therefore indispensable for maintaining voltage stability, ensuring power quality, and enabling the integration of large shares of inverter-based renewable generation.

Regarding the reactive power control requirements discussed in 2.2, one of the major differences between RCR units (Renewable, Cogeneration, and Waste) and conventional generators is that the former typically operate at a fixed power factor, whereas the latter are required by P.O. 7.4 [38] to control active and reactive power dynamically and independently. This enables synchronous generators to contribute effectively to local voltage regulation at their connection points.

Another relevant concept for understanding reactive power control in a power grid is that the network itself generates reactive power. This effect is stronger in underground cables but is present in all transmission assets due to the capacitive coupling between lines and their surroundings. The more meshed and lightly loaded the grid is, the greater this capacitive reactive power production becomes.

For instance, REE notes in its report [28] that at 12:22 h the Distribution Network was injecting 760 Mvar into the Transmission Network. Moreover, when transmission lines are lightly loaded, for example, due to reductions in international exchanges with France, less active power flows through the system, meaning the lines become discharged and produce even more reactive power.

Apart from the generators role, what TSO (REE) also operates reactances, whose connection absorbs reactive power and thus reduces voltage at the corresponding nodes. However, these reactors operate on an all-or-nothing basis and cannot provide gradual or finely tuned adjustments.

3 Spanish black-out: Timeline, Economic Consequences and Previous Insights

3.1 Timeline

This timeline follows the sequence of events presented in REE's report ([28], pp. 24–53), complemented with selected remarks from the AELEC & INESC TEC report to enhance context and technical accuracy. The differences between the reports will be addressed later.

Note: when "(. . .)" appears, it indicates that the text has been redacted in the report. The published document is the non-confidential version and therefore does not contain sensitive information.

- **PHASE 0. VOLTAGE INSTABILITY IN THE HOURS AND WEEKS PRIOR**

  Previous events

  Some agents reported previous episodes of voltage instability earlier this year, citing 31th January, 19th March, and 22th and 24th April, and have linked the conditions prior to the 28th to these precedents, particularly those of 22th and 24th April. The episodes of variation on these dates are described and analysed in greater detail in the Analysis section.

  Situation on the morning of 28A

  During the morning of 28 April, the peninsular electricity system experienced voltage volatility (sharp rises and drops in voltage), which various agents described as atypical.

  At 06:00 a schedule change of approximately 1,000 MW occurs in the interconnection with France (from exporting 2,590 MW to exporting 1,600 MW). Shortly before the start of the schedule change, voltage variations are detected across all pilot nodes of the 400 kV network, of relatively limited magnitude as shown in the graph.

  Between approximately 06:00 and 08:00, voltages decrease in general, consistent with the rise in electricity demand at those hours (higher loading levels on the networks).

  A frequency deviation in the system has been detected around 09:00. According to the System Operator, at 09:02 a frequency deviation of –148 mHz occurs, caused by international schedule changes in Europe (primarily in France, Italy, and Germany). Aside from this deviation, no abrupt frequency variations are observed until around 12:00.

From 09:00 onward, greater voltage variability is observed, initially without significant excursions. It is from 10:30 onward that a greater excursion appears, meaning larger-amplitude variations in voltage values relative to standard levels.

According to the data provided both by the System Operator and by distribution network operators, although relevant voltage variations were seen during the early hours of the morning of the event, voltage levels in the transmission network appear to remain within the limits set by operating procedures 1.1 and 1.3 (between 380 and 435 kV in the 400 kV network, and between 205 and 245 kV in the 220 kV network) throughout the period until 12:30.

- **PHASE 1. SYSTEM OSCILLATIONS**

  First oscillations

  On 28 April, before 12:00, up to five oscillations of small amplitude and limited impact on electrical variables were detected, which were damped by the system without the need for the System Operator to adopt significant measures. These oscillations occur in the frequency range of 0.2 Hz and take place at 05:49, 08:52, 10:30, 11:06, and 11:23.

  The 0.2 Hz oscillations at 05:49 and 08:52 are of very low amplitude and have an almost imperceptible effect on voltages.

  The 10:32 oscillation has a somewhat greater amplitude, causing a small voltage oscillation of up to 4 kV peak-to-peak amplitude at some nodes.

  The 11:03 oscillation causes voltage oscillations of up to 7 kV peak-to-peak amplitude and is also reflected in small-amplitude oscillations of power in the interconnection, which the system is able to damp in about 6 minutes.

  Finally, the 11:23 oscillation is damped in 2 minutes and has a similar amplitude to the previous one, causing voltage oscillations of about 6 kV peak-to-peak amplitude.

  None of these small-amplitude, 0.2 Hz oscillations causes the voltage to exceed normal operating thresholds.

  However, in response to these oscillations, the System Operator, in order to increase system damping, connects 3 circuits of 400 kV that were previously disconnected:

  - PINAR – TAJO (11:08)
  - ARCOS – CABRA (11:17)
  - PIEROLA – VANDELLOS (11:20)

Subsequently, between 12:00 and 12:30, the electricity system records two new oscillation events, this time of more significant amplitude, which are detailed below.

Oscillation at 12:03

The first relevant oscillation occurs at 12:03, has a frequency of 0.6 Hz and an amplitude of 70 mHz. It is damped in 4 minutes and 42 seconds.

This oscillation has a higher frequency (a “faster” oscillation) than the oscillations more commonly observed in the European system, and it was detected in different parts of the EU.

Several operators reported that this voltage oscillation was also recorded with large amplitude in Portugal. According to the System Operator, it was detected at least in Tavel (France), where it has been observed that the oscillation at that point is almost in counterphase with the one recorded at the 400 kV Carmona substation in the south of the Iberian Peninsula. Likewise, according to REE, this oscillation was also detected at the French substations of Loony and Albertville, where the oscillation amplitude is already less than half of what was observed in Tavel. Lastly, it is recorded that it was also detected in Freiburg (Germany), also with a smaller amplitude.

During this disturbance, strong voltage oscillations occur, not only of frequency and power, mainly in the southern and western areas of the Iberian Peninsula. Unlike the voltage variabilities previously detected that same morning or on previous days, this case involves repetitive oscillations of rising and falling voltage over the span of seconds, following a specific pattern consistent with the frequency oscillation, similar to a “swaying motion.”

The voltage oscillation reaches, at the 400 kV Almaraz and 400 kV Arroyo de San Serván substations, both in Extremadura, a peak-to-peak amplitude of 31.2 kV and 32.7 kV respectively, which causes the voltage at the 400 kV Almaraz substation to drop slightly below the threshold of 375 kV (93.75% of nominal voltage) at some moment. Oscillations also occur in the power through the interconnection with France.

During this period, some calls from agents to the System Operator are reported regarding the oscillations.

According to the System Operator, when the 12:03 oscillation appears, a sharp drop in system damping is detected (this is an indicator of the system’s vulnerability to these phenomena) regarding oscillations in the 0.2 Hz range. In other words, the calculations of the single System Operator indicate that, upon the appearance of the 12:03 oscillation, the system becomes more vulnerable or susceptible to 0.2 Hz oscillations.

In fact, toward the end of this 0.6 Hz oscillation, it is observed that an additional small frequency oscillation around 0.2 Hz has appeared superimposed on the 0.6 Hz one.

In response to this situation, a series of measures are adopted to increase damping:

- In accordance with the protocols agreed with the French TSO, RTE, at 12:04 they are contacted to apply, from 12:07 to 13:00, a reduction of the exchange with France by 800 MW, setting a program of 1,500 MW of export.
- Likewise, and also in line with these protocols, at 12:06 it is agreed with RTE to modify the operating mode of the DC circuit (HDVC) of the interconnection, switching at 12:11 from AC emulation mode (Pmode 34) to DC mode (Pmode 15) with a setpoint of 1,000 MW export, which was maintained until the end of the incident.
- The meshing of the network is increased by connecting five 400 kV circuits that were previously disconnected. The connection of the first three circuits is carried out at 12:07. According to information from the System Operator, the other two lines are added to improve system damping at 12:08.

A few seconds after 12:07, this first oscillation is damped.

At 12:15, the Spanish System Operator requests the Portuguese TSO, REN, to reduce the export exchange to 2,000 MW to reduce the loading of the 400 kV CEDILLO–FALAGUEIRA line and to improve damping by attempting to reduce the loading of the lines. REN requests to maintain it at 2,500 MW for the current hour, and it is finally agreed that the proposed reduction will apply starting at 13:00.

At 12:16:45, taking into account the information from various agents, the 0.6 Hz frequency oscillation appears again. At this moment, the amplitude attributable to the 0.6 Hz mode is around 30 mHz (somewhat less than half of the previous episode).

Oscillation at 12:19

After this new appearance of the 0.6 Hz oscillation around 12:16, several agents report the appearance, at 12:19, of the second oscillation, relevant in amplitude, with a lower frequency, in this case 0.2 Hz, but three times greater amplitude, up to 200 mHz.

During this oscillation, high-amplitude voltage oscillations are observed, reaching at Almaraz 400 kV a peak-to-peak amplitude of 23 kV. Although the voltage remained during almost the entire period within margins, at some moment at the 400 kV Almaraz substation the voltage dropped slightly below the 375 kV threshold (93.75% of nominal voltage).

This 0.2 Hz oscillation corresponds to one of the natural oscillations of the European system, specifically the East-Center-West oscillation mode, in which the Iberian Peninsula oscillates against the center of the synchronous European system —Germany, Italy, Austria, Denmark. . . — which, in turn, oscillates against Turkey. This oscillation has been detected and reported by agents in the rest of Europe.

As a consequence of these new oscillations, REE took the following damping measures:

- At 12:19, RTE is contacted to again reduce the exchange with France to 1,000 MW from 12:20 until 14:00. During this phase, the HVDC interconnection operation mode Pmode 1 already established is maintained.
- At 12:20, REN is contacted to reduce the exchange with Portugal to 2,000 MW at 12:30. Subsequently, at 12:26, it is agreed with REN to reduce the schedule additionally starting at 12:45.
- The connection of two more 400 kV circuits (at 12:21 and 12:25), which join the five connected minutes earlier and the three connected before the 12:03 oscillation.

Additionally, REE issued an order to couple thermal generation with voltage-control capability by setpoint, looking for the unit that would couple the fastest in the southern area. It turned out to be the (...) which provided the shortest time, 1 hour and 30 minutes, because it was warm from having decoupled at 9:00. At 12:26, the owner of this plant is contacted to confirm the scheduling of this unit at technical minimum for real-time technical constraints from 14:00. However, it never came to couple because the voltage collapse occurred beforehand.

On the other hand, another agent in the context of the oscillations, warned the System Operator that, under the circumstances, could disconnect, so as a precaution (in preparation for the possibility that it ended up disconnecting), the System Operator requests at that moment the start-up of another plant which was ultimately expected to couple by 15:00.

Evolution of voltages in Phase 1

During this Phase 1, the behavior of voltages continues to be volatile. Notable in this phase are the strong voltage variations around 12:05 and 12:20, which coincide with the two main frequency oscillations mentioned, with more pronounced variations in the Central and Southern areas of the 400 kV network.

The measures adopted to increase damping against the oscillations have an effect on voltages.

To control and return voltages to nominal values, the system has various tools:

- As indicated earlier, for this period several generation units were scheduled for voltage control due to technical constraints, subject to the setpoints of Operating Procedure 7.4.
- Likewise, the System Operator performs topological maneuvers in the network, coupling reactances (in nodes with high voltages) and disconnecting them otherwise. Specifically, after the 12:03 oscillation, since it caused minimum voltage values below 390 kV, the operator decides to decouple several reactances:
  - 12:04 Villaviciosa 400 kV REA 1
  - 12:04 Guadame 220 kV REA 3
  - 12:05 Rueda 400 kV REA 2
  - 12:05 Aragón 400 kV REA 1
- Later, since with the return of the oscillation at 12:16 low voltage values are reached again in some parts of the system, more reactances are disconnected:
  - 12:17 Cabra 400 kV REA 1
  - 12:21 Peñaflor 400 kV REA 1
  - 12:24 Palos 220 kV REA 1
  - 12:24 Morata 400 kV REA 4
- After the end of the second oscillation, at 12:22, a generalized trend of voltage increase is observed—from voltages close to nominal to high values (but still within the operating limit)—so the System Operator decides to couple 5 reactances (2 in the north area, 2 in the south, and 1 in the center) to reduce voltage:
  - 12:26 Vitoria 400 kV REA 2
  - 12:27 Peñaflor 400 kV REA 1
  - 12:27 Guadame 220 kV REA 3

- 12:27 Guadame 400 kV REA 2
- 12:28 Morata 400 kV REA 4

This phase ends with a downward trend in voltages that continues beyond 12:30.

In any case, with the information received from the various agents, it is not identified that during this Phase 1 (from 12:00 to 12:30) voltage values above the maximum thresholds established in the operating procedures occurred in the transmission network.

PHASE 2. GENERATION LOSSES DUE TO OVERVOLTAGES

System situation in the preceding moment

Before describing the generation loss events, a characterization of the system at that moment is provided:

At 12:30, once the previous oscillations had been damped, the system, after a voltage maximum a few minutes earlier, showed voltage values on a downward trend, but higher (between 410 and 420 kV) than nominal levels in the 400 kV grid.

Likewise, the system had a frequency around 50 Hz, low damping and, as a consequence of the actions carried out in Phase 1, limited flows in the interconnections, the HVDC interconnection with France operating with its power electronics in “DC mode” with a fixed export flow of 1,000 MW (2 x 500 MW), a 400 kV grid with a meshing level higher than initially planned after the coupling of 10 400-kV circuits in several stages since 11:10 in the morning, and less flexibility for voltage control.

At that moment, the demand of the Spanish peninsular system was 25.184 MW, a low demand but typical given the temperature (mild), the day (Monday), and the time (mid-day). At that time, there were 2,978 MW of pumping consumption (reversible hydropower plants taking advantage of low solar prices to pump water to the upper reservoir to later be turbinated to generate electricity). As a reference, the historical peninsular peak demand is 44,876 MW (17/12/2007).

The generation mix at 12:30, considering the market results and the application of technical constraints, consisted of 82% renewable generation, 10% nuclear (4 reactors connected, two at full load) and the rest gas (3%, with 6 plants connected), coal (1%), and co-generation and waste (4%).

Specifically, at 12:30 there were 11 thermal power plants connected with an obligation to regulate voltage by setpoint: 4 nuclear power plants, 1 coal-fired plant and 6 gas-fired plants, in addition to hydropower generation.

Regarding other dimensions of security of supply, the system operator indicates that before the incident, the system had sufficient levels of inertia and reserves, as detailed in the Analysis section.

In the southwest area, the units with real-time voltage control capability by setpoint, and which had been scheduled by technical constraints for voltage control, were (. . .) and the gas combined-cycle plant of (. . .) which was connected at its technical minimum.

Voltage rise at 12:32

With this situation and system conditions at 12:30, starting at 12:32:00 voltages begin to increase across the entire transmission grid almost linearly—for example, at SE Olmedilla from 413 kV to 428 kV in 57 seconds, or at SE Arroyo de San Serván 400 kV from 411 kV to 424 kV in the same time.

According to the data provided by distribution network owners, voltage rises are observed in their networks in that same minute.

Simultaneously, as shown in Graph 16, during minute 12:32 there is a sustained reduction of exports through interconnections, mainly through the interconnection with France.

First detected generation losses

Following the voltage increase in the system, a generation loss process begins, consisting of three main initially identified events. These three events are "visible" in the system variables, in the form of sudden changes in cross-border exchanges, frequency, and system voltage levels.

Additionally, interspersed with these three main events, disconnections of smaller-capacity generation have been detected.

Between 12:32:00 and 12:32:55, the system operator has identified small-capacity generation losses totalling 525 MW distributed across the territory, of which 317 MW come from distributed generation under 1 MW.

Event 1: 12:32:57.140 Generation loss due to trip (disconnection) of the generation evacuation bay (. . .) (Granada)

At that moment, 355 MW of active power were being injected and 165 MVar of reactive power were being absorbed through that bay.

With the information provided by various agents, it is concluded that the trip occurs on the generation side (that is, in the infrastructure collectively owned by the generators) due to over-voltage in the secondary of the 220/400 transformer.

The generation loss in (. . .) causes a frequency drop in the system, which recovers after a transient of about 3 seconds, and by reducing generation in the Iberian Peninsula, reduces the export flow to France by approximately 450 MW (bringing it to zero).

However, the most relevant effect for subsequent events is the contribution to over-voltages due to the disconnection of generation. These over-voltages are detected at several nodes of the grid, reaching values above 430 kV at 12:33:00, although according to the system operator, still below the 435 kV indicated by operating procedures.

AELEC & INESTEC Report: *Regarding the causes of these disconnections, the AELEC Members do not have data on the first substations that disconnected during the main incidents identified in the Report. However, the AELEC Members informed us that their plants did not experience improper disconnections.*

According to REE, the capacity lost during these events was largely due to improper disconnections by generation plants, not justified by the voltage conditions at that time. Nevertheless, the widespread and almost simultaneous nature of the disconnections, affecting dozens of plants geographically dispersed, belonging to different owners and different technologies, suggests that it cannot be attributed solely to individual failures. This pattern instead points to a systemic problem that affected a considerable part of the electricity system.

According to the information provided by the AELEC Members, a system frequency disturbance compatible with the disconnection of an estimated generation volume between 300 and 400 MW has been verified, as reported by the Analysis Committee. This disconnection occurred at a substation in the province of Granada.

The identified cause was an overvoltage: the substation reached a value of 260 kV, exceeding the operational threshold of 253 kV. After this event, the frequency recovered temporarily.

Event 2: 12:33:16.460

About 19 seconds after Event 1, another similar event occurs, reflected in a frequency drop and an increase in the import balance with France.

The generation loss occurs this time, at least, at the substation of (. . .) (Badajoz), first at the renewable collector substation (. . .) (12:33:16.460) and shortly afterwards at the collector (...) (12:33:17.520). Both collectors evacuate into the (...) substation, in the (...) position.

A joint generation loss of around 730 MW is estimated 582 MW in (...) and 118 MW in (...). The configuration of this substation is similar to the previous case: in that position, (...) plants evacuate (...), assigned to (...) control centres. With the information received from different actors, data consistent with a disconnection likely occurring within the evacuation infrastructure itself have been identified.

This new generation loss causes a further frequency drop of 55 mHz in the (...), which is damped without recovering 50 Hz, and results in the interconnection flow with France becoming an import of 895 MW.

As with the previous generation loss, this one also causes, moments later, a rise in voltages, contributing to the worsening of grid conditions.

Interspersed with the disconnections at the (...) positions, at least the following generation disconnections have been identified:

- 12:33:16.820 — The photovoltaic plant (...) connected to the (...) substation, which at that moment was generating (...) MW.
- 12:33:17.368 — 22.87 MW of wind farms at the (...) substation (Segovia).

Likewise, after the second disconnection at (...) (12:33:17.520), a disconnection of wind and photovoltaic generation of about 33.8 MW connected to the (...) substation was detected at 12:33:17.547.

AELEC & INESTEC Report: *Shortly afterward, a second disconnection occurred, with an impact on frequency consistent with a loss of between 700 and 800 MW, according to the data from the Analysis Committee. This disconnection originated in two substations in the province of Badajoz.*

The information available from the AELEC Members does not allow confirmation of whether this disconnection was caused by an overvoltage. Some of them operate plants connected to these substations and reported disconnections due to overfrequency, since the substation tripped first, isolating the plants from demand. However, as it is a substation operated by a third party, no access to its specific operational data is available. In any case, the moderate frequency drop observed at that moment is consistent with a disconnection caused by overvoltage.

Event 3: 12:33:17.780

About 20.5 seconds after Event 1 (1.3 s after Event 2), another significant generation loss occurs, reflected in a new frequency drop and an increase in imports from France.

This third generation loss takes place at the (...) substation (Seville), in the renewable evacuation position (...), where 550 MW are lost.

The configuration of that substation is similar to the previous cases: in that substation and its three positions, (...) plants evacuate energy, assigned to (...) control centres.

Immediately afterwards, the following smaller-scale generation disconnections have also been identified:

- 12:33:17.975 — Disconnection of the photovoltaic plant (...) connected to (...) (Cáceres) when it was generating (...) MW. The voltage reported by the system operator at this point, based on SCADA data, is 240.89 kV in the 220 kV transmission grid.
- 12:33:18.020 — Disconnection of the photovoltaic plants (...) owned by (...) connected to the (...) substation (Badajoz), which were generating (...) MW respectively, totalling (...) MW. The system operator reports, based on SCADA data, a voltage of 239.39 kV in the 220 kV grid.

These generation losses cause a new frequency drop of 75 mHz in the (...), which no longer damps out, and the import balance in the interconnection with France increases by 1,510 MW. Overvoltages at various nodes of the grid intensify.

AELEC & INESTEC Report: *One second later, another disconnection estimated at around 800 MW was recorded in the Sevilla area, according to the Analysis Committee. The small frequency drop observed at that moment suggests an overvoltage-related disconnection.*

The information provided by the AELEC Members does not allow confirmation or dismissal of whether this loss occurred in Sevilla. However, over-voltage-related disconnections of photovoltaic and wind plants have been identified in that same second (between 12:33:17 CET and 12:33:18 CET) in other areas of the peninsular system, including Cáceres, Huelva, and Cuenca. These plants have a combined installed capacity of 1 GW.

According to REE, in this brief interval approximately 2,000 MW of renewable generation was lost, in addition to a significant amount of distributed generation connected to the *distribution grid with capacity below 1 MW. REE attributes part of these disconnections to improper equipment responses to over-voltage conditions.*

Nevertheless, this volume of lost generation implies the almost simultaneous disconnection of dozens of substations and renewable plants of multiple technologies, located in various geographical areas and operated by numerous owners.

Given this diversity, it is highly unlikely that all these facilities failed improperly at exactly the same time. This suggests that the main cause was a systemic problem affecting a considerable portion of the electrical system, rather than a mere aggregation of individual failures, such as calibration errors or insufficient voltage control at each plant.

Following this new generation loss, occurring within just over 20 seconds, system variables continue evolving toward unsustainable values, with voltages rising and frequency falling, leading to Phase 3 of the incident, described below.

PHASE 3. COLLAPSE UNTIL ZERO VOLTAGE

Although the exact determination of the individual events in this phase is more complex -due to the high overlap of data and measurements relating to events that occurred practically simultaneously- there is a high degree of consistency between the analysed data and the assessments made by the different agents regarding its characterization.

Thus, in this phase two phenomena with a certain level of overlap are identified: first, a massive disconnection of generation occurs, mainly due to over-voltage. Superimposed on this, although a few moments later, the frequency drop reaches levels that cause, in the final moments, generation disconnection due to under-frequency.

