ESCUELA TÉCNICA SUPERIOR DE INGENIERÍA (ICAI)

GRADO EN INGENIERÍA ELECTROMECÁNICA

ANALYZING THE FUTURE VALUE OF ENERGY STORAGE IN ELECTRIC POWER SYSTEMS

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Madrid
Mayo 2015

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Madrid
Mayo 2015

ANÁLISIS DEL VALOR FUTURO DEL ALMACENAMIENTO DE ENERGÍA EN LOS SISTEMAS ELÉCTRICOS

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RESUMEN DEL PROYECTO

INTRODUCCIÓN

En los últimos años, la creciente penetración de energías renovables está transformando la operación de los sistemas eléctricos. Estas nuevas fuentes de energía, en especial eólica, solar PV y en menor medida minihidráulica (denominadas *Variable Energy Resources*, VER), se caracterizan por tener un régimen de producción intermitente, a menudo difícil de predecir y escasamente gestionable.

Estas características dificultan la integración de las VER en el sistema eléctrico. En el corto plazo, es necesario responder a la variabilidad de este tipo de recursos incrementando el requisito de reservas. Entre el corto y medio plazo las VER tienden a desplazar generadores con altos costes variables, disminuyendo así el precio de la electricidad en ciertos periodos. Sin embargo, dado que las fuentes de energía renovable están disponibles sólo de manera intermitente, los grupos térmicos siguen siendo necesarios como respaldo del sistema. Es por ello que, en un sistema con gran penetración de renovables, los grupos térmicos están obligados a hacer más ciclos de arranque-parada incrementado sus costes de operación. Esto se traspasa a las ofertas en el mercado eléctrico aumentando el precio de la electricidad. Por último, en el largo plazo, el mix de generación se debe readaptar para poder cumplir estos nuevos requerimientos de flexibilidad (como ciclos combinados).

En este nuevo contexto, los sistemas de almacenamiento de energía (ESS) reaparecen como una alternativa que puede tener un papel clave en la futura operación y planificación de los sistemas eléctricos. Como su propio nombre indica, los ESS son tecnologías capaces de almacenar la producción de electricidad para usarla cuando es más necesario. Además, estos sistemas se caracterizan por su flexibilidad (rampas y arranques rápidos). En el muy corto plazo, los ESS puedan proveer reservas rápidas de gran valor para ampliar los recursos a disposición de los operadores de los sistemas. Entre el corto y el medio plazo, los ESS permiten estabilizar los precios de mercado mediante el aprovechamiento de las diferencias de precio entre las horas de mayor y menor

requerimiento térmico. Como consecuencia, en el largo plazo, los ESS pueden convertirse en una inversión rentable capaz de respaldar una mayor penetración de tecnología renovable, reduciendo las necesidades de capacidad térmica.

El objetivo de este proyecto es analizar el valor que los ESS pueden aportar a los sistemas eléctricos tanto actualmente como en el futuro. Para ello es necesario el empleo de modelos sofisticados capaces de representar aquellas características de la operación del sistema en el corto plazo que son más relevantes para la interacción entre VER y ESS; así como la readaptación que sufre el mix de generación en el largo plazo.

Este análisis se realiza prestando especial atención a nuevos requisitos de modelado que una penetración significativa de estas tecnologías plantea. En esa línea, se realiza una evaluación crítica de una herramienta comercial de modelado (PLEXOS), detectando las potenciales limitaciones que pudieran presentarse, proponiendo mejoras y analizando el impacto que tienen las hipótesis de modelado actuales.

METODOLOGÍA

El estudio se construye sobre la base de un caso ejemplo real. Se toma como referencia un pequeño sistema eléctrico aislado (la isla de Tenerife) en el que las VER tienen un gran impacto. Inicialmente el modelo se calibra comparando los resultados obtenidos a partir de los datos recogidos para caracterizar el sistema en el año 2014[1] (parámetros técnicos, perfil de demanda, costes de operación…) con el despacho real publicado por Red Eléctrica de España (REE).

La operación del sistema eléctrico se simula hasta 2024 usando previsiones para el precio de combustibles, aumento de la demanda y penetración de renovables. Se comparan entonces dos escenarios; uno con un sistema hidráulico de bombeo (PHS) instalado y otro sin él. Este modelo permite evaluar el impacto del sistema de almacenamiento en el coste total del suministro en el sistema, evaluando al tiempo las necesidades de vertido de renovables y las emisiones de CO2.

Para evaluar el impacto de los ESS en el largo plazo se emplea un modelo de expansión de capacidad tipo “*Greenfield*”. Este modelo diseña el mix de generación óptimo para la isla (partiendo de cero, sin considerar la capacidad actualmente instalada) en el horizonte temporal analizado y para ocho escenarios distintos de penetración eólica. Esto último permite cuantificar el potencial de los ESS para reducir las necesidades de inversión en capacidad térmica aislando el efecto de la penetración renovable.

Al mismo tiempo, los resultados obtenidos sirven como base para analizar si PLEXOS es una herramienta capaz de representar correctamente los aspectos más relevantes de un sistema eléctrico con gran penetración de renovables.

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[1] Los datos se obtuvieron principalmente de la Comisión Nacional de Energía (CNE) y del Sistema Eléctrico Irlandés (Irish SEM-O), cuyas unidades generadoras son similares a las existentes en Tenerife

RESULTADOS

En primer lugar se compara la operación de corto plazo de un escenario con bombeo con uno sin bombeo, usando el sistema eléctrico de Tenerife. Para ello, se simula la operación del sistema desde 2015 hasta 2023 con resolución horaria. Este análisis muestra que instalar un bombeo tiene varios impactos relevantes en el sistema eléctrico estudiado. El bombeo desplaza a las unidades térmicas más caras de dos maneras: produciendo energía durante períodos de gran demanda (“*peak-shaving*”) y evitando el arranque de grupos térmicos mediante el suministro de reservas. Además, el bombeo almacena el exceso de generación de las energías renovables dando lugar a un mayor aprovechamiento de las mismas y al tiempo permite ahorrar costes evitando que algunas unidades térmicas deban parar durante la noche. El resultado global es que se reducen los costes de operación del sistema así como las emisiones de CO2. A continuación se ilustran estos impactos mostrando el despacho de las unidades de generación del sistema con (Figura 1) y sin bombeo (Figura 2).

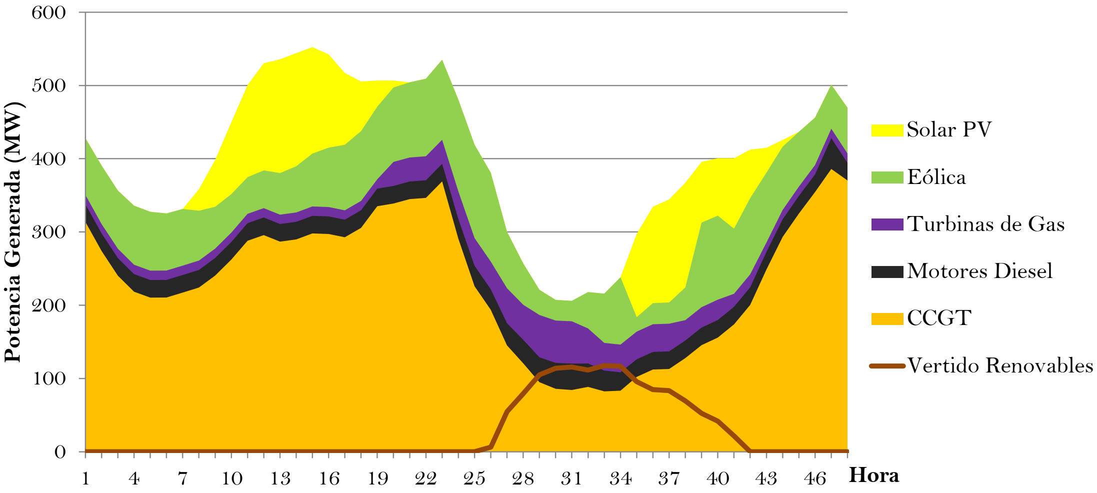

Figura 1 Despacho de dos días en un sistema sin bombeo

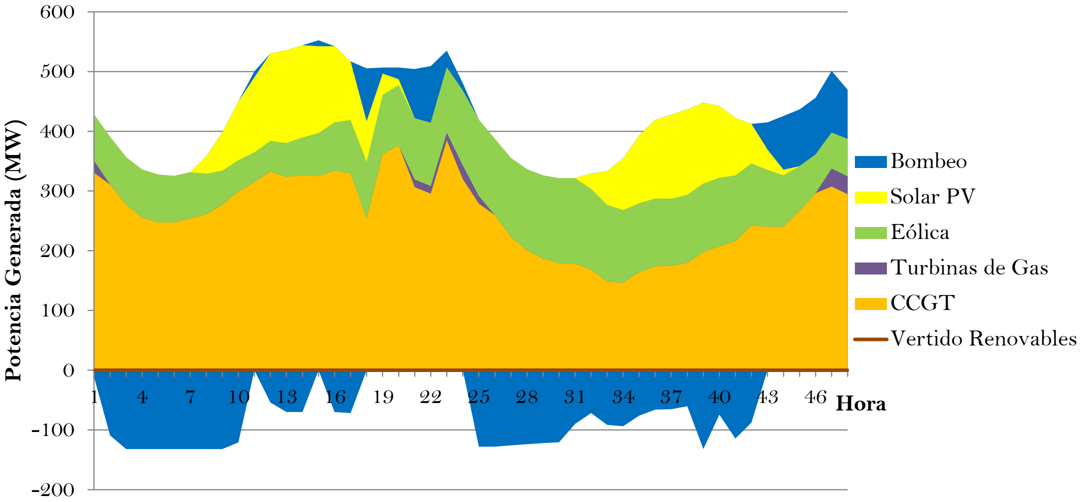

Figura 2 Despacho de dos días en un sistema con bombeo

En estas figuras se ve claramente que una central de bombeo reduce la generación térmica (especialmente de turbinas de gas y motores diésel) y reduce el vertido de renovables. Se observa también como el bombeo reduce las necesidades de despachar turbinas de gas para contar con suficiente reserva. Además, esto provoca una reducción de costes de operación del sistema (debido a los menores costes de combustibles y CO2) como se puede ver en la Figura 3.

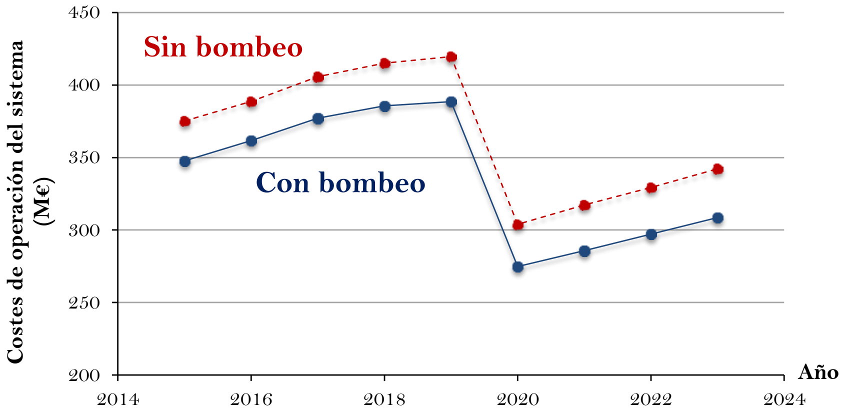

Figura 3 Costes anuales de operación del sistema en ambos escenarios

Los costes del sistema tienden a incrementarse año tras año ya que, aunque la penetración de renovables aumenta continuamente, se tomó como hipótesis de entrada que también lo hacen los precios de los combustibles y la demanda. En 2020, en cambio, hay una caída en los costes del sistema. Esto se debe a la instalación (según las previsiones empleadas) de una planta regasificadora en la isla que permite el uso de gas natural en vez de gasoil en las centrales de ciclo combinado.

Por otro lado, se concluye que la rentabilidad para el sistema de la instalación de un bombeo depende de la tasa de retorno considerada. El resultado del análisis realizado es que para el caso ejemplo la instalación de un bombeo sería rentable sólo para una tasa de retorno moderadamente baja.

Sin embargo, un sistema hidráulico de bombeo puede producir ahorros adicionales si se considera la adaptación del sistema en el largo plazo (inversiones). Para evaluar el bombeo en este horizonte temporal se calcula mix de generación óptimo en 2020 teniendo en cuenta varios escenarios de penetración eólica (Desde 0MW a 500MW).

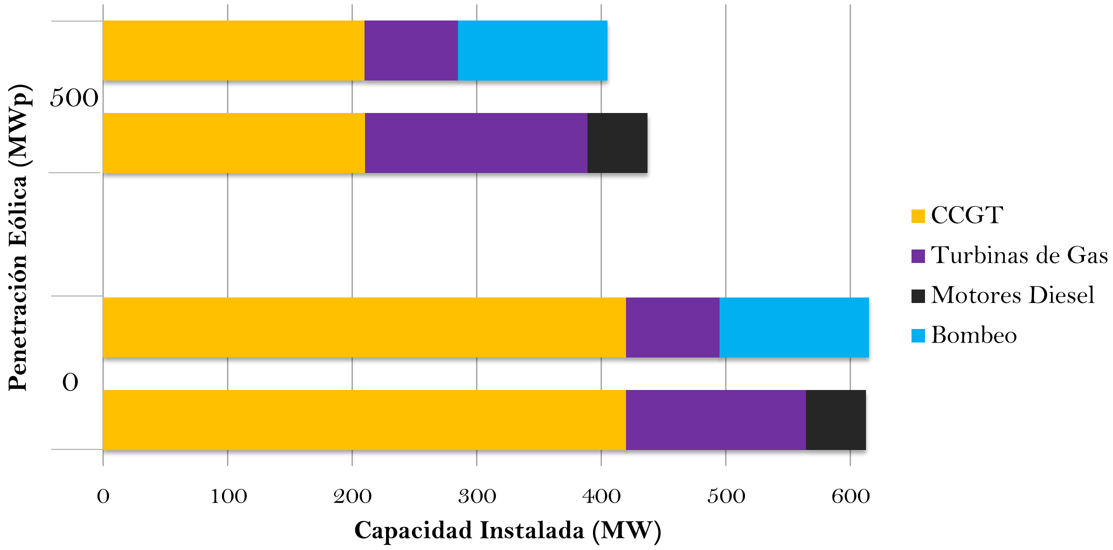

Figura 4 Mix de generación óptimo para dos escenarios de viento

La Figura 4 muestra que un bombeo evita la instalación tanto de turbinas de gas como de motores diésel, por lo que hay que considerar además del ahorro en costes de operación, el ahorro que pueda suponer en los costes de inversión necesarios en el sistema. Además, cuando la penetración eólica es alta, la capacidad de generación necesaria en el sistema es menor si se instala el sistema de bombeo debido a su capacidad de integrar la generación renovable. La Figura 5 muestra los costes totales del sistema (inversión+operación) para los distintos escenarios de viento analizados. Es posible observar que el sistema con bombeo es económico para una capacidad de viento instalada superior a 300MWp.

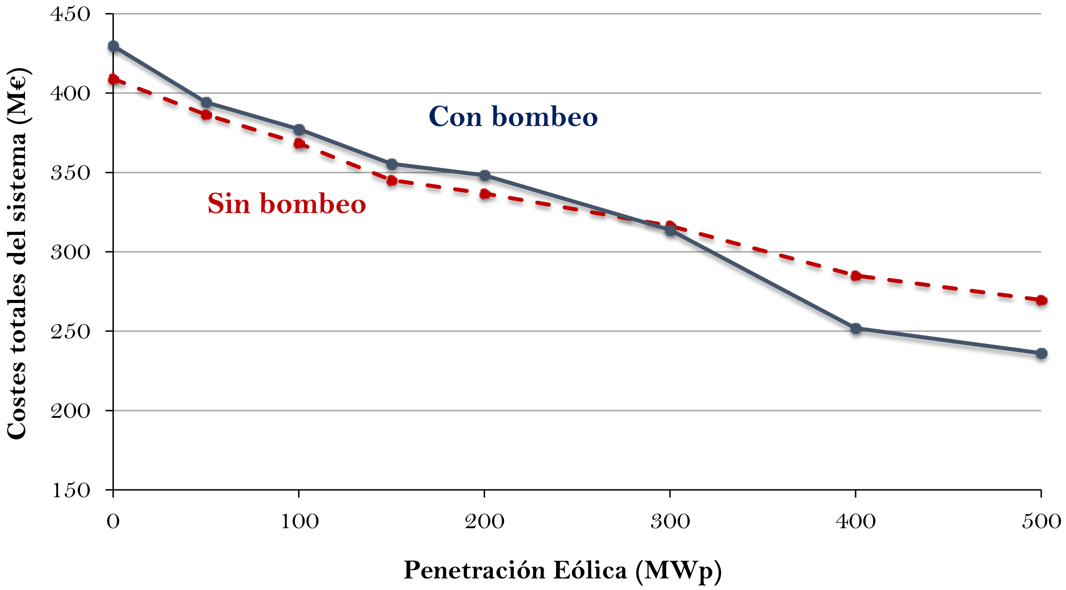

Figura 5 Costes totales del sistema para diferentes escenarios de penetración eólica

El software de modelado empleado fue evaluado prestando atención a los requisitos de modelado de sistemas con VER y ESS. En general, PLEXOS es una buena herramienta para resolver problemas de despacho hidrotérmico tradicionales. PLEXOS es también capaz de resolver grandes problemas de expansión de capacidad aunque con simplificaciones un tanto agresivas. Sin embargo, se encontraron algunas limitaciones para representar pequeños recursos de almacenamiento de energía, como puede ser la unidad de bombeo analizada o sistemas de baterías. Estos sistemas requieren una representación más detallada de la operación en el muy corto plazo, especialmente cuando se está considerando la provisión de reservas.

CONCLUSIONES

En este proyecto se realiza un análisis completo del valor de los sistemas de almacenamiento de energía en sistemas eléctricos. Se pone especial énfasis en la interacción entre fuentes de energía renovable (RES) y sistemas de almacenamiento de energía (ESS). La metodología desarrollada para este análisis está basada en simulaciones con modelos de corto y largo plazo que fueron desarrollados con un software comercial (PLEXOS). Estos modelos se han aplicado a un sistema real (Tenerife). Además, se han examinado las limitaciones que esta herramienta comercial de modelado puede presentar cuando se pretende considerar con un cierto nivel de detalle las particularidades de sistemas de almacenamiento de energía y fuentes de energía renovable.

Los principales impactos de un ESS en la operación del sistema eléctrico son: una mayor eficiencia en la operación de los grupos térmicos y una reducción del vertido de renovables. En consecuencia, un ESS reduce los costes de operación del sistema y las emisiones de CO2. En el caso ejemplo analizado, se evaluó la inversión en un sistema de bombeo y se concluyó que el ahorro en costes producido no justificaba con claridad su construcción. Sin embargo, pueden considerarse ahorros adicionales ya que los ESS también pueden reducir la necesidad de nuevas inversiones en generación térmica. Se ha mostrado que el valor de los ESS incrementa con la penetración de renovables y en el caso ejemplo la inversión en una central de bombeo sí resulta rentable a partir de ciertos niveles de penetración eólica.

La herramienta de modelado comercial evaluada (PLEXOS) fue capaz de representar lo suficientemente bien un sistema hidrotérmico pero se encontraron ciertas limitaciones al representar pequeños ESS; especialmente en los efectos de suministrar servicios de reservas con estos sistemas.

ANALYZING THE FUTURE VALUE OF ENERGY STORAGE IN ELECTRIC POWER SYSTEMS

INTRODUCTION

The operation of power systems is being transformed by the massive penetration of Renewable Energy Sources (RES). These new sources of energy, especially wind, solar and in a lesser extent run-of-the-river hydro (hereafter denoted as Variable Energy Resources, VER) are characterized by partial unpredictability and intermittency.

These characteristics make it challenging to integrate VER in electric power systems. In the short term, operational reserves requirements have to be increased to cope with the variability of VER production. In the short to medium term, VER tend to displace the highest variable cost units, lowering energy prices. However, because the natural source of energy of VER is only intermittently available, thermal units are still necessary as back-up; under large VER penetration levels, thermal units are forced to increase their cycling regime consequently rising their operational costs, which are transferred to energy offers and ultimately increase market prices. In the long term, the generation mix will readapt to meet these new requirements, giving and increasing importance to flexible generation technologies (such as CCGTs).

