*“Innovative **grid-impacting technologies** enabling a clean,*

efficient and secure electricity system in Europe”

Spanish case study on transmission grid expansion fostering large-scale RES-Electricity and storage integration

Deliverable 5.4

(Source: REE)

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Executive Summary

The major goal of the GridTech project is to conduct a fully integrated impact assessment of the implementation of innovative transmission network, bulk storage, and demand-side technologies into the European electricity system in order to exploit the full potential of RES generation across Europe, with lowest possible total electricity system cost. The time frame of GridTech analyses is up to the year 2050, with a particular focus on the target years 2020, 2030 and 2050.

Under the project framework, regional analyses focusing on grid RES integration issues to be dealt with in seven target countries – Ireland, the Netherlands, Germany, Spain, Italy, Austria and Bulgaria – within different time horizons were carried out: (i) in the short-term (from 5 to 10 years time horizon), analyses are focused on technologies that optimize the use of the existing transmission network and on the effects of these technologies on power system operation and integration of RES generation; (ii) in the long-term (target years 2030 and 2050), analyses are focused on innovative technologies implemented to integrate larger shares of RES generation.

The Spanish case study analyses comprise the assessment of different technologies in terms of their impact on system operation costs. I.e. the analyses focus on the comparison of power system operation with and without the studied technology for each time-horizon and the benefits computed are related to system operation cost savings.

The 2020 study focuses on the installation of FACTS devices in the Southern Spanish transmission network to facilitate the integration of RES power coming from Morocco, assuming a significant deployment of RES generation in North Africa by 2020. Since the analysis is focused on the installation of a single FACTS device to avoid local grid constraints in the network area close to the interconnection with Morocco, it is assumed that power flows in the remaining interconnections are not affected by the use of this device.

In the 2030 analyses the impact of CAES storage and DSM (modeled as load-shifting) is assessed. These technologies are considered to be used in the whole Spanish system and the amounts of RES production integrated through them are expected to be largely higher than in the 2020 horizon study. Hence, the effects of CAES and DSM on interconnection power flows can be significant. Therefore, for this time-horizon, both the Spanish and the French systems are modeled.

In the long-term, massive amounts of RES generation are expected to be deployed. As uncertainties related to grid developments and integration solutions applied are significantly higher than in the above-mentioned time horizons, two alternative types of solutions are analyzed in the 2050 study: the first one considers the development of an HVDC supergrid to bring RES electricity from North Africa to Europe, based on the DESERTEC vision, in which an ambitious level of interconnection capacities is considered, and the second one focus on "local" or country level solutions such as DSM and electric vehicles to integrate RES generation. For this time-horizon, the Spanish, the French, the German and the Moroccan systems are modelled. The French and the German systems are included due to the fact that they are important demand centres in Europe that can absorb part of the power imported

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from the north of Arica, and Morocco is included due to the importance of Morocco-Spain power flows under the DESERTEC vision.

Benefits obtained from the use of the aforementioned technologies in the several scenarios vary largely across the technology and time dimensions. In the short term, the increase of the amount of RES energy imported thanks to the FACTS device results in a reduction in operation costs of approximately 30M€/year. According to the estimated technology cost, FACTS devices can be a cost-efficient solution to integrate more RES generation.

In the 2030 horizon, the potential benefits of DSM and CAES in terms of operation costs savings varied between 9 M€ and 180 M€/year, approximately. This significant difference is mainly related to the different efficiency levels considered in the processes of "storing" and "generating" electricity (65% and 100%, respectively). Considering the estimated technologies' costs and the economic benefits obtained, it can be argued that the annualized investment required for the implementation load-shifting or storage solutions with very high efficiency levels could be compensated by savings in operation costs. Nevertheless, for a complete cost-benefit analysis the assessment of all possible benefits of these technologies would be required, especially for lower efficiency levels.

In the 2050 horizon, the potential benefits of the development of a supergrid were estimated in more than 3,000 M€/year in terms of operation costs savings. According to the results, the implementation of DSM added to the introduction of EVs could produce cost savings of about 515 M€/year. It important to point out that, while the supergrid scenario provides much higher economic benefits, it would also require huge investment amounts. Therefore, policy makers must take into account all infrastructure investments and transaction costs associated to the high-level coordination required, as well as all potential benefits (not only those resulting from operation cost savings) when deciding to adopt or not an EU-wide solution.

