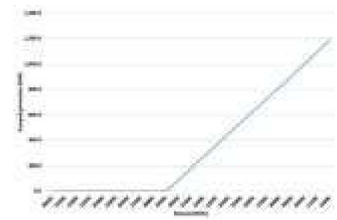

# Review and analysis of energy storage system by hydro-pumping to support a mix of electricity generation with a high percentage of renewable

## Revisión y análisis de los sistemas de almacenamiento de energía mediante hidrobombeo para mantener una combinación de generación de electricidad con un alto porcentaje de energías renovables

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**ABSTRACT**

- In some countries the planning of the electricity generation mix for the future includes a considerable increase in Renewable Energy (RE) to reduce the emissions caused by the use of fossil fuels. This trend can be reinforced if the installed power capacity of nuclear and coal plants is considerably decreased. On the other hand future electricity demand seems to increase due to population growth and greater domestic electrification, especially if transport electrification is tackled. The combination of these factors may result in an ever greater decline in Security of Supply (SoS), mainly due to the stochastic nature of electricity supply and demand behaviour.
To achieve an acceptable level of SoS when introducing renewable energy into the grid it is necessary to increase storage capacity and tackle other measures such as demand management. Many energy storage technologies can befound, and Pumped Hydro Energy Storage (PHES) is recognised as the most mature, though other technologies such as batteries are also available.
In this paper, we first review PHES and its ability to support intermittent generation from energy plants, such as wind and solar, preventing energy losses and storing energy for use at times of high demand; second we analyse the performance of PHES in Spain over five years (2014-2018); our conclusion confirms that adequate SoS cannot be guaranteed with the observed PHES management in the past
- **Keywords:** security of electricity supply, adequacy of generation, pumped hydro storage facilities, uncertainty, Tobit model.

**RESUMEN**

En algunos países, la planificación del mix de generación eléctrica para el futuro incluye un aumento considerable de la energía renovable (RE) para reducir las emisiones causadas por el uso de combustibles fósiles. Esta tendencia puede reforzarse si la capacidad de energía instalada de las centrales nucleares y de carbón disminuye considerablemente. Por otro lado, la demanda futura de electricidad puede aumentar debido al crecimiento de la población y a una mayor electrificación doméstica, especialmente si se aborda la electrificación del transporte. La combinación de estos factores puede resultar en una disminución cada vez mayor de la seguridad del suministro (SdS), principalmente debido a la naturaleza estocástica del comportamiento de la oferta y la demanda de electricidad.

Para lograr un nivel aceptable de SdS al introducir energía renovable en la red, es necesario aumentar la capacidad de almacenamiento y abordar otras medidas, como es la gestión de la demanda. Se pueden citar muchas tecnologías de almacenamiento de energía, pero el almacenamiento de energía hidroeléctrica bombeada (PHES) está reconocido como la más madura, aunque también existen otras tecnologías como son las baterías.

En este artículo, primero revisamos la tecnología PHES y su capacidad para soportar la generación intermitente de plantas de energía renovable, como son la eólica y la solar, previniendo pérdidas de energía en momentos de baja demanda y almacenando energía para usar en momentos de alta demanda; segundo, analizamos el desempeño de las PHES en España durante cinco años (2014-2018); nuestra conclusión confirma que una adecuada seguridad del suministro, SdS, no se puede garantizar con una gestión de PHES como la observada en el pasado.

**Palabras Clave:** seguridad del suministro, adecuación del mix de generación, plantas de bombeo, incertidumbre, modelo Tobit.

### 1. INTRODUCTION

Under the Paris Climate Agreement of 2015, the signatory countries are planning to reduce Greenhouse Gas (GHG) emissions [1]. The 2030 climate and energy framework includes EU-wide targets: key targets are 40% cuts in GHG emissions on 1990 levels, a 32% share for renewable energy and a 32.5% improvement in energy efficiency. The EU also aims to cut GHG by 80-95% by 2050, which means a scenario of 75% of energy from renewable sources [2]. This target only can be achieved with a number of major changes such as new fleets of electric vehicles, improved energy efficiency and the decarbonizing of electricity generation. The world population is increasing [3], and decreasing dependency on oil for vehicles augurs that electricity demand will increase significantly in the future.

