24thInternational Conference on Renewable Energies and Power Quality (ICREPQ'26)
Santander (Spain), June 10 to 12, 2026
ISBN-13: 978-84-09-82044-3

Assessing the Impact of PNIEC Implementation Delays on the Business Models of Pumped Hydro Storage Projects

Jose M. Yusta, Natalia Naval, and Lizbeth Tipán-Salazar

[1]Department of Electrical Engineering
E.I.N.A., University of Zaragoza
C/Maria de Luna 3, 50018 Zaragoza (Spain). jmyusta@unizar.es, naval@unizar.es, ltipan@unizar.es

Abstract. This article analyzes the impact of delays in implementing the objectives of the National Integrated Energy and Climate Plan (PNIEC) on the business models of stand-alone reversible pumped storage in Spain. This technology is essential for integrating renewable energies through price arbitrage, taking advantage of market volatility to pump during low-cost hours and turbine during peak hours.
Using a statistical regression model to estimate hourly prices until 2050 and an algorithm for daily selection of optimal pumping and turbining hours for a 165 MW plant, scenarios are evaluated where the PNIEC objectives are achieved in 2030, 2035, or 2040. The results reveal that the delay in renewable deployment reduces the price spread, penalizing the economic performance of the facility by 14% if postponed to 2035 and up to 28% if reached in 2040. Likewise, it is observed that increasing the operating strategy to 7 hours of daily pumping can improve financial performance by up to 46%.

Key words. Pumped Hydro Storage, Energy and Climate Plan, Regression model, Electricity market price

1. Introduction

Reversible pumped storage is a massive energy storage system that has two reservoirs located at different heights. During periods of high demand, the gravitational potential energy of the water stored in the upper reservoir is converted into electricity by turbines, while during periods of low demand, the water is pumped from the lower reservoir to the upper reservoir and stored again.

Reversible hydraulic pumping or pumped hydro storage (PHS) is the most mature and widespread storage technology worldwide in terms of installed power and energy capacity. However, it requires specific site conditions to be viable and significant investment in civil engineering works.

Closed-cycle pumping facilities are currently attracting a lot of interest, as they can be developed artificially outside the riverbed and are generally better from an environmental point of view than open-cycle facilities [1]. Once filled, water consumption is only required to replace evaporation.

The optimal operation of pumped storage plants in liberalized electricity markets is based on price arbitrage to maximize operating profitability. This strategy takes advantage of spot price volatility: the system consumes energy by pumping water to the upper reservoir during off-peak hours, when prices are low, and generates electricity by turbining during peak hours, when prices are high. To achieve this, models are used that optimize daily dispatch considering technical hydraulic constraints and market forecasts. Thus, pumping acts as a large-scale battery, essential for the economic viability and integration of renewables.

The profitability of the operation through price arbitrage depends on the difference between off-peak and peak prices (spread). This difference increases as the penetration of renewables in the generation mix grows, especially solar photovoltaic energy, which depresses electricity market prices during the middle of the day but causes an indirect effect of increasing prices at the end of the day due to the need to connect fossil fuel generation technologies at much higher prices.

The spread is expected to continue to increase in the coming years, which will favor the development of energy storage projects. However, the value of the daily price differential will depend on the installed capacity of the various generation sources, associated with the fulfillment of the objectives of the 2030 National Energy and Climate Plan (PNIEC) and the 2050 Long-Term Decarbonization Strategy (ELP). At the current rate of construction of new generation and storage facilities, the PNIEC targets will not be met by 2030, which will affect the price spread and therefore the storage business model.

This article examines the impact that the delay in the implementation of the facilities planned in the PNIEC may have on the business model of reversible pumped storage plants in Spain, using an algorithm for the daily selection of optimal pumping and turbining hours, together with an estimate of hourly electricity market prices until 2050 based on a statistical regression model.

2. Operating model of a stand-alone pumped hydro storage (PHS)

Energy storage systems fall into two categories:

- Hybridized with other electricity generation assets, mainly from renewable sources, or connected to a consumer behind the meter (BtM).
- Stand-alone, connected directly to the electricity grid, which operate by charging and discharging stored energy capacity according to the optimal balance of operating revenues and costs.