According to the information received, the bulk of this phase takes place within barely 5 seconds. For this reason, slight inaccuracies or divergences may exist in the order of events or the specific time assigned to each of them, attributable to different data sources (local records, telemetering from the asset owner or the system operator) that also, in some cases, present differences in time configuration. It is recalled that the data for the approximate reconstruction of this phase, detailed in the following sections, was provided by the agents. This does not hinder an adequate understanding of this phase, linked to a "chain reaction" of generation disconnection and over-voltage, which in turn leads to a reduction of frequency.

Disconnections due to over-voltage

Some of the events identified in this phase are listed below for illustrative purposes:

- 12:33:18.102: the disconnection of the (...) link facility occurs. At this moment it was generating (...) MW. The measured voltage at the moment of disconnection was 247.6 kV.
- 12:33:18.360: a stepwise decrease begins in the power evacuated through the (...) facility. The plants evacuating through this link facility were generating (...) MW before the incident started, and a first decrease of 16 MW occurs. The final disconnection of all generation takes place later, at 12:33:23.260.
- 12:33:18.380: the disconnection of the (...) plant in (...) occurs, which evacuates into (...) when it was generating (...) MW. With the information available, the voltage at (...) at this point was 443.8 kV, therefore exceeding the voltage that facilities connected to 400 kV are required to withstand.

From this point onward, according to the information provided by the System Operator, since system voltages exceeded the withstand capability of generation facilities, the disconnection of generation is to be expected, which in turn will continue contributing to a rise in voltages and, therefore, to disconnections in the form of a "cascading effect" or "chain reaction."

- 12:33:18.540: the disconnection of the (...) plant occurs, which was generating (...) MW and absorbing (...) Mvar.
- 12:33:18.846: the tripping of the (...) link facility occurs. The plants evacuating through this link facility were generating (...) MW.
- 12:33:18.951: the tripping of the (...) link facility occurs. The plants evacuating through this link facility were generating (...) MW.
- 12:33:19.000: a new decrease of 16 MW occurs in the production injected through the (...) link facility.
- 12:33:19.040: the disconnection of the (...) occurs when it was producing (...) MW. This wind farm evacuates at 132 kV and is associated with the transmission network node (...). The voltage at 132 kV was 146.8 kV.
- 12:33:19.095: the disconnection of the (...) of (...) occurs, through which (...) MW were being injected.
- 12:33:19.131: the (...) trip due to over-voltage of 14% (132 kV) and 15% (220 kV).

- 12:33:19.252: the disconnection of the (. . .) plant occurs, when it was generating (. . .) MW.
- 12:33:19.260: a further decrease of (. . .) MW occurs in the production injected through the (. . .) link facility.
- 12:33:19.320: another change in the derivative of the frequency is observed, becoming more negative (falling more rapidly). This is consistent with the loss of another block of additional generation.
- 12:33:19.296: the disconnection of the (. . .) plant occurs when it was generating (. . .) MW.
- 12:33:19.407: a decrease of 63.3 MW occurs in the production injected through the 400/132 kV transformer of the (. . .) collector, which in turn injects into the transmission grid at (. . .). The plants injecting through this transformer had been producing (. . .) MW prior to the incident; the transformer trips 1.24 seconds later.
- **12:33:19.620: at this moment, the maximum import exchange with France is reached, leading to loss of synchronism**
- 12:33:19,920: a decrease of MW occurs in the production injected through the link facility.
- 12:33:19,951: the disconnection of the link facility from occurs. At the moment of the trip, the plants that remained connected were generating MW, but prior to the start of the incident the link facility was carrying 263.8 MW, which means that before this instant (. . .) MW had been lost, which had been disconnected previously.
- 12:33:19,969: the park trips.
- 12:33:19,971: the line of trips due to over-voltage, without effect on generation or consumption.
- 12:33:20,020: disconnection of all generation that was injecting into occurs. 313 MW are lost.
- 12:33:20,040: the disconnection of the facility occurs when MW were being evacuated through it. The voltage at that instant was 252 kV.
- 12:33:20,100: the disconnection of occurs. This unit was generating MW in the moments prior to the incident. The voltage in was 419.6 kV and the frequency in was 49.549 Hz.

- **12:33:20,180: frequency crosses the first pumping facility load-shedding threshold —49.50 Hz—**
- 12:33:20,200: the disconnection of the link facility occurs. The plants evacuating through this link facility were generating (. . .) MW and absorbing (. . .) Mvar.
- 12:33:20,225: the disconnection of the photovoltaic plants occurs, when they were generating and MW respectively. In total, (. . .) MW are lost.
- 12:33:20,300: the disconnection of the link facility occurs. At this instant, the link facility was carrying 49 MW, but prior to the start of the incident it carried (. . .) MW, so the other (. . .) MW were disconnected before this instant. The voltage at this instant in was 255.3 kV.
- 12:33:20,420: the disconnection of the link facility occurs when it was evacuating (. . .) MW; prior to the incident it was evacuating MW, so another 49 MW had to be lost in previous instants. The voltage was 250.1 kV.
- 12:33:20,476: the disconnection of the plants associated with (. . .) MW respectively occurs, when generating (. . .) MW.
- **12:33:20,600: frequency drops below 49.00 Hz, which is the first demand-shedding threshold (non-pumping)**
- 12:33:20,650: over-voltage trip of occurs, which injects into (. . .). At the moment of this trip, (. . .) MW were being evacuated through the transformer; voltage in was 456 kV and frequency was 48.914 Hz.
- 12:33:20,740: the disconnection of (. . .) occurs when they were generating a total of (. . .) MW among the three. These plants inject into the (. . .) kV distribution network associated with.
- **12:33:20,760: frequency drops below 48.80 Hz, which is the second demand-shedding threshold**

  AELEC & INESTEC Report: *The information provided by the AELEC Members confirms that, during this period, disconnections due to overvoltage occurred in the regions of Cáceres and Badajoz.*

  During this period, at 12:33:19 CET, the Iberian Peninsula began to lose synchronism with the European System, and the threshold of 48.8 Hz was exceeded. This activated the first phase of load shedding of pumped-storage plants, meaning the disconnection of these plants when operating as consumption units to contain the imbalance between *generation and demand. However, this measure proved insufficient, as frequency continued to fall.*

The simulations carried out show that the loss of interconnection, combined with the generation loss up to 12:33:19 CET, makes the collapse of the system practically unavoidable from that moment onward.

- **12:33:21,000: frequency drops below 48.60 Hz, which is the third demand-shedding threshold**
- 12:33:21,080: the disconnection of occurs.
- 12:33:21,219: the disconnection of the facility occurs when it was transporting (...) MW, which was the amount before the incident started. The voltage at that instant in was 260.7 kV.
- **12:33:21,380: frequency drops below 48.40 Hz, which is the fourth demand-shedding threshold**
- 12:33:21,440: a decrease of 26 MW occurs in the production injected through the link facility.
- 12:33:21,503: the disconnection of the link facility occurs at the end. The disconnection at the end, 230 ms later, occurs due to receipt of remote trip. At the moment of the trip, the link facility carried (...) MW, which is approximately what it carried in the moments prior to the incident ((...) MW). Voltage was 448.4 kV.
- **12:33:21,820: frequency drops below 48.20 Hz, which is the fifth demand-shedding threshold**
- **12:33:22,040: frequency drops below 48.00 Hz, which is the sixth and final demand-shedding threshold**
- 12:33:22,160: a decrease of 55 MW occurs in the production injected through the facility.
- 12:33:22,330: the disconnection of the facility occurs. Through this link facility, (...) MW were being injected. Voltage was 465 kV.
- 12:33:22,460: a decrease of 52 MW occurs in the production injected through the facility.
- 12:33:22,470: disconnection of the link facility occurs. At the moment of disconnection, the plants evacuating through this link facility were producing (...) MW;

however, prior to the start of the incident they were producing (. . .) MW, so (. . .) MW had been disconnected earlier.

- 12:33:22,560: the frequency derivative becomes more negative again, possibly due to the loss of more generation, and having crossed all load-shedding steps, the Iberian system heads toward collapse.
- 12:33:22,600: the disconnection of half of the (. . .) that (. . .) injects into occurs. A loss of 117.5 MW occurs.
- 12:33:22,702: the disconnection of occurs when it was generating (. . .) MW. Voltage was 436 kV and frequency was 47.79 Hz, approaching the 47.5 Hz lower subfrequency limit that generators are required to withstand.
- 12:33:22,860: the disconnection of the link facility 220 kV generation occurs when it was carrying (. . .) MW, which coincides with what it carried in previous instants. At the moment of the trip, voltage was 257.5 kV.
- 12:33:22,900: the disconnection of generation injected through the link facility occurs when it was producing (. . .) MW.
- 12:33:23,076: the disconnection of the line occurs due to the over-voltage function at the end, which sends a remote trip to (. . .). The voltage threshold set for the trip is 1.2xUn, i.e., 480 kV. The measured voltage at the moment of the trip was 485 kV.
- 12:33:23,140: the disconnection of half of the plant power occurs due to the trip of one of the two transformers through which it evacuates. This plant injects into (. . .). 125 MW of generation are lost.
- 12:33:23,260: a decrease of 51 MW occurs in the production injected through the link facility occurs.
- 12:33:23,360: the disconnection of the other half of the plant power occurs due to the trip of the second of the two transformers through which it evacuates. The disconnection of occurs. These plants were not generating. They inject into (. . .). A total of (. . .) MW of generation is lost.
- 12:33:23,360: disconnection of half of the photovoltaic plant of that injects into (. . .) occurs. A loss of (. . .) MW occurs.
- 12:33:23,400: disconnection of generation from the plant occurs when it was producing (. . .) MW.

- From this point, according to information provided by the system operator, frequency has exceeded the lower subfrequency threshold marked in TED/749/2020 Order, which generation must be able to withstand.
- 12:33:23:515: disconnects due to underfrequency. It was producing (...) MW. Voltage was 433 kV and frequency was 46.15 Hz. Previously, voltage in (...) had reached 469.3 kV. According to its operator, it absorbed (...) MVAr in its attempt to stabilize the voltage in its evacuation network, causing overheating of the plant's steam condenser.
- 12:33:23,590: disconnection of occurs when they were generating (...) MW respectively. Frequency was 45.89 Hz.

  AELEC & INESTEC Report: *The frequency continued to fall rapidly until it triggered the blackout at 12:33:24 CET. During this downward trajectory of frequency, more than 5 GW of load were also disconnected in the distribution networks of Spain and Portugal, but this was still insufficient to stop the decline, which reached RoCoF values above 1.5 Hz/s.*
- 12:33:29,741: Zero voltage in after the trip of the last unit.

After this moment, zero voltage occurs in the Spanish peninsular system.

3.2 Economic consequences

The primary and most significant consequences, far beyond the economic impact, were the ten lives lost. Malfunctions in combustion-based generators, failures in life-support and oxygen-delivery equipment, and fires caused by candles were among the main contributing factors. Additional deaths are currently under investigation as potential indirect consequences of the power outage. Several people were trapped in elevators, public transportation came to a halt, and traffic congestion and accidents increased. Ambulances were unable to reach certain locations, and elderly care homes as well as patients with dependency needs had to rely on community solidarity and local police support.

In hospitals, fire stations, police stations, and schools, emergency generators and protocols had to be activated. With communications down, police and military units were deployed to distribute fuel, essential supplies, oxygen cylinders, and portable emergency generators.

In the industrial sector, machinery required replacement due to electrical damage, transportation systems were disrupted, and refrigerated goods were lost. Economic activity across both Spain and Portugal came to an abrupt halt, with estimated losses exceeding €4.5 billion.

For better or worse, this problems fall out of the scope of this thesis. The economic impact of the black-out is dominated by the increase in ancillary services costs.

The costs breakdown is showed below:

	Oct/24	Nov/24	Dec/24	Jan/25
Day-ahead market	70.1	106.7	114.0	100.4
Intraday market (MIBEL auctions and continuous)	-0.1	-0.1	-0.1	-0.1
Technical constraints PDBF	4.9	5.0	4.1	4.2
Secondary regulation band	3.1	3.2	3.7	3.3
Real-time technical constraints	5.5	4.0	3.6	3.6
Imbalance energy noncompliance	-0.1	-0.2	-0.3	-0.3
Deviation costs	0.5	0.4	0.4	0.7
Deviation balance	0.7	0.1	-0.1	0.1
Power factor control	-0.1	-0.1	-0.1	-0.1
PO 14.6 balance	0.1	0.1	0.0	0.1
Adjustment services	**14.4**	**12.4**	**11.3**	**11.6**
Capacity payments	0.2	0.2	0.3	0.3
Adjustment mechanism RD-L 10/2022	-	-	-	-
Total price (€/MWh)	**84.6**	**119.3**	**125.5**	**112.1**
Closing energy (MWh)	**19,004,643**	**18,627,464**	**20,307,045**	**21,596,984**

Table 3.1: *Monthly summary (Oct 2024–Jan 2025) [39]*

	Feb/25	Mar/25	Apr/25	May/25
Day-ahead market	110.8	55.6	29.1	17.9
Intraday market (MIBEL auctions and continuous)	-0.1	0.0	-0.1	-0.1
Technical constraints PDBF	4.0	6.6	11.3	22.0
Secondary regulation band	3.2	2.6	1.8	1.3
Real-time technical constraints	7.1	5.9	4.5	2.9
Imbalance energy noncompliance	-0.5	-0.3	-0.1	-0.1
Deviation costs	0.6	0.6	0.3	0.2
Deviation balance	0.0	0.6	0.0	0.0
Power factor control	-0.1	-0.1	-0.1	-0.1
PO 14.6 balance	0.1	0.1	0.0	0.0
Adjustment services	**16.3**	**15.9**	**18.4**	**26.2**
Capacity payments	0.3	0.2	0.1	0.1
Adjustment mechanism RD-L 10/2022	-	-	-	-
Total price (€/MWh)	**127.3**	**71.5**	**47.6**	**44.1**
Closing energy (MWh)	**19,177,656**	**20,774,406**	**16,570,300**	**18,108,806**

Table 3.2: *Monthly summary (Feb–May 2025) [39]*

Pre-blackout ancillary service costs, from October to March, were moderate, averaging in the low-to-mid teen (€13.65/MWh) In April, which included two days before/after the blackout, it was €18.4/MWh, but in May, it reached €26.2/MWh, with a grow of almost 95.1% in comparison to the average of previous months. This change was principally dominated by the growth of Technical Contraints, that almost doubled. However, the drop on wholesale prices compensated by a large margin, resulting in falling final prices, reflecting a broader downward trend due to renewable penetration.

Immediately after the blackout, Spain's grid operator (REE) dramatically increased the use of backup and balancing services, causing ancillary costs to skyrocket. May doubled the Technical Constraints relative to April, and more than quadrupled the average of previous months. It is indeed the case that in winter the grid technical requirements are usually more naturally fulfilled by hydro participation in the market, but still May 2025 was an 84% superior to May 2024 [40]. In fact, it was the highest ever recorded [41], even exceeding the energy wholesale price that month.

The reason costs soar is related to several factors:

- Reinforced Grid Operation Mode: After the blackout, REE implemented an enhanced security mode to prevent another collapse. This meant running more reserve and backup generation around the clock, especially gas-fired plants, to provide voltage and frequency support. The activation of these backup units roughly doubled compared to normal operations, as can be seen in Table 3.2

- Technical Constraints and Out-of-Market Actions: To stabilize the system post-blackout, REE frequently intervened outside the day-ahead market. In early May, REE curtailed some cheap renewable generation and replaced it with conventional thermal generation via technical constraint dispatch.Essentially, because the spot power price was very low (€17/MWh) in May, neither gas nor nuclear plants would normally run at those prices; REE had to commit them via ancillary services at higher cost.

- Voltage Control and Inertia Issues: The own REE's investigation found voltage control failures, as certain generators were unable to absorb reactive power and maintain voltage. REE had to ensure more synchronous generation online after the blackout. This need for additional reactive power and frequency regulation support meant the operator had to "throw money at the problem" by keeping conventional units running as a stop-gap.

- Supply-Demand Uncertainties: The blackout itself caused some generators (like nuclear plants) to trip offline, and it took days for certain units to return to service. Coupled with occasional forecast errors for renewables or peak demand spikes, REE had to call on reserves more aggressively.

In short, to avoid any supply shortfall or instability, the TSO erred on the side of over-procuring balancing services, at a time when those services were particularly costly (since they mostly came from fuel-burning units). The post-blackout cost spike underscores the hidden costs of grid instability. Spain's experience shows that a major blackout can have lasting market impacts. Fundamentally, the event highlighted the importance of grid infrastructure upgrades (voltage control devices, inertia support) and proper integration of renewables, to avoid exorbitant balancing costs.

3.3 Previous Insights from REE on the Spanish Power System

This statement is supported by three documents published by REE itself, shown below. They include translations made by myself, but the pages of the original documents are indicated.

- **Estudios de prospectiva del sistema y necesidades para su operabilidad / Prospective studies on the power system and its operability needs (2020)** [42] (pp. 6, 14, 21, 23, 26–28, and 30)

  In this document, different scenarios were studied for 2026 and 2030. The most defining parameters are interconnections and nuclear presence, as well as storage capacity in terms of pumped hydro and batteries, renewable deployment, and the projected variation in demand.

Study	Description	Env. Scenario	Nuclear	FR Interc.	MA Links
H2026	Base 2026	H2025 NT	7	5 GW	2
H2026_NTC	H2026 + delay in new FR interconnection	H2025 NT	7	2.8 GW	2
H2030	Base 2030 scenario	H2030 NT	3	8 GW	3
H2030_NTC	H2030 + delay in FR and MA interconnections	H2030 NT	3	5 GW	2
H2030_NUCS	H2030 without nuclear generation	H2030 NT	0	8 GW	3
H2030_SMR	H2030 without synchronous must-run units	H2030 NT	3	8 GW	3

Table 3.3: *Summary of study scenarios and system parameters [42]*

While the perspectives of the evolution of the system are great:

"The penetration of renewable energies in the peninsular system, without network constraints on electricity generation, reaches 68.9% in 2026 and 82.7% in 2030. In 2019, it

was 39%"

"The expected renewable generation curtailment without network constraints represents 1% (1.5 TWh) and 3.4% (7 TWh) of the potential wind and solar production in 2026 and 2030, respectively. CO2 emissions in the SEPE reach values of 10,935 and 9,559 kton in 2026 and 2030, respectively, which represents a reduction of 78% and 81%, respectively, compared to current values."

"The Spanish system shifts from importing 7 TWh in 2019 to exporting 6 TWh in 2026 and 22 TWh in 2030. In 2030, it becomes an exporter to France and Morocco, and an importer from Portugal"

"Variable generation costs are reduced by 68% in 2026 and 76% in 2030 compared to the variable generation costs that would result from 2019 production at 2026 and 2030 prices, respectively"

"In 2026, the ES–FR Bay of Biscay interconnection allows a reduction of curtailments by 0.6 TWh (41% of total curtailments) and a decrease in CO2 emissions by 397 kton (3.6% less). In 2030, the Aragón–Atlantic Pyrenees and Navarra–Landes projects, together with the third link with Morocco, allow renewable curtailments to be reduced by 4 TWh (59% of total curtailments)"

But in the frecuency stability chapter, inertia is analized:

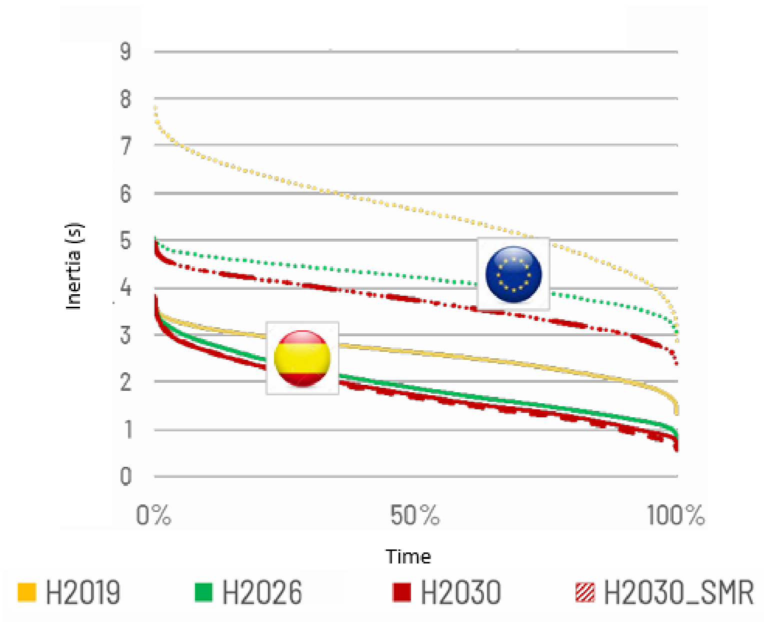

Figure 3.1: *Comparison between inertia in the European System versus in the Spanish System [42]*

*Note: SMR = Reference system scenario without synchronous must-run generation

While in 2019 the inertia is expected to be over the 2 s ENTSO-E recommendation, the predictions for 2026 and 2030 assumed to not comply with the rule in more tham 60% of the time. In relation to that, REE observes “Sustained downward trend in system inertia. The synchronous must-run ensures, for most of the time, an adequate level of inertia in the system, and it will remain necessary as long as advanced power-electronics controls are not consolidated (e.g., grid-supporting).”

The four branches of the document regarding the peninsular system (Generation balances, Adequacy study, Flexibility needs analysis and Frequency stability study) concludes remarking that:

”The development of storage and interconnections is essential to increase the integration of renewables and to ensure the operability of the system”

”The integration of renewables in the Spanish peninsular system, given its limited interconnection, has a greater impact compared to other more interconnected systems of Continental Europe (CE) with regard to frequency stability. The inertia in the Iberian Peninsula is 50% lower than that of CE”

”Decreasing inertia levels (30% lower than today in 2030) in the system could entail a risk of unacceptable frequency RoCoF under large imbalances. There is a need for additional provision of inertia (natural or through grid-forming controls in renewable generation) during 6% of the time in 2026. For more than 50% of the time in 2026 and 2030, shortages of primary reserve are observed. The capability of providing primary (FCR) by renewable generation, demand aggregators... is desirable in future scenarios to avoid post-disturbance frequencies outside the normal operating ranges of the system”

”The development of interconnections and storage facilities is essential to increase the integration of renewable generation, reduce the ramps of dispatchable generation, and ensure the operability of the system”

”A contained deterioration of frequency stability conditions is observed in the SEPE (Spanish Peninsular Electric System), showing a need for additional provision of inertia (natural or through grid-forming controls in renewable generation) and for primary regulation reserve. The capability of providing primary (FCR, Frequency Containment Reserve) by renewable generation, demand aggregators (...) is desirable in future scenarios”

- **Informe técnico-económico del proyecto demostrativo regulatorio del nuevo servicio de control de tensión / Techno-economic report of the regulatory demonstration project for the new voltage control service (2023)** [43] (pp. 2)

  This document begins by stating that:

  "At present, REE does not have sufficient tools to prevent voltages in the transmission network (RdT) from reaching very high values, occasionally exceeding the permissible ranges established in the regulations, and even, at certain moments, causing overvoltage disconnections."