Table of Contents

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Acronyms

CAES: Compressed Air Energy Storage

CSP: Concentrated solar power

DLR: Dynamic line rating

DSM: Demand-side management

EV: Electric vehicle

FACTS: Flexible AC Transmission Systems

HVDC: High-Voltage Direct Current

PHES: Pumped hydro energy storage

PSS/E: Power System Simulator for Engineering

PV: Photovoltaic

REE: Red Eléctrica de España

RES: Renewable Energy Sources

TSO: Transmission system operator

V2G: Vehicle-to-Grid

WP: Work Package

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1 Introduction

1.1 The Gridtech approach

The major goal of GridTech is to conduct a fully integrated impact assessment of the implementation of innovative transmission network, bulk storage, and demand-side technologies into the European electricity system in order to exploit the full potential of RES generation across Europe, with lowest possible total electricity system cost. The time frame of GridTech analyses is up to the year 2050, with a particular focus on the target years 2020, 2030 and 2050.

For this purpose, pan-European scenarios for future RES generation, as well as for innovative grid-impacting technologies' implementation, have been defined for each target time-horizon (i.e. 2020, 2030 and 2050). The set-up of these scenarios has required the acquisition of a comprehensive set of reliable data. Taking into account these scenarios, two types of cost-benefit analyses for innovative transmission/storage/demand-side technology investments are carried out within the project:

- Top-down, pan-European analyses which enable the analysis of electricity flows in the meshed pan-European transmission grid, and the identification of inter-regional transmission bottlenecks and possible relief actions carried out in a transnational context, through the implementation of different innovative technologies.
- Bottom-up, country-specific/regional analyses which focus on the individual peculiarities of single electricity systems (i.e. a single European target country or area and its neighboring systems).

The regional analyses carried out in WP5 of GridTech introduce the following novel aspects in relation to existing country-specific RES integration studies:

  - The regional analyses focus on grid RES integration issues to be dealt with in different time-horizons: (i) in the short-term (from 5 to 10 years time horizon), analyses are focused on technologies that optimize the use of the existing transmission network and on the effects of these technologies on power system operation and the integration of RES generation; (ii) in the long-term (target years 2030 and 2050), analyses are focused on innovative technologies deployed to integrate larger shares of RES generation.
  - Analyses are carried out of the interdependences ("breathing") that exist between a national electricity system and neighboring ones that result from the use made of regional infrastructure assets (interconnection capacity and storage capacity).
  - In-depth annual analyses of the functioning of the targeted regional systems under extreme conditions (summer/winter, high/low load, high/low wind and/or PV generation, dry/wet hydro generation situation, etc.) occurring over short periods of time (from several hours to a few days) are conducted.

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- Based on the above mentioned regional studies, cost-benefit analyses of grid-impacting technologies for different technology portfolios (available in each time-horizon) for each target country are conducted whenever this is possible.

Regional analyses were performed for seven selected countries:

- Ireland: high wind and other offshore generation potentials. Despite these potentials, the country faces the challenge of accommodating large amounts of RES production due to the lack of interconnection capacity with neighboring countries and Continental Europe.
- The Netherlands: large potentials for both onshore and offshore wind generation. The country plays a relevant role in the design of the future offshore grid in the North Sea since it may became a major transit area crossed by large power flows coming from the North Sea to supply the load in Continental Europe.
- Germany: country with the highest wind and solar PV installed capacities in Europe. Such high amounts of RES production can have significant impacts in the national and trans-national grid.
- Spain: the country has one of the largest wind penetration shares in Europe and high potentials for solar generation and it may became an important transit country with power flows coming from North Africa to supply load in Europe. High penetration of RES generation added to weak interconnection capacity with the rest of Europe is likely to increase the demand for innovative grid-impacting technologies.
- Italy: high wind and solar potentials. While these potentials are located in the South of the country, demand is concentrated in the North, which leads to the need to transport significant amounts of power over long distances. Furthermore, as well as Spain, Italy may play an important role in interconnecting Europe and North Africa and the Western Balkan.
- Austria: high shares and potentials still to be deployed of pumped hydro storage, which can be operated in combination with large amounts of wind and solar generation to be installed in Northern and Southern Europe, respectively. Nevertheless, in order to enable this combined operation an adequate and sufficient development of the transmission grid is needed.
- Bulgaria has high wind potential and considerable pumped storage capacity. This storage capacity is of strategic importance to balance generation intermittency in South-East Europe. For this purpose transmission interconnection capacity between Bulgaria and the other countries of the region is needed.