When the storage system is directly connected to the electricity grid, the objective is to identify all possible sources of income (revenue stacking) in order to build a viable business case that allows the investment to be recovered within a reasonable period of time while maximizing its economic value. In this case, it is also equally important to minimize the cost of supplying electricity for pumping to the upper reservoir, which will depend on the type of energy purchase contract held by the facility owner.

Price arbitrage in the daily market, i.e., the purchase/sale of electricity on the spot market, forms the basis of the business model for storage directly connected to the electricity grid. Pumped hydro storage systems can also operate in intraday markets to adjust positions or participate in balancing services markets, although these potential revenues are more uncertain in the long term. In short, operational decisions must take into account both the optimization of potential revenues through the technical management of pumping and turbining facilities and the level of stored water reserves.

This article considers a real 165 MW stand-alone pumped-storage project, subject to daily arbitration in the electricity market. The hourly purchase prices of electricity are calculated considering all the components of the final price of electricity through a pass-through contract. The sale prices are obtained by deducting the current 7% tax on electricity production from the hourly spot market price.

An algorithm has been designed that selects the best daily hours for pumping and turbining each day, taking as data the number of desired working hours for the PHS facility. The best pumping hours are those with the cheapest electricity market prices, ordered from lowest to highest, while the best turbine hours are those with the most expensive electricity market prices, ordered from highest to lowest. The daily pumping hours are increased by one hour compared to the daily turbining hours, and the turbining power is considered to be 150 MW to compensate for hydraulic, mechanical, and electrical losses.

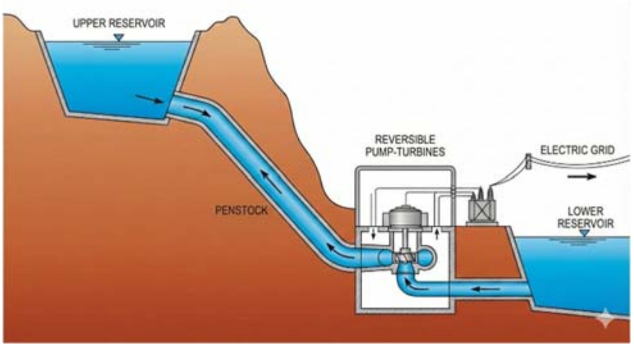


Fig. 1. Components of a pumped hydro storage system.

3. Purchase and sale price model until 2050 according to PNIEC compliance scenarios

The National Integrated Energy and Climate Plan (PNIEC) is the strategic guidance tool that integrates energy and climate policy with a time horizon to 2030, in accordance with national and European regulations [2]. National energy and climate plans, such as the PNIEC in Spain, were first formulated in the EU in 2020, following the requirements of Regulation (EU) 2018/1999, and have since been updated to incorporate the new targets set by the European Green Deal, the Fit for 55 Package legislation, and the RepowerEU plan. In addition, Spain has a Long-Term Decarbonization Strategy until 2050.

Table I shows the installed capacity between 2020 and 2025 in Spain for different renewable technologies, and the targets to be achieved by 2030 according to the PNIEC. Although installed capacity in solar photovoltaic energy has grown significantly in recent years until 50,000 MW, the cannibalization of revenues due to the collapse of wholesale electricity market prices during daylight hours will slow down deployment until 2030, making it very difficult to meet the PNIEC targets (see Fig. 2).

However, as the sun sets and solar production drops, the system faces a steep "ramp-up" in demand that must be met by more expensive Natural Gas Combined Cycle plants. This creates a sharp price spike in the evening, resulting in the distinctive "Duck Curve" profile (Fig. 2).

Table I. – Installed renewable generation capacity in Spain

	WIND (MW)	**SOLAR PV** (MW)	**PHS** (MW)
2020	27,673.20	13,998.18	3331.00
2021	28,675.68	18,918.67	3,331.00
2022	30,151.17	26,085.94	3331.00
2023	30,814.55	34,718.81	3,331.00
2024	32,123.88	44,457.03	3,331.00
2025	33,150.31	49,594.59	3,331.00
PNIEC 2030	**62,044.00**	**76,387.00**	**18,543.00**