  As some of the reasons for the operational challenges, REE mentions: the decrease in peninsular demand, particularly noting the industrial demand that used to cover the "night valley"; the substantial increase in IBR generation, which follows fixed power factors, without operating according to real-time instructions, and the decrease in synchronous generation that does comply; and the variability in power exchanges with Portugal and France, which creates volatility in reactive power balance.

  REE concludes by claiming that:

  "REE is responsible for maintaining voltage levels at the nodes of the transmission network within the permissible ranges established in the regulations, using all available resources at its disposal (...) REE uses these tools on a daily basis, pushing the available resources to their limits, disconnecting more than 100 lines from the transmission network, with an average of 70. Moreover, the average use of reactances in the SEPE (Spanish Peninsular Electric System) during 2022 reached 85% (with 1.5% unavailability), and even so, situations frequently occur in which the voltage control resource in a given area is exhausted."

- **Criterios Generales de Protección del Sistema Eléctrico Español (CGP-SEE) / General Protection Criteria of the Spanish Power System (GPC-SPS) (2024)** [44] (pp. 1, 2, 41 and 45)

  In this document, it is stated that the general criteria (GPC-SPS) for the peninsular system date back to 1996. As its role is purely technical and operational, not legislative, Red Eléctrica de España (REE), as the Transmission System Operator (TSO), does not have normative or regulatory authority. Therefore, REE proposes, and maintains documents such as the CGP-SEE, but it cannot modify them unilaterally, because as these criteria involves all the system participants, including generators, transmission companies, distributors, and large consumers, any adjustments must be approved by the CNMC (National

Commission on Markets and Competition) and the MITERD (Ministry for the Ecological Transition and the Demographic Challenge). Any regulation also requires coordination with ENTSO-E and compliance with EU Regulation 2017/1485.

In the Introduction chapter of this document is stated: *"Another of the causes that has forced the revision of the existing General Protection Criteria has been the change in the generation mix of the current electric system due to the massive entry of renewable energy sources, which have gradually displaced traditional thermal power plants (...) some of the implications of power electronics–based devices that may lead to undesired behavior in the current protection system have been identified. As long as a sufficient level of synchronous generation is maintained, no significant changes are expected; however, in the future, in areas with a high penetration of power electronics–based generation, situations could arise in which the behavior of some of the current protection functions does not perform as expected"*

In the chapter addressing the expected changes in the protection system, specifically speaking about the shor-circuit current capabilities, it states: *"For this reason, under certain types of faults, the correct operation of the protection system cannot be guaranteed, as situations may occur in which the fault is not cleared under the expected conditions, or in the most severe cases, some protection functions may fail to detect them."*

Regarding the Operation Procedures themselves: *"In the current Operation Procedures, response criteria are established for voltage dips in terms of magnitude and duration. In situations where the voltage dip exceeds the defined thresholds, or where there is a concentration of power electronics–based generation that is not adapted to these criteria, the disconnection of large amounts of renewable generation may occur, causing an imbalance between generation and demand that could trigger serious consequences for the system."*

Taken together, these documents constitute a clear call for urgent action, signaling that system operability is approaching critical stress levels. This is exemplified by the fact that the update of Operation Procedure 7.4 for the Voltage Control Service [38] was carried out on June 26$^{\text{th}}$, after the blackout, whereas the initial proposal had been made in 2020 ([43], pp. 2). It took five years and a catastrophic event for a regulatory framework update to be carried out, when asked by the System Operator, which had been alerting of extremely critical issues since 2020.

4 Methodological Approach

This chapter looks into the methodological approach used in the technical analysis of the situation present in the system at the moment before the 28^{th} blackout. Inertia is not the only but one of the most important criteria regarding the reliability and stability of an electrical power system, and that is the reason that its estimation allows us to measure the stability of the grid at the moments before the disaster. This calculation also aims to divide the inertia support provided by technology and region as it was a determining factor in the power system behaviour. By understanding and applying this approach, one can gain knowledge of the adequacy of the system to withstand changes and instabilities.

4.1 Inertia estimation

As the only source of information from the grid power distribution is the one published by REE, the P48 file of the 28^{th} is the basis for the estimation of inertia. As generation technologies exhibit significantly different inertia characteristics due to the nature of their prime movers, the design of their machines, and the way energy is converted into electricity. In the absence of specific information about every power plant, inertia constants extracted from the bibliography have been used.

The hypothesis assumed for the calculations showed below are listed here:

- Only synchronous generators provide inertia, and the inertia from non-synchronous technologies, such as IBRs or small power plants (whose specific limitations will be further assessed) is considered to be zero.
- No load contribution. On modern scenarios, this is more accurate as industrial engines provide less inertia than years ago, thanks to the popularization of frequency converters.
- Coupling between the machines and the system is ideal. It is assumed that all the KE of the rotors is available to counter frequency variations, without delays or dynamic losses.
- No local geographical or grid bottlenecks restrict the available transmission capacity.
- Inertia constants has been used, as well as assuming all units of a kind has the same inertia constant.

4.1.1 Market composition, technologies involved and roles of market participants

Conventional thermal power plants, such as coal, combined cycle, or nuclear, typically have large rotating masses in their turbines and generators, which provide substantial KE to the grid. This high inertia allows the system frequency to change more slowly in response to sudden imbalances between generation and load, giving more time for control systems and protections to respond. Hydroelectric plants also contribute to system inertia, specially large reservoir-based plants (high-head units) that generally have high inertia due to the massive turbines and synchronous generators, whereas run-of-river plants or pumped-storage facilities in pumping mode have lower or variable inertia. In pumped-storage plants, as mentioned in section 2.4, the direction of operation—generating or pumping—can change the effective inertia contribution to the grid.

Renewable technologies, such as wind and solar photovoltaic, typically provide little or no conventional inertia. This is because the generators are often decoupled from the grid through power electronics, which means the mechanical kinetic energy of the rotor does not directly support system frequency. Some advanced designs, such as synchronous wind turbines or hybrid renewable–storage systems, can partially emulate inertia through synthetic or “virtual” inertia controls. However, their response is generally faster and more limited compared to traditional synchronous machines, and these technologies are still uncommon in the Spanish grid, as the technical regulations of the power system do not yet account for them in dynamic control operations, as explained in section 2.2.

Hybrid technologies, combining renewable and conventional generation or storage, present complex inertia characteristics. Their effective inertia can vary depending on the operating mode, the proportion of renewable versus conventional generation, and the availability of storage.

Overall, the differences in inertia constants across technologies and plant designs have a direct impact on grid dynamics. The Spanish grid has a high share of inverter-based generation and an unequal regional distribution of the conventional inertia connected, specially between the north and the south parts of the country.

The different market participants connected to the grid on 28th April are listed below:

Table 4.1: *Generators, Consumers, and Intrinsic System Operators*

Market Agents
Storage (Market Purchase)
Storage (Market Sales)
Biogas
Biomass
Combined Cycle
Free Market Retailers
Last Resort Retailers
Pumping Consumption
Pumped Turbining
Auxiliary Services Consumption
Direct Market Consumption
Oil or Coal Derivatives
Residual Energy
Balearic Interconnection
Onshore Wind
Export to France
Export to Andorra
Export to Morocco
Fuel
Natural Gas
Natural Gas Cogeneration
Generic
Hydraulic non-UGH
Hydraulic UGH
Anthracite Coal
Sub-bituminous Coal
Import from Andorra
Import from France
Import from Morocco
Nuclear
Ocean and geothermal
Portfolio
Domestic and Similar Waste
Various Waste
Solar Photovoltaic
Solar Thermal
Mining By-products
Pumped Turbining

*UGH = Unidades de Gestión Hidráulica/Hydraulic Management Units

Not all of them fall under the "Generation" or "Consumption" categories, as some are simply market agents whose role is, for example, to manage the international exchange balance (International Instrumental Unit). Therefore, there are participants whose inertia constant is 0, apart from those whose inertia constant is 0 for physical reasons, such as technologies as Solar Photovoltaic or Onshore Wind.

4.1.2 Data, Documentation Sources and Reference Materials

The P48 file is a document REE uploads every day, along with many others, to provide information to both stakeholders and the general public. It consists on a .xml file of an aproximately 230 thousands lines describing all the power related information on the electric grid in 15 minutes intervals. The size of this document requires some data processing, not only to run the calculations throughout the entire file but to cross reference information with other data published by REE and produce simpler, more informative and efficient tables that allow us to locate power plants, view the power delivered by different technologies, analyze load, and examine the status of large synchronous power plants such as nuclear or combined-cycle units.

The structure of the P48 file is showed in 4.2, 4.3 and 4.4. The first row of the document is used as an example, corresponding to FSEVILL, a photovoltaic power plant situated in Sevilla, on the south of Spain.

Table 4.2: *P48 structure (part 1: v5–v11)*

v5	v6	codificación	v7	v8	codificación9	v10	v11
A01	10XES-REE——E	A01	A04	DESTINATARIO	A01	A08	2025-06-11T09:58:57Z

Table 4.3: *P48 structure (part 2: v12–v21)*

v12	v13	v14	v15	codificación16	v17	v18	v19	v20	v21
2025-04-27T22:00Z/ 2025-04-28T22:00Z	STP0	Z21	FSEVILL	NES	MWH	2025-04-27T22:00Z/ 2025-04-28T22:00Z	PT15M	1	0

Table 4.4: *P48 REE Line Column Definitions*

Column	**Example Value**	**Meaning**	**Notes**
v5	A01	Message type / document code	e.g., A01 = initial submission
v6	10XES-REE——E	Sender identification	Entity sending the message (REE in this case)
codificacion	A01	Message version / coding standard	Often repeats v5
v7	A04	Recipient type code	A04 = market participant
v8	DESTINATARIO	Recipient identification	Name or code of recipient
codificacion9	A01	Internal message categorization	Versioning or classification code
v10	A08	Message function code	A08 = actualization/update

Continued on next page

Table 4.4 continued from previous page

Column	Example Value	Meaning	Notes
v11	2025-06-11T09:58:57Z	Message creation timestamp	ISO 8601 UTC
v12	2025-04-27T22:00Z/ 2025-04-28T22:00Z	Data interval	Start and end time of the reported data
v13	STP0	Data type code	Type of schedule/data (planned/actual/etc.)
v14	Z21	Node code / location identifier	Physical point in the grid
v15	FSEVILL	Production unit / facility code	Name/code of power station
codificacion16	NES	Measurement type / unit code	NES = Net Energy Supplied
v17	MWH	Energy unit	Megawatt-hour
v18	2025-04-27T22:00Z/ 2025-04-28T22:00Z	Interval for values	Often repeats v12 for clarity
v19	PT15M	Time resolution	Data granularity (15-minute periods)
v20	1	Number of periods / values	How many data points are included
v21	0	Measured value	Actual reported value for the interval

Much of the information presented in the table above is mainly useful for understanding other REE documents, including technical requirements reports. However, for inertia estimation, it is necessary to use the NET and the time intervals to determine the average power produced or consumed during each interval. Intervals go between 1 and 96, since 96 fifteen minutes intervals make up a 24 hour day. Since power production and consumption are unlikely to vary rapidly, the average power during each 15-minute interval provides a good approximation of the actual power delivered, especially when all power plants of a kind are taken into account. It needs to be emphasized that the calculus presented in this chapter don't aim to study the very moment of the black-out, since neither the p48 file contains enough information to do it nor REE has published enough data to proceed with such work.

One important matter regarding inertia is that, since the kinetic energy present in the spinning machinery depends only on mass and angular velocity, neither the active power nor the load of the power plant affects the inertia delivered to the grid. However, the load of all power plants connected to the grid has been calculated with the intention of providing a better understanding of the system situation and regional distribution inequalities.

In order to find the nominal power and the official name of each power plant, the following two REE websites have been used: "Unidades de Programación" or "Programming Units" [45], and "Unidades Físicas" or "Physical Units" [46]. Both websites list the power plants currently operating in the Spanish power system, the first referring to the market entity and the second to the physical unit. The structure of both websites is explained below, using the same photovoltaic power plant located in the south of Spain, with the code FSEVILLA, with the aim of providing a guide to reproduce the procedure described in this article.

Table 4.5: *Programming Unit (UP) FSEVILL / FSEVILLA [45]*

Field	Value
Código de UP / UP Code	FSEVILL
Descripción corta / Short Description	FSEVILLA
Descripción larga / Long Description	UP FV SEVILLA
Potencia máxima MW / Maximum Power MW	33,2
Código EIC / EIC Code	18W000000000G28X
Tipo de producción / Type of Generation	Solar fotovoltaica / Photovoltaic solar
Negocio / Business	Venta / Sales
Zona de Regulación / Regulation Zone	NEXUS
Sujeto del Mercado / Market Entity	NEXU
Tipo de UP / UP Type	Generación / Generation

Table 4.6: *Physical Unit (UF) FSEVILL / FSEVILLA [46]*

Field	Value
Código de UF / UF Code	SEVILA
Código EIC / EIC Code	18W000000000G28X
Descripción larga / Long Description	UP FV SEVILLA
Potencia máxima MW / Maximum Power MW	33,2
Tipo de producción / Type of Generation	Solar fotovoltaica / Photovoltaic solar
Negocio / Business	Venta / Sales
Sujeto del Mercado / Market Entity	NEXU

Every term is shown translated or is self-explanatory. About 6000 power plants are listed in the file, but not all of them were connected, producing active power, or providing reactive control.

4.1.3 Data Filtering and Exclusion Criteria

Fortunately, REE states in their public report [28] that 11 power plants were required to provide voltage control and to be connected to the grid, not for market reasons, but as a technical requirement, as previously mentioned, referring to the ”Protocolo de Restricciones Técnicas” or ”Operational Procedure for Technical Constraints” that is rule by the Operational Procedure 3.2 [47]. Although initially 12 plants were expected, one power plant was declared out of operation the day before and was not substituted by REE. This issue will be discussed later.

Filtering the list of power plants connected, looking for plants producing active power or technically required by REE, the following table is obtained:

Table 4.7: *Summary of Power Plants Connected and Producing on April 28th [48]*

Type	Total	Connected	Producing on 28th	%
Anthracite Coal	2	1	1	100%
Biogas	76	46	35	76%
Biomass	54	25	22	88%
Combined Cycle	76	23	6	26%
Domestic and Similar Waste	10	7	7	100%
Fuel	2	2	0	0%
Generic	53	11	0	0%
Hydraulic non-UGH	424	153	116	76%
Hydraulic UGH	855	40	33	83%
Mining By-products	1	0	0	0%
Natural Gas	0	0	0	0%
Natural Gas Cogeneration	377	163	120	74%
Nuclear	7	4	4	100%
Oil or Coal Derivatives	51	8	3	38%
Onshore Wind	1154	350	212	61%
Ocean and Geothermal	0	0	0	0%
Pumped Storage Generation	32	7	0	0%
Pumping Consumption	65	12	8	67%
Residual Energy	7	3	1	33%
Solar Photovoltaic	1702	915	766	84%
Solar Thermal	58	46	39	85%
Storage Purchase	4	0	0	0%
Storage Sale	2	0	0	0%
Sub-bituminous Coal	0	0	0	0%
Various Waste	13	6	3	50%

It should be noted that a large proportion of renewable plants were connected and producing, with special relevance of solar technologies as expected at 12:00 hours, while few of the sicronous technologies exixting were producing or providing voltage control, just 6 of a total of 23 combined cycles, 4 out of 7 nuclear reactor (2 of them just at 70% load). REE states [28] that the generation power showed below was unavailable for the technical restrictions of the 28$^{\text{th}}$:

Technology	**Unavailable Power (MW)**
Coal	903.5
Combined Cycle	7,426.3
Fuel-gas	0.0
Nuclear	3,078.6
Pumped Turbining	1,392.1

Table 4.8: *Unavailable Power for each Technology [49]*

Using [49] and cross-referencing other REE files already mentioned in this thesis, the unavailable plants on April 26, 27, and 28 — with the last day being the one relevant for this matter — were analyzed in an attempt to determine which plants were unavailable, in order to corroborate the information from REE and to establish how many could have been called upon that day.

Regarding the coal plants, the Aboño thermal plant (903.5 MW) appears as unavailable from 14/04/2025 at 00:00:00 to 29/04/2025 at 19:59:59, with two power units of nominal power 341.7 MW (coal unit) and 561.8 MW (natural gas unit). Between both, they sum up the 903.5 MW stated.

Regarding the nuclear plants, Trillo (1003.4 MW), Almaraz I (1011.3 MW), and Cofrentes (1063.9 MW) were declared unavailable for a period between March/April and May, adding up to a total of 3078.6 MW. Ascó I was declared partially unavailable (710 MW available out of 995.8 MW) between 26/04/2025 at 06:00:00 and 28/04/2025 at 21:59:59. Four nuclear reactors were producing on the day of the blackout: Almaraz II, Vandellós II, Ascó I, and Ascó II, although both Almaraz II and Ascó I were operating at 70% load. All of them were declared unavailable on the 28$^{\text{th}}$ at 22:00, except for Almaraz II, which was declared unavailable at 12:35 — about one minute after the blackout. Other sources, such as [50], state that Trillo was unavailable due to refueling, although it does not appear in REE files (code Z08 for refueling and revisions), in a controversial context where, at the beginning of April, power plants such as Almaraz I and II, Ascó I, and Cofrentes ceased production or reduced their power, reportedly due to excessively low wholesale prices and disproportionate fiscal pressure, leading to economic uncompetitiveness. The five nuclear plants existing currently in Spain is showed below:

Plant	**Type**	**Units**	**Power (MW)**	**Speed (rpm)**	**Remarks**
Almaraz I	PWR	1	1011.3	3000	Westinghouse
Almaraz II	PWR	1	1005.8	3000	Westinghouse
Ascó I	PWR	1	995.8	3000	Westinghouse
Ascó II	PWR	1	991.7	3000	Westinghouse
Cofrentes	BWR	1	1063.9	1500	General Electric
Trillo	PWR	1	1003.4	3000	KWU, Siemens
Vandellòs II	PWR	1	1045.3	3000	Westinghouse

Table 4.9: *Spanish Nuclear Power Plants*

The pumped-turbining facilities have not been entirely detailed, as most of the unavailabilities correspond to individual turbine units rather than entire power plants, and the unavailable power of each unit is not accurately disclosed. However, it is likely that hydro facilities such as Tajo de la Encantada, Estany-Gento Sallente, Guillena, and the pumped-storage plants on the Duero and Tajo rivers, Bolarque and La Muela, account for most of the 1.4 GW unavailable, out of a total of 5.7 GW of pumping and 3.4 GW of turbining installed in Spain, .

Within the 28 combined-cycle facilities existing in Spain, comprising up to 50 generation units and 24.5 GW of power, 7.4 GW were declared unavailable before the 28th, most probably including the following: Castellón IV (839.3 MW), Besós III (411.9 MW) and IV (859 MW), Málaga I (415.5 MW), Arrúbal I (394.6 MW) and II (390 MW), Arcos de la Frontera III (260.9 out of 822.8 MW, with one gas turbine still in use) and II (363.3 MW), Aceca III (386 MW), Cartagena II (417.8 MW), Barcelona Harbour I (434.8 MW), Escombreras (815.6 MW), Castelnou (395.3 out of 790.6 MW, thanks to one gas turbine and a steam turbine at 50% load still in use), Tarragona Power (416.9 MW), and Cristóbal Colón IV (390.9 MW).

Back to the topic of Technical Constraints, initially, 12 power plants were called upon 11 (4 nuclear reactors, 1 coal power plant and 6 gas-fired plants), but the combined-cycle plant owned by Endesa, San Roque II, with 401.8 MW, was declared unavailable on the 27th at 19:47 (code B20 for unexpected shutdown) due to a small fire at the facility. Note that REE has not published either the names of any of the power plants shown on this article or the name of the power plant declared unavailable the previous day, they are the result of the filtering and exclusion criteria applied. In [28], REE states that their response was to maintain an unknown plant connected from 0:00 to 2:00 on the 28^{th}, with no impact on the weaker period of the day, which is approximately from 9:00 to 18:00, when photovoltaic production dominates the market, and when a synchronous generator can play a crucial role in southern Spain, a region dominated by inverter-based resources with no inertia or DVC. If San Roque would have been substituted with a similar combined-cycle power plant, around 2 GWs of kinetic energy would have been deployed into the grid and would have provided reactive support of at least 130 MVar (assuming reactive power as 30% of total installed capacity, as shown in [27]).

Following with the inertia calculation, non-inertia technologies, such as photovoltaic or wind, and plants with installed capacities below 50 MW has been filtered out, since they usually do not contain synchronous generators. This produces the expected outcome: combined cycles, hydro and nuclear accounts for more than 92% of all the Kinetic Energy present in the grid. Natural gas co-generation, coal and solar thermal make a small contribution. Their current situation will be discussed in **??**.

As mentioned earlier, the nominal capacity of the power plants is used to calculate inertia, so the total nominal power of all producing units is also included in the table. Although it is not used for the inertia calculation, the power produced by each technology has been calculated too. As shown in 2.3, the inertia constant H is presented in the table below:

Table 4.10: *Inertia Constants by Technology [51]*

Technology	**H (s)**
Combined Cycle	4.97
Natural Gas Co-generation	5.29
UGH Hydropower	2.40
Anthracite Coal	2.63
Nuclear	4.97
Solar Thermal	2.94
Petroleoum or Coal Derivatives	1.20

Using equation 2.3:

$$H = \frac{KE}{S_{\text{rated}}}$$

$$KE = H\, S_{\text{rated}}$$

Following this equation, the Kinetic Energy per technology is calculated. Then, the added total KE is divided by the total generation to obtain the system inertia, measured in seconds:

$$H_{\text{system}} = \frac{\sum KE_i}{P_{\text{total}}}$$

TSO-E recommends maintaining at least 2 s of system inertia as a security measure. However, inertia is an intrinsically local property. That is the reason why the methodology described in [36] and [52] has been explored, and regional inertia values were also calculated. Although the country as a whole may comply with the ENTSO-E requirement, the regional distribution is assessed to verify the reports' suggestion that certain areas may fall below the recommended limit. Inertia, as a physical property, is therefore evaluated not only on its own but also as an indicator of local stability and generation resilience.

Both reference reports relied on proprietary data from private companies or unpublished information from REE. As a consequence, regional generation values cannot be directly used. Instead, the regional distribution presented in those documents is replicated, with the aim of obtaining comparable results using the data collected in this thesis.

For this purpose, the following list of power plants has been considered, aiming to represent every sincronous generation present at the system. The exact list is located on appendix 6.