Assuming a decline in thermal power plants, generation capacity from renewables needs to be increased. Renewable generation technologies are usually hourly intermittent and their behaviour may cause instability in the future grid, affecting SoS [4]. A list of appropriate generation and system adequacy standards can be found in [5]. To offset this intermittency a major increase in installed storage capacity is required, along with other measures such as agreements for cutting off electric power if necessary at peak demand times and regulatory changes to manage storage systems.

According to [6] PHES was the main technology used for energy storage around the world, with an installed capacity of 153 GW, accounting for 96% of the total estimated storage capacity. The global trend in commissioning is positive, and it actually rose by 3 GW in 2017. Other storage tecnologies include batteries (electro-chemical) at 2.3 GW, flywheels and compressed air (electro-mechanical) at 1.3 GW and concentrating solar thermal power (CSP) at 2.3 GW. PHES is recognised as a mature technology that can be used in conjunction with other renewable generation technologies such as Wind and Solar PV and its long discharge durations can be used to cover major mismatches between electricity supply and demand.

The paper is organised as follows: Section 2 is dedicated to a literature review, Section 3 analyzes the development of renewables, Section 4 reviews the cost of PHES, Section 5 discusses the need for additional storage capacity in Spain in the future, Section 6 analyses the performance of PHES depending on electricity demand and Section 7 concludes.

## 2. LITERATURE REVIEW

Rohit et al. [7] analyse certain storage technologies including pumped hydro energy storage, compressed air, battery, thermal and flywheel energy storage. Corral et al. [8] analyse the rotor capacity of a flywheel for different materials using analytical stress calculation. For a historical review of the development of PHES see [9], and for a technological review see [10]. According to [11], PHES plants represent a fundamental asset for electric utilities and electricity network operators.

Hino and Lejeune [12] highlight some applications of pumped storage, such as (1) load management, with PHES being charged during off-peak hours and discharging during peak hours; (2) a rotating reserve for use in case of generator unit failure; (3) transmission and distribution stabilisation and voltage regulation including phase angle control and frequency regulation; (4) deferral of transmission upgrades; (5) increased distributed generation from storage capacity; (6) storage applications to solve the intermittency issue of renewable energy, facilitating the integration of renewables; and (7) end use applications. [13] also review the applications and benefits of this technology, and find similar advantages.

[12] indicates that there are some barriers to the development of PHES, such as (1) energy losses; (2) high initial capital investment; (3) uncertainty about electricity prices because of its stochastic nature; (4) uncertainty about the quantities that can be supplied because of climate variability and, in the medium and long-term, climate change; (5) uncertainty about regulation; (6) the possibility of overcapacity; and (7) the need for suitable locations.

Pumped storage systems can have overall system efficiencies of around 80-90% [6]; this is better that the 70-80% range reported by Rehman et al. [10], although these authors also consider a case of 87%. There are papers that assess investment based on short-term optimisation; they includes that of [14] who analyses the short-term optimal operation of three small hydro power plants in Slovenia together with a pumped storage plant using a a mixed integer linear program (MILP). [15] present an algorithm for the assessment and optimal operation of hydroelectric and thermal power generators and illustrate it by combining those plants with a pump storage facility.

Revenue from investment clearly depends on electricity prices. In that sense [16] use a daily optimisation model to determine the best hourly operation at a given facility according to the electricity tariff. [17] develops an optimisation of PHES plants using the spot electricity price market, because of its liquidity and transparency.