In this new context just described, Energy Storage Systems (ESS) could play an important role for the future operation and planning of electric power systems. As it name implies, ESS is a technology capable of storing energy in order to use it when most necessary and, at the same time, it features good ramping and fast start-up capabilities. In the short term, ESS can provide operational reserves and other ancillary services. In the short to medium term, ESS can lead to a more uniform spot price by selling and buying energy when large price differences occur. Consequently, in the long term ESS can become a profitable investment that can also provide back-up for RES, reducing thermal capacity needs.

The goal of this dissertation is to analyze the value of ESS in current and future power systems. This objective calls for sophisticated modeling tools that should be able to represent the short-term characteristics of a power system that become most relevant when VER and ESS come into play, as well as the long term re-adaptation of the generation mix. This dissertation strives to perform the above-mentioned analysis while focusing on new modeling requirements. Furthermore, a critical assessment of a commercial modeling tool (PLEXOS) will be made to propose improvements and gain insights on the impact of current modeling assumptions.

METHODOLOGY

The study is made on the base of a real case example. A small isolated power system (Tenerife Island) in which VER have a large impact is used as a reference. Initially, the model is calibrated by comparing the results obtained from the data gathered to represent the system in year 2014[1] (e.g. technical parameters, load profile, operational costs) with the real dispatch published by Red Eléctrica de España.

The operation of the power system is simulated up to 2024 considering consensus estimates for the evolution of fuel prices, demand growth and RES penetration. Two different scenarios are compared; one with a Pumped Hydro Storage (PHS) unit and another one without it. This model allows evaluating the impact of an ESS in the operational costs of the system, RES curtailment and CO2 emissions.

To assess the long-term impact of ESS, a Greenfield-type capacity expansion model is used. This model optimally designs the generation mix of the island for the time horizon analyzed for eight different wind penetration scenarios. This allows quantifying the potential of ESS to reduce the need for investments in thermal generation.

At the same time, the results obtained provide a basis to analyze the suitability of PLEXOS for modeling all relevant aspects of power systems with high VER penetration.

RESULTS

First, the short-term operation of Tenerife's power system with and without a PHS is compared. To do so, our model simulates with hourly resolution the operation of the power system from 2015 to 2023. This analysis shows that installing a PHS has various relevant impacts on the power system studied. The PHS replaces costly thermal generation in two different ways; it produces energy during the peak load periods (peak-shaving), and also provides reserves avoiding the start-up of thermal units. The PHS unit also stores excess generation from RES, which allows to better integrate a high share of renewable capacity. At the same time, all these effects cause a reduction in CO2 emissions. Figure 1 and Figure 2 illustrate these impacts by showing the dispatch of each unit in the system with and without a PHS in Tenerife.

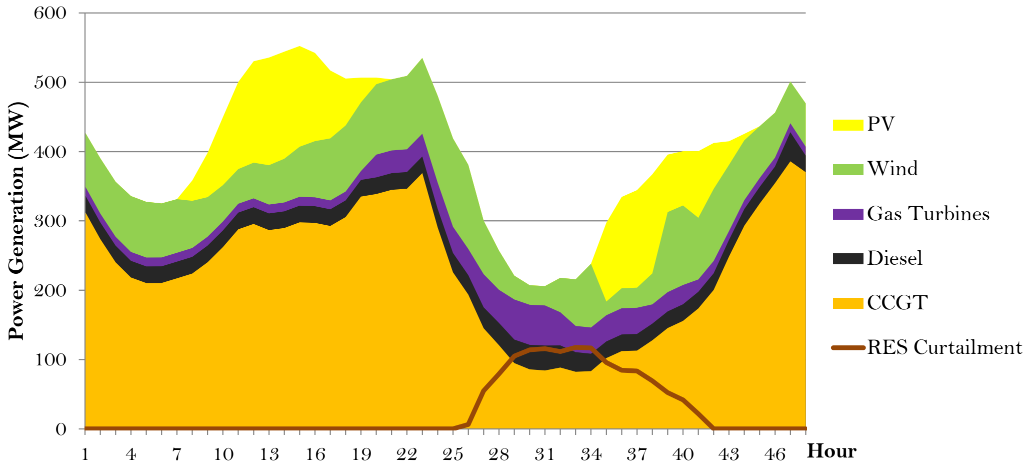

Figure 1 Two days dispatch without a PHS

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[1] This data was mainly obtained from the Comisión Nacional de Energía (CNE) and from the Irish Single Electricity Market (Irish SEM-O), which generation fleet is similar to that existing in Tenerife

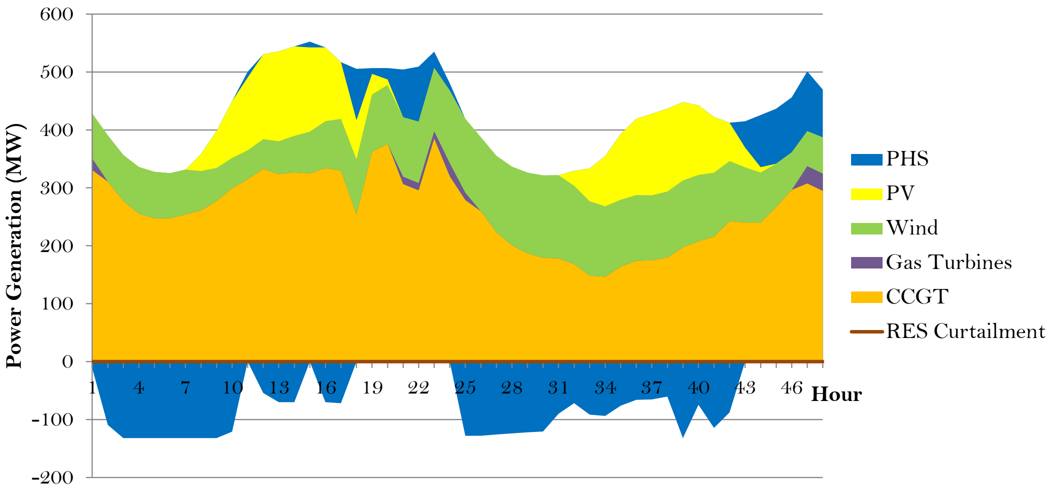

Figure 2 Two days dispatch with a PHS

In these figures it is clearly shown that the PHS reduces thermal generation (especially diesel generators and gas turbines) and decreases RES curtailment. Furthermore, all these impacts reduce system operational costs (fuel and CO2 emissions costs) as shown in Figure 3.

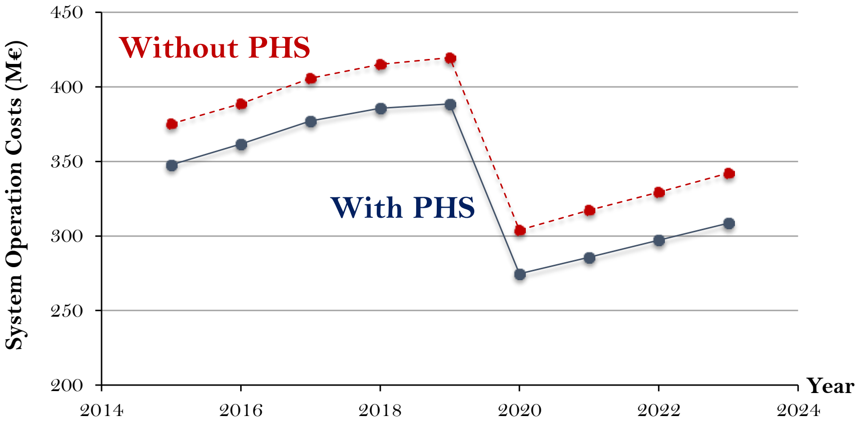

Figure 3 Annual system operation costs in two different scenarios

System's costs generally increase because, although renewables are continuously penetrating, demand and fuel prices are continuously increasing. In 2020 there is a drop in system operation costs because a regasification plant is expected to open in Tenerife and thus CCGT and OCGT plants start to operate with natural gas, a fuel which is cheaper than gasoil and has less emissions costs (less pollutant).

On the other hand it was concluded that the profitability of the PHS depends on the the rate of return considered. The result for this case example is that the installation of a PHS in Tenerife will be cost effective only for a moderately low return rate.

However, the introduction of a PHS unit can produce additional savings if the long term adaptation (investments) of the system is considered. To assess the value of PHS in this time horizon, the optimal generation mix is calculated for year 2020 considering various wind penetration scenarios (From 0MW to 500MW).

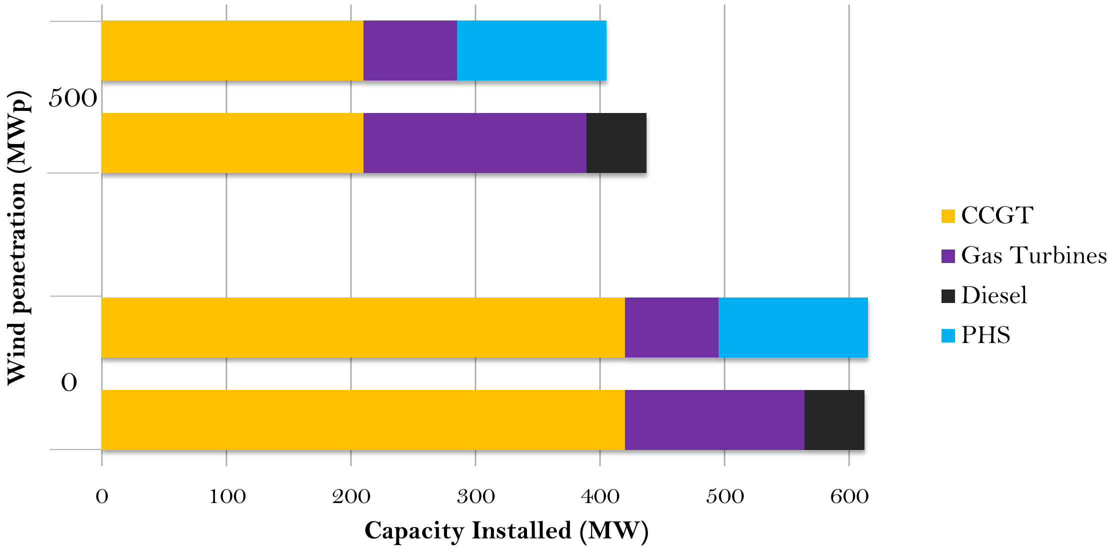

Figure 4 Optimal generation mix in two different wind scenarios

This figure shows that a PHS avoids installing gas turbines and diesel engines. Therefore operation costs savings as well as possible investment costs savings must be considered. Furthermore, when the scenario analyzed has a high wind penetration the total capacity installed is lower because of the PHS capabilities to integrate renewables. Figure 5 shows total system costs (investment + operation) for different scenarios of wind penetration. The system with a PHS unit is more economical for a wind penetration above 300 MWp.

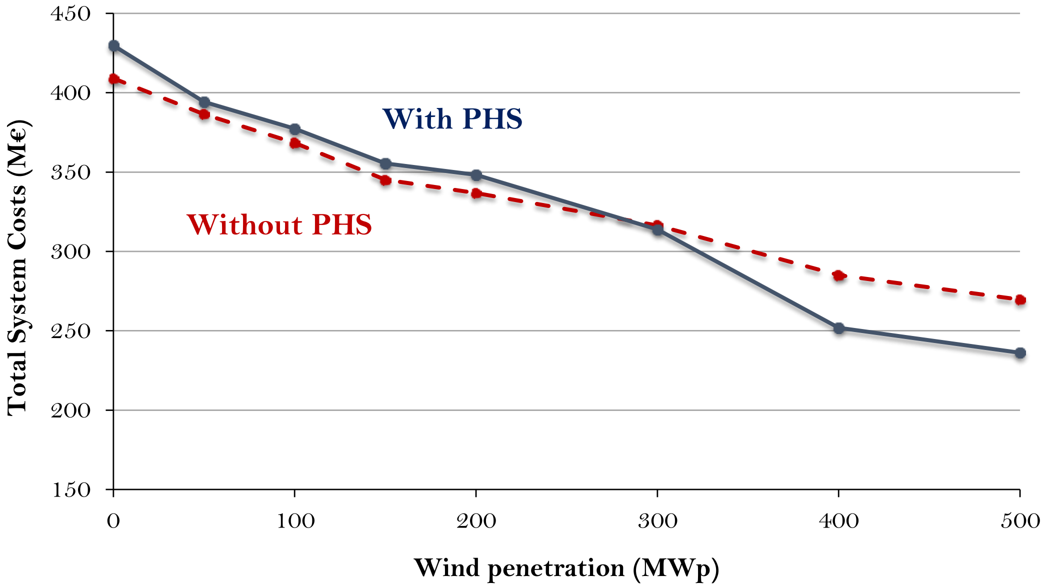

Figure 5 Total system's cost in different wind penetration scenarios

The modeling software used was evaluated focusing on the modeling requirements of systems with VER and ESS. In general, PLEXOS was found to be a good tool for the traditional hydro-thermal unit commitment problem. PLEXOS is also capable of solving large capacity expansion problems although some aggressive simplifications were necessary. Some limitations were identified in the representation of small energy storage systems, such as the PHS unit evaluated, or battery storage systems. These systems require a more detailed representation of the short-term, especially when the provision of reserves is considered.

CONCLUSIONS

This project has carried out a complete analysis on the value of energy storage in electric power systems. The emphasis of this study is on the interaction between renewable energy sources (RES) and energy storage systems (ESS). The methodology developed for the analysis is based on short-term and long-term simulation models that were developed using a commercial power systems modeling tool (PLEXOS). These models have been applied to a real-size case example in a small isolated power system (Tenerife Island). Additionally, the limitations of the modeling tools employed have been examined in order to identify new requirements in power systems models dealing with storage systems and renewable energy sources.

The main impacts produced in the operation of the power system by an ESS are: a more efficient operation of the thermal fleet, and a reduction of RES curtailment. Therefore, an ESS reduces system operational costs and a CO2 emissions. In the case-example, an investment in a pumped hydro storage unit was evaluated, concluding that operational costs savings were not sufficient to clearly make the investment cost-effective. However, ESS can also reduce the need for investments in thermal capacity; it was shown that the value of ESS increases with the penetration of RES, and the investment analyzed was found to be cost-effective under a large enough penetration of wind energy in Tenerife.

The commercial modeling tool evaluated (PLEXOS) was capable of a sufficiently good representation of hydro-thermal systems, although some limitations were identified when modeling small ESS, especially to represent the effects of operational reserve provision in the very short-term.

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CHAPTER 1.
INTRODUCTION AND OBJECTIVES

1.1 Introduction and motivation

1.1.1 The role of energy storage systems in a context of high renewable energy penetration

The operation of power systems is being transformed by the massive penetration of Renewable Energy Sources (RES), most of them having zero or very low variable costs and producing zero pollutant emissions. Among these technologies, wind and solar generation and in a lesser extent small run-of-the-river hydro (hereafter denoted as Variable Energy Resources, VER) are characterized by partial unpredictability and intermittency.

These characteristics (intermittency and unpredictability) make it challenging to integrate VER in electric power systems. In the short term, operational reserves (entailing flexible generation resources with fast start and ramping capabilities) requirements need to be increased to accommodate VER production. In the short to medium term (e.g. in the day-ahead market), VER tend to displace the most expensive variable cost units (such as fossil-fuel electricity production), lowering energy prices. However, because their natural source of energy (e.g. wind or solar irradiance) is only intermittently available, conventional thermal generation is still necessary as back-up; under large VER penetration levels, thermal units are forced to increase their cycling regime (implying more frequent start-up and ramping) consequently rising their operational costs, which are transferred to energy offers and, ultimately, increase market prices (Rodilla et al., 2014). The result, in those power systems with low storage capability (mostly thermal systems without hydro reservoirs) is higher spot price volatility. In the long term, the generation mix will re-adapt to meet these new requirements, giving an increasing importance to flexible generation technologies such as CCGT (Combined Cycle Gas Turbines), which provide predictable and adaptable operation at a better efficiency than other thermal technologies. Figure 1 shows the generation mix in a system with large VER penetration, the variability of VER production (green) requires very flexible operation from CCGTs (orange).

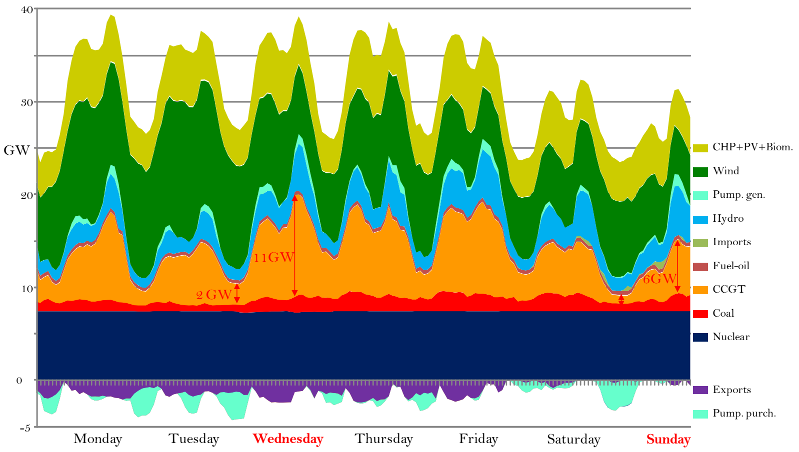

Figure 1 Generation mix representing the interaction between VER and CCGT

In this new context just described, Energy Storage Systems (ESS) could play an important role for the future operation and planning of electric power systems. As it name implies, ESS is a technology capable of storing energy in order to use it when most necessary and, at the same time, it features good ramping and fast start-up characteristics. ESS can be used to smooth the production of VER in various timescales.

In the short term, ESS can provide operational reserves and other ancillary services required for maintaining the stability of the system. In general, resources providing ancillary services are dispatched by the System Operator (SO) to balance active and reactive power in the grid and to solve congestions. Some resources are required to respond to imbalances immediately (primary reserves) or in short periods of time (secondary reserves) and ESS could be a suitable technology to provide these services efficiently. In the short to medium term, ESS can buy and store energy when the price is lower (during off-peak hours or when excessive renewable energy is being injected to the grid), to later sell it at a higher price (during high demand periods or low VER production intervals) resulting in a more uniform spot price. Consequently, ESS can have great market value in a context of large VER penetration, turning in the long term, into a potential investment that could considerably reduce capacity needs.

The goal of this dissertation is to analyze the value of ESS in current and future power systems. This objective calls for sophisticated modeling tools that should be able to represent the short term characteristics of a power system that become most relevant when VER and ESS come into play (VER intermittency, thermal units cycling, reserve requirements…) as well as the long term re-adaptation of the generation mix. Traditional modeling tools fall short for some of these purposes since simplifications considered valid until now, may no longer be appropriate. Consequently, this dissertation strives to perform the above-mentioned analysis while focusing on new modeling requirements; a critical assessment of a commercial modeling tool will be made to propose improvements and gain insights on the impact of current modeling assumptions.

In the next section, a review of the most relevant Energy Storage Systems to date is made.

1.1.2 Energy Storage Systems classification

Pumped Hydro Storage (PHS)

Pumped Hydro Storage is the most mature technology used to store electricity in a power system. It is based on the gravitational potential energy of large quantities of water. A PHS system consumes electricity to pump water from a lower reservoir or a river to an upper reservoir; the energy stored in this form can be released as in any hydropower system, passing the water through turbines as it is returned to the lower reservoir. Depending on the capacity of these reservoirs, the planning cycle can be daily, weekly, or even monthly. PHS systems are typically characterized by a round trip efficiency between 65% and 75% and high investment costs. Furthermore, suitable locations to build this type of power plants are scarce and they fully determine the size of the PHS system that can be installed; therefore, this technology is not easily scalable.

Battery Energy Storage Systems (BESS)

A battery is a type of ESS, based on chemical principles, such as electrolysis. The first batteries were not rechargeable (first voltaic battery - 1800) but the first rechargeable batteries were invented as early as 1859, thus, rechargeable batteries are a relatively mature technology. However, batteries have been mainly designed for domestic and industrial applications and have, so far, not been considered economic for large scale grid support. The first pilot projects aimed at integrating batteries in electric power systems were developed in Japan and North-America. Additionally, some attempts revolve around vehicle-to-grid technology, with which electrical rechargeable vehicles could take advantage of wholesale electricity prices.