- Nuclear
- Combined Cycle
- Natural Gas Co-generation above 50 MW
- Coal

- Petroleum or Coal Derivatives
- Solar Thermal above 45 MW
- Hydraulic above 5 MW

Each Power plant is located on a Spanish counties (with an exception on Extremadura, but that will be explained later) and then associated on a bigger division, following the distribution of the reports mentioned. The reason for the inertia estimation not being realized for each community are mainly three:

1.- The differences in size, population, and degree of industrialization are so significant that they affect the use of inertia as a measure of stability. Regions such as Madrid or the Basque Country have great populations and large industries, but generates only a small portion of the energy they consume, since in many cases the power system has been designed so that large, sparsely populated regions act as major energy producers for more industrialized regions that represent major consumers.

2.- Moreover, the geographical differences between communities make an individual, representative analysis impossible: northern regions have highly distributed hydropower generation; regions such as Catalonia rely on large, highly localized nuclear generation centers; and big southern regions, are characterized by widely distributed non-synchronous renewable generation and a few synchronous generation centers that are located far apart.

3.- Last but not least, the process of locating each power plant has been carried out manually and with limited information, especially regarding small UGH (Hydraulic Generation Units) hydropower plants. This has led to some regions appearing to have no generation, while in reality they include small hydro units that are grouped into larger UGHs, usually associated with a river or a section of it, but geographically assigned by REE to another region.

The next table shows the rated power per region and the KE, showing some of the problems cited above:

threeparttable

Table 4.11: *Regional KE and Synchronous Capacity by Autonomous Community at 12:00h on 28th*

Autonomous Community	Rated Power (MW)	KE (MWs)
Galicia	3384.2	10303.3
Asturias	1302.0	3204.4
Cantabria	0	0
País Vasco	785.3	3902.9
Navarra	0	0
Aragón	1171.4	2963.6
Cataluña	4329.5	19076.1
Valencia	796.2	2963.8
La Rioja	0	0
Castilla y León	4335.0	10404
Cáceres*	3233	10452.1
Badajoz*	499.4	1468.2
Extremadura*(undetermined)	279.6	822
Castilla-La Mancha	1069.9	3409.9
Madrid	0	0
Murcia	510.6	2569
Andalucía	1090.7	3048.3

* The autonomous community of Extremadura is divided into its two provinces, Cáceres (north) and Badajoz (south). This division, while not explicitly defined in the original report [52], has been interpreted to provide a consistent basis for comparison. The undetermined power plants are solar thermal unknown plants, whose installed capacity has been divided equally between both provinces.

The case for Cantabria, Navarra and La Rioja is perfectly explained on point 3, and the case for Madrid and País Vasco is detailed by point 1. Apart from that, although generation per regions has not been published, we can already notice how little syncronous generation is present at southern and central regions with large renewable solar generation.

At ENTSO-E report, regional division is not used to calculate regional inertia but to study the presence of PSS (Power System Stabilisers) in each regions:

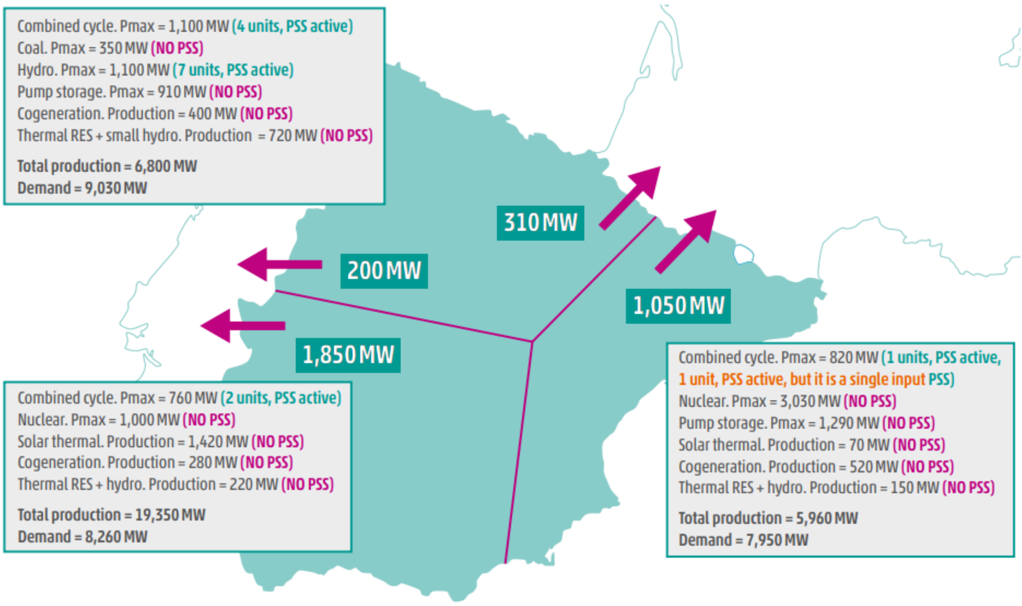

Figure 4.1: *PSS presence [36]*

The division proposed by ENTSO-E is dividing Iberian Peninsula in three regions, that have been named as North, South and Mediterranean.

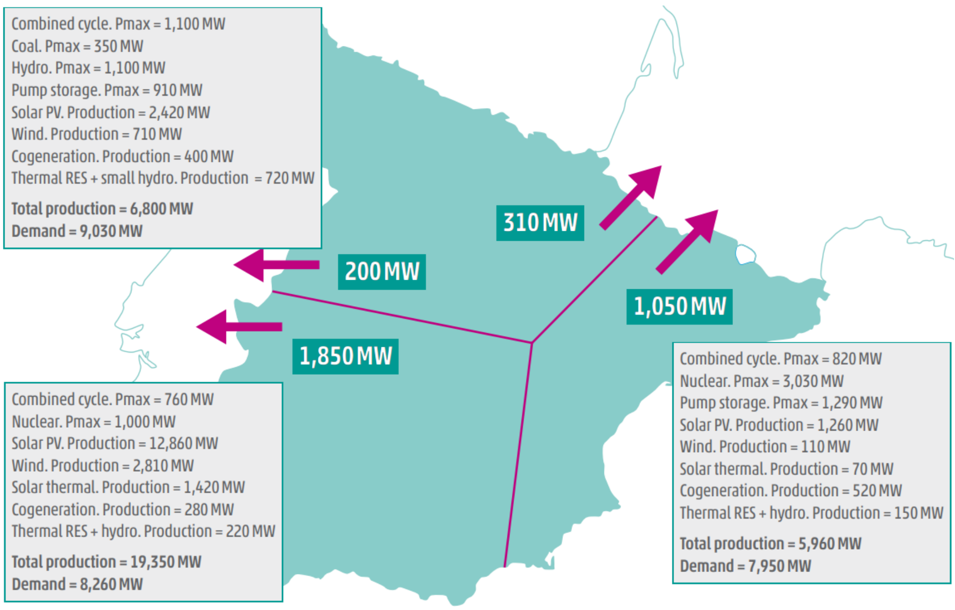

Figure 4.2: *Northern, Southern and Mediterranean regional divisions by ENTSO-E [36]*

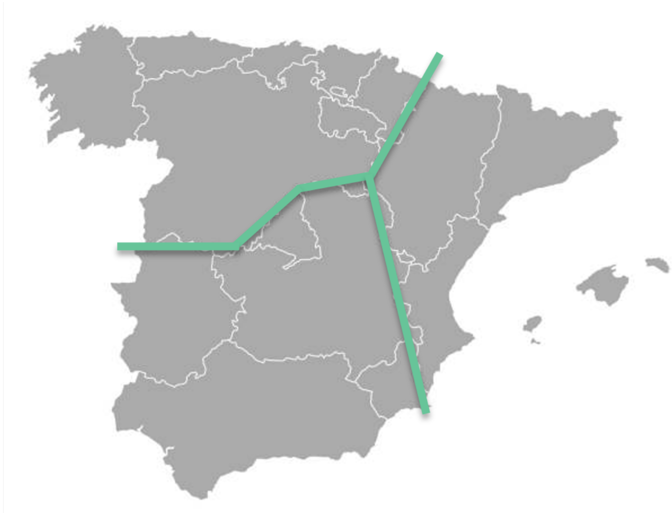

Figure 4.3: *Northern, Southern and Mediterranean regional divisions by ENTSO-E [36]*

Using this division, each region is assumed to be integrated by the autonomous comunities of:

- Northern region: Galicia, Asturias, Cantabria, País Vasco, Navarra, La Rioja and Castilla y León.
- Mediterranean region: Aragón, Cataluña and Valencia.
- Southern region: Extremadura, Castilla-La Mancha, Madrid, Murcia and Andalucía.

The methodology proposed by professors Luis Rouco Rodríguez, Enrique Lobato Miguélez, and Francisco M. Echavarren Cerezo of the Comillas Pontifical University ICAI divides the territory in northwest (1), north (2), east (3), central (4) and south (5), as shown below.

These divisions are assumed to be integrated in the following way:

- Northwest: Galicia, Asturias and Cantabria
- North: País Vasco, Navarra, La Rioja and Castilla y León
- East: Aragón and Cataluña
- Central: Valencia, Madrid, Castilla-La Mancha and Cáceres
- South: Andalucía, Murcia and Badajoz

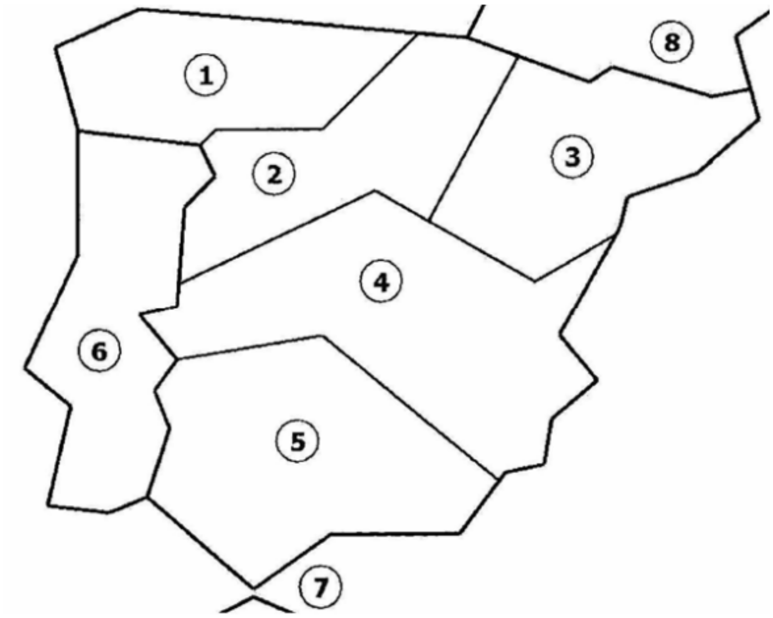

Figure 4.4: *Northwest, north, east, centre and south division proposed by ICAI [52]*

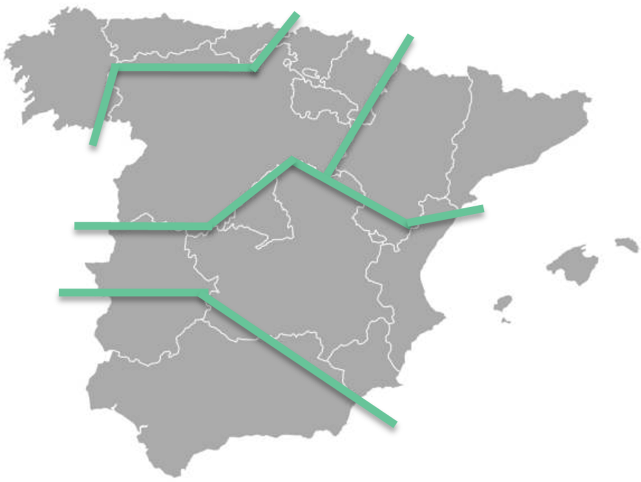

Figure 4.5: *Northwest, north, east, centre and south division proposed by ICAI [52]*

In the report, national and regional demand is used to calculate inertia. It has been assumed that the regional demand distribution can be extrapolated to generation. The relative error between our results and the IIT results is calculated as:

$$\text{Error (\%)} = \frac{\text{Ours} - \text{IIT}}{\text{IIT}} \times 100 \tag{4.1}$$

5 Analysis and Case Studies

This chapter aims to provide both national and international context to enhance the understanding of the incident. On one hand, it conducts a comparative analysis of previous blackouts, situating the Iberian blackout within a historical perspective and examining its differences and similarities with other occurrences. On the other hand, it examines the internal context of the event, including the actors involved as well as the political and social conditions surrounding it.

5.1 Comparative Analysis of Previous Blackout Incidents

2003 North American Blackout (USA & Canada)

In August 2003 a massive power outage struck the northeastern United States and Ontario, Canada. About 50 million people (Ohio, Michigan, New York and Ontario) lost electricity; most were restored within hours, though some areas (notably parts of Ohio and southern Ontario) took up to two days to recover. The event contributed to at least 11 deaths and cost an estimated $6 billion. The blackout was triggered by a sequence of equipment failures at FirstEnergy's Ohio grid: a high-voltage transmission line brushed overgrown trees and tripped, but the local alarm failed. In the next hour more lines sagged and tripped under high load. This cascading effect caused heavy overloads and line trips across the grid by about 4:05 PM, plunging New York City, Cleveland, Detroit, Toronto and surrounding areas into darkness [51].

The event prompted intense scrutiny: an official U.S.–Canada task force blamed "human error and equipment failures" and issued recommendations to improve reliability. In response, U.S. regulators moved to make grid standards mandatory. Congress passed the Energy Policy Act of 2005, expanding FERC's authority to enforce reliability rules (e.g. requiring utilities to keep trees cleared from lines and to train operators). Industry commentators noted that, as the IEEE Spectrum reported, the Northeast grid had long been "thinly stretched" and experts had warned a major blackout was "waiting to happen".

Politically, the blackout ignited partisan blame games. Leaders on both sides seized on it to justify prior agendas: some criticized deregulation and market competition in electricity, others blamed lack of investment. State and federal politicians called for tougher oversight of utilities. Notably, U.S.

and Canadian officials coordinated closely (the interconnection crosses the border), and no major political scandal arose between countries. Overall, the incident strengthened calls for a more resilient grid, and led to legislation mandating reliability standards (implementing the task force's "trees, training, tools" checklist).

2003 Italy and Switzerland Blackout

On 28 September 2003 nearly the entire Italian peninsula and its 56 million inhabitants went dark in one of Europe's largest outages. By the next day power was fully restored nationwide, although some areas of southern Italy remained without electricity for up to 18 hours. The blackout followed storm damage to cross-border transmission lines. Severe weather in France and Switzerland interrupted power imports into northern Italy around 3 AM, triggering a cascade. Italian operators (GRTN) denied any negligence, but foreign grid operators expressed "incredulity" that minor faults abroad could cause such a wide loss. Meanwhile Italy's heavy reliance on imports (about 16% of its power comes from other countries) and lack of spare generation were highlighted. [53].

The blackout exposed Italy's vulnerability: it lacked large domestic backup (it had no nuclear plants and three-quarters of generation was fossil-fueled). President Carlo Azeglio Ciampi immediately called for building new power stations "without delay". Parliament rushed a bill to increase generation capacity by 25%, even considering tying it to a confidence vote due to opposition amendments. Environmentalists and industry clashed: some argued for reviving nuclear power (Italy had dismantled its four nuclear plants after a 1987 referendum, making it reliant on imported energy and oil/gas plants), others said better efficiency and distribution would solve shortages.

2006 Europe-Wide Blackout (Western/Central Europe)

On 4 November 2006, a major outage swept much of continental Europe. It left an estimated of several tens of millions of people without power for about two hours. Outages spread from Poland in the north-east across to France, Spain and Portugal in the west, and into Italy, Greece and the Balkans in the south. The disturbance even affected Morocco via interconnections.

The trigger was a routine line shut-off in north-west Germany to let a cruise ship pass. The schedule was abruptly advanced by Germany's E.ON Netz but communicated too late to neighbouring grid operators. This violated the "N-1" security criterion. When E.ON disconnected a second 380 kV circuit, power flows overloaded a nearby line (Landesbergen–Wehrendorf) and it tripped. Within seconds the grid split: a power swing cascaded unrestrained across the interconnected system.

European TSOs quickly islanded the network into three areas and isolated faults. Automatic defences and manual actions then stabilized each segment. Within 38 minutes the two split sections were resynchronized, and a "normal situation" was fully restored in all countries in under two hours. System reports praised the TSOs' decentralized response for averting a continent-wide collapse.

The outage prompted calls for stronger EU grid coordination. The European Energy Commissioner (Piebalgs) called the event "unacceptable" and urged a coherent European energy policy. In essence, this incident fuelled debate in Brussels on building a pan-European "supergrid" and tightening regulation of cross-border trades, highlighting deficiencies in how national TSOs coordinate in the liberalized market [54].

2009 Brazil and Paraguay Blackout

On the evening of 10 November 2009 a storm-related failure cascaded through Brazil's Southeast grid. The outage left tens of millions in darkness across 18 states – including all of São Paulo and Rio de Janeiro as well as an entire blackout in Paraguay. Power was lost at 10:13 PM, causing chaos in São Paulo, Rio and other major urban areas. Within three hours partial restoration had begun in São Paulo, but much of the metro area remained dark that night. Officials later traced the cause to severe storms that "downed three transmission lines" carrying power from the Itaipu hydroelectric plant on the Brazil–Paraguay border. The Itaipu dam kept generating but could not feed the grid due to the line trips. [55]. The outage lasted roughly 5–6 hours in most places.

Officials and media questioned why the grid collapsed so quickly. President Mr. Da Silva, awakened to the crisis, defended his government, denying underinvestment and saying the fault was "in the transmission line," not generation. He held emergency meetings with energy officials in Brasília. Meanwhile opposition critics and analysts pointed to chronic maintenance shortfalls. One infrastructure expert warned that Brazil's "very long transmission lines" were poorly maintained and left the country "hostage to accidents". Brazil's energy ministry acknowledged that the system was designed to handle only two simultaneous line failures, but three had been knocked out by the storm.

2016 South Australia Blackout

On 28 September 2016 extreme storms knocked out transmission towers across South Australia, plunging the entire state (population 1.7 million) into darkness. The weather felled 22 transmission towers and cut multiple lines; by 3:50 PM nearly the whole state's grid was "cut out". The outage was instantaneous and total. Blackout hours varied – most residents regained power by evening or the next day, but some regional areas required extended backup generation for weeks.

Immediately federal and state leaders blamed each other. The Turnbull federal government, through Industry Minister Greg Hunt, attacked South Australia's pro-renewables policies, arguing that shutting reliable baseload plants (like the Northern coal plant) had weakened the system. By contrast, the Labor opposition and state government emphasized that the storm itself, not wind turbines, had caused the loss. Opposition Leader Bill Shorten and the state's Labour Premier noted that no new generation would have prevented lines from falling, emphasizing "renewable energy didn't cause the storm… this was a failure of the transmission system" and "those wires don't generate electricity; they transmit it" [56].

Politically, the episode intensified Australia's national debate on energy policy. South Australia had already set aggressive renewable targets, and critics used the blackout to argue for more "baseload" power and interconnections to the rest of the grid. Meanwhile the South Australian state government defended its investment in renewables, highlighting that coal plants also failed and that no system could have avoided the storm damage.

2017 Taiwan Blackout

On 15 August 2017 at 4:52 pm local time, a power plant accident caused a blackout of northern Taiwan. Approximately half the island's population of 23 million were affected. The outage was traced to human error during maintenance at CPC's Ta-tan gas-fired power plant. Workers had closed two LNG fuel valves without switching the control system to manual mode. This stopped the gas supply for about two minutes, causing six of the plant's generators (4 GW total) to trip offline. No extreme weather or grid attack was involved, it was an operational mistake.

By around 9:40 pm, about 5 hours later, power was fully restored island-wide. The state-owned energy company Taipower later cut one day's bill to every household to compensate. President Tsai Ing-wen apologised to the public and called electricity supply a matter of national security, and launched a comprehensive review of Taiwan's grid reliability [**?**]

June 2019 Southern Cone Blackout (Argentina, Uruguay, Paraguay)

On 16 June 2019 a colossal outage darkened much of South America's southern cone. Argentina (44 million people), Uruguay (3.5 million) and parts of Paraguay lost power around 7 AM Father's Day Sunday. By Sunday night electricity had been fully restored across the networks, but the blackout lasted about 14 hours in many areas and seriously disrupted daily life.

The cause was unclear: Argentina's energy secretary reported the event began with a fault in the national "interconnection system" and then cascaded through the grid. Investigators considered equipment failure; cyberattack or sabotage were deemed "unlikely". Ultimately no single root cause was immediately identified, though it was seen as an extraordinary and unprecedented grid collapse.[57]

Politically, the blackout hit just months before Argentina's elections. President Mauricio Macri's government quickly ordered a full inquiry, calling the outage "unprecedented". Critics seized on it to lambast years of underinvestment in the power system, arguing that budget cuts and austerity had left the grid brittle, blaming his energy policies for neglecting the grid; the incident likely fuelled protests against his administration just as voters prepared for re-election. In neighbouring Uruguay and Paraguay (which were mostly dependent on Argentine and Brazilian grids), leaders expressed solidarity and launched their own probes, but no international dispute arose. Instead, the countries collaborated to restore and analyse the shared grid.

2021 Texas Winter Blackout

During Winter Storm Uri in mid-February 2021, almost all of Texas (population 29 million) suffered rolling blackouts and outages. At the peak on 15–16 February, over 10 million people and business customers were without power. Sub-zero temperatures and snowfall descended on a grid largely unprepared for winter extremes. Electricity generation froze across the board: wind turbines iced up, many natural gas wells and pipelines froze without winterization, coal and nuclear plants also tripped off, and demand surged as people desperately ran heaters.

The Texas grid (ERCOT), which uniquely operates almost entirely within the state's borders to avoid federal regulation, was pushed to the brink of collapse. To prevent a complete blackout, ERCOT implemented controlled rolling outages, leaving consumers in the cold for hours or days at a time. The restoration progressed unevenly: by 17–18 February most supply returned, but millions went 2–4 days without electricity or fresh water. Over 80 hours of outages occurred in some areas [58]. Across the state, 246 people died as a result of the storm, and the Texas Comptroller's office estimated that the financial fallout landed somewhere in the range of $80 to $130 billion [59].

In the aftermath, state politics turned acrimonious. Governor Greg Abbott and other Republican officials immediately blamed Texas's wind and solar for the outages, casting the crisis as a "Green New Deal" failure. However, experts and Democratic leaders countered that all energy sources failed: "wind turbines and solar panels froze, a major nuclear plant lost half its output, and there were massive failures in coal, oil and natural gas". The event reopened debates on ERCOT's governance and Texas's grid design. Many critics noted that Texas's choice to remain electrically "isolated" (with only limited ties to other states) meant it could not import emergency power.