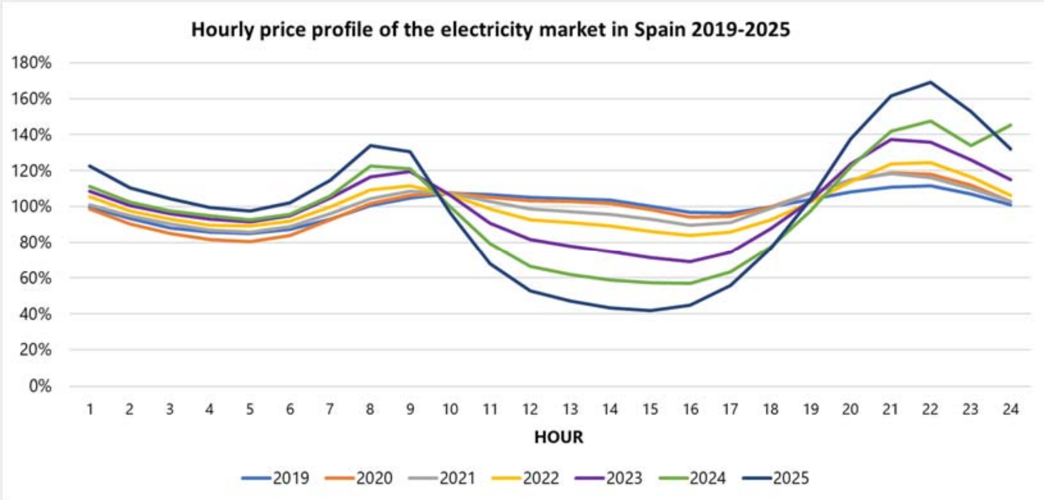


Fig. 2. Annual average hourly price of the wholesale electricity market in Spain from 2019 to 2025.

In the case of wind energy, the pace of construction has slowed for various reasons (increased costs, supply chain problems, delays in permitting), but it is expected to improve in the coming years because, unlike solar energy, wind energy is capturing the average annual market price, making it a more attractive investment in the immediate future.

In short, it is virtually impossible to achieve the PNIEC targets by 2030, but they could be achieved by 2035 or 2040 if the annual construction rates indicated in Table II are maintained.

Table II. – Annual installation rate required to meet PNIEC targets in 2030, 2035, or 2040

	WIND	SOLAR PV	PHS	
2030	5,778.74	5,358.48	3,042.40	MW/year
2035	2,889.37	2,679.24	1,521.20	MW/year
2040	1,926.25	1,786.16	1,014.13	MW/year

Hourly prices on the Spanish electricity market from 2026 to 2050 have been obtained by estimating a statistical regression model, following the methodology in [3].

The model considers a set of 19 explanatory variables, among which those shown in Table III are ultimately significant, with an R^2 of 84.1%. The p-values obtained show that the predictor variables are significant in explaining the dependent variable (p-value < 0.05) and the variance inflation factor values reflect that the variables are not strongly correlated with each other (VIF < 5), indicating a reliable, stable model with good explanatory power.

The model uses data from various sources to estimate the evolution of prices and installed capacity. This analysis utilizes the World Energy Outlook 2025 report [4] as the primary benchmark for crude oil, natural gas, and CO2 pricing. Because the report focuses on specific milestone years, prices for the intermediate periods between 2030 and 2050 are determined via linear interpolation.

The framework for installed power generation capacity is divided into two phases. For the immediate future through 2030, the model adopts the targets established by the National Energy and Climate Plan (PNIEC) [2]. For the subsequent transition toward 2050, the analysis incorporates Mark Z. Jacobson's 100% renewable energy scenario [5], supplemented by the Spanish Energy Storage Strategy, which aims for 30 GW of storage capacity in 2050 [6].

The model employs three sensitivity scenarios based on different implementation speeds. These scenarios test the impact of achieving the PNIEC objectives by three possible milestones: 2030, 2035, or 2040, respectively, based on the trend of recent years. This assumption is used for the regression model to be applied in three different scenarios.