Researchers are now focusing on improving existing battery technologies (e.g. Lithium-ion, advanced Lead-Acid) and developing new BESS based on different chemistries (e.g. Nickel-Cadmium, Sodium-Sulfur) that are better suited for grid applications (Díaz González et al. 2012; Mahlia et al. 2014). Each of these technologies has different characteristics that condition their applicability to electric power systems:

- Lead-Acid batteries, which are the most mature type of BESS, are characterized by medium-high round trip efficiency (75%-80%), low daily self-discharge (<0.1%) and reasonable cycle life (1200-1800 cycles). However, these systems are bulky and heavy (low specific energy) and have low power capabilities; some of these shortcomings may be fixed by future developments in Advanced Lead-Acid batteries.

- Lithium-ion batteries were made popular by electronic devices and, recently, electric vehicles. They have numerous advantages such as high energy density, fast charge and discharge capability and high round trip efficiency (80%-90%) that make them ideal for short-term applications (operating reserves). However, these batteries are still too expensive to consider its use to store large volumes of energy.
- Nickel-Cadmium batteries provide good cycle life (>3500 cycles) and quick charge and discharge capabilities at the expense of low efficiency compared to other technologies (60-70%), and high toxicity.
- Sodium-Sulfur batteries can only operate at high temperatures (≈350ºC). Under this conditions, they provide very high energy density, high efficiency (≈80%), nearly zero self-discharge and good cycle life (>4000 cycles). Furthermore, they need low maintenance and are 99% recyclable.
- Flow battery energy storage systems (FBESS) are a relatively novel type of rechargeable batteries composed of two chemicals dissolved in liquids contained within the system and separated by a membrane. Depending on these chemicals, flow batteries have different characteristics but they are generally characterized by high efficiencies and good cycle life at a lower cost than other technologies.

Compressed Air Storage System (CAES)

CAES systems consume energy to compress and store air in a pressurized deposit, the energy is released expanding the air in a turbine that drives a generator. Prior to the expansion, it is necessary to increase the air temperature, this can be done using different heat sources such as combustion of natural gas, residual heat from another process or the heat generated during the compression using some form of thermal storage. Large scale systems of this kind use underground caverns to store the compressed air; round trip efficiencies between 50% and 70% have been achieved.

Others

In addition to these technologies, there is another set of ESS that are currently in earlier stages of development. For example, Flywheel Energy Storage Systems (FESS), whose storage capability is achieved through a mass rotating at high speed suspended by magnetic bearings to decrease friction, provides high round trip efficiency and good cycle life added to high power an high energy density for short-term applications; Supercapacitor Energy Storage Systems (SCESS) store electrical charge achieving medium efficiency, good cycle life and high specific power; Superconducting Magnetic Energy Storage (SMES) uses a coil made of a superconducting material at cryogenic temperatures to store energy in a magnetic field; or Hydrogen-based Energy Storage System (HESS), that are based on electrolysis to extract hydrogen from water and on fuel cells to generate back electricity from the hydrogen.

1.2 Objectives

This section describes the main objectives of this dissertation. These objectives are not independent, each objective will provide individual results but the most relevant conclusions are derived from the joint analysis of the whole set of objectives.

1.2.1 Power System simulation. Interplay between VER and ESS.

This dissertation strives to evaluate, using a commercial software tool, the value of Energy Storage Systems (ESS) in future power systems. As already introduced, the increasing penetration of VER has altered the operation of electric power system and has brought a growing interest in flexible generation technologies, such as ESS. In particular, a small isolated power system, in which impacts of VER are higher and thus, the use of ESS could render especially beneficial, will be the object of our analysis. For the purposes of this dissertation, a small isolated power system with VER and a planned ESS, has been chosen: the island of Tenerife. The characteristics of this system will be described in the next section.

The modeling tools used for this assessment will consider various timescales. In the short term, special attention will be paid to the proper representation of flexibility requirements (reserves, ramps, start-ups…). This will be combined with longer term models to evaluate the cost savings derived from the use of ESS.

In particular, the potentially beneficial effects of the introduction of a pumped-hydro system will be evaluated in both timescales explained above (short and long term).

1.2.2 Critical evaluation of a commercial modeling software

PLEXOS is an electric power system and market simulator that will be used to obtain the results aimed in the previous objective. PLEXOS is a powerful software widely used in the industry.

This tool was chosen because it is capable of simulating electric power systems in the long term (e.g. capacity expansion planning), in the medium term (e.g. hydro-thermal coordination or maintenance planning) and in the short term (e.g. unit commitment). Depending on the time horizon simulated and the situation analyzed it offers a variety of features. Notably for this dissertation, in which a good representation of the interplay between ESS and VER is to be achieved, PLEXOS claims to allow for a detailed modeling of operational reserves, ramping capabilities, start-ups, operation and maintenance costs, and energy storage systems.

The second goal of this dissertation is to, through the analysis of the results obtained with PLEXOS, evaluate the degree of detail with which the problem is being represented. A critical evaluation of PLEXOS will be made, emphasizing its possible limitations and new requirements.

CHAPTER 2. BACKGROUND

This chapter provides some useful background to help fully comprehend the discussion presented in this dissertation. First, in Section 2.1, the main and most common power systems modeling problems implemented in practice are classified and reviewed. Section 2.2 points out how these models might be affected when introducing ESS. This analysis suggests that a strong presence of intermittent renewable generation may increase the value of ESS in power systems.

Section 2.3 reviews the peculiarities of Tenerife's electric power system in terms of pricing, reserves requirements or capacity margin. This section will help to understand some assumptions made in the development of the model.

2.1 Power systems' modeling

A model is a mathematical simplified representation of a complex reality. It is characterized by a series of simplifications that do not comprise the final solution. In other words, a model is a tool that helps us to take decisions. Because of this, a model must provide clear results that are relatively easy to interpret.

In the case of electric power systems, a fundamental model is the Unit Commitment (UC). This general problem consists in dispatching a series of generators in an optimal way, given a demand profile and a generation mix. The classical problem focuses on dispatching thermal units (Carrión & Arroyo 2006; Morales-España et al. 2013), but the most general problem can include any generation technology. For instance, UC models can cope with the dispatch of hydropower plants (Garcia-Gonzalez & Castro, 2001), flexible demand resources (Parvania & Fotuhi-Firuzabad 2010) and, integration of RES (Dietrich et al. 2009).

The Unit Commitment problem can be extended to include investment decisions; this is generally referred to as the Capacity Expansion Planning (CEP) problem. The goal of this problem is to find the optimal combination of new generation investments and existing units' retirements that minimizes the cost of supplying electricity over a long-term planning horizon (Hobbs 1995) A particular case in which no previously existing generation is present in the system, and therefore the whole generation mix has to be designed, is called a greenfield scenario. When the existing power plants are considered, the problem is called a brownfield-type capacity expansion. CEP models are widely used in the industry to help making investment decisions.

These models can include various levels of detail depending on how much precision is needed in the results obtained. There are plenty of references in this field that go from the simpler one to the most complex; in general, the more long-term the analysis is, the more simplifications are needed. For the goals of this dissertation, some of the issues that will require more complexity are the proper representation of thermal units' cycling capabilities, and their interaction with VER. For instance, CCGTs are composed of various units, it is possible to represent each of these units and the interaction among them (Chang et al., 2008), but in very large problems it is common to use a simplified formulation (Veiga et al. 2015). As for VER production, depending on the purpose of the model, it can be considered as deterministic or stochastic (Tuohy et al. 2009).

In the next section a review of some contributions to the modeling of the interplay between VER and ESS will be presented.

2.2 ESS and VER interplay modeling

In the last few years, an increasing interest in ESS modeling is emerging owing to the beneficial effects that these technologies can provide to the operation and planning of electric power systems that must deal with a high penetration of VER.

The most classical attempts when modeling ESS in power systems are based in pumped-hydro systems operating in the day-ahead market. For example Castronuovo & Peças Lopes (2004) studies the PHS ability to improve wind operational economic gains; García-González et al. (2008) investigates the combined optimization of a wind farm and a pumped hydro storage that operates in electricity markets. However, nowadays is becoming important to model PHS providing ancillary services. Meibom et al. (2011) models the Irish power system (in which there is a PHS) taking into account the reserves requirements with a statistical model that combines load and wind forecasts. Last works in PHS modeling can be seen in Gu et al. (2014) in which two interleaved models are simulated with PLEXOS to see how a PHS operate in day-ahead and real-time markets.

There are also models that consider other energy storage technologies. Among these Daneshi and Srivastava (2012) propose a UC formulation that includes CAES; Ortega-Vazquez (2014) and Vergara (2014) make significant contributions to the representation of BESS in UC models.

Finally, and closer to the objectives pursued in this dissertation, there are some authors that have economically assessed ESS in small isolated power system. For instance, Sigrist et al. (2013) present a model that evaluates the economic value of ESS providing primary reserves in two different Spanish islands.

2.3 Small isolated power systems

As mentioned in the introduction, the model developed in this dissertation is applied to a small isolated power system, since the impact of renewables in this type of power systems can be more acute, increasing the potential value of ESS. Indeed, there is a lot of energy storage projects that are currently being developed in small isolated power systems.

For instance, in Oahu isolated power system (Hawaii), the high solar peak produced in midday is resulting in expensive oil-fired power plants ramping down, increasing their operation costs. To solve this problem, HECO (Hawaii utility) will invest in ESS able to store between 60 and 200MW during 30 minutes in order to maintain system equilibrium if there is a drop-off in wind or sun production while bringing other running reserves into play.

Another prime example is the STORE project carried out by Endesa in the Canary Islands (Spain). STORE is the Europe's most important project about energy storage in isolated power systems and its main goal is to assess the economic and technical viability of large-scale energy storage. In particular, Li-ion batteries, ultracapacitors and flywheels are the technologies deployed and they are already installed and currently being tested.

In this dissertation, the power system of Tenerife will be used to analyze the value of a projected pumped hydro storage that was going to be installed in 2020. Since it is a small isolated power system, it is expected that this storage technology will be useful to cope with VER characteristics as mentioned above.

2.3.1 Tenerife

Tenerife, although being close to Africa and other islands, is not electrically interconnected with other systems, and thus it is considered a small isolated power system. In the following points some peculiarities that were considered in the model about this power system are explained.

Generation Mix

Tenerife has a peak demand of roughly 540 MW. It fulfils most of this demand with thermal units while some renewable power plants (solar & wind) are also available. In Figure 2, a map of the current electric power system is shown; it comprises four power plants with different generation technologies. These include Diesel motors, Open Cycle Gas Turbines (OCGT) and Combined Cycle Gas Turbines (CCGT) yielding a total thermal power of 1008.8MW. There are no natural gas (NG) facilities in Tenerife, so gas turbines run with diesel.

Figure 2 Map of Tenerife's electric power system

Pricing model

In Tenerife there is no electricity market like in other power systems; electricity prices here are regulated by the Spanish government. These prices are divided into two different components. First of all, generators are paid the marginal price of Iberian system each period they generate as if they were a part of Spanish market and after that each generator is given an individual uplift depending on their start-up costs, operation and maintenance costs and investment costs.

Reserve requirements

Another important characteristic of Tenerife's electric power system is the reserve requirement. Since small isolated power systems have more sensitivity to deviations in generation or demand, the reserve requirements are higher than in large interconnected power systems. In Tenerife the sum of primary and secondary reserves requirement must be equal to one of these quantities (Ministerio de Industria, Energía y Turismo, 2012):

- Highest net power provided among units generating
- Forecasted growth of the demand between one period and the following
- Most likely wind loss in an hour that will be calculated multiplying the wind output by a coefficient given by the System Operator.

In Tenerife there is also tertiary regulation; however it is beyond the scope of this dissertation.

CHAPTER 3. METHODOLOGY

This chapter describes the approach followed in this dissertation to complete the objectives previously described: analyzing the role of energy storage in power systems with increasing VER penetration and, making a critical assessment of a commercial modeling tool. This analysis is based on different simulations that go from the short to the long term.

The first model developed aims at representing Tenerife's electric power system at its present status; comprehensive data on the system's parameters are collected and introduced into a short-term unit commitment model. The model is validated by comparing its output with the actual historical behavior of the system.

Building from this model, a PHS system is added to the system to evaluate the impact of this new investment in the short term (i.e. operational costs, CO2 emissions or wind curtailment). This analysis is carried out for different years (2014-2024), in which several system parameters (demand, new investments in renewable generation, etc) evolve according to given forecasts. The impact of the PHS system in the long term (i.e. investment deferral) is evaluated by means of a Greenfield capacity expansion model. Furthermore, the results obtained are used to present the advantages and drawbacks of the modeling tool used.

3.1 Tenerife's power system data collection

An essential part in the development of this dissertation is to collect all the relevant data on the power system used as a case example. This section describes the data collection process and several modelling decisions based on data availability.

3.1.1 Thermal generation mix

Endesa's website provides a set of basic data on the installed capacity in Tenerife. However, these data had to be extended to model Tenerife's power system with sufficient level of detail.

The majority of the remaining data, regarding the technical parameters of the existing power plants, was obtained from a Spanish electric sector's guideline published by the Spanish regulatory authority (*Comisión Nacional de Energía*, CNE) (CNE 2008). This data is publicly available because Tenerife's power system assets, as it is the case in the rest of the Spanish insular power systems, are remunerated under cost-of-service regulation. This means that the government is required to publish the settlement process followed, including the cost parameters considered. Specifically, this information can be found in the 10th volume of the afore-mentioned guideline. The most relevant data obtained from this source were heat rate functions and start-up costs.

The dataset was completed using as a reference the Irish electric power system. Every year, Ireland's power system operator (Single Electricity Market Operator, SEM-O), publishes detailed data about its power system (Comission for Energy Regulation, 2015). Since it is an isolated power system, the technology choice for its power plants is similar to Tenerife's. Several technical parameters, such as ramping capabilities and minimum stable load, has been obtained from this source.

The consolidated dataset is shown in Table i and Table ii.

Table i Heat Rate Functions[1]

Plant	Technology	Fuel Used	Max. Power (MW)	Min. Stable Load (MW)	Heat Rate Base β (GJ/h)	Heat Rate Slope α (GJ/MWh)	Heat Rate Quadratic Slope γ (GJ/MWh2)
GRANADILLA	TG1	Gasoil	37,0	12,0	122,9	9,3	0,006
	TG2	Gasoil	42,0	12,8	115,4	9,0	0,005
	D1	Diesel	24,0	6,0	31,9	5,8	0,064
	D2	Diesel	24,0	6,0	31,9	5,8	0,064
	CV1	Fuel Oil	80,0	35,0	89,0	9,0	0,001
	CV2	Fuel Oil	80,0	35,0	89,0	9,0	0,001
	CCGT1	Gasoil	210,0	70,0	340,0	4,9	0,005
	CCGT2	Gasoil	210,0	70,0	340,0	4,9	0,005
CANDELARIA	TG1	Gasoil	17,2	5,0	97,4	11,5	0,026
	TG2	Gasoil	37,5	12,0	122,9	9,3	0,006
	TG3	Gasoil	37,5	12,0	122,9	9,3	0,006
	D1	Diesel	12,0	2,0	5,4	10,5	0,026
	D2	Diesel	12,0	2,0	5,4	10,5	0,026
	D3	Diesel	12,0	2,0	5,4	10,5	0,026
	CV1	Fuel Oil	40,0	20,0	35,1	12,0	0,002
	CV2	Fuel Oil	40,0	20,0	35,1	12,0	0,002
ARONA	TG1	Gasoil	24,3	10,0	85,0	9,3	0,000
	TG2	Gasoil	24,3	10,0	85,0	9,3	0,000
GUÍAS DE ISORA	TG1	Gasoil	22,5	10,0	85,0	9,3	0,000
	TG2	Gasoil	22,5	10,0	85,0	9,3	0,000

Table ii Ramping capabilities and start-up parameters

Plant	Technology	Ramp up (MW/min)	Ramp down (MW/min)	Start Up Energy (GJ)	Fixed Start Up Costs (€/start)
GRANADILLA	TG1	5,0	10,0	42,5	3577,0
	TG2	10,0	10,0	42,5	3577,0
	D1	4,0	5,0	280,0	188,4

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[1] The Heat Rate function is a second order polynomial function expressed as follow

$$HR = \beta + \alpha \cdot E_{MWh} + \gamma \cdot E_{MWh}^{2}$$

	D2	4,0	5,0	280,0	188,4
	CV1	0,7	1,0	1.100,0	11.117,0
	CV2	0,7	1,0	1.100,0	11.117,0
	CCGT1	15,0	20,0	1.700,0	30.847,2
	CCGT2	15,0	20,0	1.700,0	30.847,2
CANDELARIA	TG1	6,0	6,0	42,5	3.577,0
	TG2	5,0	10,0	59,5	3.577,0
	TG3	5,0	10,0	59,5	3.577,0
	D1	2,0	3,0	60,5	118,2
	D2	2,0	3,0	60,5	118,2
	D3	2,0	3,0	60,5	118,2
	CV1	0,7	1,0	770,0	8.356,0
	CV2	0,7	1,0	770,0	8.356,0
ARONA	TG1	5,0	5,0	34,0	700,2
	TG2	5,0	5,0	34,0	700,2
GUÍAS DE ISORA	TG1	5,0	5,0	34,0	700,2
	TG2	5,0	5,0	34,0	700,2

Figure 3 shows the different thermal units ordered from lower to higher variable operation costs:

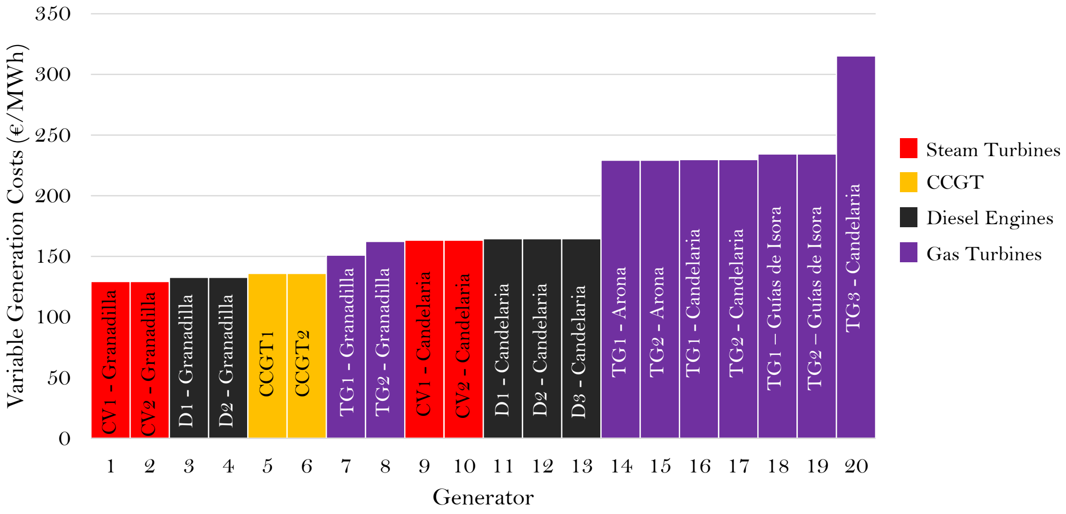


Figure 3 Merit order of Tenerife's thermal generation

3.1.2 Energy Storage Systems – Pumped Hydro Storage

The PHS system evaluated in this dissertation is based on a project developed to build a new PHS plant to start operating in 2020. The upper reservoir of this PHS is projected to be in "El Tanque" while its lower reservoir would be in "Los Silos", both in the north of Tenerife. Figure 4 shows a map of the location.

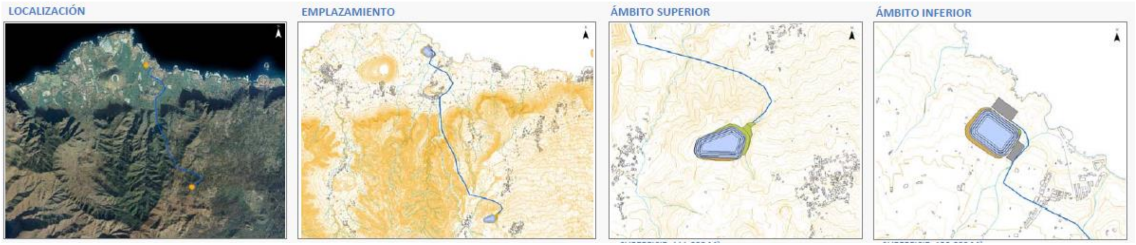


Figure 4 Location map of PHS "Los Silos"

Table iii shows the main characteristics of this pumped hydro system.