[18] propose a new pricing model based on demand and supply. This model helps to obtain the optimal operation policy for a PHES. [19] develop a model for an optimal pumped-storage unit related to bidding strategies in a competitive electricity market.

A list of PHES's can be found in Energy Storage Sense 2018 [20]. According to [9] and [21] Europe has the largest PHES capacity in the world, with most facilities commissioned beteween 1950 and 1990.

For the case of Spain, according to [22] Spain made an enormous effort to build hydroelectric plants throughout the 20th century. PHES can be classified as (i) pure or closed-loop, when the electricity is generated only out of water pumped to an upper reservoir; and (ii) mixed or open-loop, when water from rivers contributes to generation.

Gomez et al. [23] present a comparative analysis of the integration of renewable energies in Spain, specifically wind and solar in 2013 and 2015, to define the perspectives based on the EU Reference Scenario for Energy, Transport and GHG Emissions [24]. The projection is for an increase of 2.5 in wind generation and 8.0 in solar. In this case there would be excess generation for periods of strong winds (autumn and winter) and high radiation (summer). [22] foresee an energy storage issue that PHES could solve. [25] affirm that the uncertainty of weather forecasting means that the forecasts for generated energy are very different from the real figures. To improve performance [24] proposes PHES as a solution. According to [26], Solar Thermal power installed in Spain accounted for the 60% of worldwide capacity in 2010: the installation of more than 15 GW was projected under the subsidised regime for renewables, but only 2.4 GW was finally installed.

According to [27], small wind power has not yet been used in Spain to provide renewable energy in a distributed manner associated especially with consumption points on the distribution network. These facilities have the advantage of greater efficiency due to the avoidance of losses in the transmission and distribution networks.

The environmental and economic effects of using renewable energy in residential thermal installations has been analyzed by [28].

## 3. PHES AND DEVELOPMENT OF OTHER RENEWABLES

Figure 1 shows the distribution of the world's installed capacity for renewables: nearly half of the pie corresponds to hydropower, a little less than a quarter to windpower and 18% to solar. The sum of solar and wind is 42%. This percentage represents technologies that can be combined with PHES.

Table 1 shows the number of PHES plants (pure+mixed) and their installed capacity in some countries. Figure 2 shows the installed pure PHES capacity in Spain, broken down by

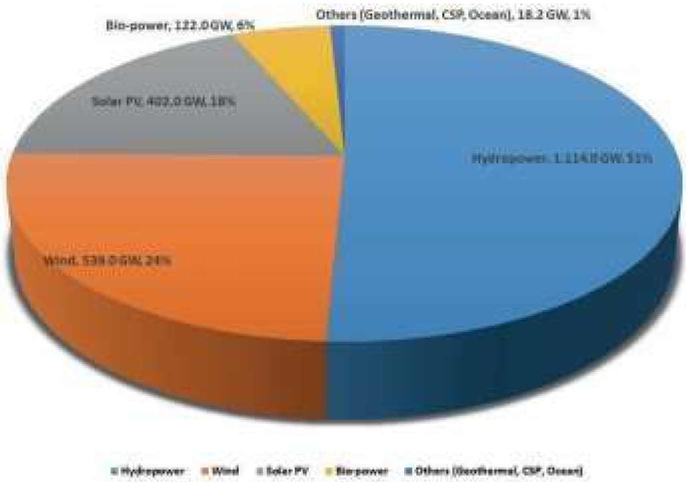


*Figure 1: World Installed Capacity for Renewables, 2017 . Source: Developed by the authors with data from Renewables 2018. Global Status Report [6].*

| Country | Nº of PHES plants | Capacity (MW) |
|---|---|---|
| Japón | 35 | 26.25 |
| China | 30 | 22.267 |
| EEUU | 36 | 20.403 |
| Italy | 18 | 7.071 |
| Spain | 20 | 6.327 |
| Germany | 25 | 6.282 |
| France | 11 | 5.841 |
| India | 11 | 4.962 |
| Austria | 16 | 4.801 |
| UK | 4 | 2.828 |
| Switzerland | 11 | 2.546 |
| Poland | 6 | 1.745 |
| Portugal | 4 | 1.626 |
| Belgium | 2 | 1.307 |
| Czech Republic | 3 | 1.145 |
| Norway | 4 | 967 |
| Ireland | 1 | 292 |
| Luxembourg | 1 | 220 |
| Total | 238 | 116.882 |