Table III. – Variables of the statistical model for hourly price prediction

Term	Coef	P-Value	VIF
Constant	-356.56	0.000	
BRENT PRICE	1.7210	0.000	2.60
GAS PRICE	0.8534	0.000	4.03
CO2 PRICE	0.9685	0.000	2.33
WIND	-0.001937	0.000	2.05
PV	-0.000479	0.000	4.35
SOLAR	-0.006846	0.000	2.99
HYDRO	0.001293	0.000	3.37
PUMPED-HYDRO	0.019514	0.000	2.15
OTHER RENEWABLES	-0.01175	0.016	1.9
NUCLEAR	0.002971	0.000	2.25
NATURAL GAS	0.003555	0.000	1.51
COGENERATION	0.06968	0.000	2.77
WASTE	0.10901	0.000	2.21
FRANCE EXP.	-0.001332	0.000	1.63
AVAILABLE CAPACITY	0.000900	0.000	1.59

4. Results

Applying the algorithm for selecting the optimal hours for pumping and turbining each day, the pumped hydro storage operation is determined and the plant's daily costs and revenues are obtained. To do this, the hourly purchase and sale prices of the electricity market are used, calculated from the hourly price of the electricity market estimated by the statistical regression model.

The hourly electricity purchase prices have been calculated using a pass-through acquisition formula that incorporates all the components of the electricity price in Spain. Billing is calculated according to the following hourly formula for a 220 kV level connection, excluding network access tariffs:

$$\sum_h \left[\left(PMD_h + RRTT_h + POS_h + PC_i + R\_OMIE + R\_OS \right) \times \left(1+CPe_h \right) + G \right] \times TM \times IE \times MWh_{OMIEh}$$

Where:

- **Daily Market Price (PMD)**: hourly value of the Daily Market Price of electricity for customers supplied by retailers and direct consumers established by the Iberian Energy Market Operator - Polo Español, S.A. (OMIE). Values published by CNMC or legally established body. It is expressed in euro/MWh.
- **Technical Restrictions (RRTT) and System Operator Processes (POS)**: hourly value for clients supplied by retailers and direct consumers of the cost of solving technical restrictions and the system's technical operation processes (imbalance management and ancillary services). Values published by CNMC or legally established body. It is expressed in euro/MWh.
- **Capacity payment (PC)**: value corresponding to the application of the regulatory provision in force for each tariff period. It is expressed in euro/MWh.
- **Remuneration to the Market Operator (R_OMIE)**: value to be considered in application of the current regulatory provision. It is expressed in euro/MWh (0.04096 €/MWh in 2025).
- **Remuneration to the System Operator (R_OS) (Red Eléctrica de España, S.A.U.)**: value to be considered in application of the current regulatory provision. It is expressed in euro/MWh (0.17498 €/MWh in 2025).
- **Loss coefficient (CPe)**: loss coefficient published by Red Eléctrica de España, S.A.U. (REE) per tariff period in accordance with the provisions of current legislation. Values published by the System Operator. It is expressed in %.
- **G:** value of management and supply costs. Where appropriate, amounts for guarantee of origin and financial costs can be included.
- **TM**: municipal tax (1.5%).
- **MWh_{OMIEh}:** hourly energy at the supply point to be billed in an OMIE-indexed mode. It is expressed in MWh.
- **IE:** Electricity tax (5.11269632%)

h: each hour of the billing period.
n: number of hours corresponding to the billing period.
i: tariff period.

Tariff periods are established in accordance with legal regulations and are structured into six time periods throughout the year (Fig. 3).

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
0 - 1 h 1 - 2 h 2 - 3 h 3 - 4 h 4 - 5 h 5 - 6 h 6 - 7 h 7 - 8 h	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6
8 - 9 h	P2	P2	P3	P5	P5	P4	P2	P4	P4	P5	P3	P2
9 - 10 h 10 - 11 h 11 - 12 h 12 - 13 h 13 - 14 h	P1	P1	P2	P4	P4	P3	P1	P3	P3	P4	P2	P1
14 - 15 h 15 - 16 h 16 - 17 h 17 - 18 h	P2	P2	P3	P5	P5	P4	P2	P4	P4	P5	P3	P2
18 - 19 h 19 - 20 h 20 - 21 h 21 - 22 h	P1	P1	P2	P4	P4	P3	P1	P3	P3	P4	P2	P1
22 - 23 h 23 - 24 h	P2	P2	P3	P5	P5	P4	P2	P4	P4	P5	P3	P2

Fig. 3. Tariff periods schedule

Energy tolls and energy charges have not been considered, as stand-alone or hybrid storage is exempt from paying tolls and charges on the purchase of electricity if that energy is subsequently fed into the electricity grid (toll exemption [7], charge exemption [8]).