In order to guarantee robust methodology implementation, critical discussion and review of preliminary results of regional case studies with regional target groups and stakeholders, a regional workshop was organized in each one of the seven target countries. More specifically, the regional workshops aimed at:

- Presenting the interim results of the project to the national energy community;
- Gathering feedback from national target groups and stakeholders in order to incorporate the received opinions into the study in order to fine-tune or modify the analyses whenever needed;
- Attracting attention to the final dissemination and communication activities of the overall GridTech project.

The main discussions and conclusions obtained from the regional workshops can be found in (Burgholzer et al., 2015).

1.2 Overview of the regional approach

Spain has one of the largest wind penetration shares in Europe and high potentials for solar generation. In 2013, the share of the total Spanish demand represented by RES power production reached 32%[1]. Within this overall amount, wind energy reached 69% and solar power 16%. According to current European (and Spanish) regulation, RES generation enjoys dispatch priority. Nevertheless, if system security is threatened, RES curtailment can be applied as a last resort measure. This mainly occurs in situations where grid congestion exists, preventing RES power output to be shifted to other areas in the system or when there is an excess of generation in the overall system. Figure 1.1 shows, for each of the last 5 years, the total annual wind power production curtailed due to local network congestion and overall excesses of available power production. Wind energy curtailment is expressed as shares of the total wind power production[2].

[1] This value does not include generation from large hydro power plants (i.e. typically power plants larger than 10MW).
[2] The value for the year 2014 was computed based on data available for the months of January until October 2014.

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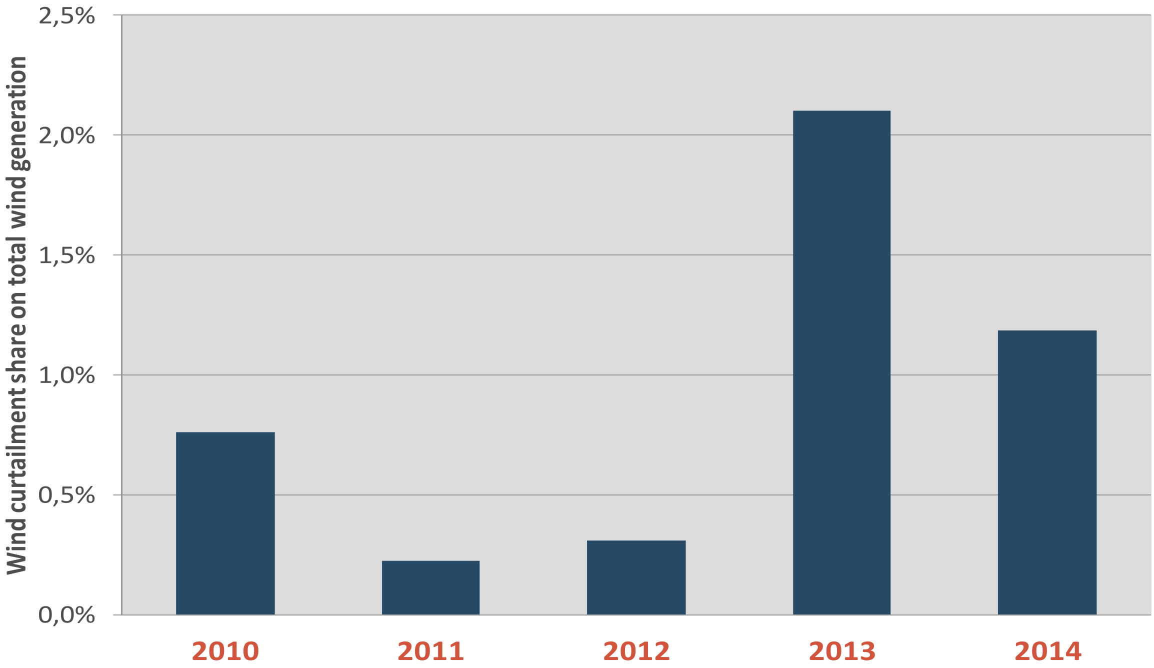