*Table 1: World Installed Capacity (pure + mixed)*
*Source: Developed by the authors with data from Renewables 2018 [20].*

Autonomous Regions. The total pure PHES is 3,329 MW, 1,512 of which is in the Valencia autonomous region. In 2017 pure PHES contributed only 0.9% to electric generation in Spain.

However, on the day of maximum demand (January 25) its contribution was 6.7% [29].

## 4. PHES COSTS AND INVESTMENT

The cost of this type of plant depends on geology and topography, on the choice of equipment, on installed capacity and on the country where the work is carried out.

According to [21] the capital cost is €470/kW and €2,170/kW (binary units). They also affirm that these costs depend on the region, site and project specifics.

Others authors such as [30] to [34] analyse PHES costs, in some cases depending on the installed capacity.

In the Iberian Peninsula Enegías de Portugal (EDP) and Iberdrola, major owners of PHES in the region, have recently constructed several plants. Table 2 shows the generating capacity of these plants, the published cost and the operational date.

It is observed that the average construction time is about seven years and the the expected lifetime of this type of storage plant is 80 years [35]. Although the Capex of such plants is high, the Opex is minimal compared to other types of electricity generation plants.

In investment in PHES three business revenue models can be identified: i) cost of service business, in which the cost of the project is paid by the regulator; ii) direct participation, in which participants provide competitive services and in the absence of special agreements the return on investment comes from the energy arbitrage, i.e. energy is consumed in valley peroids and generated in peaks; and iii) behind the meter, which is when the PHES is located close to a wind/solar plant and the end consumer.

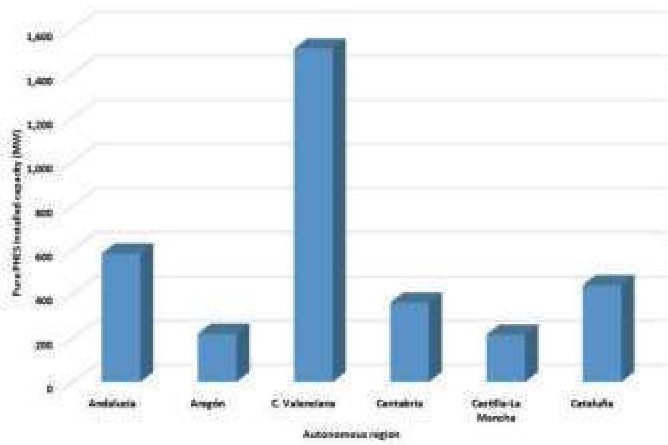


*Figure 2: installed pure PHES capacity in Spain by Autonomous Regions. Source: Developed by the authors with data from REE (Spanish Electricity System) [29].*

| Plant | Alto Tamega | Baixo Sabor | Foz Tua | Fridao/Alvito | Alqueva II | La Muela II |
|---|---|---|---|---|---|---|
| Generating capacity (MW) | 1,200 | 170 | 251 | 392 | 260 | 850 |
| Published cost in €M | 1,700 | 369 | 340 | 510 | 150 | 350 |
| Capex €/kW | 1,416.6 | 2,170.5 | 1,354.5 | 1,301 | 576.9 | 411.7 |
| Years of construction | 9 | 8 | 6 | 9 | 5 | 7 |
| Annual energy production (GWh) | 1,766 | 460 | 667 | 361 | 381 | 800 |
| Operational date | 2018 | 2013 | 2018 | 2016 | 2012 | 2012 |
| Country | Portugal | Portugal | Portugal | Portugal | Portugal | Spain |