Table iii "Los Silos" PHS characteristics

Project Name	Max. Power	Max. Pumping Power	Upper Reservoir	Lower Reservoir	Height (h)	Operation time	Units	Inv. Cost
-	*MW*	*MW*	*GWh*	*GWh*	*m*	*hours*	*#*	*M€*
PHS Los Silos	120	132	2,92	3,23	882	24,31	2	300

This is a relatively small PHS, with a daily/weekly planning cycle, since it can operate at most during 24 hours at maximum power. Like other hydro projects, it is characterized by a high investment cost.

3.1.3 Load and VER profiles

Tenerife's load profile is published in E-SIOS, which is the Spanish system operator's information server. From this database (REE 2015), the load profile for 2012 was obtained and scaled until 2024 using GDP consensus projections.

The historical wind and PV generation profiles in Tenerife are not available at the moment. An estimate was obtained from the Spanish peninsula profile scaled to Tenerife's monthly VER generation peak and total production.

3.1.4 Fuel and CO2 emissions costs

Regulated fuel costs in the Canary Islands are published every year by the Spanish Government (Ministerio de Industria, Energía y Turismo, 2015), current fuel costs were taken from this source in order to have a reference. The fuel costs' forecasts until 2024 are based on consensus projections.

Finally, CO2 emissions prices, including forecasted values until 2024 are based on consensus estimates.

Current and consensus estimates, fuel and CO2 prices can be consulted in Bloomberg. (See Appendix A)

3.2 Modeling tools

3.2.1 Detailed short-term model of Tenerife's electric power system

The first step in this analysis is to develop a unit commitment model representing Tenerife's power system at its present status. This model obtains the least-cost dispatch of each power plant in the system to meet a given demand profile. Especial attention is paid to the short-term characteristics of the system (e.g. ramps, start-ups or reserves). The model is tuned comparing its output with the actual dispatch provided by Red Eléctrica de España (E-Sios, 2013).

3.2.2 Long-term unit commitment (base case)

Building from the previous step, the unit commitment model is run to analyze the power system's operation until 2024. This represents a business as usual scenario to be compared with results obtained in following steps. This scenario has the following characteristics:

- The demand is expected to increase 1.5% per year until 2024.
- Wind and solar penetration is expected to increase, current forecasts will be used in the simulation. Furthermore, some generators' openings and retirements will be considered.
- A regasification plant close to Granadilla Power Plant will soon be in operation (in 2020). Thus, OCGTs and CCGTs will run with natural gas (NG) from 2020 onwards.
- Fuel and CO2 prices will vary from one year to another. Current price forecasts will be used in the simulation.

At the same time, an additional scenario in which the pumped-hydro storage system is added to the power system will be compared with the 'business as usual' scenario. This comparison will focus on various system characteristics such as operational cost savings, CO2 emissions or wind curtailment.

3.2.3 Greenfield-type capacity expansion problem

The last model developed is a Greenfield-type capacity expansion model. This model optimally designs the generation mix of the island (finds the optimal investment decisions) for the time horizon analyzed and considers eight different wind penetration scenarios. This model helps to assess to what extent a combination of VER and PHS can avoid the need to invest in fossil-fueled thermal power plants. Therefore, the model is run under two different setups; in one case the optimal mix is obtained considering the PHS is installed, in the other it will not be possible to invest in a PHS. Some relevant considerations for this model are:

- Investment candidates considered are CCGTs, OCGTs and diesel engines. The technical parameters used to represent these technologies are the same values used in the previous unit commitment model.
- Simulations are made for one year, therefore, annualized investment costs are used to evaluate investment decisions. Table iv shows the costs and characteristics of investment candidates.

Table iv Annualized investment costs

Plant	**Technology**	**Max Power**	**Capital Costs**	**Total Costs**	**Economic Life**	**WACC**	**Annualized costs**
		(MW)	**(€/kW)**	**(M€)**	**(years)**	**(%)**	**(€/kW.year)**
GRANADILLA	CCGT	210	917	192,6	25	8%	85,90
	CCGT	210	917	192,6	25	8%	85,90
	Diesel	24	1.200	28,8	30	8%	106,59
	Diesel	24	1.200	28,8	30	8%	106,59
	Gas Turbine	75	650	48,8	18	8%	69,36
	Gas Turbine	37	973	36,0	12	8%	129,11
	Gas Turbine	42	973	40,9	12	8%	129,11
CANDELARIA	Diesel	12	1.400	16,8	10	8%	208,64
	Diesel	12	1.400	16,8	10	8%	208,64
	Diesel	12	1.400	16,8	10	8%	208,64
	Diesel	18	1.100	19,8	40	8%	92,25
	Diesel	18	1100	19,8	40	8%	92,25
	Gas Turbine	37,5	973	36,5	12	8%	129,11
	Gas Turbine	37,5	973	36,5	12	8%	129,11
	Gas Turbine	17,2	973	16,7	12	8%	129,11
GUÍAS DE ISORA	Gas Turbine	22,5	676	15,2	14	8%	82,00
	Gas Turbine	22,5	676	15,2	14	8%	82,00
ARONA	Gas Turbine	24,3	676	16,4	14	8%	82,00
	Gas Turbine	24,3	676	16,4	12	8%	89,70
EXTRA	CCGT@2012	210	1.023	214,8	25	8%	95,83
	PHS	120	2.500	300,0	30	8%	222,07

- The value of lost load is set to 5,000 €/MWh and the value of reserves shortage to 1,000 €/MWh.
- Simplifications are made to the generators' heat rate functions, considering only an average heat rate. (See PLEXOS Heat Rate Function in Chapter 5)
- Four weeks are used as a representative sample of the whole year. (See PLEXOS Sampled Chronology in Chapter 5)

3.2.4 ESS value and modelling tools limitations

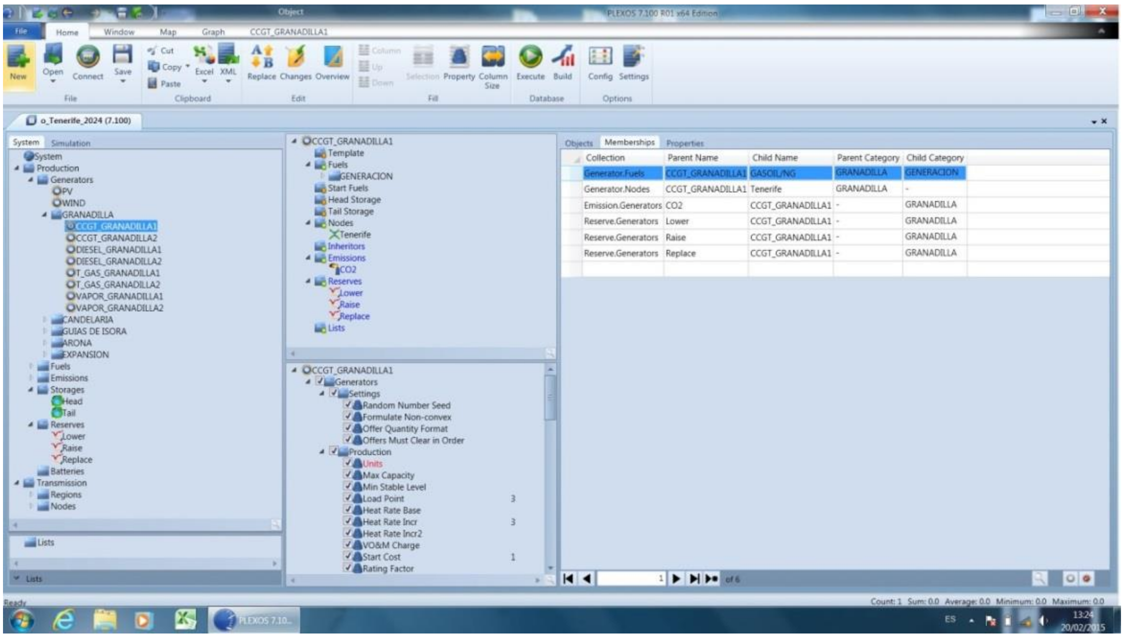
The results obtained from the previously described models allow to make a comprehensive analysis of the value delivered by an ESS in the power system. The base scenario is compared with the results obtained by the scenario with an installed PHS to evaluate the benefits of ESS options for the island. VER curtailment, CO2 emissions, and total system costs are quantified for these comparisons. A similar analysis is made with the results from the capacity expansion problem attending to the impacts of wind penetration. Here, an additional analysis of how the generation mix varies in different wind scenarios is performed. At the same time, these models are used to analyze the capabilities of the chosen modeling tool, advantages and drawbacks found in this software are presented.

3.3 Materials

The models used in this project have been implemented by the author, using mainly two computing tools. PLEXOS has been used to model and run optimization based models. EXCEL has been used as a user friendly data input interface and to perform data processing and analysis.

3.3.1 PLEXOS

PLEXOS Integrated Energy Model is a commercial tool capable of simulating power systems in the short, medium and long term. PLEXOS provides a simple graphical user interface that facilitates the implementation of the most usual models used in the energy industry. PLEXOS offers a choice of solver packages to perform the optimization computation. In this case, Xpress-MP was the optimizer used. This software and its main characteristics will be covered in more detail in Chapter 5.

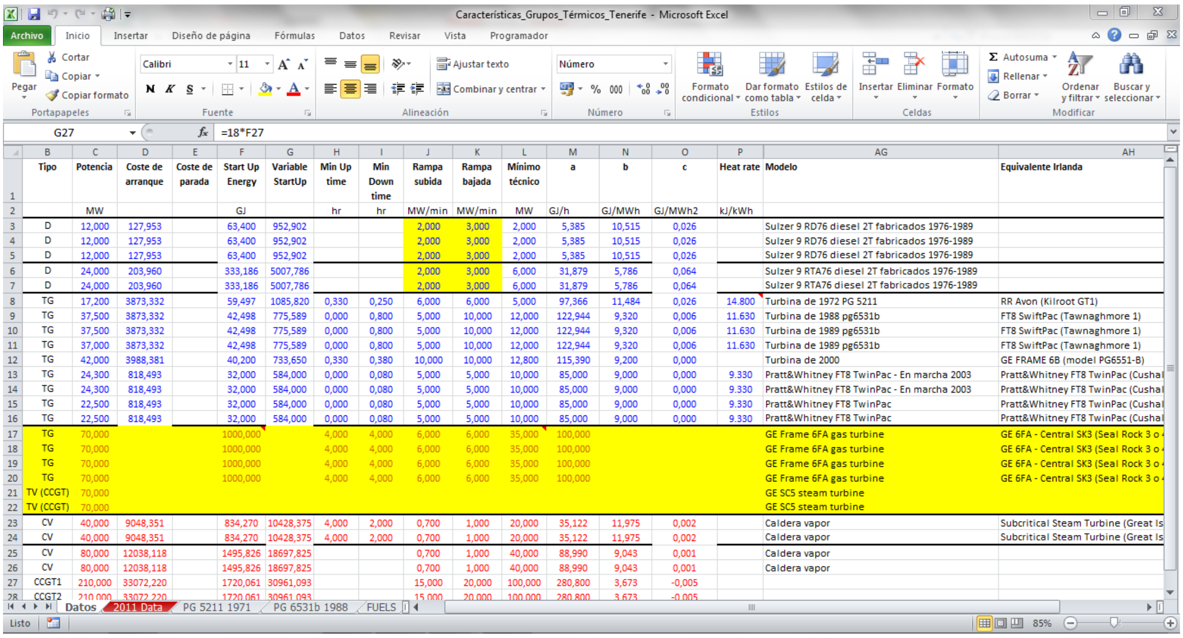


Collection	Parent Name	Child Name	Parent Category	Child Category
Generator.Fuels	CCGT_GRANADILLA1	GASOIL/NG	GRANADILLA	GENERACION
Generator.Nodes	CCGT_GRANADILLA1	Tenerife	GRANADILLA	-
Emission.Generators	CO2	CCGT_GRANADILLA1	-	GRANADILLA
Reserve.Generators	Lower	CCGT_GRANADILLA1	-	GRANADILLA
Reserve.Generators	Raise	CCGT_GRANADILLA1	-	GRANADILLA
Reserve.Generators	Replace	CCGT_GRANADILLA1	-	GRANADILLA

Figure 5 PLEXOS Interface Sample

3.3.2 EXCEL

Excel is a spreadsheet application developed by Microsoft and is part of the Microsoft Office software package. It allows for simple data analysis and representation. Excel was used in this dissertation for input data processing and for results plotting.



G27 =18*F27

	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	AG	AH
1	Tipo	Potencia	Coste de arranque	Coste de parada	Start Up Energy	Variable StartUp	Min Up time	Min Down time	Rampa subida	Rampa bajada	Mínimo técnico	a	b	c	Heat rate	Modelo	Equivalente Irlanda
2		MW			GJ		hr	hr	MW/min	MW/min	MW	GJ/h	GJ/MWh	GJ/MWh2	kJ/kWh		
3	D	12,000	127,953		63,400	952,902			2,000	3,000	2,000	5,385	10,515	0,026		Sulzer 9 RD76 diesel 2T fabricados 1976-1989	
4	D	12,000	127,953		63,400	952,902			2,000	3,000	2,000	5,385	10,515	0,026		Sulzer 9 RD76 diesel 2T fabricados 1976-1989	
5	D	12,000	127,953		63,400	952,902			2,000	3,000	2,000	5,385	10,515	0,026		Sulzer 9 RD76 diesel 2T fabricados 1976-1989	
6	D	24,000	203,960		333,186	5007,786			2,000	3,000	6,000	31,879	5,786	0,064		Sulzer 9 RTA76 diesel 2T fabricados 1976-1989	
7	D	24,000	203,960		333,186	5007,786			2,000	3,000	6,000	31,879	5,786	0,064		Sulzer 9 RTA76 diesel 2T fabricados 1976-1989	
8	TG	17,200	3873,332		59,497	1085,820	0,330	0,250	6,000	6,000	5,000	97,366	11,484	0,026	14.800	Turbina de 1972 PG 5211	RR Avon (Kilroot GT1)
9	TG	37,500	3873,332		42,498	775,589	0,000	0,800	5,000	10,000	12,000	122,944	9,320	0,006	11.630	Turbina de 1988 pg6531b	FT8 SwiftPac (Tawnaghmore 1)
10	TG	37,500	3873,332		42,498	775,589	0,000	0,800	5,000	10,000	12,000	122,944	9,320	0,006	11.630	Turbina de 1989 pg6531b	FT8 SwiftPac (Tawnaghmore 1)
11	TG	37,000	3873,332		42,498	775,589	0,000	0,800	5,000	10,000	12,000	122,944	9,320	0,006	11.630	Turbina de 1989 pg6531b	FT8 SwiftPac (Tawnaghmore 1)
12	TG	42,000	3988,381		40,200	733,650	0,330	0,380	10,000	10,000	12,800	115,390	9,200	0,000		Turbina de 2000	GE FRAME 6B (model PG6551-B)
13	TG	24,300	818,493		32,000	584,000	0,000	0,080	5,000	5,000	10,000	85,000	9,000	0,000	9.330	Pratt&Whitney FT8 TwinPac - En marcha 2003	Pratt&Whitney FT8 TwinPac (Cushal
14	TG	24,300	818,493		32,000	584,000	0,000	0,080	5,000	5,000	10,000	85,000	9,000	0,000	9.330	Pratt&Whitney FT8 TwinPac - En marcha 2003	Pratt&Whitney FT8 TwinPac (Cushal
15	TG	22,500	818,493		32,000	584,000	0,000	0,080	5,000	5,000	10,000	85,000	9,000	0,000	9.330	Pratt&Whitney FT8 TwinPac	Pratt&Whitney FT8 TwinPac (Cushal
16	TG	22,500	818,493		32,000	584,000	0,000	0,080	5,000	5,000	10,000	85,000	9,000	0,000	9.330	Pratt&Whitney FT8 TwinPac	Pratt&Whitney FT8 TwinPac (Cushal
17	TG	70,000			1000,000		4,000	4,000	6,000	6,000	35,000	100,000				GE Frame 6FA gas turbine	GE 6FA - Central SK3 (Seal Rock 3 o
18	TG	70,000			1000,000		4,000	4,000	6,000	6,000	35,000	100,000				GE Frame 6FA gas turbine	GE 6FA - Central SK3 (Seal Rock 3 o
19	TG	70,000			1000,000		4,000	4,000	6,000	6,000	35,000	100,000				GE Frame 6FA gas turbine	GE 6FA - Central SK3 (Seal Rock 3 o
20	TG	70,000			1000,000		4,000	4,000	6,000	6,000	35,000	100,000				GE Frame 6FA gas turbine	GE 6FA - Central SK3 (Seal Rock 3 o
21	TV (CCGT)	70,000														GE SC5 steam turbine	
22	TV (CCGT)	70,000														GE SC5 steam turbine	
23	CV	40,000	9048,351		834,270	10428,375	4,000	2,000	0,700	1,000	20,000	35,122	11,975	0,002		Caldera vapor	Subcritical Steam Turbine (Great Is
24	CV	40,000	9048,351		834,270	10428,375	4,000	2,000	0,700	1,000	20,000	35,122	11,975	0,002		Caldera vapor	Subcritical Steam Turbine (Great Is
25	CV	80,000	12038,118		1495,826	18697,825			0,700	1,000	40,000	88,990	9,043	0,001		Caldera vapor	
26	CV	80,000	12038,118		1495,826	18697,825			0,700	1,000	40,000	88,990	9,043	0,001		Caldera vapor	
27	CCGT1	210,000	33072,220		1720,061	30961,093			15,000	20,000	100,000	280,800	3,673	-0,005			
28	CCGT2	210,000	33072,220		1720,061	30961,093			15,000	20,000	100,000	280,800	3,673	-0,005			

Figure 6 Excel Sample Interface

CHAPTER 4.
RESULTS AND DISCUSSION

4.1 Comparison of short-term results with Tenerife's real generation dispatch

Before simulating long-term models, a short-term unit commitment is made in order to assess the accuracy of the model. In this section single week results are presented considering a co-optimization of generation dispatch and secondary reserves provision.

The first solutions obtained did not accomplish the expected results and thus the model had to be continuously calibrated by making various simulations and modifying some parameters like ramping capabilities or heat rate functions. It was observed that the dispatch of flexible generation units, like CCGTs or OCGTs, is greatly influenced by the operational reserves requirements. Given the relevance of flexibility in a small power system, it was crucial to co-optimize energy and reserves to make model results coherent with actual dispatch data.

Figure 7 shows Tenerife's actual generation dispatch in a week from March 2013. Steam turbines, combined cycle gas turbines and diesel engines are continuously generating in order to fulfill the level of reserves required by the system, while open cycle gas turbines only generate in peak hours covering the demand and supporting the rest of generation in periods in which demand is very high. As shown in the figure, renewable penetration was relatively small in 2013, therefore, it has a small effect on the flexibility requirements of the system. In comparison with Figure 8, which represents the dispatch calculated by PLEXOS, it can be seen at first glance that the dispatch resulting from the simulation model is very similar to the actual dispatch provided by Red Eléctrica de España (REE). These results suggest that the model is an acceptable representation of Tenerife's electric power system, however, additional analysis is made in the next paragraphs.