On the other hand, the hourly selling price of electricity produced by the PHS plant is calculated as the hourly price of the spot electricity market minus the 7% legally established sales tax on electricity production.

Following the proposed methodology, Table IV shows the results obtained from the economic balance of pumped-storage operation from 2026 to 2050 in 12 different cases:

– Applying a strategy of 4, 5, 6, or 7 hours of pumping per day
– Applying estimated hourly prices until 2050, assuming that the PNIEC targets are met in 2030, 2035, or 2040

The values in Table IV show that increasing the number of pumping hours improves the economic performance of pumping, by up to 46% in the case of 7 hours of pumping. On the other hand, delays in meeting the PNIEC targets penalize the economic performance of the facility by 14% if they are delayed until 2035 and by up to 28% if the targets are achieved in 2040 instead of 2030.

Table IV. – Economic balance for different cases

	PNIEC 2030	PNIEC 2035	PNIEC 2040
4 h	€885,875,578	€765,363,758	€645,043,039
5 h	€1,054,960,292	€911,093,729	€767,472,695
6 h	€1,188,456,527	€1,025,218,277	€862,340,411
7 h	€1,293,602,126	€1,114,059,180	€935,003,617

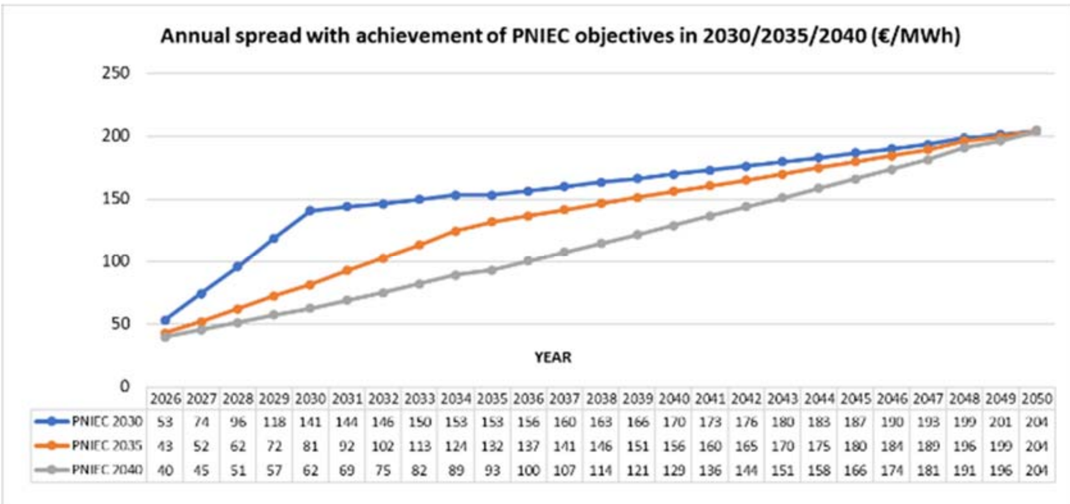
Figure 4 shows the average annual spread between the daily purchase and sale prices of electricity in the PHS system for the three scenarios for meeting the PNIEC targets in 2030, 2035, and 2040, respectively. It can be seen how the spread increases more between 2026 and 2030 in the PNIEC 2030 case, with the economic performance of the PHS improving rapidly in the early years and more slowly thereafter. In the PNIEC 2035 and 2040 cases, the spread improves more slowly as the deployment of renewable generation is being delayed.

The annual economic balance of the plant is shown in Figure 5 for four different plant operating scenarios, with 4, 5, 6, or 7 hours of daily pumping, assuming that the PNIEC targets would be achieved in 2035. As expected, greater use of the PHS facility improves the profitability of the operation, and the difference in performance increases over the years as the daily price spread increases and, therefore, the difference between annual revenues and costs as 2050 approaches.

5. Conclusion

Pumped hydro storage is confirmed as a key technology for the integration of renewable energies through price arbitrage. This study concludes that the economic viability of these projects is intrinsically linked to the fulfillment of the PNIEC objectives. A delay in the implementation of this plan reduces the price spread, which penalizes the economic performance of the facility by 14% by 2035 and up to 28% if postponed to 2040.