*Table 2: Recently constructed plants in the Iberian Peninsula.*
*Source: Data collected by authors from PHES owners*

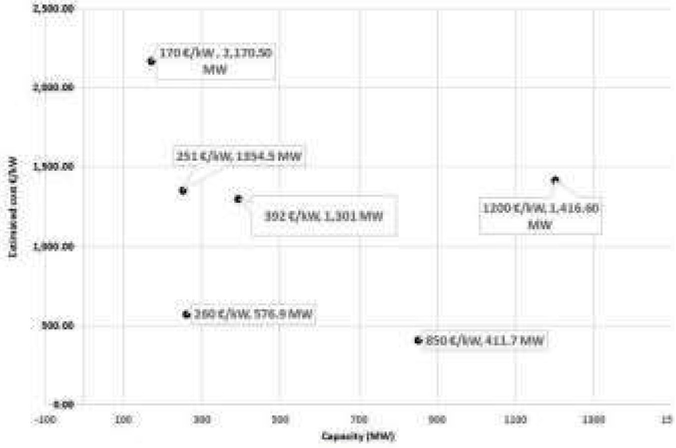


*Figure 3: Capacity and Capex of PHES recently constructed in the Iberian Peninsula. Source: Data collected by the authors from PHES owners.*

Construction usually takes place under monopoly market conditions. This means that the role of the operator is determinant, and that in liberalised markets there are no incentives. In Europe most developments occurred before 1990. The scenario that a private investor sees is a long payback period that may be exposed to risks arising from unstable short term regulations, as can be seen in [36].

## 5. NEED FOR FUTURE ADDITIONAL STORAGE CAPACITY IN SPAIN

### 5.1. THE DRAFT INTEGRATED NATIONAL ENERGY AND CLIMATE PLAN FOR SPAIN

February 2019 saw the publication of the draft Integrated National Energy and Climate Plan (PNIEC) [37]. Table 3 shows the proposed target scenario with installed capacity broken down by technologies and years.

A significant reduction is observed in base load installed capacity (coal and nuclear) and a significant increase in renewable technologies of 74% by 2030, with electricity demand set to grow by 7% in ten years. Pure PHES installed capacity is projected to increase by 3.5 GW and the plan also includes 2.5 GW for battteries. The plan does not anticipate any need for additional gas fired plants for periods of lower renewable generation due to intermittency. This plan is expected to reduce $CO_2$ emissions by 70% from 2017 to 2030.

### 5.2. REMARKS ON RENEWABLE ENERGY DEVELOPMENT

There are three aspects that we believe to be key in the development of renewable energies:

#### A) Impact on SoS

SoS at maximum hourly peak demand for each day can be affected by (1) the intermittency and seasonality of renewable generation; (2) the peak demand level; and (3) the availability of base load energy. For example, if the maximum hourly demand is at night then solar capacity without storage cannot be generated at that time. The three factors listed behave stochastically in matching supply and demand. However, the Spanish expert report [38] only considers a deterministic SoS indicator based on the reserve margin (RM) with some deterministic adjustments. This measure is calculated by dividing the expected available capacity into the maximum hourly demand for the year. There are other measures for SoS; [4] calculate them in the Spanish case study as (1) RM; (2) Expected energy not supplied (EENS); (3) Loss of load expectation (LOLE); (4)