Figure 1.1: Wind curtailment in Spain (Source: REE)

The graph shows that in 2013 and 2014 the amount of wind energy curtailed increased significantly with respect to previous years and reached more than 2% of the total wind power production in 2013. In a near future, when higher RES installed capacities are achieved, curtailment levels can increase significantly in Spain, especially due to the fact that the Iberian Peninsula is still poorly interconnected with the rest of Europe (through the interconnection between Spain and France, featuring 1.4 GW of existing transfer capacity plus 1.4 GW of additional capacity corresponding to the new HVDC link).

Avoiding curtailment and integrating significant amounts of RES generation require investing in network capacity (including interconnection capacity) and/or storage and demand-side management (DSM) solutions. The analyses performed within the GridTech project for the Spanish system consider solutions for RES integration issues to be dealt with in different time horizons, i.e. 2020, 2030 and 2050. These are briefly described next:

- **2020**: The short-term analysis focuses on the use of technologies that allow a higher use of the existing transmission grid without jeopardizing system reliability, such as Flexible AC Transmission Systems (FACTS) devices. In this analysis, the FACTS technology considered refers to a device that re-directs through parallel corridors having extra available capacity power flows occurring on congested lines. By avoiding or reducing local grid congestion, this device contributes to RES generation integration. More specifically, the 2020 study focuses on the installation of a FACTS device in the Southern Spanish transmission network to facilitate integration of RES power imported from Morocco, assuming a significant deployment of RES generation in North Africa by 2020. Since the analysis is focused on the installation of a single FACTS device to avoid local grid constraints in the network area close to the interconnection with Morocco, it is assumed that power flows in the remaining interconnections are not affected by this device.

- **2030**: The mid to long-term analysis focuses on the use of innovative technologies including DSM and advanced storage to integrate higher amounts of RES generation and avoid significant RES generation curtailment. More specifically, CAES storage and load-shifting are separately analyzed. Since these technologies are considered to be deployed at the whole Spanish system level and the amounts of RES production integrated are expected to be higher than in the 2020 horizon study, the effects on interconnection power flows can be significant. Therefore, in the 2030 horizon, both the Spanish and the French systems are modeled.
- **2050**: In the long-term, massive amounts of RES generation are expected to be deployed. As uncertainties related to grid developments and RES integration solutions are significantly higher than in the above-mentioned time horizons, two alternative types of solutions are analyzed in the 2050 study: the first one considers the development of an HVDC supergrid to bring RES electricity from North Africa to Europe based on the DESERTEC vision[3] (in which ambitious levels of RES generation and transmission interconnection capacity between Europe and Africa are deemed to be achieved); the second one focuses on the implementation of "local" or country level solutions such as DSM and electric vehicles to integrate RES generation.

The remainder of this document describes the case studies assembled, the applied methodologies, the main assumptions made, the results computed and conclusions and policy recommendations drawn from the 2020, 2030 and 2050 analyses.

[3] http://www.dii-eumena.com/

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2 2020 Analysis

2.1 Case study description

The 2020 analysis focuses on the use of technologies that allow a higher use of the existing transmission grid without jeopardizing system reliability, such as FACTS devices. More specifically, this study aims at analyzing up to what extent a FACTS device could contribute to integrate RES electricity production imported from North Africa into the Spanish transmission network.

Currently, power in the Spanish-Moroccan interconnection flows from Spain into Morocco during almost 100% of the time. The 2020 study considers the possibility of Spain importing power through this interconnection during some hours of the year, as a consequence of the installation of significant RES generation capacity in North Africa. RES power coming from North Africa together with the existing large generation capacity connected to the Southern Spanish transmission grid may cause overloads if contingencies occur in the 400 kV Southern corridors. If overloads occur, RES imports from Morocco may be limited. In this study, a FACTS device is used to prevent overloads from occurring in those situations where Spain imports RES power from North Africa. Figure 2.1 shows the Southern Spanish transmission network and the generation connected to it, as well as the interconnection with Morocco.