2025 Chile Blackout

On 25 February 2025, a transmission line fault in northern Chile triggered a nationwide outage, plunging most of the country (19 million people) into darkness. Chile's President Mr. Boric reported that about 8 million households were affected, with Santiago and major mining regions particularly impacted. The event occurred at 12:30, when solar irradiance was at its peak and PV generation was at maximum output. The cascading sequence that followed the initial fault unfolded faster than the protection systems could respond [60].

Chile's Interior Minister said the culprit was a failure in the high-voltage grid: electronic protection systems malfunctioned and disconnected a northern transmission line. The Ministry explicitly ruled out any cyberattack. ISA Interchile (a local grid operator owned by Colombia's Ecopetrol) was identified as responsible for that line, and investigations focused on its equipment and protocols.

By early Wednesday morning over 90% of residential demand was restored. The incident drew immediate political attention. President Boric, amid a state of emergency and curfew, denounced the outage as "outrageous" and said it was intolerable that failures at a few companies could impact millions. He vowed to hold the responsible firms accountable. Interior Minister Toha revealed multiple safeguards had failed during the crisis. In Congress and media, opposition leaders and regulators questioned Chile's energy infrastructure and the role of private operators like ISA. The blackout coincided with debates over Chile's reformist energy agenda, pushing demands for stricter oversight of transmission assets and faster modernization of the grid [61].

The blackouts examined in this article focus primarily on failures in developed power grids, since both the characteristics and the consequences discussed arise within the context of modern electrical networks.

A general conclusion drawn from the cases analyzed is that all major blackouts tend to follow a similar pattern. An unpredictable or only partially predictable event occurs. It can be storm, a line tripping by contacting trees, a power plant failure or an unnoticed switching operation, but the consequence is the same: the system is unable to withstand the resulting disturbance. Restoration typically takes from several hours to several days, usually progressing more quickly in major urban areas than in rural regions. Afterward, debates frequently emerge regarding whether the event violated the N-1 security criterion, whether the system was inadequately prepared, or whether human error played a role. Politically, the opposition often criticizes the government's renewable-energy agenda, the response to the crisis, and the lack of investment in grid security. This is generally followed by an official investigation aimed at identifying the underlying causes, revising operational protocols, and, over time, implementing improvements that gradually reduce the likelihood of severe, system-wide blackouts.

When compared to these general patterns, the Iberian case shares many notable similarities. Politically, it resembles situations such as the South Australian blackout of 2016, where the rapid integration of renewable generation was questioned as a contributing factor to system fragility. From a technical standpoint, the Iberian Peninsula also parallels the 2003 Italian blackout in that limited interconnection capacity represented a significant structural weakness. Furthermore, the cascading failures observed in Spain have been compared in national media to the 2025 Chilean blackout, where simultaneous line disconnections triggered a chain reaction similar to what was reported in the Spanish grid.

On the other hand, the Spanish recovery was faster than in the other cases, even though it was categorized as an example of starting up a network from zero voltage with such a high share of renewable generation connected. The rapid response of both the protection devices and the technical workforce prevented any electrical equipment from suffering damage, allowing the service to be restored more quickly.

However, the root difference and what makes the Iberian blackout particularly significant for any developed country with a high share of renewable generation in its energy mix, is that the event had no obvious trigger. There was no accident, no storm, just a network that had drifted so far from its stable operating range that it could not sustain normal operation. Grids around the world are facing new risks and exhibiting new behaviours under critical events; that is why the study of this event is crucial.

5.2 Published Reports: Analysis, Comparative and Context

This section aims to provide the necessary context needed to properly understand the five reports published to date:

- *"Informe del Operador del Sistema en relación con el incidente del 28 de abril de 2025"* "Report of the System Operator regarding the incident of 28 April 2025" by REE
- *"Informe no confidencial del Comité de Análisis de la crisis eléctrica del 28 de abril de 2025"* "Non-confidential Report of the Committee for the Analysis of the Electricity Crisis of 28 April 2025" by the MITERD
- *"Análisis de los acontecimientos que condujeron al apagón peninsular del 28 de abril de 2025"* "Analysis of the events leading to the peninsular blackout of 28 April 2025" by Compass Lexecon and INESCTEC, ordered by AELEC
- *"Que el apagón nos ilumine (IIT Comillas Working Paper IIT-25-128WP)"* "May the Blackout Illuminate Us (IIT Comillas Working Paper IIT-25-128WP)" by IIT of the Universidad Pontificia Comillas
- "Factual Report on the Grid Incident in Spain and Portugal on 28 April 2025" by ENTOSO-E

The table depicted below has followed the structure presented in Compass Lexecon and INESTEC report [27] on page 3, and shows the differences between the mentioned reports in 9 specific fields.

	REE	**MITERD**	**Compass + INESC**	**IIT Comillas**	**ENTSO-E**
Constituents	Private company but state controled and partially owned	Ministry for the Ecological Transition and the Demographic Challenge	Financed by AELEC (Spanish Association of Electric Energy Companies) integrated by Iberdrola, Endesa and EDP	IIT (Institute for Technological Investigations) part of the Engineering School of the Universidad de Comillas. Report financed by Iberdola and Endesa	European TSOs
Public / Private	Public (government)	Public (government)	Private	Private	Public (EU)
Date	18/06/2025	17/06/2025	28/06/2025	29/09/2025	03/10/2025

	REE	MITERD	CL+I	IIT Comillas	ENTSO-E
1. Previous overvoltages	Not analysed	Not analysed	Increased in the last years and previous days	Analysed	Not analysed
2. Previous fluctuations	Not analysed	Fluctuations occurred	Relevant fluctuations occurred	Not analysed	Fluctuations occurred
3. Program D-1*	Appropriate	Lowest number of thermal groups	Lower control capacity	Insufficient control on southern/central regions	Insufficient control on southern/central regions
4. Fluct. between 10:00–12:00	Stable	Fluctuations occurred	Fluctuations occurred	Fluctuations occurred	Fluctuations occurred
5. Oscillation control maneuvers	The change of interconnection to fixed mode DID NOT worsen the situation	The change of interconnection to fixed mode DID worsen the situation	The change of interconnection to fixed mode DID worsen the situation	Not analysed	Maneuvers are described but not analized
6. Connection of lines	Contributed to dampen oscillations	Contributed to dampen oscillations	Contributed to dampen oscillations but worsen reactive control	Contributed to dampen oscillations but worsen reactive control	Maneuvers are described but not analized
7. Voltage control (PO 7.4 [38])	Did not comply with regulations	Did not comply with regulations	Attributed to insufficient conventional generation	Not analysed	Not analysed
8. Cause of initial trips	Incorrect trips	Vicious cycle + incorrect trips	Simultaneous failures without a systemic cause seem unlikely	Not analysed	Mentioned but not analysed
9. Operation in the following days	Not analysed	Not analysed	More conventional generation, less fluctuations and more technical constraints	Voltage behaviour returns to normality	Not analysed

Table 5.1: *Comparison between the 5 reports published about the April 28th blackout*

Notes:

* Program D-1: Program on the day before

* CL+I stands for Compass Lexecon and INESTEC

It is necessary to make two notes on this topic. First, ENTSO-E has been left aside, as it is considered as impartial and their document is still a factual report. And last but not least, either the work of the IIT, Compass Lexecon and INESCTEC, nor the technical work of REE is questioned in this section.

The overall conclusions about the reports is that there is a clear division between government/state and the private companies side. There is some critical breakpoints in the succession of events where both sides clearly differ:

- Sudden and reportedly ”random” disconnection of small power plants under 1 MW
- Voltage control service (PO 7.4 [38]) provided by conventional thermal plants
- The previous situation of the system and the role of REE on it
- Overall conclusions and causal explanations

The perspectives presented in the REE and MITERD reports treat the system as a given, almost as if it had been put in place only yesterday. They provide no comparison with previous days or months, offer no contextualization of system conditions, and do not present REE in its actual role as the operator. According to the Spanish Electricity Sector Law (Ley 54/1997, as amended by Ley 17/2007 [62]), Red Eléctrica de España (REE) functions as the transmission network manager, acting as a regulated monopoly within the Spanish electricity system. That makes REE the ultimate party responsible for everything that happens in the transmission network.

REE's report settles for little explanation, blaming private power plants for disconnections of hundreds of MWs of small power plants, without looking into root-causes. In general, government response relied on blaming private companies about everything that went wrong,

In contrast, IIT Comillas and CL+I do compare the situation of the system with previous days or years. They don't blame specific causes for the small plants disconnections but state that some systemic error or fault must be behind it. The biggest two differences is that the explain the underlying causes of the event, as well as they try to explain why the system failed attending to its weaknesses:

- In the case of IIT Comillas, the regional ineffective distribution of inertia and voltage control capabilities
- For CL+I, the lack of sufficient conventional generation

This aspect is not investigated in either the REE or MITERD reports. It is a key distinguishing factor, as neither report even attempts to explain the underlying causes of the blackout.

The last point of this section is dedicated to advocating for REE's engineering work, despite the political context in which they operate. The third-party consultancies and institutes selected by private companies to investigate the case have a renowned reputation in the sector, based on their experience, technical expertise, and scientific rigour. There is no reason to believe that their work is biased; in fact, they are not directly involved in the operation of the electric system. They were commissioned by a private company to investigate an event, the company's name appears on the report, and while their work is likely impartial, impartiality is not their inherent role. REE, on the other hand, is designed to be impartial. Its mission is as objective as the physical laws themselves, ensuring that the electric system operates according to the laws of physics, which ultimately govern it beyond any human legislation.

REE's impartiality has been questioned due to its governmental participation: the largest stakeholder, holding a 20% share, is SEPI (State Industrial Holdings Company), and its Board of Directors is presided over by Beatriz Corredor, who is affiliated with the Spanish ruling party, has a political career, and lacks a technical background. Additionally, five out of the twelve board members have profiles related to the current ruling party in Spain [63, 64].

6 Results and discussion

6.1 Energy mix and its Prospects

The energy mix founded on the very moments before the blackout is listed below.

Table 6.1: *Power Production by Technology on April 28th (MW and %)*

Technology	Power (MW)	%
Storage Purchase	0	0%
Storage Sale	0	0%
Biogas	49.3	0%
Biomass	281.068	1%
Combined Cycle	931.7	3%
Pumped Consumption	3041	9%
Auxiliary Services Consumption	92.7	0%
Direct Market Consumption	845.4	2%
Petroleum Or Coal Derivatives	61	0%
Residual Energy	2.2	0%
Balearic Link	102	0%
Onshore Wind	2780.252	8%
Fuel	0	0%
Natural Gas	0	0%
Natural Gas Cogeneration	1408.6	4%
Non-UGH Hydropower	704.7	2%
UGH Hydropower	2643.2	7%
Anthracite Coal	230	1%
Sub-bituminous Coal	0	0%
Nuclear	3380.2	10%
Ocean And Geothermal	0	0%
Household And Similar Waste	115	0%
Various Waste	21.5	0%
Photovoltaic Solar	17375.664	49%
Thermal Solar	1444.2	4%
Mining Byproducts	0	0%
Pumped Turbining	0	0%

More than the 80% of the energy was from a renewable source, an about a 92% of a non-carbon origin.

Of those, the only technologies that matter in most of the non-energy services are gas-fired plants, hydro, coal, nuclear, solar thermal and petroleum or coal derivatives power plants.

Analysing the technologies connected, the only coal plant connected is one of the few still active in Spain, and the PNIEC ("Plan Nacional Integrado de Energía y Clima" or "National Integrated Energy and Climate Plan") includes the shutdown of every coal-fired power plant in Spain in 2025. Therefore, as of the publication date of this document, there will be no more coal plants in Spain.

As [65] shows, between 2019 and 2025, 40% of the natural gas cogeneration plants were closed, and their contribution to grid power generation fell from 12% to 6%. Natural gas prices, deindustrialization, and CO_2 emissions regulations are considered the main causes. Although different measures have been taken to assess this, the sector is still in decline. Moreover, most of the cogeneration units have rated powers of less than 50 MW and consist of small non-synchronous generators, providing little to no inertia. As they are not designed for the electric system, systems such as PSS or AVR are far from common. Petroleum and coal derivatives share with cogeneration their small presence in the energy mix and the fact that they are related to refineries or petrochemical treatment plants, serving an industrial purpose rather than electricity production.

Solar thermal was a promising technology, but their real share in the mix is not enugh to make a real contribution to the realiability of the system.

Hydropower is a well developed technology in Spain. It is considered by many to be one of the best options for energy production: renewable, low carbon, dispatchable, and synchronous, and pump storage is. However, it has two major problems: it relies on water availability and competes with human consumption for water resources. This makes it almost impossible for hydropower to serve as the main source of electricity generation in a country with the size and the climate of Spain. Hydropower is only dispatchable in the short term, as it is heavily influenced by weather conditions and seasonal variations. Needless to say, hydroelectric production depends not only on the rainy seasons but also on how wet a particular year is. Furthermore, it is a non-scalable technology, since there are very few suitable locations, and in developed countries these sites are typically already fully utilized. The next chart obtained from REE illustrate the issues discussed above.

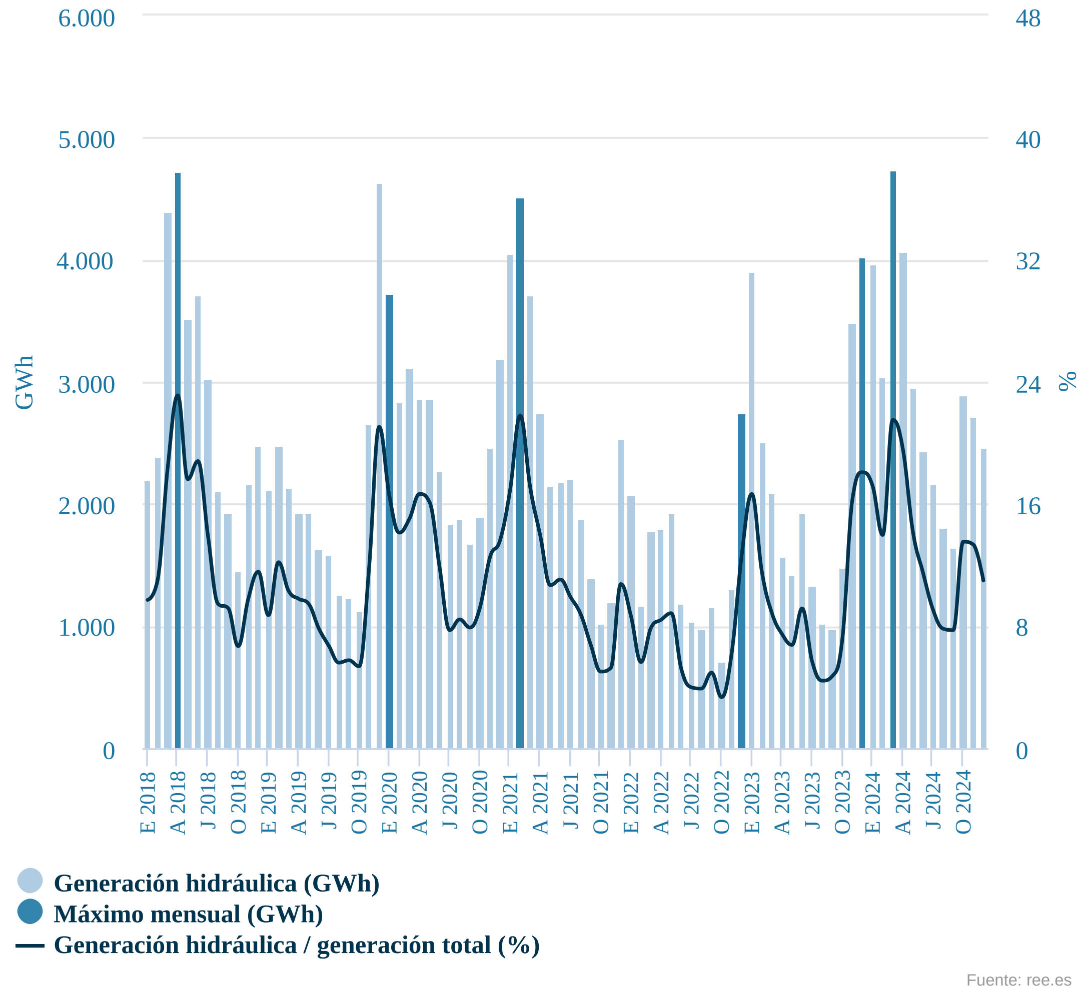

Figure 6.1: *Hydraulic production in the last 6 years [66]*

Note: the chart is obtained from the REE webpage, English translation is not available.

E = January, A = April, J = June, O = October.

Generación hidráulica = Hydraulic Generation.

Máximo mensual = Monthly maximum.

As we can see in the chart, maximum production has a seasonal character but not easy to predict, as it varies from April, December, February... with months with over 3 or 4 thousands GWh produced, to months with less than a thousand GWh produced, often meaning a variability of more than 200%. Between close years as 2021 and 2022, hydro production were cut in almost half. That implies a power system cannot relay on an energy source that can be reduced by 50% in just a year.

Last but not least, nuclear power is one of the biggest contributors regarding energy and non-energy services in Spanish network, and this will be showed later. Unfortunately, between 2027 and 2035, Spain plans a gradual shutdown of its nuclear power plants. According to the official schedule, Almaraz I is expected to close in November 2027, followed by Almaraz II in October 2028. Ascó I is scheduled to shut down in October 2030, while Cofrentes will close in November 2030. Ascó II is planned to cease operation in September 2032. Finally, Vandellós II and Trillo are expected to close in February 2035 and May 2035, respectively. The objective of this schedule is to have all commercial nuclear power plants in Spain closed by 2035.

6.2 Situation before the blackout

The situation at the 12:00 hours was as it follows.

The 11 power plants dispatched by REE for technical constraints are shown below. Those were the facilities under obligation to provide voltage control under Operation Procedure 7.4 [38] .

Table 6.2: *Power Plants Connected by Technical Constraints at 12:00 on April 28th*

Name	Power at 12:00 (MW)	Nominal Power (MW)	Load (%)	Technology
Aceca IV	116.6	372.6	31%	Combined Cycle
Bahía de Bizkaia	173.0	785.3	22%	Combined Cycle
As Pontes García Rodríguez V	136.0	855.6	16%	Combined Cycle
Cartagena III	165.0	412.7	40%	Combined Cycle
Sagunto I	165.1	409.7	40%	Combined Cycle
Arcos I	176.0	389.2	45%	Combined Cycle
Almaraz II	646.5	1005.8	64%	Nuclear
Vandellòs II	1044.0	1045.3	100%	Nuclear
Ascó I	698.0	995.8	70%	Nuclear
Ascó II	991.7	991.7	100%	Nuclear
Soto de Ribera III	230.0	346.2	66%	Anthracite Coal

This was the lowest number of conventional units connected during the month of April, where the average was 14. After the 28$^{\text{th}}$, the average became 24, with at least 7 facilities added in the southern and central areas ([27] pp 51). The unavailabilities of the day of the event has been detailed in section 4.1.3. Considering that, the combined-cycle power units producing energy from 0:00 to 11:00 on the 28$^{\text{th}}$ are listed in the table below.

Table 6.3: *Combined-Cycle Power Units Producing from 1:00 to 11:00 on April 28th*

Name	**1:00**	**2:00**	**3:00**	**4:00**	**5:00**	**6:00**	**7:00**	**8:00**	**9:00**	**10:00**	**11:00**
Aceca IV	0	125	126	126	126	127	127	127	127	126	117
Escombrera III	0	0	0	0	0	0	0	155	155	0	0
Escombrera II	0	0	0	0	0	0	13	0	0	0	0
Bahia de Bizkaia I	173	173	173	173	173	173	173	173	173	173	173
Algeciras I	450	450	145	145	145	145	305	450	450	30	0
As Pontes G. R. V	136	136	136	136	136	136	136	136	136	136	136
San Roque I	126	126	126	126	126	126	126	126	113	0	0
San Roque II	0	0	0	0	0	0	0	0	0	0	0
Palos de la Frontera I	180	180	180	180	180	190	190	191	180	0	0
Soto de Ribera IV	170	170	170	170	170	170	170	170	167	0	0
Soto de Ribera V	80	80	80	80	80	80	80	80	67	0	0
Campo de Gibraltar I	152	152	152	152	152	152	152	152	88	0	0
Campo de Gibraltar II	145	145	145	145	145	145	145	145	0	0	0
Puerto de Barcelona II	172	172	173	174	174	175	175	175	170	0	0
Cartagena III	165	165	165	165	165	165	165	165	167	165	165
Cartagena I	165	165	165	165	165	165	165	179	165	0	0
Amorebieta I	194	194	194	194	194	194	194	194	0	0	0
Sagunto I	166	166	166	166	166	167	167	167	167	166	165
Sagunto II	164	164	164	164	164	164	164	164	155	0	0
Sabón III	134	134	134	134	134	134	139	139	48	0	0
Arcos I	170	170	170	170	170	170	176	170	170	170	176
Santurce IV	0	0	0	0	0	0	55	170	170	0	0
Plana del Vent II	146	146	146	146	146	146	146	146	32	0	0

This table shows that 19 units were connected at 2:00 while only 6 units at 11:00. This shows that even with the unavailable power shown before, there were sufficient units available and ready to continue providing energy, inertia, voltage, and reactive power control for REE to call them for technical constraints.

Nonetheless, the situation prior to the blackout is as it was, and accordingly, the estimation of the system inertia continues from this point onward. The result of the inertia calculation is presented here:

Table 6.4: *Total Inertia and Contribution by Technology at 12:00 on April 28th*

Technology	**Rated Power (MW)**	**H (s)**	**KE (MWs)**
Combined Cycle	3225.1	4.97	16028.7
Natural Gas Co-generation	402	5.29	2126.6
UGH Hydropower	14152.8	2.4	33966.7
Anthracite Coal	346.2	2.63	910.5
Nuclear	4038.6	4.97	20071.8
Solar Thermal	999.8	2.94	2939.4
Petroleoum or Coal Derivatives	94.1	1.2	112.8
		Total KE:	76435.4
		Total Power:	33082.1
		Inertia (s):	2.31

As shown, the Spanish power system was above the 2-second threshold. This result is consistent with the calculations presented in three different reports: those of IIT, ENTSO-E and REE.