| Technology | Year | | | |
|---|---|---|---|---|
| | 2015 | 2020 | 2025 | 2030 |
| Wind | 22.925 | 27.968 | 40.258 | 50.258 |
| Solar PV | 4.854 | 8.409 | 23.404 | 36.882 |
| Solar Thermal | 2.300 | 2.303 | 4.803 | 7.303 |
| Hydro without PHES | 14.104 | 14.109 | 14.359 | 14.609 |
| Mixed PHES | 2.687 | 2.687 | 2.687 | 2.687 |
| Pure PHES | 3.337 | 3.337 | 4.212 | 6.837 |
| Biogas | 223 | 235 | 235 | 235 |
| Geothermal | 0 | 0 | 15 | 30 |
| Marine energy | 0 | 0 | 25 | 50 |
| Biomass | 677 | 877 | 1.077 | 1.677 |
| Coal | 11.311 | 10.524 | 4.532 | 0 |
| Natural Gas Combined Cycle | 27.531 | 27.146 | 27.146 | 27.146 |
| Coal Cogeneration | 44 | 44 | 0 | 0 |
| Gas Cogeneration | 4.055 | 4.001 | 3.373 | 3.000 |
| Petroleum products Cogeneration | 585 | 570 | 400 | 230 |
| Fuel/Gas | 2.790 | 2.790 | 2.441 | 2.093 |
| Renewable Cogeneration | 535 | 491 | 491 | 491 |
| Waste Cogeneration | 30 | 28 | 28 | 24 |
| Urban Solid Waste Cogeneration | 234 | 234 | 234 | 234 |
| Nuclear | 7.399 | 7.399 | 7.399 | 2.138 |
| Total Installed Capacity (MW) | 105.621 | 113.151 | 137.117 | 156.965 |
| Demand | 281.021 | 288.843 | 305.518 | 337.48 |

*Table 3: Target Scenario in the Integrated National Energy and Climate Plan. Source: Spanish Integrated National Energy and Climate Plan, 2019 draft [37].*

Loss of load probability (LOLP); and (5) 95th percentiles of EENS, LOLE and LOLP. The reserve margin is a deterministic measure, but (2)-(5) are stochastic measures. The European Commision [5] indicates that EENS is the preferred metric.

**B) Regulatory framework for the development of investment in renewables:**

To increase renewable energy capacity the right expected profitability and risk levels are needed for the long-lived investments required. The draft PNIEC includes investment in 3,000 MW/year from renewables but the regulatory framework has not yet been set up. It is claimed that development of renewables will be based on recognition of a fixed price for the electricity generated, competitively set.

**C) Investment in storage and management:**

The PNIEC establishes that there will be regulatory changes for PHES operation, oriented towards integrating renewable technologies, and that they will be managed by the system grid operator (Red Eléctrica Española, REE).

## 6. ANALYSIS OF PHES PERFORMANCE DEPENDING ON ELECTRICITY DEMAND

This section analyzes the performance of pure PHES in mainland Spain from 2014 to 2018, using hourly data. The goal is to determine PHES performance in terms of when power is being generated and when it is not (pumping mode or idle mode). The link between PHES-generated electricity and total electricity demand when power is being generated is then analysed. This reveals whether the performance of PHES technology at the time considered can help to offset peak demand and if so to what extent.

Our data comprise 43,824 hourly observations for pumped electricity generation, pumped consumption and total electricity demand, plus the total installed capacity pumped. It is possible that some PHES units may be generating electricity while others are consuming electricity or in idle mode at the same time, so we transform the original data into hourly net generation or net consumption.

There are 22,159 cases (50.6%) with PHES net generation and 21,665 (49.4%) with net PHES consumption. A histogram of positive PHES generation is shown in Figure 4, revealing that the capacity used for generating electricity usually is well below the installed capacity (2,451 MW in 2014 and 3,329 MW from 2015 onwards). There are 2,910 hours with generation of 50 MWh or less (the first segment in the Figure) and there are very few cases in the higher segments.