Figure 2.1: Area of study in the 2020 horizon

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The FACTS technology considered in this analysis is a mobile Overload Line Controller which comprises mechanically switched reactances connected in series. This is the same technology that has been installed by the Spanish TSO in the 220 kV Magallón-Entrerríos line in Aragón (North of Spain) under the framework of the Twenties project (Sánchez, 2011). This device allows power flows to be redirected from a congested line to parallel corridors, through the modification of the impedance introduced in the former, avoiding overloads and, consequently, contributing to a higher integration of RES generation.

The 2020 study is divided into two parts. First, a detailed technical analysis of the impact of the FACTS device on power flows in the Southern Spanish (Andalusia) transmission network is performed. The Power System Simulator for Engineering – PSS/E – is the tool used to perform power flow analyses in order to identify overloads, which drive the selection of the location of the FACTS device, and to calculate the additional RES power that could be imported from North Africa thanks to this FACTS device. Once the additional RES imports made possible are computed, a mid-term operation model (the ROM model) is used to analyze the impact of these imports on the Spanish power system operation variables and costs.

2.2 Brief Methodology overview and assumptions

The methodology applied in the 2020 analysis is divided into three steps: 1) calculation of power flows in the Spanish-Moroccan interconnection; 2) identification of overloads in the Southern Spanish network during hours of RES imports and computation of additional RES generation being imported from North Africa in these hours thanks to the installation of the FACTS device; 3) analysis of the impact of the additional RES power imports on the Spanish power system operation.

1) Computation of power flows in the Spanish-Moroccan interconnection

Power flows in the Spanish-Moroccan interconnection were computed considering the following simplifying hypotheses regarding the Moroccan power system:

- Moroccan demand: 5% growth rate per year during the period 2012-2020. Demand profile is assumed to be similar to the Spanish one;
- RES installed capacity: 2,000 MW of wind; 2,000 MW of concentrated solar power (CSP); and 2,000 MW of hydro power. Additional 5 GW of CSP were considered as a result of industrial initiatives in North Africa, such as MEDGRID[4] and DESERTEC[5]. Due to the lack available data regarding RES generation in Morocco RES production profiles are considered to be similar to the Spanish ones.
- Power flows in the interconnection:

[4] http://www.medgrid-psm.com/en/project/
[5] http://www.dii-eumena.com/

- MO → ES: if hourly RES generation ouput in Morocco plus the minimum required thermal generation production from generation that needs to remain committed (considered to be equal to 20% of the hourly demand) is higher than the hourly demand, then Morocco is assumed to export to Spain this excess of generation output.
- ES → MO: if hourly RES generation production plus the maximum thermal generation output (assumed to be equal to 60% of the hourly demand) is lower than the hourly demand, then Morocco is assumed to import power from Spain.
- It is assumed that the interconnection capacity between Spain and Morocco is not increased by 2020 with respect to 2014 levels. The maximum transfer capacity in this interconnection is 900 MW in the Spain-Morocco direction and 600 MW in the inverse direction.

2) Selection of FACTS location and computation of additional RES imports from North Africa

In order to decide where to locate the FACTS device and to compute the additional RES imports from North Africa allowed by it, a routine developed in Python Programming Language was used to automate simulations in PSS/E and run power flow analyses for several hourly scenarios of demand and generation production in the South of Spain combined with different levels of hourly RES imports from North Africa. This routine is presented in Figure 2.2 and is based on the routine developed under the Twenties project to assess the impact of the FACTS device installed by REE in Spain (García-González, 2013).