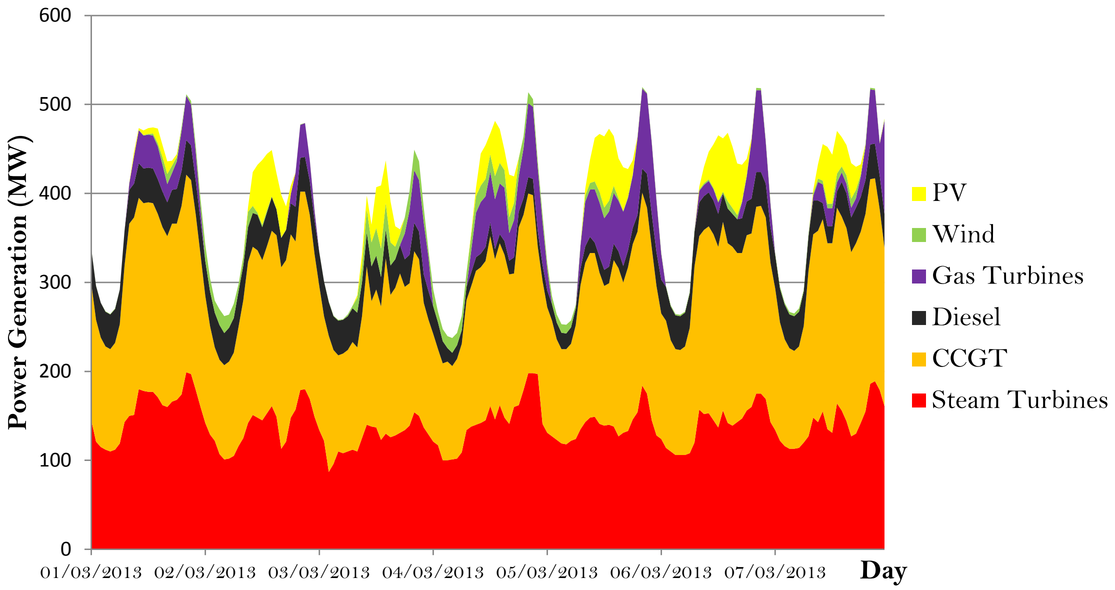


Figure 7 Generation provided by REE for the first week of March 2013

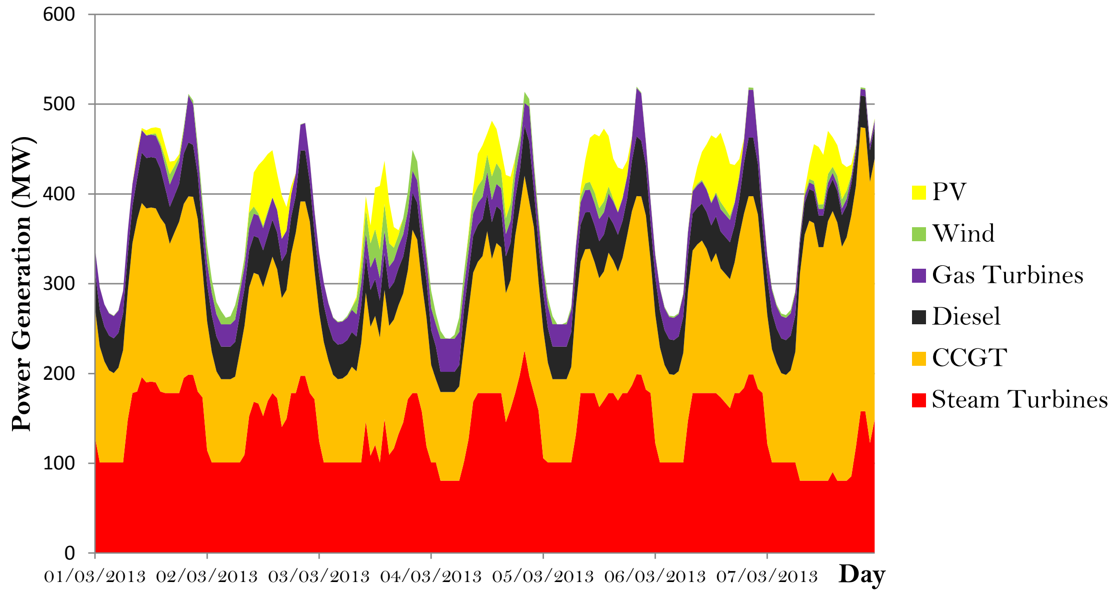


Figure 8 Generation obtained from PLEXOS model for the first week of March 2013

As seen in these two figures, there are still some differences in gas turbines generation and in steam turbines ramping. The main cause of these differences is that the actual dispatch accounts for program adjustments made throughout the day, with a high time resolution, while the model developed is simulating a day-ahead dispatch (deterministic) which does not consider real time adjustments. Another reason is that the REE's dispatch is considering network constraints (congestion) and reactive power balance, while the model considers a single node and only active power. Additionally, estimations were required to obtain some parameters (ramps and heat rate functions) so some small differences are to be expected. In any event, to clarify the results presented above, Figure 9 shows another comparison considering the energy provided by each generation technology during the same week.

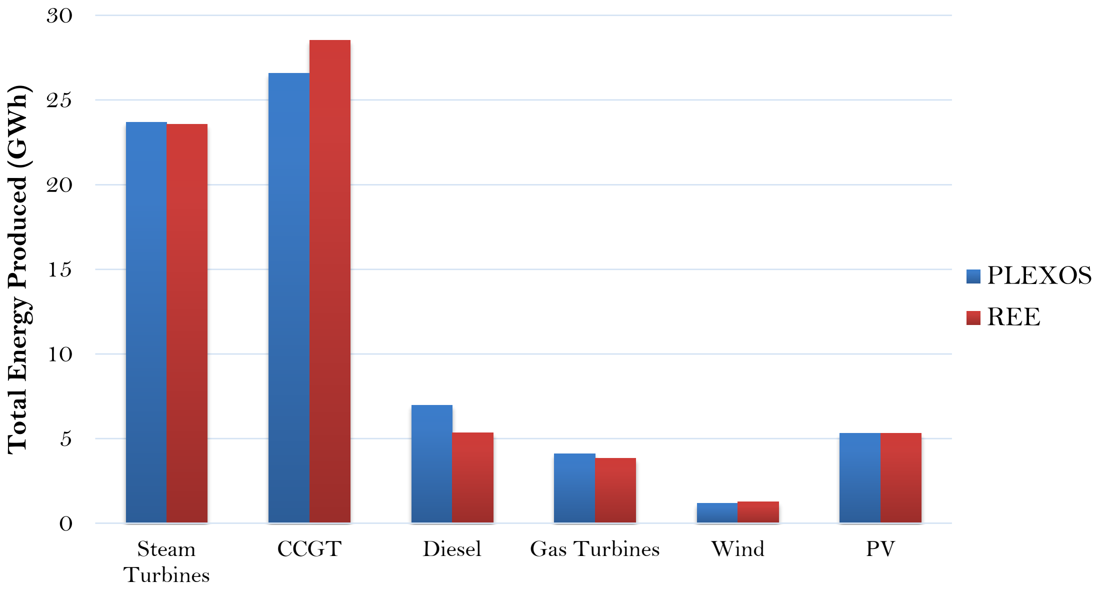


Figure 9 Comparison between PLEXOS and REE considering energy provided by technology

The main differences observed are in CCGT and Diesel generation. A possible reason for this gap can lie on the difference between day-ahead and real-time reserve provision. In the model results, CCGTs reserve some capacity to adapt to real-time changes in load (reducing the energy provided); however, in the actual dispatch the energy provided for the reserve service is included. There are not public data showing the reserve provision per unit in Tenerife so this cannot be contrasted.

Although there are some differences between REE's real dispatch and the obtained with the model, these are virtually negligible and do not affect the achievement of the objectives in this dissertation. Therefore, we consider the model as a valid representation of Tenerife's electric power system.

4.2 Short-term operation of a Pumped Hydro Storage

The introduction of new generation assets in an electric power system affects the short-term operation of the system in multiple ways. In the particular case of adding an energy storage system, like a PHS, the most important change is potentially, a saving in total system's operation costs. Furthermore, this is not the only relevant modification that must be taken into account in this analysis because a PHS is also capable of reducing RES curtailment and CO2 emissions. Therefore, this section, in addition to the impact of a PHS in system's costs, also analyzes other relevant system's characteristics.

To do so, various simulations are made, from 2014 until 2023 considering two different scenarios; one with an installed PHS and another one without it.

4.2.1 Impact of a PHS on system's operation costs

When introducing a pumped hydro storage in an electric power system the most important change observed is a reduction in total operation costs. As already introduced in this dissertation, a PHS uses water to generate electricity, which supposes null variable generation costs and zero CO2 emission, avoiding fuel and emissions costs. Furthermore, since it has storage capabilities it is possible to reduce RES curtailment in periods in which VER production is very high, to use this energy when it is most needed. Also, the flexibility of the PHS allows to operate thermal power plants more efficiently, reducing the number of start-ups and the amount of time these units are operating at the minimum stable load.

Figure 10 shows the system costs incurred per year in the system, with and without a PHS.

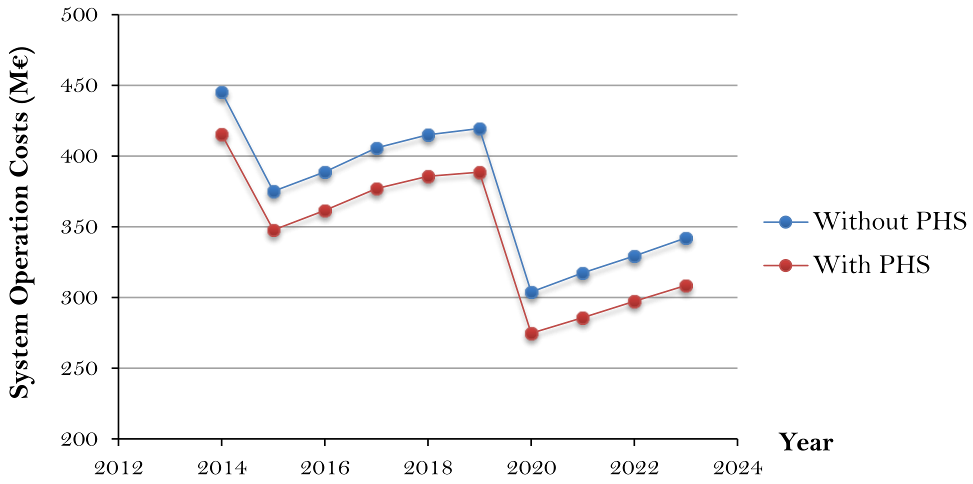


Figure 10 Annual system operation costs incurred in both scenarios

In both scenarios, system costs generally increase because, although renewables are increasingly penetrating, demand and fuel prices are continuously increasing. However, it is shown that in 2015 the total systems costs decrease. This is because of an expected fall in fuel prices. Another drop in system costs is observed in 2020, this is because a regasification plant is expected to open in Tenerife and thus CCGT and OCGT plants start to operate with natural gas, a fuel which is cheaper than gasoil and has less emissions costs (less pollutant).

The differences between both cost functions are the annual savings of the power system produced by the installation of a pumped hydro storage unit. The results presented are only from 2014 to 2023 and the PHS is expected to be installed in 2020 with an economic life of about 20-30 years. Thus, cash flows needed to evaluate this investment are those from 2020 onwards. Since there is not enough data available to simulate beyond 2023, a cash flow projection is made based on the results obtained in the 2014-2023 simulations. A conservative projection is made by assuming that all cash flows are constant and equal to the mean value of the 2014-2023 cash flows. Figure 11 shows the estimation made.

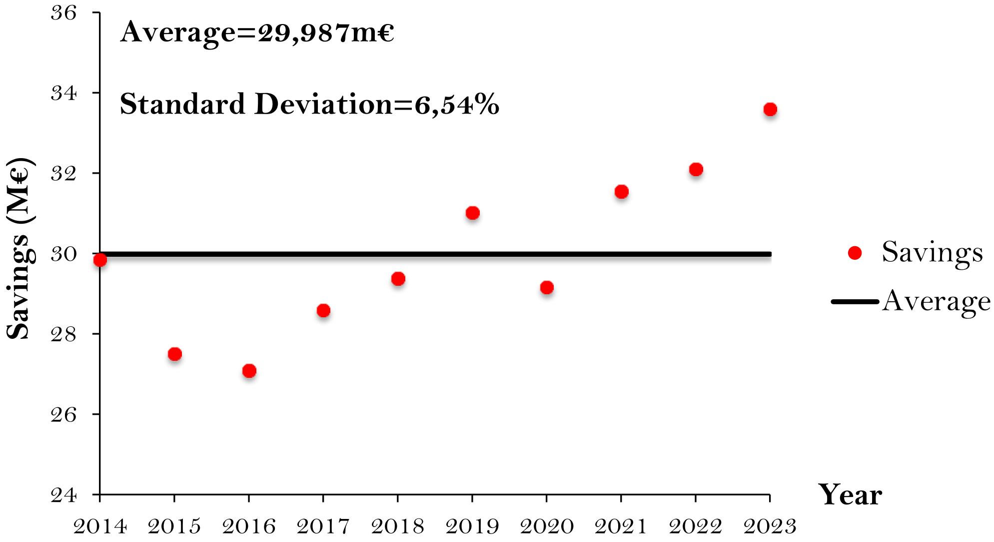


Figure 11 Average savings estimation

It is observed that cost savings follow an upward trend, which could lead to the conclusion that savings will continue to increase every year. This would not be a bad estimation if the increase of VER capacity per year remains constant. However, the penetration of renewables is expected to decrease from 2023 onwards, since there is a maximum quantity of VER penetration that can be integrated in the system. Therefore, it is more reasonable to follow a conservative hypothesis. In this case, the cash flows from 2020 onwards will be considered constant and equal to 29,987 M€.

Once system savings are calculated, there are two different approaches to perform the financial valuation of the investment:

- When an investment is considered in Tenerife, or in the Canary Islands in general, is a normal practice to consider the following return rate:

$$R = 10\ years\ bond\ yield\ (Spain) + 2\%$$

Then, if the forecast of the yield of a Spanish 10 years bond is known it is possible to calculate the net present value (NPV) of the investment to see whether it is profitable or not. Figure 12 shows the difference between initial investment and the accumulated NPV of the PHS.

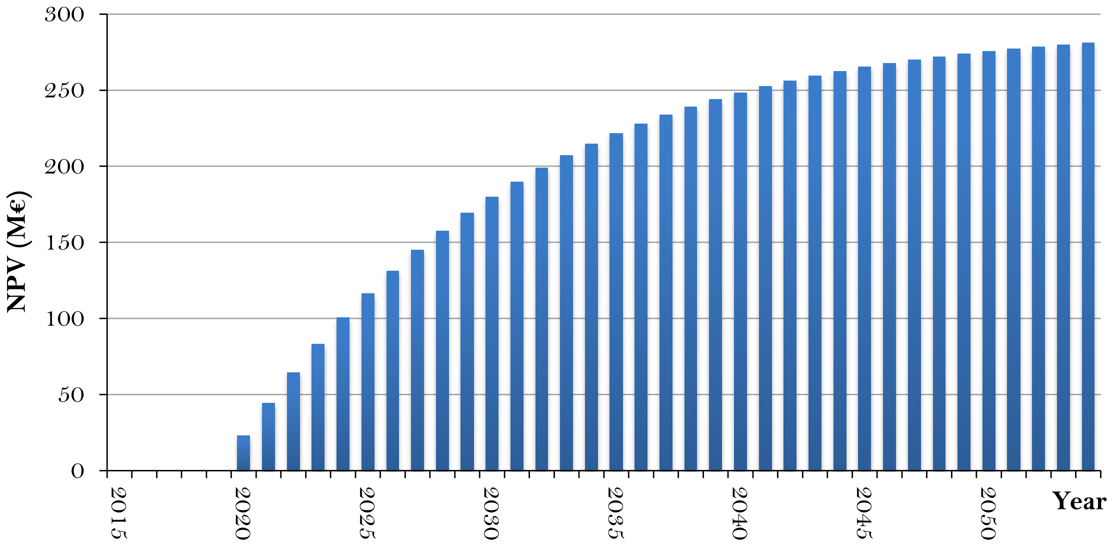


Figure 12 NPV of investing in a PHS

In this figure it is shown that from 2015 to 2020 the NPV remain constant and equal to 0€ because it is the period between the investment and the PHS construction. From 2020 onwards, the net present value starts to increase; however it never reaches 300M€ and the PHS would not be a profitable investment given these conditions.

- The second approach is based on calculating the return rate needed to recover the capital costs, or in other words, calculate the internal rate of return (IRR).

Then, given the investment costs and a series of cash flows, the IRR can be calculated directly with the following formula:

$$-300m€ + \sum_{1}^{year} \frac{cashflows_{year}}{(1+IRR)^{year}} = 0$$

In Figure 13 the IRR is represented as a function of the life time of the PHS.

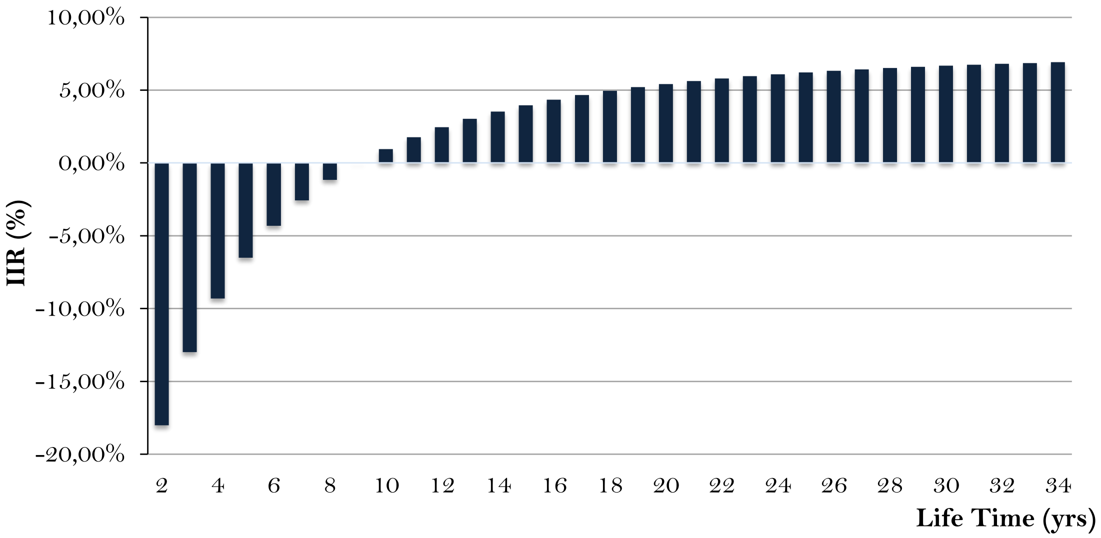


Figure 13 Internal Return Rate when investing on a PHS

In this case, the system will seek the highest possible IRR and a project with negative IRR will never be viable. Thus, with this approach PHS should never have a life time lower than 10 years in order to consider its construction.

Extra: Reserve's Energy Usage

The simulation model used for the results presented above co-optimizes energy and reserves considering the cost of providing energy and the cost of making a power band available for the operating reserves (which entails starting additional units or operating units at a less efficient power level). However, the model does not take in account the energy that the system will use from the operating reserves band in real time. If this energy is taken into account, system's savings may be higher since the PHS is expected to provide a relevant part of these reserves. In this section, the model is modified to include an approximation of the energy used for reserves. The energy used for upwards reserves is set to a 30% of the reserve band and the energy used for downwards reserves is set to 20%. Figure 14 shows the net present value of a PHS when this assumption is made.

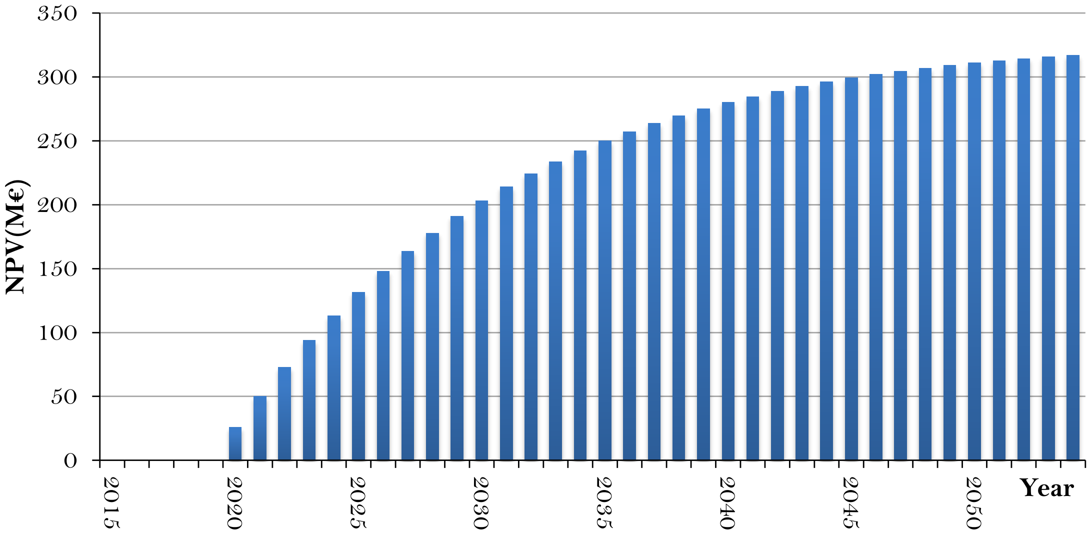


Figure 14 NPV of a PHS when considering energy used from reserves in real time

In this case the net present value increases from 2020 onwards, reaching 300M€, which is the investment costs of the PHS analyzed, in 2045. From this year on PHS would be profitable for the system. Therefore, if the PHS life time is higher than 25 years, its installation would be considered.