Table 6.5: *System Inertia at 12:00 on April 28th by IIT ([52] pp 13)*

Area	**Total Rotational Energy (MWs)**	**Estimated Demand(MW)**	**Inertia (s)**
TOTAL	57097	24708	2.31

Table 6.6: *System Inertia at 12:00 on April 28th by ENTSO-E ([36] pp 36)*

Spain		**Portugal**		**Iberian Peninsula**	
KE (MWs)	**H_{tot} (s)**	**KE (MWs)**	**H_{tot} (s)**	**KE (MWs)**	**H_{tot} (s)**
97,590	2.17–2.67	21,884	2.45–2.95	119,474	2.21–2.71

In REE's report ([28] pp 107) is stated: "Regarding inertia, the system operator indicates that before the incident the system had inertia levels of 2.3 s (not including contributions through the interconnections), which is a value higher than the 2 s recommended by ENTSO-E in its INERTIA project, published in January 2025."

The total inertia estimated by IIT and ENTSO-E differs from the calculation performed in this thesis, but the final values are very close. In the case of REE, their report does not provide any evidence or calculation, yet it would be risky to claim that their inertia value is inaccurate or not representative of the system, as no other entity has comparable visibility or data coverage of the transmission network.

It is reasonable to assume that their methodology is more complex and accurate, given that the data and computational resources they possess are undoubtedly greater than those publicly available. Nevertheless, the fact that their results and those obtained in this thesis are nearly identical supports the accuracy and validity of the calculations presented here.

Concluding with treating the system as a whole, it can clearly be affirmed that the Spanish system was above the 2 s threshold recommended by ENTSO-E. Nevertheless, inertia is intrinsically a local property. For that reason, in a system the size of Spain, the kinetic energy stored in the rotor of a hydraulic turbine in Galicia (a region in the northwest) or a steam turbine of a nuclear reactor in Cataluña (a region in the northeast) cannot effectively support a frequency decrease in southern regions, where, furthermore, IBRs are significantly more common. In the same way that inertia functions to slow and safeguard frequency variations in its surrounding area, systems such as PSS or dynamic voltage control can only be effective and fast regionally.

For that reason, regional inertia and its use as a measure of regional system stability are presented in the tables below, following the structure outlined in the ENTSO-E and IIT reports.

The results obtained following ENTSO-E regional divisions are:

Table 6.7: *Regional inertia distribution following ENTSO-E methodology [36]*

Region	**Kinnetic Energy (GWs)**	**Generation (MW)**	**Inertia (s)**
North	25003	5960	4.2
Mediterranean	27815	6800	4.1
South	21770	19350	1.1

This the results obtained by the IIT:

Table 6.8: *Distribution of inertia at 12:00 on April[28] by IIT ([52] pp 13)*

Area	Rotational Kinetic Energy [MWs]				Total	Demand		Estimation [MW]	Inertia [s]
	Nuclear	Combined Cycle	Coal	Hydro		Case raw e-sios [MW]	Case raw e-sios [%]		
NORTHWEST	0	3714	1746	6652	12111	3194	13%	3152	3.84
NORTH	0	2995	0	7843	10837	3633	15%	3585	3.02
EAST	9642	0	0	4105	13747	5988	24%	5909	2.33
CENTER	2906	8875	0	4204	15984	8780	35%	8664	1.84
SOUTH	0	2881	0	1535	4417	3443	14%	3398	1.30
TOTAL	12547	18465	1746	24339	57097	25038	100%	24708	2.31

On the other hand, the results produced following IIT regional divisions are:

Table 6.9: *Regional inertia distribution following IIT methodology [52]*

Region	Kinnetic Energy (GWs)	Generation (MW)	Inertia (s)
Northwest	13507.8	4221.5	3.2
North	14306.9	4801.7	3.0
East	22039.8	7914.3	2.8
Central	17236.8	11604.5	1.5
South	7496.5	4550.6	1.6

It is believed that IIT used different inertia constants or a different process to calculate this values. For that reason, a comparison between their results and this study is carried out:

Table 6.10: *Comparison with IIT results*

Region	This study	IIT	Error
Northwest	3.2	3.84	-16.7%
North	3.3	3.02	9.3%
East	2.8	2.33	20.2%
Central	1.5	1.84	-18.5%
South	1.6	1.30	23.1%

Another piece of information provided by the Comillas Pontifical University regarding the electrical network is that, for various reasons, the proportion of transmission lines out of service reached 22.9%

of the total network length, and 35.8% of the 400 kV network in the southern area and 34.3% in the central area were disconnected at 9:00 a.m.

The first conclusion is that, in both cases, the southern and central parts of the power system are clearly below the 2-second ENTSO-E recommendation. Moreover, if we consider inertia and the presence of synchronous generation, which is evidently lacking in the southern half, along with the presence of dynamic voltage control, the results reported by ENTSO-E regarding the absence of PSS in the connected power plants, and the information from Comillas Pontifical University about the share of the network out of service, the outcome is that the power grid, including voltage and reactive power control, was weak and unable to maintain stable operation, even in the absence of abnormal events.

7 Conclusions and Further Work

In the concluding chapter of this thesis, the key findings and insights gained by the author throughout the writing process and research journey are presented. The statements included here represent not only the final conclusions but also the qualitative results derived from the analysis of published data, official reports, and the main findings to which this analysis has led.

Various obstacles were encountered. Many of these challenges were successfully overcome, but it is important to acknowledge that not all obstacles could be resolved. These barriers are mainly due to the lack of published information, its intricateness, and the tremendous complexity of the electric system and its constituent components.

7.1 Conclusions

The conditions that led to the blackout in Spain was primarily caused by the rapid expansion of IBR-based generation, without a corresponding development of the transmission network, regulatory framework, or the diplomatic and physical infrastructure needed to export the resulting energy surplus. The evolution of renewable generation has largely taken place in isolation from the power system, treating it as a fixed, black-box entity, a passive sink for generation rather than a dynamic infrastructure whose operation and management it actively contribute to. Renewable deployment have maintained the role of its first steps, an energy service role, relaying on the rest of the integrants of the system to maintain the system itself providing the non-energy services. This structure works when technologies as solar or wind represents a small part of the generation, but when the share of them in the power mix reaches 60, 70 or 80%, it can and it might collapse under its own weight. There were clear indications that such a situation could arise, but the power system continued to be operated under increasingly challenging conditions until it ultimately failed.

The blackout was ultimately caused by a cascade of overvoltage-driven disconnections, originating from a reactive power imbalance in the system.

Although inertia is the main topic of this thesis, it was not directly involved in the incident. In an attempt to damp the oscillations that developed in the minutes preceding the contingency, the system operator performed several switching maneuvers to increase the system's damping capability, such as reconfiguring the network by energizing lines and reducing interconnections. However, these actions depleted the available voltage-control resources and caused lightly loaded lines that generated more reactive power than the system was able to absorb. This imbalance in reactive power progressively increased voltage levels, eventually triggering the cascading process.

In this context, the inertia of the system is used as an indicator of synchronous generation presence and its reliability, and it reveals that some areas were insufficiently prepared to withstand the disturbance. Although the system as a whole had **2.31 s** of inertia, above the bare minimum inertia requirements, southern and central regions showed extremely low levels of inertia:

Table 7.1: *Regional inertia distribution*

Region	**Inertia (s)**
IIT methodology [52]	
Northwest	3.2
North	3.0
East	2.8
Central	1.5
South	1.6
ENTSO-E methodology [36]	
North	4.2
Mediterranean	4.1
South	1.1

The electricity mix consisted of 81% renewable energy, with only 11 power plants providing voltage control, the lowest value ever recorded. Three out of the seven power plants were disconnected, and among the remaining four, two were operating at partial load. The availability of power plants capable of supplying reactive power and voltage control in those southern regions was exceptionally low.

Politics has interfered in what should remain a technical and scientific domain. Of those 11 plants, 5 are scheduled to be dismantled before 2035 (4 nuclear reactors and 1 coal-fired plant). In fact, the only synchronous power plant operating in the province where the first trips occurred, Almaraz II, is planned to be shut down in just three years.

”Excusatio non petita, accusatio manifesta”

An unrequested excuse is a clear admission of guilt. The fact that REE initiated “reinforced mode” after the blackout implies that the mode applied before was not reinforced. The “reinforcement” consists in operating more conventional power plants in order to prevent another accident from happening. It is completely coherent to ensure that the system does not incur another fault after the event, but the detail of securing the system by increasing the number of traditional power plants implies that when this number was reduced, the system was not secure.

Apart from that, from a monetary perspective, the skyrocketing increase in ancillary services costs shows that the economic design of the energy transition was not well designed. These costs have been above wholesale prices, which implies that the cost of operating the system has grown beyond its intended purpose of transmitting energy.

Crucial measures must be adopted:

- Increasing interconnection capacity with the rest of Europe
- Updating the technological and regulatory framework to allow power-electronic systems to provide synthetic inertia and reactive power control
- Implementing grid-forming systems
- Deferring nuclear dismantling

Otherwise, events like the one described here will become more frequent, and the energy transition will be delayed for decades.

7.2 Further work

Throughout the development of this thesis, several initial ideas and approaches were either not implemented or did not lead to the expected results. Nevertheless, these findings have opened a wide range of opportunities for further research and for the natural continuation of this work.

Since full power system simulations are beyond the scope of a bachelor's thesis, the expectation now lies with the scientific community and institutions such as ENTSO-E to shed further light on the incident and take the next steps in the right direction.

References

[1] R. Villena-Ruiz, B. Silva, A. Honrubia-Escribano, and E. Gómez-Lázaro, "Requirements for new grid codes: A review in spain & portugal," Renewable Energy Research Institute and DIEEAC-ETSII-AB, Universidad de Castilla-La Mancha, 2021, accessed: 2025-11-10. [Online]. Available: https://www.researchgate.net/publication/349891351_Requirements_for_New_Grid_Codes_A_Review_in_Spain_Portugal

[2] P. Wang and L. Badesa, "Imperfect competition in markets for short-circuit current services," arXiv preprint arXiv:2508.09425, 2025, accessed: 2025-11-10. [Online]. Available: https://arxiv.org/abs/2508.09425v1

[3] J. K. Nøland, M. N. Hjelmeland, C. Hartmann, and L. B. Tjernberg, "Overview of small modular and advanced nuclear reactors and their role in the energy transition," IEEE Transactions on Energy Conversion, 2025, accepted for publication; author's version not fully edited. Accessed: 2025-11-10.

[4] J. K. Nøland, M. Hjelmeland, T. Øyvang, M. Korpås, C. Hartmann, and L. B. Tjernberg, "Running renewable-rich power grids with small modular reactors: Their grid-forming role in the future power system," IEEE Transactions on Energy Conversion, 2025, accepted for publication; author's version not fully edited. Accessed: 2025-11-10.

[5] R. E. de España, "Potencia instalada informe del sistema eléctrico 1990–2014," Red Eléctrica de España–Datos de generación, 2024, accessed: 11-11-2025. [Online]. Available: https://www.ree.es/es/datos/generacion/potencia-instalada

[6] ——, "Avance informe del sistema eléctrico 2015," Red Eléctrica de España, 2015, accessed: Nov. 11, 2025. [Online]. Available: https://www.ree.es/sites/default/files/downloadable/avance_informe_sistema_electrico_2015_v2.pdf

[7] ——, "Informe del sistema eléctrico español 2016," Red Eléctrica de España, 2016, accessed: Nov. 11, 2025. [Online]. Available: https://www.ree.es/sites/default/files/11_PUBLICACIONES/Documentos/InformesSistemaElectrico/2016/inf_sis_elec_ree_2016.pdf

[8] ——, "Avance informe del sistema eléctrico 2017," Red Eléctrica de España, 2017, accessed: Nov. 11, 2025. [Online]. Available: https://www.ree.es/sites/default/files/downloadable/avance_informe_sistema_electrico_2017_v3.pdf

[9] ——, "Informe del sistema eléctrico español 2018," Red Eléctrica de España, 2018, accessed: Nov. 11, 2025. [Online]. Available: https://www.ree.es/sites/default/files/11_PUBLICACIONES/Documentos/InformesSistemaElectrico/2018/inf_sis_elec_ree_2018.pdf

[10] ——, "Informe del sistema eléctrico español 2019," Red Eléctrica de España, 2019, accessed: Nov. 11, 2025. [Online]. Available: https://www.ree.es/sites/default/files/11_PUBLICACIONES/Documentos/InformesSistemaElectrico/2019/inf_sis_elec_ree_2019_v2.pdf

[11] ——, "Informe del sistema eléctrico español 2020," Red Eléctrica de España, 2020, accessed: Nov. 11, 2025. [Online]. Available: https://www.ree.es/sites/default/files/publication/2022/05/downloadable/inf_sis_elec_ree_2020_0.pdf

[12] ——, "Potencia instalada informe del sistema eléctrico 2021," Red Eléctrica de España, 2021, accessed: Nov. 11, 2025. [Online]. Available: https://www.sistemaelectrico-ree.es/es/2021/informe-del-sistema-electrico/generacion/potencia-instalada

[13] ——, "Potencia instalada informe del sistema eléctrico 2022," Red Eléctrica de España, 2022, accessed: Nov. 11, 2025. [Online]. Available: https://www.sistemaelectrico-ree.es/es/2022/informe-del-sistema-electrico/generacion/potencia-instalada

[14] ——, "Potencia instalada informe del sistema eléctrico 2023," Red Eléctrica de España, 2023, accessed: Nov. 11, 2025. [Online]. Available: https://www.sistemaelectrico-ree.es/es/2023/informe-del-sistema-electrico/generacion/potencia-instalada

[15] ——, "Potencia instalada informe del sistema eléctrico," Red Eléctrica de España, vol. –, p. –, 2024, accessed: 2025-11-11. [Online]. Available: https://www.sistemaelectrico-ree.es/es/informe-del-sistema-electrico/potencia-instalada

[16] S. M. C. Combinado, "Ciclos combinados en españa," https://www.seccionmunicipiosciclocombinado.es/ciclos-combinados-en-espana/, 2025, accessed: 2025-11-16.

[17] W. B. . ESMAP, "Global solar atlas – solar resource and photovoltaic potential map," Online tool, 2025, accessed: 2025-11-XX. [Online]. Available: https://globalsolaratlas.info/map

[18] G. Kavlak, C. L. L. Hubbert, and J. D. Jenkins, "Evaluating the causes of cost reduction in photovoltaic modules," Energy Policy, vol. 123, pp. 700–710, 2018. [Online]. Available: https://hdl.handle.net/1721.1/123492

[19] R. E. de España, "Generación total de energía eléctrica," https://www.sistemaelectrico-ree.es/es/informe-del-sistema-electrico/generacion/generacion-de-energia-electrica/generacion-total-de-energia-electrica, 2025, accessed: 2025-11-12.

[20] ——, "Intercambios internacionales de electricidad con francia — informe del sistema eléctrico 2022," online report, 2023, accessed: 2025-11-XX. [Online]. Available: https://www.sistemaelectrico-ree.es/es/2022/informe-del-sistema-electrico/intercambios/francia

[21] S. de España, "Comparecencia ante la comisión de transición ecológica y reto demográfico," https://www.senado.es/web/actividadparlamentaria/actualidad/video/index.html?s=15_S015004_012_01, 2024, accessed: 2025-11-12.

[22] I. Guaita-Pradas and A. Blasco-Ruiz, "Analyzing profitability and discount rates for solar pv plants: A spanish case," Energies, vol. 13, no. 8, p. 1910, 2020, received: 26 February 2020; Accepted: 12 April 2020; Published: 14 April 2020. [Online]. Available: https://doi.org/10.3390/en13081910

[23] R. E. de España, "Informe del sistema eléctrico 2024," https://www.sistemaelectrico-ree.es/sites/default/files/2025-03/ISE$_2$024.pdf, 2025, $accessed : Nov.12, 2025$.

[24] ——, "Interconexiones," https://www.ree.es/es/transicion-ecologica/interconexiones, 2025, accessed: Nov. 12, 2025.

[25] A. de Empresas de Energía Eléctrica (AELEC), "Mapas de capacidad y saturación de la red de distribución eléctrica," https://aelec.es/mapas-de-capacidad-saturacion-de-la-red/, 2025, accessed: Nov. 12, 2025.

[26] R. E. de España, "Evolución de la demanda eléctrica en españa," Online report, REE – Informe del sistema eléctrico, 2025, accessed: 2025-11-XX. [Online]. Available: https://www.sistemaelectrico-ree.es/es/informe-del-sistema-electrico/demanda/evolucion-demanda

[27] A. García, A. Riera, A. Martín, J. P. Lopes, F. Fernandes, and R. Sousa, "Análisis de los acontecimientos que condujeron al apagón peninsular del 28 de abril de 2025," Compass Lexecon e INESC TEC, Tech. Rep., Jul. 2025, informe técnico sobre el evento del sistema eléctrico peninsular del 28 de abril de 2025.

[28] R. E. de España, "Informe no confidencial: Evento del 28 de abril," Red Eléctrica de España, Tech. Rep., 2025, documento no confidencial relativo al evento del sistema eléctrico del 28 de abril.

[29] N. Butto, “The nature and origin of inertia,” Journal of High Energy Physics, Gravitation and Cosmology, vol. 7, pp. 761–772, 2021. [Online]. Available: https://doi.org/10.4236/jhepgc.2021.72044

[30] X. Yuan, “Research on impact of synchronous condenser excitation on reactive power characteristics,” Energy Reports, vol. 10, pp. 1234–1245, 2024, accessed: 2025-10-08. [Online]. Available: https://doi.org/10.1016/j.egyr.2024.02.045

[31] P. S. Molina, “La cnmc somete a consulta pública los procedimientos de operación para la respuesta activa de la demanda,” pv magazine España, 2025, accedido: 2025-10-21. [Online]. Available: https://www.pv-magazine.es/2025/07/16/la-cnmc-somete-a-consulta-publica-los-procedimientos-de-operacion-para-la-respuesta-activa-de-la-demanda

[32] R. E. de España, “El sistema eléctrico peninsular contará en 2025 con 1.148 mw de respuesta activa de la demanda,” 2024, accedido: 2025-10-21. [Online]. Available: https://www.ree.es/es/sala-de-prensa/actualidad/2024/11/el-sistema-electrico-peninsular-contara-en-2025-con-1148-MW-servicio-respuesta-activa-demanda-srad

[33] Redacción, “La central nuclear de ascó hace temblar el sistema eléctrico: Red eléctrica desconecta a la gran industria por segundo día consecutivo,” El Periódico de la Energía, 2024, accedido: 2025-10-21. [Online]. Available: https://elperiodicodelaenergia.com/la-central-nuclear-de-asco-hace-temblar-el-sistema-electrico-red-electrica-desconecta-a-la-gran-industria-por

[34] J. Pérez, “The blackout in spain. . . ,” LinkedIn post, 12 Nov. 2025, accessed: 25-11-2025. [Online]. Available: https://www.linkedin.com/feed/update/urn:li:activity:7392833369895514112/

[35] S. Gao, H. Zhang, X. Meng, and Y. Zhang, “A review of dynamic voltage support for power grids with renewable energy integration,” Frontiers in Energy Research, vol. 13, p. 6725, 2025, accessed: 8-10-025. [Online]. Available: https://www.frontiersin.org/articles/10.3389/fenrg.2025.1606725/full

[36] ENTSO-E, “Factual report on the grid incident in spain and portugal on 28 april 2025,” European Network of Transmission System Operators for Electricity (ENTSO-E), Brussels, Belgium, Tech. Rep., October 2025, accessed: November 2025. [Online]. Available: https://eepublicdownloads.blob.core.windows.net/public-cdn-container/clean-documents/Publications/2025/entso-e_incident_report_ES-PT_April_2025_06.pdf

[37] ——, “Frequency stability evaluation criteria for the synchronous zone of continental europe,” European Network of Transmission System Operators for Elec-

tricity (ENTSO-E), Tech. Rep., 2018, accessed: 2025-10-08. [Online]. Available: https://eepublicdownloads.entsoe.eu/clean-documents/SOC%20documents/Regional_Groups_Continental_Europe/201903_Frequency_Stability_Evaluation_Criteria.pdf

[38] C. N. de los Mercados y la Competencia (CNMC), "Resolución de 12 de junio de 2025, por la que se modifican los procedimientos de operación para el desarrollo de un servicio de control de tensión en el sistema eléctrico peninsular español," Boletín Oficial del Estado, Sec. III, Pág. 84733, Jun. 2025, published 26 Jun. 2025; BOE No. 13076. [Online]. Available: https://www.boe.es/

[39] C. Energía, "Costes de los servicios de ajuste del sistema eléctrico," https://cye-energia.com/costes-servicios-de-ajuste-sistema-electrico/, 2025, accessed: Nov. 12, 2025.

[40] M. Giorgi, "Independent energy suppliers under pressure: alarm over blackout-related cost overruns," Strategic Energy Europe, Jun. 2025, accessed: Nov. 12, 2025. [Online]. Available: https://strategicenergy.eu/independent-energy-suppliers-blackout/

[41] E. Renovables, "Red eléctrica responde al apagón con los servicios de ajuste más caros de la historia," https://www.energias-renovables.com/panorama/red-el-ctrica-responde-al-apag-n-20250827, Aug. 2025, accessed: Nov. 12, 2025.

[42] R. E. de España, "Estudios de prospectiva del sistema y necesidades para su operabilidad: Afrontamos juntos los retos de la transición energética," Presentation for the Planning Monitoring Group, 2020, madrid, 29 Sep. 2020. [Online]. Available: https://www.ree.es/

[43] D. d. C. d. C. E. Red Eléctrica de España, Dirección de Operación, "Informe técnico-económico del proyecto demostrativo regulatorio del nuevo servicio de control de tensión," Sep. 2023, madrid, Sep. 2023. [Online]. Available: https://www.ree.es/

[44] R. E. de España, "Criterios generales de protección del sistema eléctrico español (cgp-see)," May 2024, madrid, May 2024. [Online]. Available: https://www.ree.es/

[45] R. E. de España, "Unidades de programación," Online, 2025, accedido: 2025-09-23. [Online]. Available: https://www.esios.ree.es/es/unidades-de-programacion

[46] ——, "Unidades físicas," Online, 2025, accedido: 2025-10-09. [Online]. Available: https://www.esios.ree.es/es/unidades-fisicas

[47] ——, "Procedimiento de operación 3.2: Restricciones técnicas," Red Eléctrica de España, Tech. Rep., 2025. [Online]. Available: https://www.boe.es/diario_boe/txt.php?id=BOE-A-2025-5342

[48] ——, "E-sios download – file p48 (28 april 2025)," Online, Apr. 2025, accessed: 2025-11-19. [Online]. Available: https://www.esios.ree.es/es/descargas?date_type=publicacion&start_date=27-04-2025&end_date=28-04-2025

[49] Red Eléctrica de España (ESIOS), "Generation and consumption outages: April 27–29, 2025 [excel file]," ESIOS Data Portal, 2025, accessed: 2025-09-24. [Online]. Available: https://www.esios.ree.es/es/descargas?date_type=publicacion&start_date=27-04-2025&end_date=29-04-2025

[50] R. Roca, "Histórico apagón nuclear en españa ante la caída de precios eléctricos por la semana santa," El Periódico de la Energía, Apr. 2025, accessed: 2025-10-13. [Online]. Available: https://elperiodicodelaenergia.com/historico-apagon-nuclear-en-espana-ante-la-caida-de-precios-electricos-por-la-semana-santa/

[51] S. C. Johnson, D. J. Papageorgiou, D. S. Mallapragada, T. A. Deetjen, J. D. Rhodes, and M. E. Webber, "Evaluating rotational inertia as a component of grid reliability with high penetrations of variable renewable energy," Applied Energy, vol. 279, p. 115801, 2020.