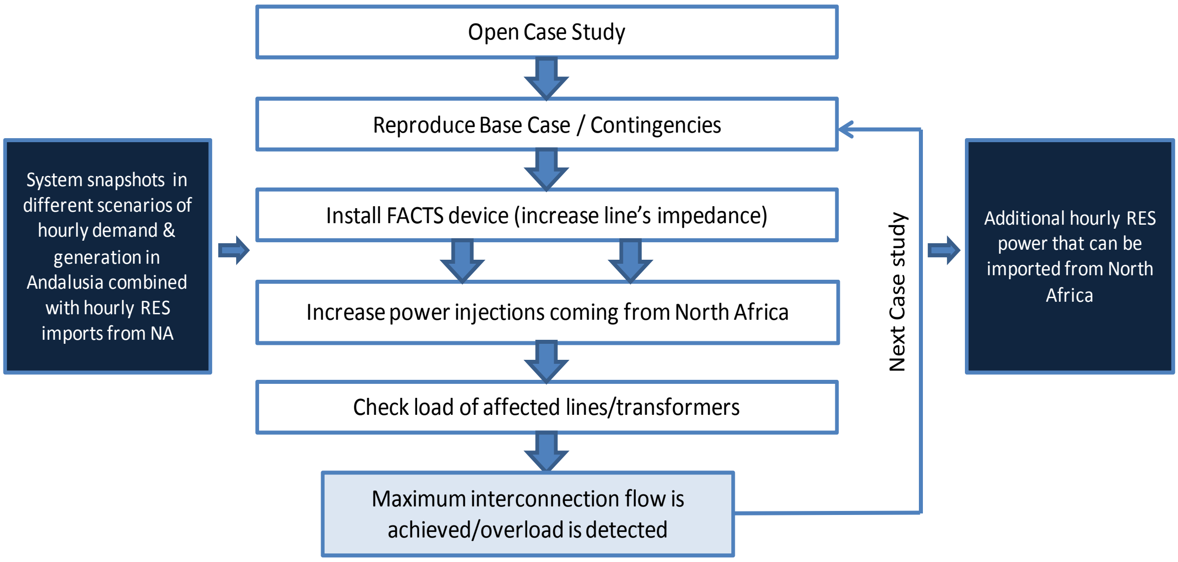

Figure 2.2: Python routine

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In Figure 2.2, the case study corresponds to a PSS/E saved case file representing the whole Spanish transmission system, including nodes, as well generation and load units connected to them, lines and other network elements parameters, and power flows during a certain operation hour.

First, power flows were computed for several case studies corresponding to different scenarios of demand and generation in Andalusia combined with different levels of RES imports from North Africa under normal operation conditions and under N-1 contingencies, in order to detect overloads. Several possible locations were considered for the FACTS device corresponding to those network elements where recurrent overloads were detected. The installation of a FACTS device in a line was simulated by increasing this element's impedance. Since the placement of this device can alleviate congestion in one element but provoke congestions in other elements, overload checking in nearby lines/transformers was performed. The location of the device was finally decided based on the availability of non-congested parallel corridors to that where the installation of the device was being considered.

Once the location of the FACTS device had been selected, the python routine was run for the several relevant case studies defined both considering the FACTS device and not considering it.

3) Impact of the additional RES generation in the Spanish power system operation

In order to analyze the effect of the additional RES imports coming from North Africa on the Spanish power system, a mid-term unit commitment model that optimizes the generation dispatch over one year, considering daily and hourly sub-periods, is used. The ROM model (see Appendix 7.1) is represented in Figure 2.3 and it is described by Ramos et al. (2011) and Fernandes et al. (2012).

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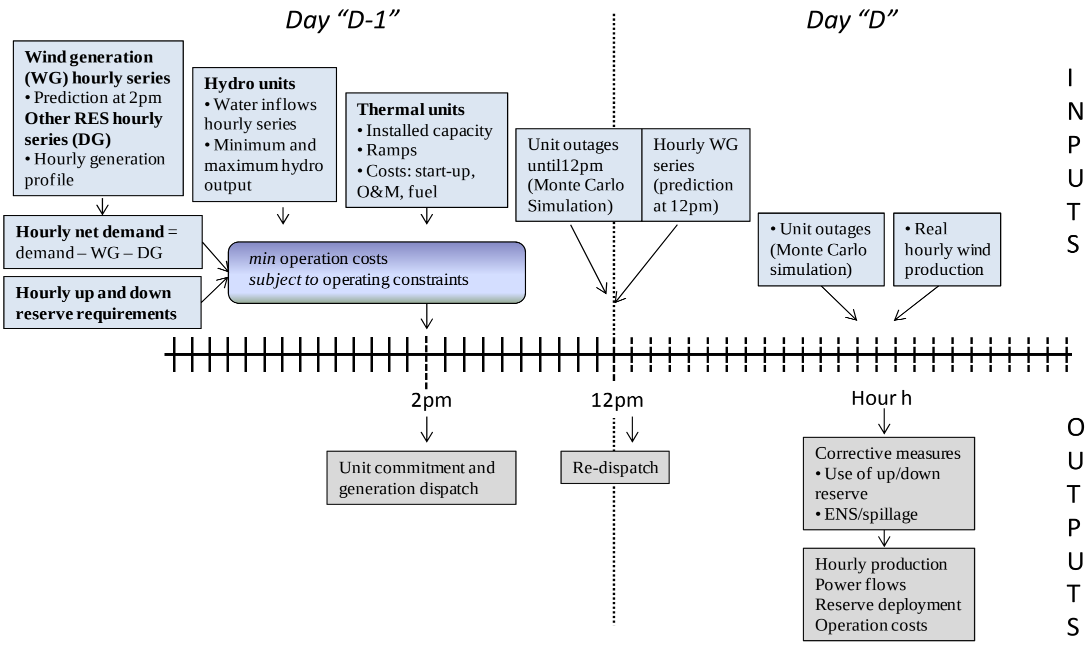