4.2.2 Impact of a PHS on RES curtailment

RES production always has lower variable costs than thermal technologies; however, it might be more economical sometimes to use thermal power instead of RES generation. This is because using all the variable output of renewable power plants might force thermal power plants to operate at their minimum power output (at which efficiency is reduced) or to completely shut-down only to start-up again in a few hours. Unused available RES production is called curtailed energy.

Thermal systems with large RES penetration are forced to curtail renewable production frequently; this provides a great opportunity for ESS, which can store excess renewable energy for later use in a controllable way. Using this excess energy that would otherwise be curtailed reduces system operational costs. Figure 15 and Figure 16 show a comparison between the energy dispatches for the same two days that result when a PHS is introduced in the system.

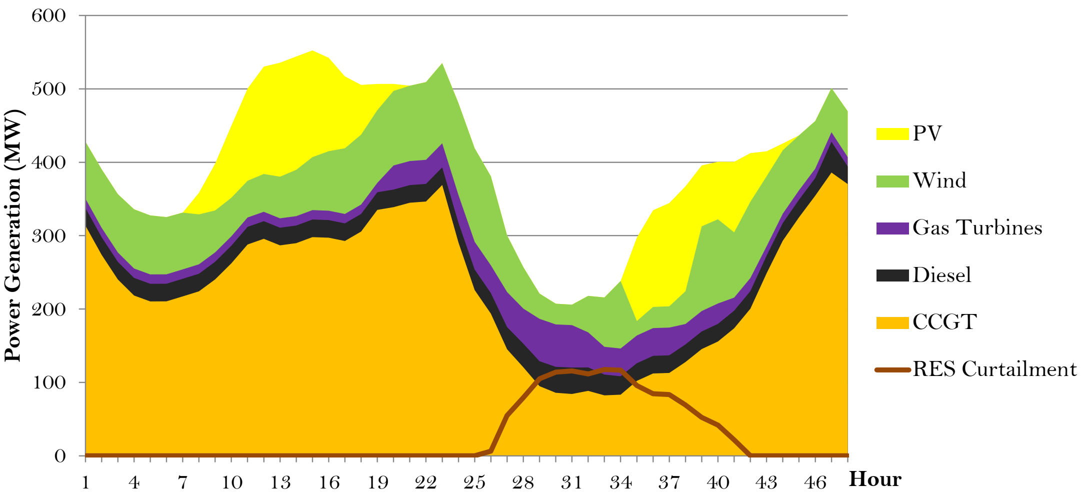


Figure 15 2-days dispatch without PHS

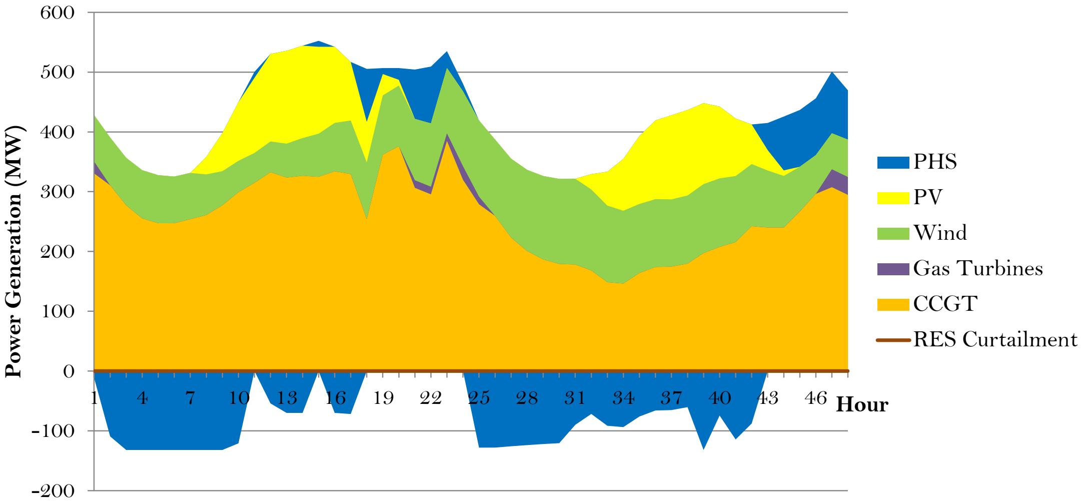


Figure 16 2-days dispatch with a PHS

Figure 15 shows that a lot of RES generation is curtailed when a PHS is not installed (represented with a brown line) while Figure 16, where a PHS is added, shows that RES generation is fully exploited achieving a null curtailment. Furthermore, a PHS reduces gas turbines and diesel engines generation. Then, it is observed that for the same two days, if an ESS is operating there is less RES curtailment and consequently lower operation costs and lower CO2 emissions.

This effect is most pronounced as RES penetration increases. Figure 17 shows the RES curtailment produced with and without PHS from 2014 to 2023. As a reminder, RES penetration increases every year in Tenerife.

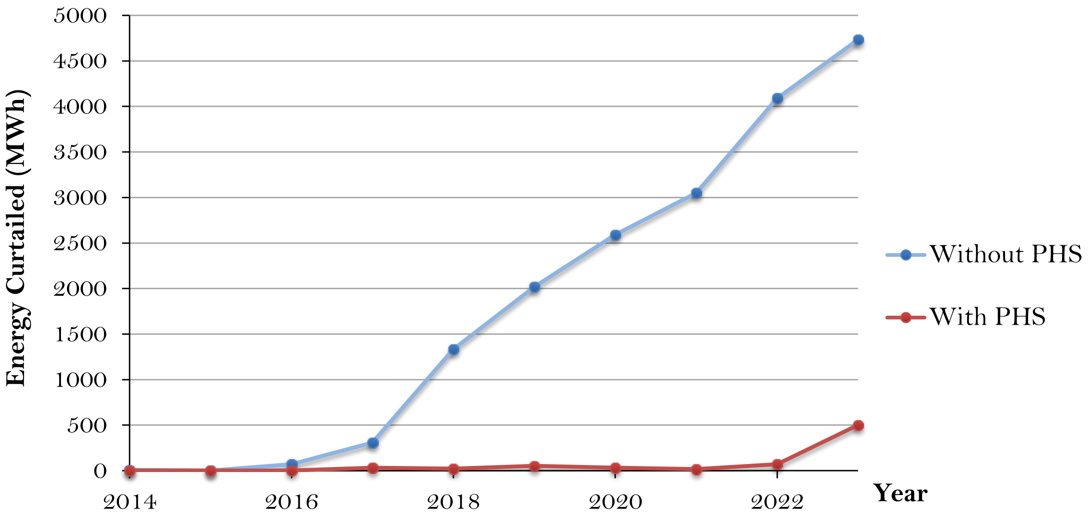


Figure 17 RES curtailment comparison from 2014 to 2023

The effect of a PHS unit on RES curtailment is almost irrelevant in the first few years of the simulation (2014-2016). However, from 2016 onwards, when RES penetration greatly increases, the PHS unit is necessary to avoid a very significant amount of RES curtailment.

4.2.3 Impact of a PHS on CO2 emissions

The previous section have shown that a pumped hydro storage can integrate a huge amount of renewables into the power system. A direct consequence that result from this integration process is the CO2 emissions abatement, which facilitates the compliance of the relatively recent greenhouse emissions policies. Figure 18 shows the impact that a PHS has on CO2 emissions.

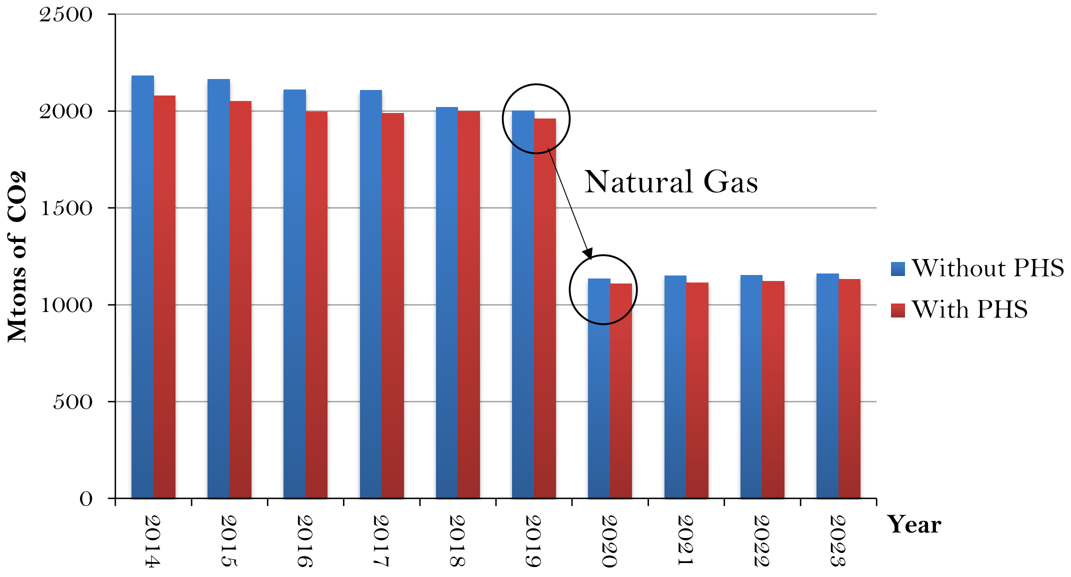


Figure 18 CO2 emissions comparison from 2014 to 2023

As already said, CO2 emissions are always lower in a scenario with an installed PHS. Furthermore, it is seen that while from 2014 to 2019 this emissions hardly decrease, in 2020 emissions are reduced around 50%. This is because in 2020 a regasification plant is expected to open in Tenerife and CCGTs will start to run with natural gas which is less pollutant than gasoil.

4.2.4 Impact of a PHS on thermal generation

Another relevant change in electric power systems when introducing an energy storage technology is that the total thermal energy dispatched, especially the part produced by peaking plants, decreases. Figure 19 shows the total thermal generation dispatched in both scenarios (with and without PHS) for the 9 years simulated.

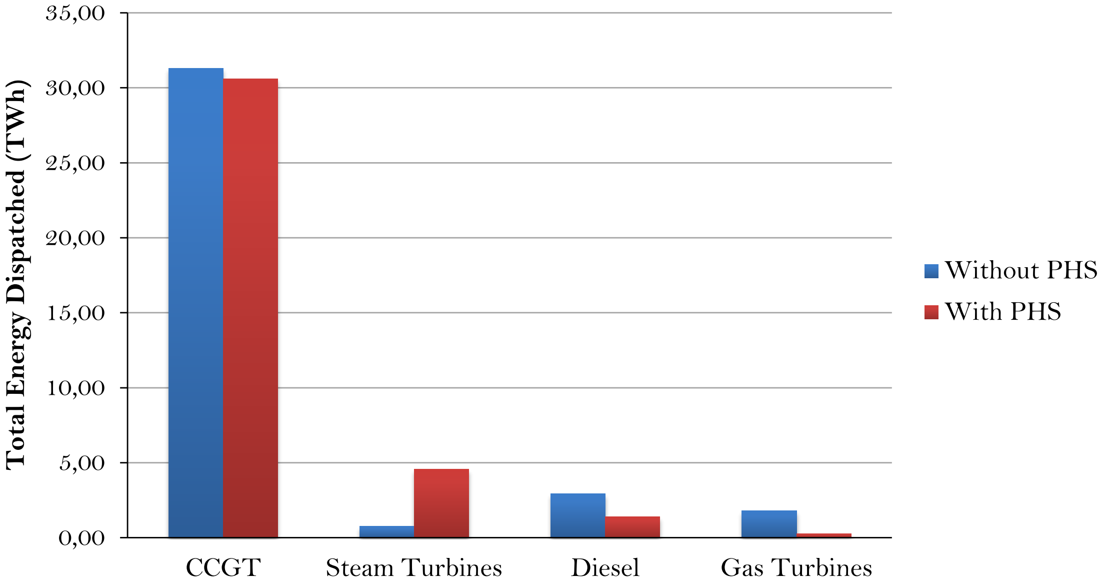


Figure 19 Thermal energy dispatched in Tenerife's short term operation

In a PHS scenario the total energy dispatched by thermal peaking plants, like CCGT, OCGT and diesel engines decreases. However, steam turbines generation increases. This is because a PHS provides more flexibility to the system enabling steam turbines, which have worse ramping capabilities but lower variable costs, to increase their generation share with respect to CCGTs and other thermal units with higher generation costs.

4.3 Long-term operation of a Pumped Hydro Storage

The results presented in the previous section assess the value of a pumped hydro storage in the short-term on the basis of cost savings, wind curtailment and CO2 emissions. That study was carried out in a specific electric power system (Tenerife) in which many variable parameters were considered through data forecasts and estimations.

This section strives to analyze to what extent the penetration of RES has an impact on the previous discussion by isolating the effect of wind in 2020. In this case, a capacity expansion problem is presented considering 8 different wind scenarios from 0MW to 500MW as shown in Table v, where the wind penetration of each scenario is presented.

Table v Wind penetration for each scenario

Scenario	1	2	3	4	5	6	7	8
Wind penetration (MWp)	0	50	100	150	200	300	400	500

Fuel costs, CO2 emissions costs, load and PV generation profile remain constant in every wind scenario. Thus, the results presented in this section will show only the impact of wind penetration on curtailment, CO2 emissions, system's costs and generation investments in a system with an installed PHS and without it.

As previously explained in Section 2.1, a capacity expansion problem consists on finding the optimal combination of investment candidates and existing units that minimize the cost of supplying electricity over a long-term planning horizon. In this case, a greenfield-type capacity expansion was solved, considering that there are no thermal generation units installed in Tenerife.

4.3.1 *Impact of PHS on generation mix*

Depending on the wind penetration and on whether there is a PHS installed or not the generation mix of Tenerife is different. Figure 20 reflects this:

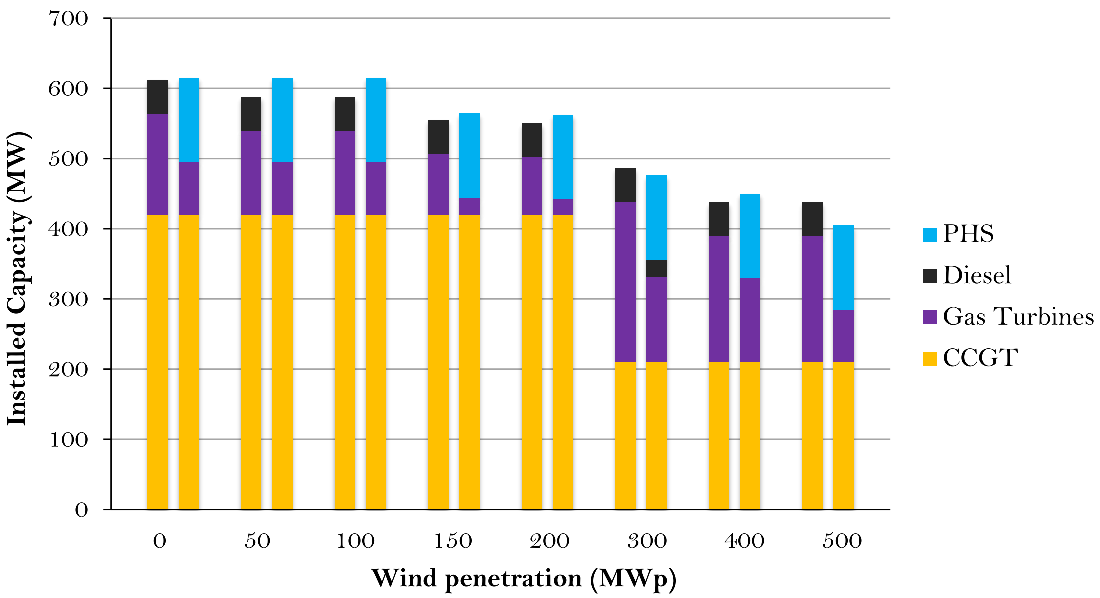


Figure 20 Generation mix in different wind scenarios

In this figure there are two possible dimensions to compare. First of all, how the generation mix vary in a scenario with an installed PHS with respect to a scenario without it; and secondly how the generation mix is altered in different wind penetration scenarios.

When a PHS is installed it is seen that there is less thermal generation deployed. In particular there are less gas turbine generation and there are no diesel engines (except for a little capacity installed in scenario 6). Since the PHS avoid installing some thermal units it is producing cost savings to the system which will be useful to assess the value of this energy storage unit.

In the case of analyzing the different wind scenarios, it can be said that as wind penetration increases less thermal units are deployed. This is because when wind penetration is high thermal units installed are required to generate less, reducing their load factor and it is possible that at some point it is preferable not to supply some energy better than pay for new capacity. Then, the cost of not supplying energy is what finally determine the results of the capacity expansion problem. In this case, the mix should always remain constant in order to cover the demand; however, thermal generation deployed decrease as wind increases and thus, part of energy is not supplied. Apart from that, it is remarkable that from scenario 6 onwards CCGT installed capacity decreases a lot. This is because the model does not decide the amount of megawatts installed (continuous problem) but the units installed (integer problem). In this case the solver decides to install one CCGT instead of two (From 420MW to 210MW). Technically speaking this is referred to as lumpiness.

4.3.2 Impact of a PHS on total system costs

In a capacity expansion problem it is crucial to add build costs to the total operation costs when evaluating total system's costs. In this dissertation, the build costs of thermal units were directly introduced in the model, however the PHS costs are added after the simulations were made. Furthermore, wind turbines' generation costs are not included. This is because wind is considered as a technology that although not being competitive is going to be deployed due to its numerous advantages. Apart from that, adding wind generation costs would not affect to the difference between both PHS scenarios analyzed in this section. Figure 21 shows the total system's costs for every scenario simulated:

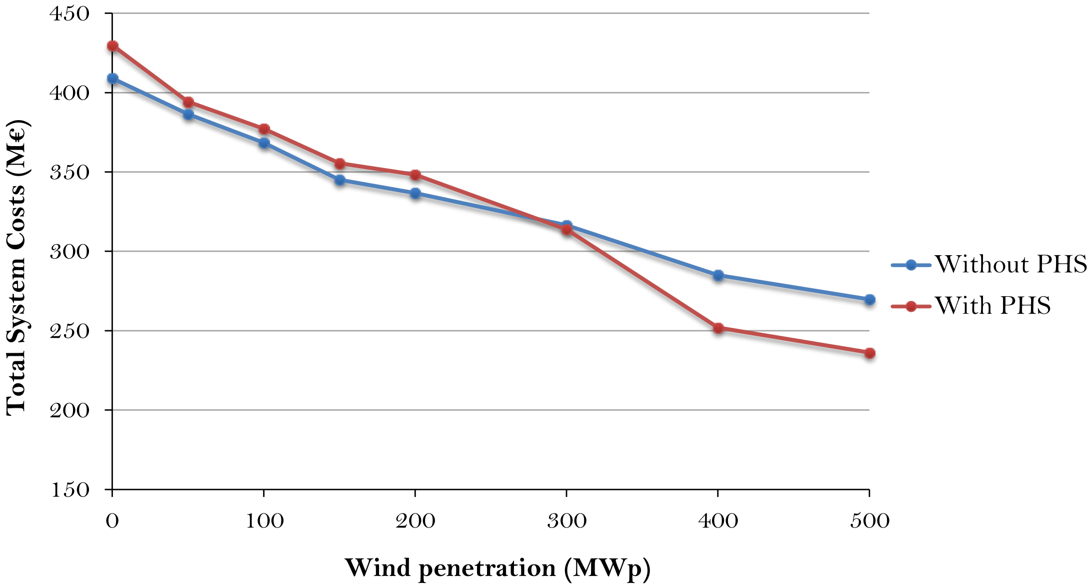


Figure 21 Total system costs in both PHS scenarios

The differences between these two functions are the system savings that are shown in Table vi:

Table vi System Savings when installing a PHS

Wind (MWp)	0	50	100	150	200	300	400	500
Savings (M€)	-20.81	-7.78	-8.83	-10.36	-10.53	2.55	33.17	33.54

It is directly observed that for the first five wind scenarios the PHS would not be profitable (savings are negative) but from the sixth scenario (300MW of wind) it starts to be a profitable investment. Therefore, it is proved that a high wind penetration scenario uplifts the value of energy storage systems. In this case the optimal wind installed capacity in order to install a PHS would be from 300MW onwards.