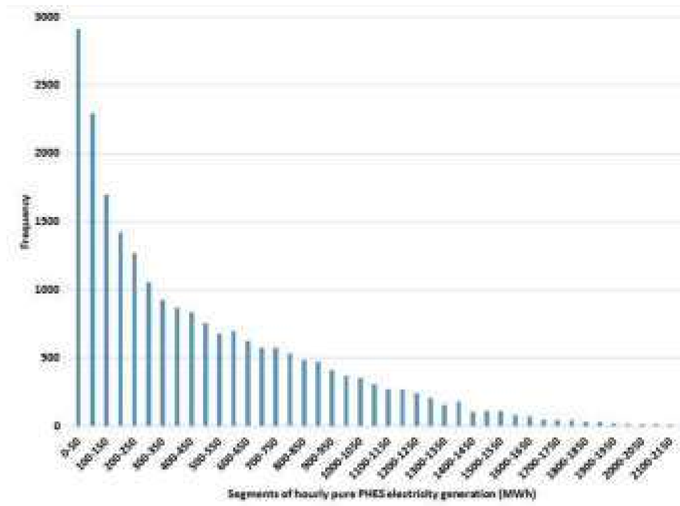


*Figure 4: Frequency of positive net PHES hourly electricity generation (MWh). (MWh). Source: Graph drawn up by the authors based on REE data.*

All this leads us to conclude that the use of installed pure PHES capacity for generating electricity is usually very moderate. It is known that PHES technology usually generates electricity in high demand hours and consumes electricity in low demand hours, benefiting from the price difference between the two periods but assuming losses depending on efficiency. In other words, the decision to generate and how much is to be generated are made by the owner, depending on electricity demand among other things. Our data reveal that the output from pumped storage has a positive correlation of 0.225 with demand. This section focuses exclusively on the impact of hourly demand in PHES generation; other variables such as the water stored in upper PHES reservoirs lie outside the scope of the section.

The data used in analysing PHES generation are left-censored, because there are no negative values. We select the Tobit model to analyse this dataset.

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$$y_i^* = \beta' \mathbf{x}_i + \varepsilon_i$$
$$y_i = 0 \ \text{if} \ y_i^* \leq 0$$
$$y_i = y_i^* \ \text{if} \ y_i^* > 0 \quad (1)$$

| | | Predicted | |
|---|---|---|---|
| | | Generation | No Generation |
| Real | Generation | 16,462 | 5,697 |
| | No generation | 4,397 | 17,268 |

*Table 5: Real and predicted decision on pumped electricity generation*

| | | | | | | |
|---|---|---|---|---|---|---|
| | | | | Number of Obs. | | 43.824 |
| | | | | LR chi2(1) = | | 17.781 |
| | | | | Prob > chi2 = | | 0,0000. |
| Log likelihood= -180.072 | | | | Pseudo R2 = | | 0,047 |
| Net pumped | Coef. | Std. Err. | T | P>\|t\| | [95% Conf | Interval] |
| Transportation Demand | 0,091465 | 0,00075 | 121,72 | 0,000 | 0,089993 | 0,092938 |
| Const | -2.659,39 | 23,1033 | -115,11 | 0,000 | -2704,677 | -2614,111 |
| /Sigma | 517,0932 | 2,603103 | | | 511,9911 | 522,1954 |
| 21.665 | observaciones con censura | | | | | |
| 22.159 | Observaciones sin censura | | | | | |

*Table 4: Tobit Regression Model*

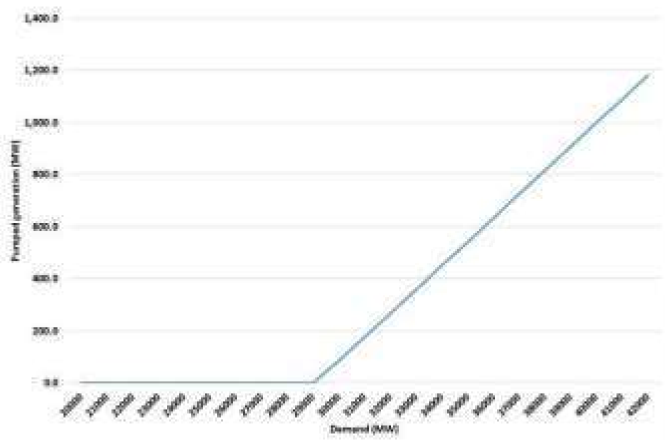


*Figure 5: Effect of demand on expected pumped electricity generation.*

Where $x_i$ is the set of independent variables (in our case electricity demand only), the constant term, $y_i^*$, is the latent variable, which is unobservable, and $\varepsilon_i$ is a normally distributed error tem.