Figure 2.3: The ROM model

In the model, generation and regulation reserves are dispatched as in a single node, representing the network-unconstrained energy and secondary and tertiary reserve dispatch in the day-ahead. The effect of the installation of the FACTS device on the Spanish system operation is modeled by modifying the RES hourly power production curve in Spain to include in it additional imports made possible by the FACTS device. The RES power production curve is part of the input data to the model. Therefore, the impact of the FACTS device is calculated as the difference between the system operation results produced by the model for the base case (original RES generation curve) and those for the case with the FACTS device (adapted RES generation curve).

2.3 Input data

Input data used for the 2020 analysis include demand and RES generation output time series for each technology and conventional generation installed capacity for each technology for Spain, Andalusia and Morocco, as well as variable production costs per technology and CO2 emission costs and the size of the interconnection capacity for the Spanish-Moroccan interconnection. Relevant variables characterizing input data in the case study considered are shown in Table 2.1.

Table 2.1: Demand and RES generation input data

	Spain	Andalusia	Morocco
Demand (TWh)	**292.2**	**50.6**	**45.9**
Peak demand (MW)	49,758	8,618	7,814

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Total RES installed capacity (MW)	45,486	7,872	11,000
Solar	12,050	3,451	7,000
Wind	31,486	4,421	2,000
Biomass	1,950	-	-
Small hydro	2,185	-	2,000

2.4 Results

Results are presented separately for each one of the analyses carried out within the 2020 study. First, the power flows in the Spanish-Moroccan interconnection computed according to the hypotheses described in Section 2.2 are shown. After that, the results regarding the FACTS location selection and the additional RES imports facilitated by the installation of this device are presented. Finally, the impact of the device on the Spanish power system operation is discussed.

1) Computation of power flows in the Spanish-Moroccan interconnection

The resulting power flows in the Spanish-Moroccan interconnection computed according to the hypotheses described in Section 2.2 when they are deemed not to be constrained by network bottlenecks in the Spanish system are shown in Figure 2.4, as a percentage of the transfer capacity between both systems.