On the other hand, operational optimization plays a crucial role; increasing the strategy to 7 hours of daily pumping can increase financial performance by 46%. Given the current difficulty in meeting the 2030 targets, it is necessary to accelerate the pace of renewable infrastructure construction to ensure profitable business cases for storage. Ultimately, meeting strategic decarbonization deadlines is essential to attract the necessary investment in these facilities, which are technologically mature and essential to the stability of the electricity system.



	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047	2048	2049	2050
PNIEC 2030	53	74	96	118	141	144	146	150	153	153	156	160	163	166	170	173	176	180	183	187	190	193	199	201	204
PNIEC 2035	43	52	62	72	81	92	102	113	124	132	137	141	146	151	156	160	165	170	175	180	184	189	196	199	204
PNIEC 2040	40	45	51	57	62	69	75	82	89	93	100	107	114	121	129	136	144	151	158	166	174	181	191	196	204

Fig. 4. Annual average spread of sale and purchase electricity prices for the pumped-hydro storage (€/MWh) in three scenarios

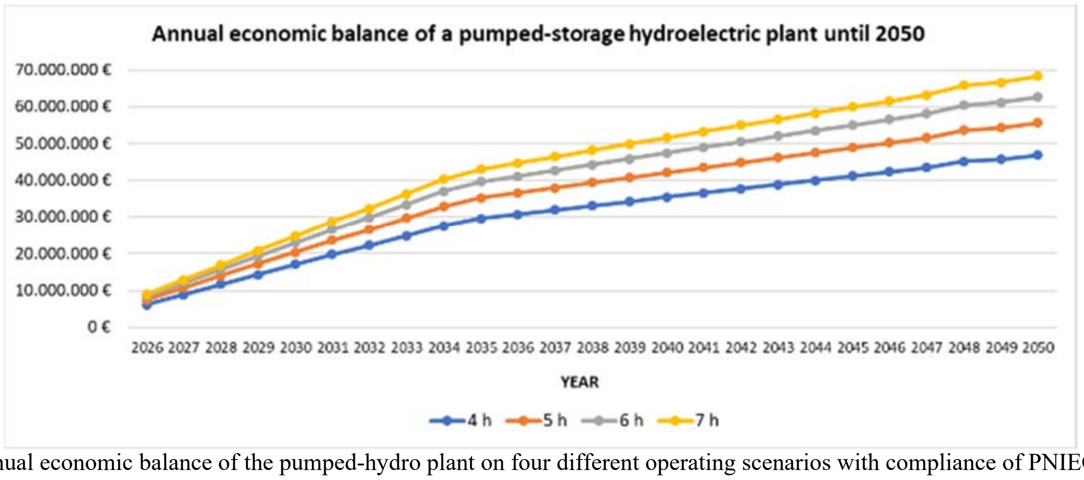


Fig. 5. Annual economic balance of the pumped-hydro plant on four different operating scenarios with compliance of PNIEC targets in 2035

References

[1] Blakers, A., Stocks, M., Lu, B., Cheng, C., A review of pumped hydro energy storage, Prog. Energy 3 (2) (2021) 022003

[2] Ministry for Ecological Transition and Demographic Challenge. PNIEC, Spanish Energy and Climate Plan 2021-2030. Updated on September, 2024. Available online: https://www.miteco.gob.es/es/energia/estrategia-normativa/pniec-23-30.html

[3] N. Naval, L. Tipán-Salazar, and J.M Yusta. Statistical Regression Model for Annual Hourly Price Estimation in the Spanish Electricity Market. 23rd International Conference on Renewable Energies and Power Quality (ICREPQ'25)

[4] International Energy Agency. World Energy Outlook, 2025.

[5 M. Z. Jacobson. The cost of grid stability with 100% clean, renewable energy for all purposes when countries are isolated versus interconnected. Renewable Energy. 2021. vol. 179. pp. 1065–1075. doi: 0.1016/j.renene.2021.07.115.

[6] Ministry for Ecological Transition and Demographic Challenge. Energy Storage Strategy. Available online: https://www.miteco.gob.es/es/prensa/ultimasnoticias/2021/02/el_gobierno_apruebalaestrategiadealmacenamientoenergeticoclavepa.html

[7] Circular 3/2020, of January 15, of the National Commission for Markets and Competition, establishing the methodology for calculating electricity transmission and distribution tolls.

[8] Royal Decree 148/2021, of March 9, establishing the methodology for calculating electricity system charges.