4.3.3 RES curtailment in different wind scenarios

Another interesting property is the RES curtailment, as already said when analyzing the short-term operation of a pumped hydro storage. Figure 22 shows the RES curtailment produced with and without PHS for the eight different wind scenarios considered:

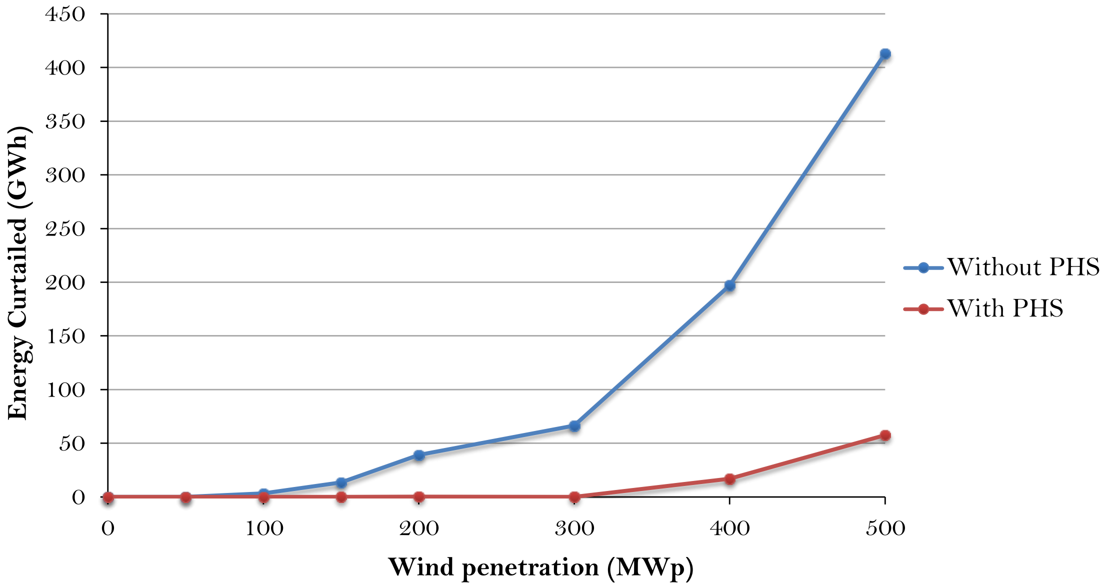


Figure 22 RES curtailment in different wind scenarios

When a PHS is operating, the system can cope with more wind power. In the power system analyzed, if there is a PHS, wind power can be up to 300MW without requiring any curtailment; however, if there is no energy storage, RES production is curtailed when wind output is higher than 100MW.

4.3.4 CO2 emissions

Finally, a direct consequence of introducing a PHS to a system with increasing wind penetration is that it reduces CO2 emissions, as already explained in Section 4.2.3, contributing to a system's costs decrease. Figure 23 shows the CO2 emissions abatement in different scenarios.

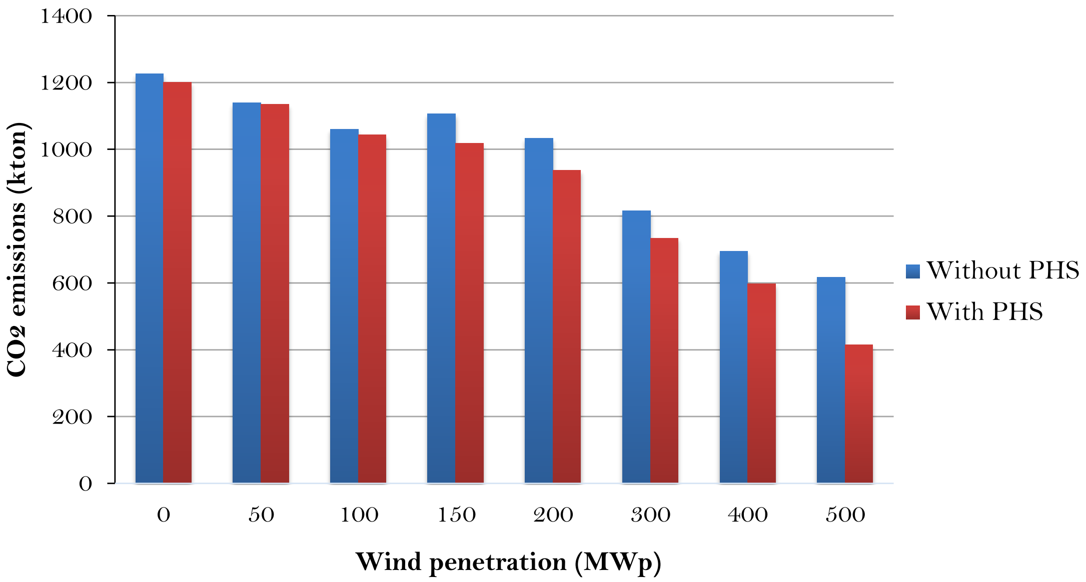


Figure 23 CO2 Emissions abatement in different wind scenarios

When a PHS is operating in a power system, CO2 emissions are lower. Furthermore, a high wind penetration exacerbates the CO2 emissions abatement.

CHAPTER 5.
CRITICAL ASSESMENT OF A COMMERCIAL MODELING TOOL

The previous chapter accomplishes the first goal of this dissertation, which was to analyze the interplay between VER and ESS. To do so, a set of models was used and different results were presented. These models have been developed with a commercial modeling tool called PLEXOS, see Section 3.3.1. This chapter presents a critical assessment of this commercial modeling tool, highlighting advantages and drawbacks found in the development of models for different timescales.

5.1 Short-term modeling

In PLEXOS, the short-term scheduling of generation units is simulated using a traditional unit commitment model which, as presented in Section 2.1, is based on economically optimizing power plants dispatch under a given a demand profile with a specific time resolution (usually 1-hour). PLEXOS allows to model different generation technologies as well as reserves constraints and CO2 emissions. Furthermore, it features some simplifications in chronology to reduce computation time in the case of solving complex problems.

5.1.1 Generators

As many other modeling tools, PLEXOS uses a generalized representation of generation units that the user can customize adjusting a set of parameters to model any generation technology. The generators modeled in this dissertation can be divided into thermal units, renewable energy sources and pumped hydro storage.

Thermal generation were modelled defining the most relevant parameters and constraints. These are maximum capacity, minimum stable load, start-up and shut-down costs, ramping capabilities and heat rate function (variable costs function). These parameters are typically found in classical unit commitment problems (Pang & Chen, 1976) and there are not many differences between PLEXOS and classical formulations found in the literature.

As for Variable Energy Resources (VER), they were deterministically modeled. In this way, it is a common practice to subtract VER production from the load profile. PLEXOS allows modeling these technologies with different approaches; however it finally turns everything in a load subtracting problem in which spills are taken into account. To clarify this approach, a possible formulation is presented:

$$Generation + NonSuppliedEnergy = Demand - VER + Spills$$

In this equation VER profile is subtracted to the demand but considering an additional term to model renewables spillage, which was relevant to obtain RES curtailment results in this dissertation. Apart from this approach, PLEXOS also allows modeling VER stochastically; however, this feature was not tested for this dissertation.

Finally, PLEXOS can also model pumped hydro storage with the expected level of detail. Properties modelled here are maximum and minimum generating capacity, maximum and minimum pumping load, pumping and generating efficiency and limits for the reservoir.

5.1.2 Reserves

In PLEXOS, reserves are co-optimized with the energy dispatch. This is, the cost of dispatching energy is optimized at the same time as the cost of reserving a band that is capable to respond to the generation and demand variations in real-time. This approach is very common and there are many references in which this co-optimization is presented (Tan & Kirschen, 2006). In thermal systems this approach can be enough to represent the short-term system's operation costs; however, when considering a PHS this problem becomes more complex.

In our analysis, the focus was on the savings produced by the introduction of a PHS. When providing reserves, PHS avoids the start-up of thermal units reducing operational costs. However, since PHS is an energy-limited resource, a reserve band does not guarantee full energy availability in real-time. To represent this limitation, PLEXOS defines reserves with a property called 'Duration'. This property defines the maximum time the reserve band might be used in real time operation, therefore, it allows the model to take into account that the PHS can only provide reserves if sufficient energy is stored in the reservoirs. For instance, a reservoir storing 1 MWh should only be able to provide 1MW of raise reserves if a 1-hour duration is defined for this type of reserves. However, when this feature was tested, the results clearly showed that PLEXOS was not properly including this constraint. This issue was reported to PLEXOS technical service and it is expected to be fixed in future releases.

Another source of potential cost savings derived from the PHS operation is because of its zero variable generation costs. To evaluate these savings, all the energy produced by the PHS units has to be accounted for. This includes the energy dispatched in the hourly program produced by our model, but also the energy delivered to provide reserves in real time. PLEXOS allows an approximate model of the reserves energy usage through the 'Energy Usage' property. This property indicates the percentage of the reserves band that is expected to be used in a hypothetical real time operation.

Finally, it is important to consider the ramping capabilities of units allowed to provide reserves. In real-time, extra-generation (in the case of raise reserves) is required within a certain time. The 'Timeframe' defines the ramping capability required to provide a certain type of reserves.

5.1.3 Major simplifications

When the problem modelled is too complex to solve or the level of detail required from the results is not high it is possible to make some simplifications. In this dissertation two simplifications were tested:

Heat Rate Function

The heat rate is one of the most relevant properties of a generator because it expresses the efficiency in fuel consumption. PLEXOS allows modeling this property in different ways:

- A linear heat input function with constant average and marginal heat rates
- A linear heat input function with constant marginal heat rate
- A polynomial heat input function
- Pairs of loading points and marginal heat rates
- Pairs of loading points and marginal heat rates with no-load cost defined as an average heat rate
- Pairs of loading points and average heat rates

In this dissertation, the heat rate function was represented as a second order polynomial function; this would make the optimization problem non-linear and therefore required some simplifications. PLEXOS divides this function in even length tranches from the minimum stable level. After that, it calculates the piecewise linear approximation to the marginal heat rate function based on the average marginal heat rate in each tranche. Transforming a polynomial function in a piecewise linear function is a common practice in power systems' modeling since it allows to deal with linear problems (Frangioni et al. 2009). To clarify this Figure 24 shows an example:

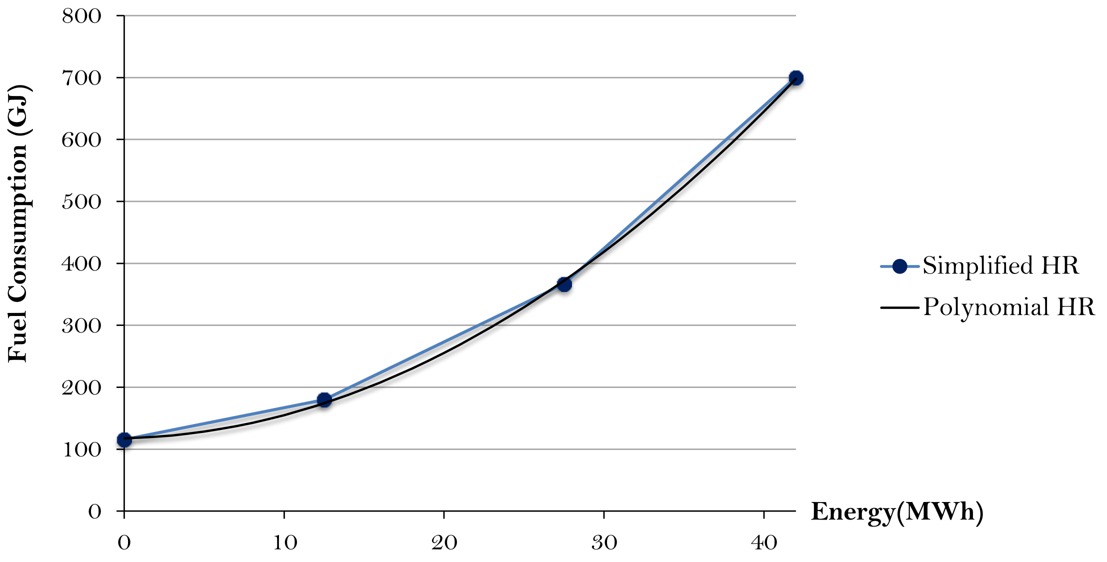


Figure 24 Convex Heat Rate Function

In this figure, the black line is the polynomial second order function requested by PLEXOS and the blue line is the piece-wise linear function. In this example there are three tranches but PLEXOS can divide the function in as many tranches as needed.

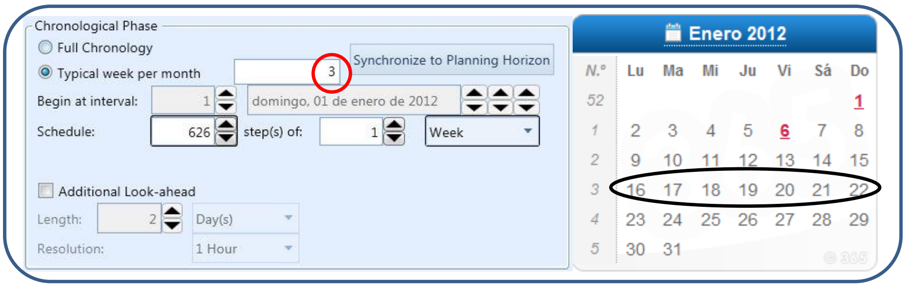
Piecewise linear representation of heat rate functions is a practical simplification when the function is convex. In this case, each of the segment introduces a linear constraint to the problem, which does not produce a huge increase in computational time. However, when the heat-rate function is non-convex, a different approach is required. In this case PLEXOS offers different options. One option is to allow PLEXOS to turn that curve into a convex one. This option completes the simulation process but it is changing the data introduced by the user and the output may not be as expected. Another option, is to use a formulation that allows to correctly represent non-convex piecewise linear functions. The drawback of this approach is that binary variables are introduced to the problem, greatly increasing computational time. This is a common approach found in the literature (Chang et al., 2008) (Anders et al., 2005).

Non-convex heat rate functions are typically used to represent CCGT units ("aggregated methodology"), but a more detailed representation is possible using a "configuration-based" methodology. This approach represents CCGTs with diverse mutually exclusive modes whose number depend on the possible combinations between steam and gas turbines and on the predefined transition path that must be followed. (Morales-España et al. 2015). The configuration-based methodology considers each unit's convex heat rate function separately using linear constraints; however, the transition between different configurations introduces binary variables, slowing down the problem. This is the most detailed representation allowed by PLEXOS and it is similar to the formulations typically found in the literature (Ammari & Cheung, 2013).

Chronology

The computational time required to run long-term simulations might make the model impractical in some cases. Some simplifications to the chronology of the problem are possible to reduce computational time, such as simulating just one hour per day, one day per week or one week per month, depending on the time horizon chosen. It is always necessary to ensure that using these simplifications will not completely compromise the results.

For instance, suppose that we choose to represent a full month using only one week per month. In PLEXOS, the user will specify the week to be used (First, second…) and the simulation will consider that the selected week is repeated four times. See Figure 25.



Chronological Phase

○ Full Chronology

● Typical week per month 3

Begin at interval: 1 domingo, 01 de enero de 2012

Schedule: 626 step(s) of: 1 Week

☐ Additional Look-ahead

Length: 2 Day(s)

Resolution: 1 Hour

Enero 2012

N.º	Lu	Ma	Mi	Ju	Vi	Sá	Do
52							1
1	2	3	4	5	6	7	8
2	9	10	11	12	13	14	15
3	16	17	18	19	20	21	22
4	23	24	25	26	27	28	29
5	30	31					

Figure 25 Example of short-term simplification

In this dissertation, some models were tested using this simplification. It is an acceptable approach when the weeks chosen are representative of the whole month however it can pose some problems when an unusual week is chosen as a sample. For example, imagine that the third week of the month (chosen as sample week) has an unusually high RES production, reporting a RES curtailment of 5GWh. This simplification will then assume that there is a curtailment of 20GWh in that month, which can be completely wrong. To clarify this, Figure 26 shows the RES curtailment obtained applying the one week per month simplification in a 12 year simulation.

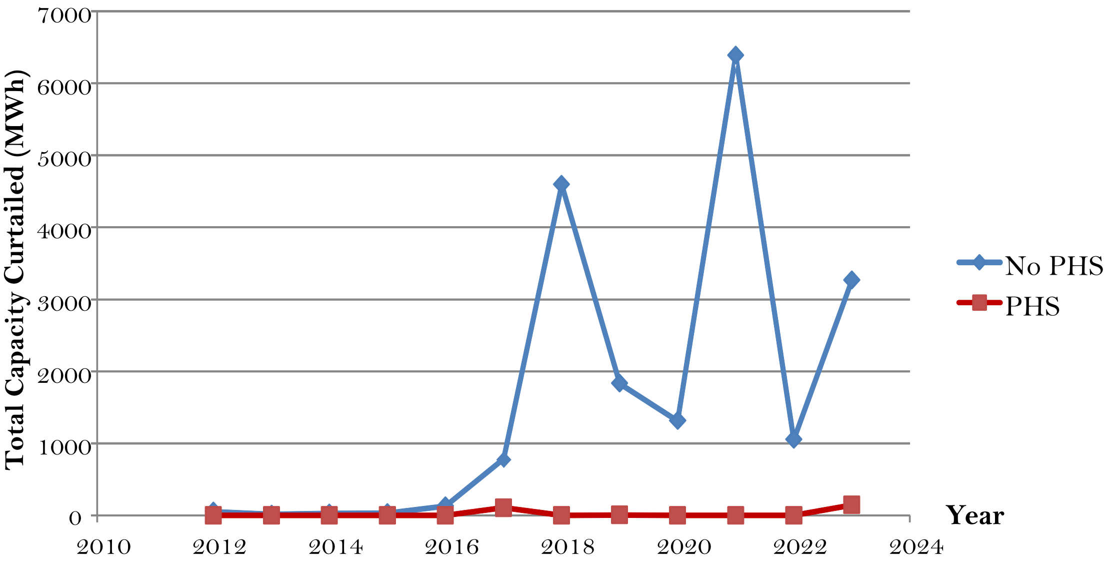


Figure 26 RES Curtailment obtained from simplified short-term simulations

As shown in this figure, there is more RES curtailment in 2018 than in 2020 or 2023, which is not a logical result because RES penetration increases yearly and thus the curtailment should also increase. As shown in previous chapters, when the full chronology is considered the results reported are smoother.

Another problem found in this simplification method is that it does not take into account the reservoir level between weeks within the same month, which can be an acceptable approximation depending on the results pursued or the system being modeled. In this dissertation a higher level of detail is required and thus, every simulation made was finally run at full chronology.

5.2 Long-term modelling

5.2.1 Capacity expansion problem

The term "capacity expansion" refers to the problem of finding the optimal generation mix that minimizes the total net present value of the total system's costs over a long-term planning horizon. To that end, PLEXOS requests a set of investment and retirements candidates that will be installed or retired depending on some parameters. In our case, these parameters are: non-supplied energy cost, reserves shortage cost and annualized investment costs.

The non-supplied energy cost is defined as the amount of money that consumers would pay in order to have a continuous electricity service. The estimation of this value is not simple and thus in this dissertation a typical academic value was used. PLEXOS allows modeling this parameter with different approaches. The most common one is the Value of Loss Load (VoLL) which is expressed in € that the system must pay per each MWh non-supplied. However, there are more ways to model the non-supplied energy such as LOLP (Lost of Load Probability, expressed in h/year) or minimum capacity (expressed in MW).

Another relevant property, if reserves have been modeled, is the reserves shortage cost which is how much will the system pay if reserve requirement is not covered. This parameter is also difficult to estimate, so an academic value was taken. To model this, PLEXOS has a property called Value of Reserve Shortage (VoRS) and it is expressed in € per MW of reserve not supplied.

Finally, PLEXOS is able to internally calculate annual investment costs by introducing a Weighted Average Cost of Capital (WACC), Economic Life and total investment costs of each investment candidate. Once introduced it calculates the annuities with the following formula:

$$Annuity = \frac{InvestmentCosts}{1-(1+WACC)^{-EconomicLife}}$$

In this dissertation annual investment costs were externally calculated with this formula and directly introduced to PLEXOS; however both approaches yield the same results.

5.2.2 Major simplifications

As said before it is not possible to solve the capacity expansion problem considering full chronology. There are three different simplifications offered by PLEXOS:

Partial Chronology

The time horizon is divided in days, weeks, months or years depending on the specification of the user. Then, a load duration curve (LDC) is created for each of these periods by ordering the original dispatch intervals from highest to lowest. The intervals in each duration curve are then grouped into a number of blocks which are created according to the user inputs.

In partial chronology, all system constraints are applied, except those that deal with unit commitment and other inter-temporal constraints that imply a chronological relationship between individual intervals. Storage is balanced between duration curves, but not within the curves and thus it was not an acceptable simplification in our simulations.