When the latent variable is negative or zero the Tobit model predicts no PHES electricity generation, when it is positive the model indicates the expected PHES positive electricity generation, i.e. there is a level of the latent variable above which net electricity generation by the PHES system is expected. In the model the latent variable is positive above a certain figure for electricity demand, which we determine using the Tobit model.

The Tobit model is shown in Table 4. It enables us to estimate when to generate and estimates how much electricity is expected to be generated (MW).

The likelihood ratio (LR) chi.square with p-value=0.0000 indicates that the Tobit model is significantly better than an empty model. The coefficients are statistically significant. There is a 0.0914 increase in $y_i^*$ (net pumped generation if $y_i^* > 0$). The statistic /sigma with a value of 517.0932 is the estimated standard error of the regression.

Figure 5 shows the value of $y_i$ depending on demand.

Table 5 shows that the Tobit model predicts 33,730 hours correctly, i.e. 77.0%. Other effects and volatility may influence the 23% incorrectly predicted in this model.

The statistic /sigma with a value of 517.0932 is the estimated standard error of the regression.

This Table is calculated using the real electricity demand for the 43,824 hours, obtaining the value of $y_i^*$ in each case. When that value is positive the model predicts electricity generation from PHES, but this only holds in 16,461 cases: there are 4,397 cases in which the Tobit model predicts generation but the real data show none. Similarly, in predicting when there is no generation the model is right in 17,268 cases and wrong in 5,697.

Our results show that PHES electricity generation is positively correlated with demand, but its actual performance does not guarantee a utilization of storage that is compatible with strong development of renewable generation assets.

Note that the draft legislation on climate change and energy transition establishes that there will be changes in the law on the operation of PHES oriented towards integrating renewable technologies managed by the system grid operator.

## CONCLUSIONS

Spain's energy plan is considering a major increase in installed capacity for renewables in the future and a decrease in base load capacity (mainly nuclear and coal-fired power plants). Due to hourly intermittency, this new generation mix can result in mismatches between the electricity supply and demand, affecting SoS. There is therefore a need to increase energy storage and make other improvements on the demand management side such as electricity cut- off agreements.

Storage capacity can be increased by investing in new PHES and/or other storage technologies such as batteries, flywheels, compressed air and concentrating solar thermal power (CSP).

PHES is a recognised, mature storage technology that accounts for 96% of the total global storage capacity [6]. It can help in the integration of renewables, generating electricity in peak demand hours and storing it in low demand hours and thus preventing the loss of excess energy from renewables and reaching a suitable level of SoS. In the case of PHES, these investments have high capital costs and long useful lifetimes, so they are exposed to substantial risks.

In this paper we first review the academic literature on PHES plants. Then we analyse the actual performance of pure PHES plants. We conclude that current PHES performance in a scenario with substantial development of renewable energies does not guarantee sufficient electricity generation from storage because of its moderate contribution in peak hours. Its use in those hours is well below the total installed capacity.

The Integrated National Energy and Climate Plan (2019) [7] envisages an increase in pure PHES installed capacity from the current 3,337 MW to 6,837 MW by 2030. However, with current PHES performance its contibution to SoS will probably be moderate.

It is also necessary for investors to consider all the expected benefits and risks in further increases in PHES installed capacity. Investments in assets for renewable PHES capacity therefore need a regulatory framework for development to ensure that this technology is able to generate enough electricity at peak times.

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