[52] L. Rouco Rodríguez, E. Lobato Miguélez, and F. M. Echavarren Cerezo, "Resumen del informe preliminar sobre el "cero de tensión" acaecido en el sistema eléctrico ibérico el día 28 de abril de 2025," Instituto de Investigación Tecnológica (IIT), Escuela Técnica Superior de Ingeniería (ICAI), Universidad Pontificia Comillas, Madrid, España, Tech. Rep., September 2025, accessed: November 2025. [Online]. Available: https://files.griddo.comillas.edu/resumen-informe-preliminar-comillas-iit-rouco-lobato-echavarren-v16_1.pdf

[53] J. Hooper, "Italy's blackout raises questions," The Guardian, Sep. 2003, accessed: Nov. 12, 2025. [Online]. Available: https://www.theguardian.com/world/2003/sep/30/italy.johnhooper

[54] E. Commission, "El apagón de noviembre de 2006: importantes lecciones que aprender (ip/07/110)," Press release, Brussels, 30 Jan. 2007, 2007, accessed: Nov. 15, 2025. [Online]. Available: https://ec.europa.eu/commission/presscorner/api/files/document/print/es/ip_07_110/IP_07_110_ES.pdf

[55] E. Simões, "Blackout raises doubts over brazil infrastructure," Reuters, Nov. 2009, accessed: Nov. 12, 2025. [Online]. Available: https://www.reuters.com/article/world/blackout-raises-doubts-over-brazil-infrastructure-idUSTRE5AA07M

[56] A. Beech, “Sa government’s energy policy worsened state-wide blackout, greg hunt says,” ABC News, Oct. 2016, accessed: Nov. 12, 2025. [Online]. Available: https://www.abc.net.au/news/2016-10-03/sa-government-energy-policy-exacerbated-blackout-greg-hunt-says/7897298

[57] C. News, “Hunt on for cause of massive south america power outage,” CBS News, Jun. 2019, accessed: Nov. 14, 2025. [Online]. Available: https://www.cbsnews.com/news/with-massive-south-america-blackout-over-hunt-is-on-for-the-cause/

[58] A. D’Innocenzio and M. Anderson, “Power failure: How a winter storm pushed texas into crisis,” Associated Press, Feb. 2021, accessed: 13-11-2025. [Online]. Available: https://www.apnews.com/article/houston-football-storms-coronavirus-pandemic-hurricanes-5fd491ed5bfd9aa0ae08426c6078539e

[59] B. Energy, “Winter storm uri: There are times when your resiliency is tested,” https://www.bkv.com/winter-storm-uri, 2021, accessed: 16-11-2025.

[60] U. de Chile, “Detalles del corte masivo de luz en españa y portugal,” https://uchile.cl/noticias/227588/detalles-del-corte-masivo-de-luz-en-espana-y-portugal, Apr. 2025, accessed: 16-11-2025.

[61] F. Cambero and A. Villegas, “Power outage hits vast swaths of chile, including santiago and major copper mines,” Reuters, Feb. 2025, accessed: 16-11-2025. [Online]. Available: https://www.reuters.com/world/americas/power-outage-hits-vast-swaths-chile-largest-copper-mine-santiago-streets-2025-02-25/

[62] “Ley 17/2007, de 4 de julio, por la que se modifica la ley 54/1997, del sector eléctrico,” https://www.boe.es/eli/es/l/2007/07/04/17, 2007, artículo 34: el operador del sistema será el gestor de la red de transporte.

[63] L. M. García and I. Carrascón, “Así es la propiedad de red eléctrica, con el estado como principal accionista,” Newtral.es, Apr. 2025, accessed: 2025-11-27. [Online]. Available: https://www.newtral.es/red-electrica-publica/20250430/

[64] J. Guirado, “Seis ex altos cargos del psoe forman parte del consejo de administración de red eléctrica,” Vozpópuli, May 2025, accessed: 2025-11-27. [Online]. Available: https://www.vozpopuli.com/espana/politica/seis-exaltos-cargos-del-psoe-forman-parte-del-consejo-de-administracion-de-red-electrica.html

[65] R. Esteller, “La cogeneración pierde la mitad de sus plantas y reclama un ’rescate urgente’,” elEconomista, Sep. 2025, accessed: 2025-10-17. [Online]. Available: https://www.eleconomista.es/energia/noticias/13565481/09/25/la-cogeneracion-pierde-la-mitad-de-sus-plantas-y-reclama-un-rescate-urgente.html

[66] R. E. de España, “Generation (water),” online report, REE — Informe de Energías Renovables, 2024, accessed: 2025-11-16. [Online]. Available: https://www.sistemaelectrico-ree.es/index.php/en/renewable-energies-report/water/generation-water

Appendices

A Installed Power Capacity per Year and Technology in Spanish Peninsula

Table 1: *Installed Power by Technology (1990–1996) [5]*

Technology	1990	1991	1992	1993	1994	1995	1996
Batteries	-	-	-	-	-	-	-
Conventional and mixed hydro	13793	13795	13849	13849	14064	14088	14143
Pumping	2428	2428	2428	2428	2428	2428	2428
Nuclear	7329	7343	7391	7391	7391	7391	7391
Coal	10243	10310	10310	10310	10310	10310	10310
Fuel + Gas	7259	7247	7247	7247	7247	7247	7521
Combined Cycle	-	-	-	-	-	-	-
Hydro (others)	594	644	728	794	897	1124	1186
Wind	1	1	30	34	39	97	146
Solar photovoltaic	0	0	0	0	1	1	1
Solar thermal	-	-	-	-	-	-	-
Thermal renewable / others	-	-	15	21	21	62	80
Thermal non-renewable / others	159	226	334	535	682	1163	1834
Non renewable waste	-	-	-	-	-	-	-
Renewable waste	-	-	-	-	-	-	-
Total	41807	41995	42334	42608	43081	43911	45042

Table 2: *Installed Power by Technology (1997–2003) [5]*

Technology	1997	1998	1999	2000	2001	2002	2003
Batteries	-	-	-	-	-	-	-
Conventional and mixed hydro	14143	14143	14299	14299	14301	14305	14462
Pumping	2428	2428	2428	2428	2428	2428	2428
Nuclear	7559	7606	7650	7677	7694	7694	7614
Coal	10860	10860	10860	11049	11059	11051	11053
Fuel + Gas	7521	7521	7521	7521	7521	7220	6655
Combined Cycle	-	-	-	-	-	2619	4123
Hydro (others)	1233	1279	1332	1391	1473	1512	1567
Wind	375	634	1022	1829	2817	4391	5816

Technology	1997	1998	1999	2000	2001	2002	2003
Solar photovoltaic	1	1	1	2	2	5	11
Solar thermal	-	-	-	-	-	-	-
Thermal renewable / others	102	115	129	181	229	341	433
Thermal non-renewable / others	2337	2956	3611	4216	4969	5377	5732
Non renewable waste	-	-	-	-	-	-	-
Renewable waste	-	-	-	-	-	-	-
Total	46560	47544	48853	50594	52495	56945	59896

Table 3: *Installed Power by Technology (2004–2010) [5]*

Technology	2004	2005	2006	2007	2008	2009	2010
Batteries	-	-	-	-	-	-	-
Conventional and mixed hydro	14492	14534	14566	14579	14636	14636	14655
Pumping	2428	2428	2451	2451	2451	2451	2451
Nuclear	7590	7597	7456	7456	7456	7456	7515
Coal	11037	10910	10924	10858	10856	10856	10874
Fuel + Gas	6664	6370	6370	4522	4180	2826	2145
Combined Cycle	8062	11992	15305	20672	21374	22750	24844
Hydro (others)	1630	1695	1796	1870	1977	2020	2031
Wind	7777	9654	11286	13526	15993	18714	19561
Solar photovoltaic	21	43	119	594	3205	3243	3645
Solar thermal	-	-	11	11	61	232	532
Thermal renewable / others	451	479	554	573	612	740	779
Thermal non-renewable / others	5987	6163	6371	6483	6737	6968	7098
Non renewable waste	-	-	-	-	-	-	-
Renewable waste	-	-	-	-	-	-	-
Total	66140	71865	77209	83594	89538	92893	96131

Table 4: *Installed Power by Technology (2011–2017) [5, 6, 7, 8]*

Technology	2011	2012	2013	2014	2015	2016	2017
Batteries	-	-	-	-	-	-	-
Conventional and mixed hydro	14667	14887	14890	14896	15297	17023	17002
Pumping	2451	2451	2451	2451	-	-	-
Nuclear	7573	7573	7573	7573	7866	7573	7117
Coal	11103	10595	10610	10468	10972	9536	9536
Fuel + Gas	807	506	506	506	0	0	0

Technology	2011	2012	2013	2014	2015	2016	2017
Combined Cycle	24912	24948	24948	24948	25348	24948	24948
Hydro (others)	2036	2040	2095	2095	2109	-	-
Wind	21018	22609	22853	22871	22845	22900	22863
Solar photovoltaic	4032	4294	4397	4403	4423	4430	4431
Solar thermal	999	1950	2299	2299	2300	2299	2299
Thermal renewable / others	883	968	944	982	984	743	743
Thermal non-renewable / others	7179	7117	7058	7048	7098	6600	6373
Non renewable waste	-	-	-	-	-	677	670
Renewable waste	-	-	-	-	-	-	-
Total	97659	99937	100623	100539	102613	100059	99311

Table 5: *Installed Power by Technology (2018–2024) [9, 10, 11, 12, 13, 14, 15]*

Technology	2018	2019	2020	2021	2022	2023	2024
Batteries	-	-	-	-	-	-	23
Conventional and mixed hydro	17047	17083	17096	17093	17093	17096	17096
Pumping	3329	3329	3331	3331	3331	3331	3331
Nuclear	7117	7117	7117	7117	7117	7117	7117
Coal	9562	9215	5492	3523	3223	3223	1820
Fuel + Gas	0	0	8	8	8	8	8
Combined Cycle	24562	24562	24562	24562	24562	24562	24562
Hydro (others)	-	-	-	-	-	-	-
Wind	23091	25325	27031	27772	29417	30162	31452
Solar photovoltaic	4466	8665	11443	14840	19348	24982	31719
Solar thermal	2304	2304	2304	2304	2304	2304	2302
Thermal renewable / others	859	1071	1084	1087	1087	1087	1097
Thermal non-renewable / others	5730	5666	5661	5613	5593	5534	5531
Non renewable waste	452	451	390	402	387	387	387
Renewable waste	123	122	119	132	132	132	132
Total	98643	104950	105638	107884	113602	119925	126577

Installed Power Capacity by Technology

Table 6: *Rated Capacity on Power Plants Considered for Regional Inertia*

Name	Power (MW)	Region	Technology
CC AS PONTES G.RODRI.G5 T.GAS1	276.6	Galicia	Combined Cycle
CC AS PONTES G.RODRI.G5 T.GAS2	276.3	Galicia	Combined Cycle
CC AS PONTES G.RODRI.G5 T.VAP.	302.7	Galicia	Combined Cycle
C. C. ACECA 4	372.6	Castilla-La Mancha	Combined Cycle
BAHIAB TG1	256.6	País Vasco	Combined Cycle
BAHIAB TG2	257.4	País Vasco	Combined Cycle
BAHIAB TV	271.3	País Vasco	Combined Cycle
CARTAGENA3	412.7	Murcia	Combined Cycle
CC SAGUNTO GRUPO 1	409.7	Valencia	Combined Cycle
ARCOS G1	389.2	Cádiz	Combined Cycle
C.N. ALMARAZ 2	1005.8	Cáceres	Nuclear
C.N. VANDELLOS II	1045.3	Cataluña	Nuclear
C.N. ASCO 1	995.8	Cataluña	Nuclear
C.N. ASCO 2	991.7	Cataluña	Nuclear
C.T. SOTO DE RIBERA 3	346.2	Asturias	Anthracite Coal
GE PLASTICS	97.9	Murcia	Natural Gas Cogeneration
CERÁMICA DOBON	52.7	Aragón	Natural Gas Cogeneration
COBANE A.I.E.	132.3	Cataluña	Natural Gas Cogeneration
REPSOL PET. TARRAGONA	85.1	Cataluña	Natural Gas Cogeneration
REPSOL Q. EL MORELL-PERAFOR	86.7	Cataluña	Natural Gas Cogeneration
COGENERACIÓN UNEMSA	14.7	Galicia	Petro. Or Coal Derivatives
REPSOL PETROLEO	94.1	Castilla-La Mancha	Petro. Or Coal Derivatives
MOVIALSA	23.7	Castilla-La Mancha	Petro. Or Coal Derivatives
PLANTA TERMOSOLAR LEBRIJA	49.9	Andalucía	Thermal Solar
PS20	20	Andalucía	Thermal Solar
ARCOSOL 50	50	Andalucía	Thermal Solar
AFRICANAA	49.9	Andalucía	Thermal Solar
PST MORON	49.9	Andalucía	Thermal Solar
SOLNOVA ELECTRICIDAD	50	Andalucía	Thermal Solar
SOLNOVA ELECTRICIDAD TRES	50	Andalucía	Thermal Solar
SOLNOVA ELECTRICIDAD CUATRO	50	Andalucía	Thermal Solar
PALMA DEL RIO I	100	Andalucía	Thermal Solar

Name	Power (MW)	Region	Technology
BORGES	22.5	Cataluña	Thermal Solar
GEXTRESOLII	49.9	Badajoz	Thermal Solar
18WERRADO2-123-Q	30	Extremadura	Thermal Solar
GEXTRESOLIII	49.9	Badajoz	Thermal Solar
TERMOLLANO	48	Castilla-La Mancha	Thermal Solar
18WASTEXO2-123-9	49.9	Extremadura	Thermal Solar
TERMOSOLAR MAJADAS	50	Badajoz	Thermal Solar
TGST148	49.9	Extremadura	Thermal Solar
TGST149	49.9	Extremadura	Thermal Solar
OLIVENZA	50	Badajoz	Thermal Solar
18WARENALE-12–X	49.9	Extremadura	Thermal Solar
GEXT1	50	Extremadura	Thermal Solar
HELIOENERGY 1	50	Andalucía	Thermal Solar
LA RISCA	50	Badajoz	Thermal Solar
TERMESOL 50	50	Badajoz	Thermal Solar
TERMOSOLAR GEMASOLAR	17	Andalucía	Thermal Solar
SOLACOR1	50	Andalucía	Thermal Solar
SOLABEN TERMOSOLAR 6	50	Cáceres	Thermal Solar
SOLABEN ELECTRICIDAD TRES	50	Cáceres	Thermal Solar
SOLABEN ELECTRICIDAD UNO	50	Cáceres	Thermal Solar
SOLABEN 2	50	Cáceres	Thermal Solar
SOLACOR2	50	Andalucía	Thermal Solar
CASABLANCA	49.9	Badajoz	Thermal Solar
TERMOSOLAR ORELLANA	49.9	Badajoz	Thermal Solar
ANDASOL-3	49.9	Andalucía	Thermal Solar
ANDASOL-2	49.9	Andalucía	Thermal Solar
ANDASOL I	49.9	Andalucía	Thermal Solar
PL SOLAR TERMELÉCTRICA PS 10	11	Andalucía	Thermal Solar
UF VILLENA	49.9	Comunidad Valenciana	Thermal Solar
AIGUAMOIX	31.5	Cataluña	UGH Hydropower
NTRA. Sª AGAVANZAL 1	11.2	Castilla y León	UGH Hydropower
NTRA. Sª AGAVANZAL 2	11.3	Castilla y León	UGH Hydropower
ALDEADAVILA I 1	132.9	Castilla y León	UGH Hydropower
ALDEADAVILA I 2	132.7	Castilla y León	UGH Hydropower
ALDEADAVILA I 3	133	Castilla y León	UGH Hydropower
ALDEADAVILA I 4	133.1	Castilla y León	UGH Hydropower

Name	**Power (MW)**	**Region**	**Technology**
ALDEADAVILA I 5	131.8	Castilla y León	UGH Hydropower
ALDEADAVILA I 6	134.3	Castilla y León	UGH Hydropower
ALDEADAVILA II GR.1 GENERAC.	216.2	Castilla y León	UGH Hydropower
ALDEADAVILA II GR.2 GENERAC.	212.2	Castilla y León	UGH Hydropower
ALBARELLOS	67.6	Galicia	UGH Hydropower
ALCOBA	7.7	Castilla y Léon	UGH Hydropower
ANZANIGO	7.7	Aragón	UGH Hydropower
ARBON 1	24.7	Asturias	UGH Hydropower
ARBON 2	24.7	Asturias	UGH Hydropower
ARGONE 1	7,6	Aragón	Hidráulica UGH
ARGONE 2	7,2	Aragón	Hidráulica UGH
ARTIES 1	33,4	Cataluña	Hidráulica UGH
ARTIES 2	33,4	Cataluña	Hidráulica UGH
AZUTAN 1	67,4	Castilla-La Mancha	Hidráulica UGH
AZUTAN 2	65,5	Castilla-La Mancha	Hidráulica UGH
AZUTAN 3	65	Castilla-La Mancha	Hidráulica UGH
BALAGUER	7,3	Cataluña	Hidráulica UGH
BALIERA	5,2	Cataluña	Hidráulica UGH
BARRIOS DE LUNA 1	16,3	Castilla y León	Hidráulica UGH
BARRIOS DE LUNA 2	16,4	Castilla y León	Hidráulica UGH
BARRIOS DE LUNA 3	7,6	Castilla y León	Hidráulica UGH
BARRIOS DE LUNA 4	7,5	Castilla y León	Hidráulica UGH
BASERCA	5,9	Aragón	Hidráulica UGH
LA BARCA 1	25,8	Asturias	Hidráulica UGH
LA BARCA 2	26,2	Asturias	Hidráulica UGH
BELESAR 1	102,5	Galicia	Hidráulica UGH
BELESAR 2	104,8	Galicia	Hidráulica UGH
BELESAR 3	102,9	Galicia	Hidráulica UGH
BEMBEZAR	14,8	Andalucía	Hidráulica UGH
BENAGEBER 2	14,9	Andalucia	Hidráulica UGH
BIESCAS 21	30,7	Aragón	Hidráulica UGH
BIESCAS 22	30,7	Aragón	Hidráulica UGH
PUENTE BIBEY 1	79,3	Galicia	Hidráulica UGH
PUENTE BIBEY 2	78,8	Galicia	Hidráulica UGH
PUENTE BIBEY 3	78	Galicia	Hidráulica UGH
PUENTE BIBEY GR.4 GENERAC.	76,2	Galicia	Hidráulica UGH

Name	**Power (MW)**	**Region**	**Technology**
BENOS 1	7,8	Aragón	Hidráulica UGH
BENOS 2	7,8	Aragón	Hidráulica UGH
BOHI 1	7,8	Cataluña	Hidráulica UGH
BOHI 2	7,8	Cataluña	Hidráulica UGH
BOLARQUE I 1	13,9	Castilla-La Mancha	Hidráulica UGH
BOLARQUE I 2	13,9	Castilla-La Mancha	Hidráulica UGH
BARRADOS	15,7	Cataluña	Hidráulica UGH
BARAZAR 1	41,3	Pais Vasco	Hidráulica UGH
BARAZAR 2	40,6	Pais Vasco	Hidráulica UGH
BOSOST 1	10,6	Cataluña	Hidráulica UGH
BOSOST 2	10,8	Cataluña	Hidráulica UGH
BUENDIA 1	18,1	Castilla-La Mancha	Hidráulica UGH
BUENDIA 2	18,1	Castilla-La Mancha	Hidráulica UGH
BUENDIA 3	18,1	Castilla-La Mancha	Hidráulica UGH
BURGUILLO 1	19,7	Castilla y León	Hidráulica UGH
BURGUILLO 2	21,2	Castilla y León	Hidráulica UGH
BURGUILLO 3	21	Castilla y León	Hidráulica UGH
CASTRO I 1	41,5	Asturias	Hidráulica UGH
CASTRO I 2	41,5	Asturias	Hidráulica UGH
CASTRO II	112,1	Asturias	Hidráulica UGH
CANALROYA	6,7	Aragón	Hidráulica UGH
CALA 1	6,3	Andalucía	Hidráulica UGH
CALA 2	6,3	Andalucía	Hidráulica UGH
CAMARMEÑA 1	6,5	Asturias	Hidráulica UGH
CAMARMEÑA 2	6,2	Asturias	Hidráulica UGH
CANALES 1	8	Andalucía	Hidráulica UGH
LAS CONCHAS 1	12,5	Castilla y León	Hidráulica UGH
LAS CONCHAS 2	12,6	Castilla y León	Hidráulica UGH
LAS CONCHAS 3	24,1	Castilla y León	Hidráulica UGH
CEDILLO 1	121,3	Cáceres	Hidráulica UGH
CEDILLO 2	120,6	Cáceres	Hidráulica UGH
CEDILLO 3	127,4	Cáceres	Hidráulica UGH
CEDILLO 4	125,6	Cáceres	Hidráulica UGH
CERNADILLA	33,3	Castilla y León	Hidráulica UGH
COFRENTES 1 HIDRA.	40,2	Valencia	Hidráulica UGH
COFRENTES 2 HIDRA.	40,5	Valencia	Hidráulica UGH