Fitted Chronology

LT Schedule preserves the original order of intervals, but instead of simulating every interval it combines them together so that only the designated number of blocks is modeled in each day/week/month/year. The fitting is done using the weighted-least squares method.

For the fitted chronology simulation, all system constraints are applied including generator unit commitment, and storage is balanced every simulation period. The compromise here is that the duration of each simulation period can vary according to the result of the fitting and thus some accuracy is lost in modeling ramp and unit start-up and shutdown. Since ramping and start-ups were something crucial to represent in this project, this simplification was not considered valid either.

Sampled Chronology

With this approach, periods are preserved but only the specified number of those periods is selected for modeling. The remaining periods are mapped to the samples so that a full set of results is obtained and elements such as storage and inter-temporal constraint objects evaluate correctly. Since the goal of this dissertation is to correctly analyze storage, inter-temporal constraint assessment is vital and thus sampled chronology is the one used for long-term simulations.

It is very common to find this simplification in practice, using some representative weeks to represent the whole year. In our case, four weeks were taken to represent a full year. The main drawback of this method is the loss of resolution that may exacerbate or underestimate the impact of rare events. Although it is far from perfect, this was considered the best method available for the goals of this dissertation. When running large simulation models it is always necessary to use some simplifications, in our case it was preferred to use simplifications in the chronology while keeping all the details necessary in the representation of power plants.

5.3 Solver and Simulation parameters

Other relevant features of PLEXOS are briefly presented here.

Xpress-MP Solver

Xpress-MP is a solver engine developed by Dash Optimization which solves from linear programming problems to mixed-integer quadratic problems with relatively good performance. In Table vii the speed and optimality gap achieved when simulating the different models is shown.

Table vii Xpress-MP solving speed[2]

	Simulation time	**Optimality Gap**
1-Week Short-term Simulation	7.093s	0.9075%
9-Years Short-term without PHS	17 min 54.63s	0.6887%
9-Years Short-term with PHS	3h 9min 59.7s	0.9149%
Greenfield Scenarios (Without PHS)	46s - 2min 36s	0.23-0.953%
Greenfield Scenarios (With PHS)	1min 23s - 5min 36s	1.4816 – 1.8920%

Solving a 1-week unit commitment in which reserves are modelled takes 7 seconds, which is an acceptable time. If the same problem is solved for nine years it takes much more time. Furthermore, it is remarkable to see the way in which introducing a PHS increases the simulation time. The PHS increases the number of variables and constraints in the problem, and produces a much harder to solve optimization problem. The Greenfield scenarios (capacity expansion problems) take a much shorter time to solve than the short term model despite their higher complexity (additional binary variables because of investment decisions), this is because they only consider a one year time horizon that is further simplified to four weeks.

No major drawbacks were identified on the interaction between PLEXOS and the solver. The only problem found was that PLEXOS version 7.100 had some compatibility issues with the Xpress-MP solver which affected its multi-thread capabilities and slowed down the computation time.[3]

Unit commitment optimality

The unit commitment optimality is used to express how integer variables are treated in the optimization. There are three options:

- Integer Optimal. The usual method to solve a Mixed Integer Program (MIP) without simplifications. The solution reported is integer and guaranteed to be within a given threshold (optimality gap) of the optimal solution. This was the option used in this project.
- Rounded Linear Relaxation. Initially, the mixed integer problem is solved relaxing the integer variables and allowing non-integer solutions. The solver then rounds those non-integer values to the closest integer depending on the rounding up

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[2] The optimization was run on an Intel Core i7-4710MQ CPU@ 2.50GHz, 64bits 16GB RAM

[3] This error was provisionally fixed and it is expected to be completely solved in future software releases

threshold defined[4]. It is an acceptable method when a fast solution is required; however, the gain in computational time was not found to be sufficient to justify the loss of accuracy for the objectives of this dissertation.

- Linear Relaxation. The integer constraints on unit commitment are relaxed and non-integer values are now accepted. This simplification method can greatly distort the outputs and, although it is the fastest option, it considered valid in this project.

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[4] The roundig up threshold indicates a limit from which non-integer values are rounding up. For instance, if the solution is 0.8, and the rounding up threshold is defined to be 0.7, the solver will round up this value to 0; however if the threshold is 0.6 it will turn into 1.

CHAPTER 6. CONCLUSIONS

This project has carried out a complete analysis on the value of energy storage in electric power systems. The emphasis of this study is on the interaction between renewable energy sources and energy storage systems (ESS). The methodology developed for the analysis is based on short-term and long-term simulation models that were developed using a commercial power systems modeling tool (PLEXOS). These models have been applied to a real-size case example in a small isolated power system (Tenerife Island). Additionally, the limitations of the modeling tools employed have been examined in order to identify new requirements in power systems models dealing with storage systems and renewable energy sources.

The main impacts produced in the operation of the power system by an ESS are: a more efficient operation of the thermal fleet, and a reduction of RES curtailment. Therefore, an ESS reduces system operational costs and a CO_2 emissions. In the case-example, an investment in a pumped hydro storage unit was evaluated, concluding that operational costs savings were not sufficient to clearly make the investment cost-effective. However, ESS can also reduce the need for investments in thermal capacity; it was shown that the value of ESS increases with the penetration of RES, and the investment analyzed was found to be cost-effective under a large enough penetration of wind energy in Tenerife.

The commercial modeling tool evaluated (PLEXOS) was capable of a sufficiently good representation of hydro-thermal systems, although some limitations were identified when modeling small ESS, especially to represent the effects of operational reserve provision in the very short-term.

LIST OF REFERENCES

Ammari, S., & Cheung, K. W. (2013, June). Advanced combined-cycle modeling. In PowerTech (POWERTECH), 2013 IEEE Grenoble (pp. 1-5). IEEE.

Anders, G., Eng, P., England, I. N., & Morched, A. (2005). Commitment techniques for combined-cycle generating units. Kinectrics Inc., Report T053700-3103.

Carrión, M., & Arroyo, J. M. (2006). A computationally efficient mixed-integer linear formulation for the thermal unit commitment problem. Power Systems, IEEE Transactions on, 21(3), 1371-1378.

Castronuovo, E. D., & Peas Lopes, J. A. (2004). On the optimization of the daily operation of a wind-hydro power plant. Power Systems, IEEE Transactions on, 19(3), 1599-1606.

Chang, G. W., Chuang, G. S., & Lu, T. K. (2008, July). A simplified combined-cycle unit model for mixed integer linear programming-based unit commitment. In Power and Energy Society General Meeting-Conversion and Delivery of Electrical Energy in the 21st Century, 2008 IEEE (pp. 1-6). IEEE.

Comission for Energy Regulation, (2015). Decision Documents. [online] Available at: http://www.allislandproject.org/en/market_decision_documents.aspx?article=261a5576-bd83-4544-b250-7b18b55bd9ba [Accessed 14 November 2014].

Daneshi, H., Srivastava, A., 2012. Security-constrained unit commitment with wind generation and compressed air energy storage. IET Generation, Transmission Distribution 6, 167–175. doi:10.1049/iet-gtd.2010.0763

Red Electrica De España, (2015).– *Seguimiento de la demanda de energía eléctrica - Canarias.* [online] Available at: https://demanda.ree.es/visionaCan/VisionaTenerife.html# [Accessed 6 March 2015].

Desarrollo Normativo de la Ley del Sector Eléctrico. (2008). In: 1st ed. Madrid: CNE, vol.10, pp.126-138.

Díaz-González, F., Sumper, A., Gomis-Bellmunt, O., & Villafáfila-Robles, R. (2012). A review of energy storage technologies for wind power applications.*Renewable and Sustainable Energy Reviews*, *16*(4), 2154-2171.

Dietrich, K., Latorre, J., Olmos, L., Ramos, A., & Perez-Arriaga, I. (2009, April). Stochastic unit commitment considering uncertain wind production in an isolated system. In *4th Conference on Energy Economics and Technology, Dresden, Germany* (pp. 1-6).

E-Sios, (2012). *Red Eléctrica de España, S. A. U. Sistema de Información del Operador del Sistema..* [online] Available at: http://www.esios.ree.es/web-publica/ [Accessed 20 October 2014].

Frangioni, A., Gentile, C., & Lacalandra, F. (2009). Tighter approximated MILP formulations for unit commitment problems. Power Systems, IEEE Transactions on, 24(1), 105-113.

Garcia-Gonzalez, J., de la Muela, R. R., Santos, L. M., & González, A. M. (2008). Stochastic joint optimization of wind generation and pumped-storage units in an electricity market. Power Systems, IEEE Transactions on, 23(2), 460-468.

Gu, Y., Bakke, J., & McCalley, J. (2014). Day-Ahead and Real-Time Markets Simulation Methodology on Hydro Storage. Energy Storage for Smart Grids: Planning and Operation for Renewable and Variable Energy Resources (VERs), 201.

Hobbs, B. F. (1995). Optimization methods for electric utility resource planning. *European Journal of Operational Research*, *83*(1), 1-20.

Mahlia, T. M. I., Saktisahdan, T. J., Jannifar, A., Hasan, M. H., & Matseelar, H. S. C. (2014). A review of available methods and development on energy storage; technology update. *Renewable and Sustainable Energy Reviews, 33, 532-545.*

Meibom, P., Barth, R., Hasche, B., Brand, H., Weber, C., & O'Malley, M. (2011). Stochastic optimization model to study the operational impacts of high wind penetrations in Ireland. Power Systems, IEEE Transactions on, 26(3), 1367-1379.

Ministerio de Industria, Energía y Turismo. Resolución de 24 de julio de 2012, de la Secretaría de Estado de Energía, por la que se aprueba la modificación de los procedimientos de operación del Sistema Eléctrico Peninsular (SEP) P.O.-3.1; P.O.-3.2; P.O.-9 y P.O.-14.4 y los procedimientos de operación de los Sistemas eléctricos Insulares y Extrapeninsulares (SEIE) P.O. SEIE-1 P.O. SEIE-2.2; P.O. SEIE-3.1; P.O. SEIE-7.1; P.O. SEIE-7.2; P.O. SEIE-8.2; P.O. SEIE-9 y P.O. SEIE-2.3 para su adaptación a la nueva normativa eléctrica. Boletín Oficial del Estado, 2012. p. 57263

Ministerio de Industria, Energía y Turismo. Resolución de 9 de febrero de 2015, de la Dirección General de Política Energética y Minas, por la que se fijan los precios de los combustibles de los años 2012, 2013 y 2014 distintos del gas natural a aplicar en el cálculo de la prima de funcionamiento de cada grupo generador y los precios provisionales del primer semestre de 2015 en los sistemas eléctricos de los territorios no peninsulares. Boletín Oficial del Estado, 2015. p.11575

Morales-España, G., Latorre, J.M., Ramos, A., 2013. Tight and Compact MILP Formulation for the Thermal Unit Commitment Problem. IEEE Transactions on Power Systems 28, 4897–4908. doi:10.1109/TPWRS.2013.2251373

Morales-España, G., Correa-Posada, C. M., & Ramos, A. Tight and Compact MIP Formulation of Configuration-Based Combined-Cycle Units.

Ortega-Vazquez, M. A. (2014). Optimal scheduling of electric vehicle charging and vehicle-to-grid services at household level including battery degradation and price uncertainty. *IET Generation, Transmission & Distribution, 8*(6), 1007-1016.

Pang, C. K., & Chen, H. C. (1976). Optimal short-term thermal unit commitment. Power Apparatus and Systems, IEEE Transactions on, 95(4), 1336-1346.

Parvania, M., & Fotuhi-Firuzabad, M. (2010). Demand response scheduling by stochastic SCUC. Smart Grid, IEEE Transactions on, 1(1), 89-98.

Rodilla, P., Cerisola, S., Batlle, C. (2014). Modeling the Major Overhaul Cost of Gas-Fired Plants in the Unit Commitment Problem. *IEEE Transactions on Power Systems*, 29(3), 1001-1011.

Sigrist, L., Lobato, E., & Rouco, L. (2013). Energy storage systems providing primary reserve and peak shaving in small isolated power systems: an economic assessment. International Journal of Electrical Power & Energy Systems, 53, 675-683.

Tan, Y. T., & Kirschen, D. S. (2006, October). Co-optimization of energy and reserve in electricity markets with demand-side participation in reserve services. In Power Systems Conference and Exposition, 2006. PSCE'06. 2006 IEEE PES (pp. 1182-1189). IEEE.

Tuohy, A., Meibom, P., Denny, E., & O'Malley, M. (2009). Unit commitment for systems with significant wind penetration. Power Systems, IEEE Transactions on, 24(2), 592-601.

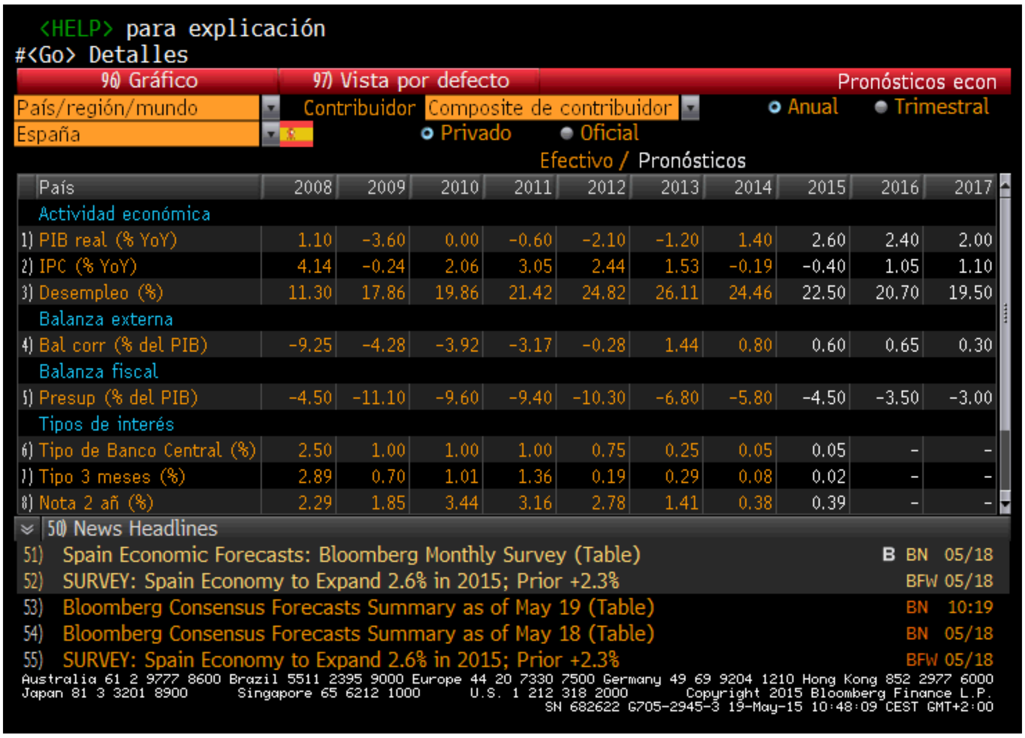
Veiga, A., Rodilla, P., Herrero, I., & Batlle, C. (2015). Intermittent RES-E, cycling and spot prices: the role of pricing rules. Electric Power Systems Research, 121, 134-144.

Vergara, C.R., 2014. Representing Battery Energy Storage in Electric Power Systems Studies. PhD Thesis, University of Port

TABLE OF APPENDIXES

Appendix A. Bloomberg Forward Curves

Figure 27 Brent barrel forward curve



Efectivo / Pronósticos

País	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Actividad económica										
1) PIB real (% YoY)	1.10	-3.60	0.00	-0.60	-2.10	-1.20	1.40	2.60	2.40	2.00
2) IPC (% YoY)	4.14	-0.24	2.06	3.05	2.44	1.53	-0.19	-0.40	1.05	1.10
3) Desempleo (%)	11.30	17.86	19.86	21.42	24.82	26.11	24.46	22.50	20.70	19.50
Balanza externa										
4) Bal corr (% del PIB)	-9.25	-4.28	-3.92	-3.17	-0.28	1.44	0.80	0.60	0.65	0.30
Balanza fiscal										
5) Presup (% del PIB)	-4.50	-11.10	-9.60	-9.40	-10.30	-6.80	-5.80	-4.50	-3.50	-3.00
Tipos de interés										
6) Tipo de Banco Central (%)	2.50	1.00	1.00	1.00	0.75	0.25	0.05	0.05	-	-
7) Tipo 3 meses (%)	2.89	0.70	1.01	1.36	0.19	0.29	0.08	0.02	-	-
8) Nota 2 añ (%)	2.29	1.85	3.44	3.16	2.78	1.41	0.38	0.39	-	-

50) News Headlines

51) Spain Economic Forecasts: Bloomberg Monthly Survey (Table) B BN 05/18
52) SURVEY: Spain Economy to Expand 2.6% in 2015; Prior +2.3% BFW 05/18
53) Bloomberg Consensus Forecasts Summary as of May 19 (Table) BN 10:19
54) Bloomberg Consensus Forecasts Summary as of May 18 (Table) BN 05/18
55) SURVEY: Spain Economy to Expand 2.6% in 2015; Prior +2.3% BFW 05/18

Figure 28 GDP Consensus Estimations

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<HELP> para explicación. <MENU> para más funciones.
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Australia 61 2 9777 8600 Brazil 5511 2395 9000 Europe 44 20 7330 7500 Germany 49 69 9204 1210 Hong Kong 852 2977 6000
Japan 81 3 3201 8900       Singapore 65 6212 1000       U.S. 1 212 318 2000       Copyright 2015 Bloomberg Finance L.P.
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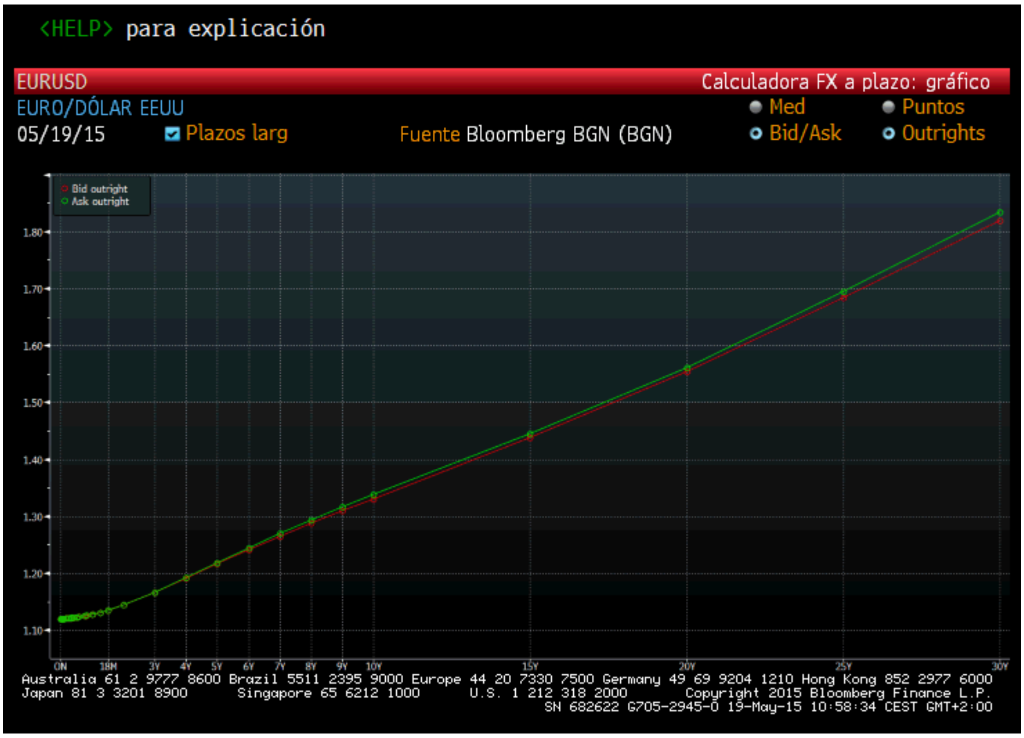
Figure 29 Gasoil forward curve



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Japan 81 3 3201 8900       Singapore 65 6212 1000       U.S. 1 212 318 2000       Copyright 2015 Bloomberg Finance L.P.
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Figure 30 €/$ currency exchange forward curve

<HELP> para explicación. <MENU> para más funciones.

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Japan 81 3 3201 8900       Singapore 65 6212 1000       U.S. 1 212 318 2000         Copyright 2015 Bloomberg Finance L.P.
                                                          SN 682622 G705-2945-3 19-May-15 12:19:50 CEST GMT+2:00
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Figure 31 CO2 prices forward curv