Name	**Power (MW)**	**Region**	**Technology**
COFRENTES 3 HIDRA.	39,7	Valencia	Hidráulica UGH
CIMANES	7,7	Castilla y León	Hidráulica UGH
CIRAT 2	7,3	Valencia	Hidráulica UGH
CALDES 1	16	Cataluña	Hidráulica UGH
CALDES 2	16	Cataluña	Hidráulica UGH
CAMARASA 1	14,7	Cataluña	Hidráulica UGH
CAMARASA 2	14,5	Cataluña	Hidráulica UGH
CAMARASA 3	14,3	Cataluña	Hidráulica UGH
CAMARASA 4	14,7	Cataluña	Hidráulica UGH
CANELLES 1	35,4	Aragón	Hidráulica UGH
CANELLES 2	35,4	Aragón	Hidráulica UGH
CANELLES 3	35,4	Aragón	Hidráulica UGH
CONTRERAS II 1	13,9	Castilla-La Mancha	Hidráulica UGH
CONTRERAS II 2	36,9	Castilla-La Mancha	Hidráulica UGH
CORTES II-1	141,9	Andalucia	Hidráulica UGH
CORTES II-2	148	Andalucia	Hidráulica UGH
CONSO GR.1 GENERAC	89,3	Galicia	Hidráulica UGH
CONSO GR.2 GENERAC.	90,5	Galicia	Hidráulica UGH
CONSO GR.3 GENERAC.	88	Galicia	Hidráulica UGH
EL CORCHADO 2	5,1	Andalucía	Hidráulica UGH
EL CORCHADO 3	5,1	Andalucía	Hidráulica UGH
CAPDELLA (AUX)	6,2	Cataluña	Hidráulica UGH
CAPDELLA 1	6,2	Cataluña	Hidráulica UGH
CAPDELLA 2	6,2	Cataluña	Hidráulica UGH
CAPDELLA 3	6,2	Cataluña	Hidráulica UGH
CAPDELLA 4	6,2	Cataluña	Hidráulica UGH
CASTREJON 1	20,1	Castilla y León	Hidráulica UGH
CASTREJON 2	20,7	Castilla y León	Hidráulica UGH
CASTREJON 3	20,3	Castilla y León	Hidráulica UGH
CASTREJON 4	19,5	Castilla y León	Hidráulica UGH
CASTRELO 1	67,5	Galicia	Hidráulica UGH
CASTRELO 2	68	Galicia	Hidráulica UGH
COMPUERTO 1	9,8	Galicia	Hidráulica UGH
COMPUERTO 2	9,8	Galicia	Hidráulica UGH
CORNATEL 1	65,2	Galicia	Hidráulica UGH
CORNATEL 2	65,4	Galicia	Hidráulica UGH

Name	Power (MW)	Region	Technology
DOÑA ALDONZA 1	5,1	Galicia	Hidráulica UGH
DOÑA ALDONZA 2	5,1	Galicia	Hidráulica UGH
DOIRAS 1	23,7	Galicia	Hidráulica UGH
DOIRAS 2	23,7	Galicia	Hidráulica UGH
DOIRAS 3	14,1	Galicia	Hidráulica UGH
DUQUE	12,5	Andalucía	Hidráulica UGH
EL BERBEL 1	6,2	Aragón	Hidráulica UGH
EL BERBEL 2	6,2	Aragón	Hidráulica UGH
EL BERBEL 3	6,2	Aragón	Hidráulica UGH
EL PICAZO 1	8,3	Castilla-La Mancha	Hidráulica UGH
EL PICAZO 2	8,9	Castilla-La Mancha	Hidráulica UGH
ENTREPEÑAS 1	20,3	Castilla-La Mancha	Hidráulica UGH
ENTREPEÑAS 2	20,4	Castilla-La Mancha	Hidráulica UGH
ERISTE 1	44	Aragón	Hidráulica UGH
ERISTE 2	43,6	Aragón	Hidráulica UGH
ESCALES 1	12	Aragón	Hidráulica UGH
ESCALES 2	11,9	Aragón	Hidráulica UGH
ESCALES 3	11,9	Aragón	Hidráulica UGH
ESPINOSA	7,9	Castilla y León	Hidráulica UGH
SAN ESTEBAN 1	63,9	Castilla y León	Hidráulica UGH
SAN ESTEBAN 2	63,8	Castilla y León	Hidráulica UGH
SAN ESTEBAN II G1	185,3	Castilla y León	Hidráulica UGH
SAN ESTEBAN 3	62,7	Castilla y León	Hidráulica UGH
SAN ESTEBAN 4	62,5	Castilla y León	Hidráulica UGH
ESTERRI 1	9,3	Cataluña	Hidráulica UGH
ESTERRI 2	8,9	Cataluña	Hidráulica UGH
ESTERRI 3	9,2	Cataluña	Hidráulica UGH
EUME 1	26,7	Galicia	Hidráulica UGH
EUME 2	26,7	Galicia	Hidráulica UGH
FLIX 1	11,1	Cataluña	Hidráulica UGH
FLIX 2	10,4	Cataluña	Hidráulica UGH
FLIX 3	11,1	Cataluña	Hidráulica UGH
FLIX 4	11,1	Cataluña	Hidráulica UGH
FRIEIRA 1	80,5	Galicia	Hidráulica UGH
FRIEIRA 2	80,1	Galicia	Hidráulica UGH
GABET 1	11,4	Cataluña	Hidráulica UGH

Name	Power (MW)	Region	Technology
GABET 2	11,5	Cataluña	Hidráulica UGH
GUADALMELLATO	5,1	Andalucía	Hidráulica UGH
GUADALMENA 1	14,9	Andalucía	Hidráulica UGH
GUIJO GRANADILLA GR.1 GENERAC.	26,3	Cáceres	Hidráulica UGH
GUIJO GRANADILLA GR.2 GENERAC.	25,8	Cáceres	Hidráulica UGH
GRADO I 1	9,2	Aragón	Hidráulica UGH
GRADO I 2	9,2	Aragón	Hidráulica UGH
GRADO II 1	12	Aragón	Hidráulica UGH
GRADO II 2	13,6	Aragón	Hidráulica UGH
GABRIEL Y GALAN GR.1 GENERAC.	110,4	Cáceres	Hidráulica UGH
IZNAJAR 1	37,8	Andalucía	Hidráulica UGH
IZNAJAR 2	38,3	Andalucía	Hidráulica UGH
JACA 1	7,6	Aragón	Hidráulica UGH
JACA 2	8,2	Aragón	Hidráulica UGH
JANDULA 2	5,8	Andalucía	Hidráulica UGH
JANDULA 3	5,9	Andalucía	Hidráulica UGH
SANTIAGO-JARES GR.1 GENERAC.	25,9	Galicia	Hidráulica UGH
SANTIAGO-JARES GR.2 GENERAC.	27,1	Galicia	Hidráulica UGH
JAVIERRELATRE 1	5,2	Aragón	Hidráulica UGH
JAVIERRELATRE 2	5,2	Aragón	Hidráulica UGH
JOSE MARIA ORIOL 1	237	Cáceres	Hidráulica UGH
JOSE MARIA ORIOL 2	239	Cáceres	Hidráulica UGH
JOSE MARIA ORIOL 3	239,3	Cáceres	Hidráulica UGH
JOSE MARIA ORIOL 4	237,8	Cáceres	Hidráulica UGH
JUEU	20	Cataluña	Hidráulica UGH
LA BAELLS	6,9	Cataluña	Hidráulica UGH
LAFORTUNADA-CINCA GR.1	13,8	Aragón	Hidráulica UGH
LAFORTUNADA-CINCA GR.2	13,8	Aragón	Hidráulica UGH
LAFORTUNADA-CINCA GR.3	13,8	Aragón	Hidráulica UGH
LASPUÑA 1	7,1	Aragón	Hidráulica UGH
LASPUÑA 2	7,1	Aragón	Hidráulica UGH
LERIDA	11,8	Cataluña	Hidráulica UGH
LLAVORSI CARDOS 1	26	Cataluña	Hidráulica UGH
LLAVORSI CARDOS 2	26	Cataluña	Hidráulica UGH
LANUZA 1	26,9	Aragón	Hidráulica UGH
LANUZA 2	25,7	Aragón	Hidráulica UGH

Name	**Power (MW)**	**Region**	**Technology**
LA RIBEIRA	5,9	Galicia	Hidráulica UGH
LLESP 1	6,1	Cataluña	Hidráulica UGH
LLESP 2	6,1	Cataluña	Hidráulica UGH
LUCAS DE URQUIJO 1	5,9	Andalucia	Hidráulica UGH
LUCAS DE URQUIJO 2	5,9	Andalucia	Hidráulica UGH
LUCAS DE URQUIJO 3	13,4	Andalucia	Hidráulica UGH
LUCAS DE URQUIJO 4	13,7	Andalucia	Hidráulica UGH
MEDIANO 1	33,5	Aragón	Hidráulica UGH
MEDIANO 2	33,4	Aragón	Hidráulica UGH
MILLER 1	8,2	Andalucia	Hidráulica UGH
MILLER 2	8,6	Andalucia	Hidráulica UGH
MILLER 3	8,1	Andalucia	Hidráulica UGH
MILLARES II 1	34,9	Andalucia	Hidráulica UGH
MILLARES II 2	35,2	Andalucia	Hidráulica UGH
BARCENA DEL SIL 1	30,1	Castilla y León	Hidráulica UGH
BARCENA DEL SIL 2	31	Castilla y León	Hidráulica UGH
MONTAMARA GR.1 GENERAC.	45,8	Cataluña	Hidráulica UGH
MONTAMARA GR.2 GENERAC.	46,5	Cataluña	Hidráulica UGH
MEQUINENZA 1	79,7	Aragón	Hidráulica UGH
MEQUINENZA 2	79,7	Aragón	Hidráulica UGH
MEQUINENZA 3	79,7	Aragón	Hidráulica UGH
MEQUINENZA 4	79,7	Aragón	Hidráulica UGH
MIRANDA 1 (HC)	17,9	Castilla y León	Hidráulica UGH
MIRANDA 2 (HC)	17,9	Castilla y León	Hidráulica UGH
MIRANDA 3 (HC)	17,8	Castilla y León	Hidráulica UGH
MIRANDA 4 (HC)	18,1	Castilla y León	Hidráulica UGH
MARMOLEJO 1	8,3	Andalucía	Hidráulica UGH
MARMOLEJO 2	8,3	Andalucía	Hidráulica UGH
MONTEFURADO 1	14,7	Galicia	Hidráulica UGH
MONTEFURADO 2	15	Galicia	Hidráulica UGH
MONTEFURADO 3	14,5	Galicia	Hidráulica UGH
SAN MARTIN	10,2	Castilla y león	Hidráulica UGH
NUEVO CHORRO	9,9	Andalucía	Hidráulica UGH
NEGRATIN	6,5	Andalucía	Hidráulica UGH
OLIANA 1	12,4	Cataluña	Hidráulica UGH
OLIANA 2	12,4	Cataluña	Hidráulica UGH

Name	**Power (MW)**	**Region**	**Technology**
OLIANA 3	12,4	Cataluña	Hidráulica UGH
LAS ONDINAS 1	40,9	Castilla y León	Hidráulica UGH
LAS ONDINAS 2	41,5	Castilla y León	Hidráulica UGH
PAMPANEIRA 1	12,6	Andalucía	Hidráulica UGH
LAS PICADAS 1	12,1	Castilla-La Mancha	Hidráulica UGH
LAS PICADAS 2	12,2	Castilla-La Mancha	Hidráulica UGH
PORTODEMOUROS 1	44	Galicia	Hidráulica UGH
PORTODEMOUROS 2	44,1	Galicia	Hidráulica UGH
PORTO	17,3	Castilla y León	Hidráulica UGH
LOS PEARES 1	59,9	Galicia	Hidráulica UGH
LOS PEARES 2	60,3	Galicia	Hidráulica UGH
LOS PEARES 3	60,6	Galicia	Hidráulica UGH
PEÑADRADA 1	18,4	Castilla y León	Hidráulica UGH
PEÑADRADA 2	19,7	Castilla y León	Hidráulica UGH
PINTADO 1	12,2	Andalucía	Hidráulica UGH
PINTADO 2	6,3	Andalucía	Hidráulica UGH
PINTADO 3	14,1	Andalucía	Hidráulica UGH
PEDRO MARIN 1	5,1	Castilla-La Mancha	Hidráulica UGH
PEDRO MARIN 2	7,8	Castilla-La Mancha	Hidráulica UGH
PUENTE MONTAÑANA 1	22	Aragón	Hidráulica UGH
PUENTE MONTAÑANA 2	22	Aragón	Hidráulica UGH
PONTE NOVO 1	12,7	Galicia	Hidráulica UGH
PONTE NOVO 2	13	Galicia	Hidráulica UGH
PONTE NOVO 3	6	Galicia	Hidráulica UGH
PONTE NOVO 4	6,2	Galicia	Hidráulica UGH
LA POBLA DE SEGUR GR. 1	6,5	Cataluña	Hidráulica UGH
LA POBLA DE SEGUR GR. 2	6,5	Cataluña	Hidráulica UGH
POQUEIRA 1	5,1	Andalucía	Hidráulica UGH
POQUEIRA 2	5,1	Andalucía	Hidráulica UGH
PRADA 1	35,5	Asturias	Hidráulica UGH
PRADA 2	35,2	Asturias	Hidráulica UGH
PONT DE REI GR.1 (ARTIES)	22,8	Cataluña	Hidráulica UGH
PONT DE REI GR.2 (ARTIES)	22,8	Cataluña	Hidráulica UGH
PRIAÑES 3	9,8	Asturias	Hidráulica UGH
PROAZA 1	24,7	Asturias	Hidráulica UGH
PROAZA 2	24,7	Asturias	Hidráulica UGH

Name	Power (MW)	Region	Technology
PONT DE SUERT 1	7,7	Cataluña	Hidráulica UGH
PONT DE SUERT 2	7,7	Cataluña	Hidráulica UGH
PUENTE NUEVO 1 HIDRAUL.	6,5	Castilla-La Mancha	Hidráulica UGH
PUENTE NUEVO 1 HIDRAUL.	6,7	Castilla-La Mancha	Hidráulica UGH
PUENTE NUEVO 1 HIDRAUL.	6,7	Castilla-La Mancha	Hidráulica UGH
QUEREÑO GR. 1	18,2	Asturias	Hidráulica UGH
QUEREÑO GR. 2	18,2	Asturias	Hidráulica UGH
QUINTANA	7,6	Castilla y León	Hidráulica UGH
REGUEIRO (MAO) 1	14,3	Asturias	Hidráulica UGH
REGUEIRO (MAO) 2	14,3	Asturias	Hidráulica UGH
REMOLINA 1	41,8	Asturias	Hidráulica UGH
REMOLINA 2	41,3	Asturias	Hidráulica UGH
RICOBAYO 1	42,4	Castilla y León	Hidráulica UGH
RICOBAYO 2	44	Castilla y León	Hidráulica UGH
RICOBAYO 220 TM1/15	153	Castilla y León	Hidráulica UGH
RICOBAYO 3	41,9	Castilla y León	Hidráulica UGH
RICOBAYO 4	45,1	Castilla y León	Hidráulica UGH
RIOSCURO 1	7,6	Castilla y León	Hidráulica UGH
RIOSCURO 2	7,5	Castilla y León	Hidráulica UGH
RIBARROJA 1	64,7	Valencia	Hidráulica UGH
RIBARROJA 2	64,7	Valencia	Hidráulica UGH
RIBARROJA 3	64,7	Valencia	Hidráulica UGH
RIBARROJA 4	64,7	Valencia	Hidráulica UGH
SAUCELLE I 1	62	Castilla y León	Hidráulica UGH
SAUCELLE I 2	63,3	Castilla y León	Hidráulica UGH
SAUCELLE I 3	62,2	Castilla y León	Hidráulica UGH
SAUCELLE I 4	62,2	Castilla y León	Hidráulica UGH
SAUCELLE II 1	136,1	Castilla y León	Hidráulica UGH
SAUCELLE II 2	135,7	Castilla y León	Hidráulica UGH
SAN AGUSTIN 1	31	Castilla-La Mancha	Hidráulica UGH
SAN AGUSTIN 2	31,8	Castilla-La Mancha	Hidráulica UGH
ALBENTOSA 1 (S. AGUSTIN-JUCAR)	5,9	Castilla-La Mancha	Hidráulica UGH
ALBENTOSA 2 (S. AGUSTIN-JUCAR)	5,9	Castilla-La Mancha	Hidráulica UGH
SALAS	52,8	Asturias	Hidráulica UGH
SOBRON 1	13,5	Castilla y León	Hidráulica UGH
SOBRON 2	14,2	Castilla y León	Hidráulica UGH

Name	Power (MW)	Region	Technology
SAN CLODIO	19,5	Galicia	Hidráulica UGH
SAN CRISTOBAL 1	6	Galicia	Hidráulica UGH
SAN CRISTOBAL 2	6,3	Galicia	Hidráulica UGH
SAN SEBASTIAN 1	8,8	Galicia	Hidráulica UGH
SAN SEBASTIAN 2	8,8	Galicia	Hidráulica UGH
SEIRA 1	8,7	Aragón	Hidráulica UGH
SEIRA 2	8,6	Aragón	Hidráulica UGH
SEIRA 3	19	Aragón	Hidráulica UGH
SILVON 1	40,3	Galicia	Hidráulica UGH
SILVON 2	41,2	Galicia	Hidráulica UGH
SAN JUAN 1	19	Aragón	Hidráulica UGH
SAN JUAN 2	19,8	Aragón	Hidráulica UGH
SAN JUAN TORAN	13	Aragón	Hidráulica UGH
SALIME 1	39,4	Asturias	Hidráulica UGH
SALIME 2	39,2	Asturias	Hidráulica UGH
SANTA MARINA 1	10,5	Asturias	Hidráulica UGH
SANTA MARINA 2	10,1	Asturias	Hidráulica UGH
SANTA MARINA 3	13,9	Asturias	Hidráulica UGH
S. MAURI 3	5,1	Cataluña	Hidráulica UGH
SOBRADELO 1	22,6	Galicia	Hidráulica UGH
SOBRADELO 2	21,6	Galicia	Hidráulica UGH
SOUTELO GR.1	131,9	Galicia	Hidráulica UGH
SOUTELO GR.2 GENERAC	81,6	Galicia	Hidráulica UGH
SAN PEDRO 1	17,2	Galicia	Hidráulica UGH
SAN PEDRO 2	17,1	Galicia	Hidráulica UGH
SAN PEDRO2 1	25,8	Galicia	Hidráulica UGH
SEQUEIROS 1	6,6	Galicia	Hidráulica UGH
SEQUEIROS 2	6,2	Galicia	Hidráulica UGH
SEQUEIROS 3	6,5	Galicia	Hidráulica UGH
SAN ROMAN	5,5	Galicia	Hidráulica UGH
SEROS 1	10,9	Aragón	Hidráulica UGH
SEROS 2	10,9	Aragón	Hidráulica UGH
SEROS 3	10,9	Aragón	Hidráulica UGH
SEROS 4	10,9	Aragón	Hidráulica UGH
SANTIAGO-SIL 1	7,4	Galicia	Hidráulica UGH
SANTIAGO-SIL 2	7,4	Galicia	Hidráulica UGH

Name	**Power (MW)**	**Region**	**Technology**
SANTA ANA 1	15	Cataluña	Hidráulica UGH
SANTA ANA 2	15	Cataluña	Hidráulica UGH
SANTA TERESA 1	10,3	Castilla y León	Hidráulica UGH
SANTA TERESA 2	10,3	Castilla y León	Hidráulica UGH
TABESCAN 1	31,5	Cataluña	Hidráulica UGH
TABESCAN 2	59,3	Cataluña	Hidráulica UGH
TABESCAN 3	59,3	Cataluña	Hidráulica UGH
TAMBRE 4 (TAMBRE I G4)	10,3	Asturias	Hidráulica UGH
TAMBRE 5 (TAMBRE II G1)	62,7	Asturias	Hidráulica UGH
TANES GR.1 GENERAC.	62,3	Asturias	Hidráulica UGH
TANES GR.2 GENERAC.	61,8	Asturias	Hidráulica UGH
TERMENS	11,8	Cataluña	Hidráulica UGH
TALARN 1	8,6	Cataluña	Hidráulica UGH
TALARN 2	8,6	Cataluña	Hidráulica UGH
TALARN 3	8,6	Cataluña	Hidráulica UGH
TALARN 4	8,6	Cataluña	Hidráulica UGH
TORREJON GR.1 GENERAC.	32,1	Cáceres	Hidráulica UGH
TORREJON GR.2 GENERAC.	32,3	Cáceres	Hidráulica UGH
TORREJON GR.3 GENERAC.	32,3	Cáceres	Hidráulica UGH
TORREJON GR.4 GENERAC.	33,6	Cáceres	Hidráulica UGH
TORINA 3	5,6	Asturias	Hidráulica UGH
TRANCO DE BEAS 1	15,7	Andalucía	Hidráulica UGH
TRANCO DE BEAS 2	7,6	Andalucía	Hidráulica UGH
TRANCO DE BEAS 3	15,7	Andalucía	Hidráulica UGH
TERRADETS 1	16	Cataluña	Hidráulica UGH
TERRADETS 2	16	Cataluña	Hidráulica UGH
TRESPADERNE 1	7,4	Castilla y León	Hidráulica UGH
TRESPADERNE 2	7,4	Castilla y León	Hidráulica UGH
UNARRE	7,8	Aragón	Hidráulica UGH
VALPARAISO GR.1 GENERAC.	32,6	Castilla y León	Hidráulica UGH
VALPARAISO GR.2 GENERAC.	32,4	Castilla y León	Hidráulica UGH
VILLALCAMPO I 1	32,5	Castilla y León	Hidráulica UGH
VILLALCAMPO I 2	32,2	Castilla y León	Hidráulica UGH
VILLALCAMPO I 3	32,4	Castilla y León	Hidráulica UGH
VILLALCAMPO II	118,5	Castilla y León	Hidráulica UGH
VALDECAÑAS GR.1 GENERAC.	82,7	Cáceres	Hidráulica UGH

Name	Power (MW)	Region	Technology
VALDECAÑAS GR.2 GENERAC.	82,3	Cáceres	Hidráulica UGH
VALDECAÑAS GR.3 GENERAC.	82	Cáceres	Hidráulica UGH
VELLE 1	45,7	Galicia	Hidráulica UGH
VELLE 2	40,7	Galicia	Hidráulica UGH
VIELLA 1	10,8	Cataluña	Hidráulica UGH
VIELLA 2	10,8	Cataluña	Hidráulica UGH
VILLALBA DE LA SIERRA 1	5,6	Castilla-La Mancha	Hidráulica UGH
VILLALBA DE LA SIERRA 2	5,5	Castilla-La Mancha	Hidráulica UGH
VILLALBA 1	6,9	Castilla y León	Hidráulica UGH
VILLALBA 2	6,9	Castilla y León	Hidráulica UGH
VALLAT 2	7,1	Andalucía	Hidráulica UGH
VALDEOBISPO 1	19,7	Cáceres	Hidráulica UGH
VALDEOBISPO 2	19,7	Cáceres	Hidráulica UGH
VILLARINO GR.1 GENERAC.	138,9	Castilla y León	Hidráulica UGH
VILLARINO GR.2 GENERAC.	137,4	Castilla y León	Hidráulica UGH
VILLARINO GR.3 GENERAC.	138,3	Castilla y León	Hidráulica UGH
VILLARINO GR.4 GENERAC.	138,7	Castilla y León	Hidráulica UGH
VILLARINO GR.5 GENERAC.	148,9	Castilla y León	Hidráulica UGH
VILLARINO GR.6 GENERAC.	148,6	Castilla y León	Hidráulica UGH
VILLANUA	10,8	Aragón	Hidráulica UGH