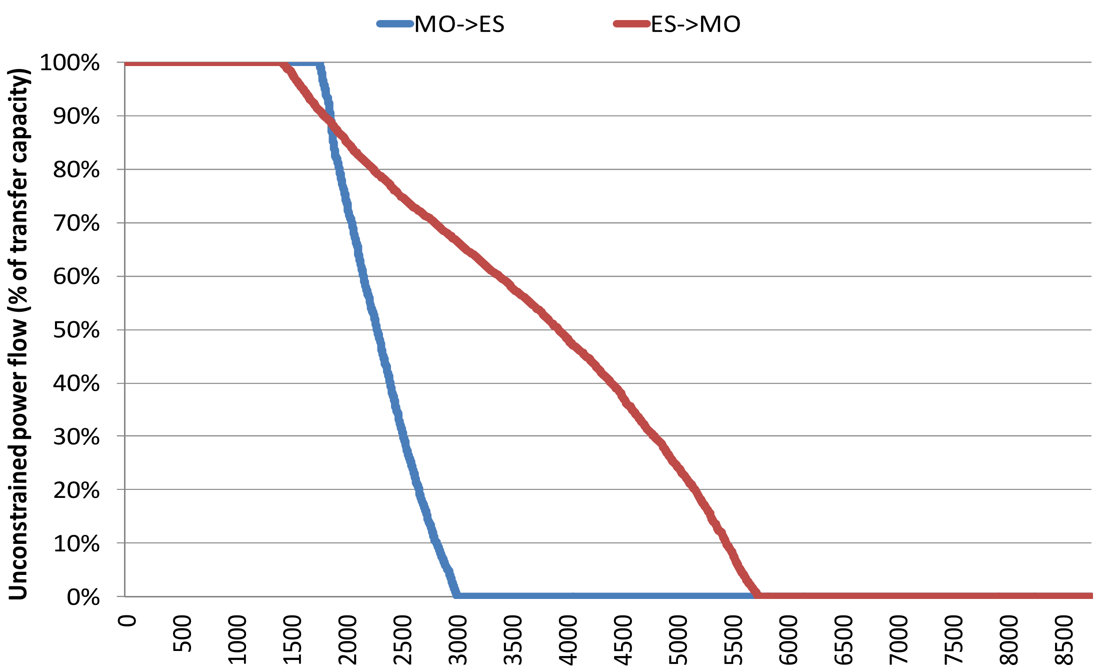

Figure 2.4: Unconstrained power flows in the Spanish-Moroccan interconnection

As previously mentioned, it is assumed that the NTC of this interconnector is not increased by 2020, which means that in the Spain-Morocco direction the NTC is equal to 900 MW and

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in the Morocco-Spain direction the NTC is 600 MW. The results presented in the figure only consider the limitations imposed by the interconnector capacity (unconstrained power flows). It can be observed in Figure 2.4 that, according to the assumptions considered in this analysis, Spain remains a net exporter in the ES-MO interconnection. The annual average unconstrained hourly power flow in the Spain-Morocco direction is 368 MW, while the average hourly power flow in the inverse direction is 158 MW. According to these results, if there were no constraints in the Spanish transmission network due to operation conditions, Spain would be importing from Morocco during 3,013 hours a year.

2) Selection of FACTS location and computation of additional RES imports from North Africa

Once the power flows in the ES-MO interconnection had been computed, the python routine was run in two types of analyses: (i) first to identify network overloads in several operation situations considering specific levels of power production by generation, demand and imports from Morocco and, based on computed overloads, to select the location of the FACTS device to be installed; and (ii) second to compute the additional RES imports that are made possible by the installation of the device in the selected location. For this purpose, the following simulations were performed:

- Identification of relevant N-1 contingencies for the contingency analyses: the python routine was run for 144 base cases considering specific combinations of demand and generation in the South of Spain and RES imports from Morocco. This allowed the computation of network flows in each case and determine which contingencies would result in overloads of some lines in each situation;
- Selection of the FACTS location: analysis of overloaded lines/transformers under the identified contingencies applied to each of the 144 base cases; the FACTS location was selected so as to be able to redirect power flows through overloaded lines to uncongested parallel paths;
- Additional RES imports computation: a python routine was run for 63 base cases for which imports into Spain from Morocco would be limited by line/transformers overloads. For each base case, 88 simulations were performed considering different contingencies and different impedance levels to determine how much power could be imported while complying with reliability criteria.

Figure 2.5 shows the map of the area of the Spanish transmission network were the FACTS device was located and its representation in PSS/E. The location selected for this device was the 400/220 kV Pinar del Rey transformer, were important overloads were detected in the event of important contingencies such as the failure of the 400kV double-circuit Pinar del Rey-Jordana/Tajo de la Encantada.

Table 2.2 presents the aggregated results for the simulations run in PSS/E routines. It can be seen that in operation situations of high load in Andalusia (i.e. demand higher than 85% of the peak load in this region) combined with high RES generation output (from 40% to 70% of the total RES installed capacity) the FACTS device cannot alleviate overloads in the studied area. Therefore, during these hours no additional RES can be imported due to the FACTS device. It is also observed that in situations of high demand where RES power is not high, this device enables relatively low additional RES imports. The situations for which high levels of RES can be imported due the FACTS device are the ones of plateau demand. In these situations, RES imports were initially limited by overloads in the studied area. With the FACTS device, flows in overloaded lines can be re-directed to partially loaded lines. Finally, in situations of low demand the device does not contribute to additional RES imports since no congestion occurs.

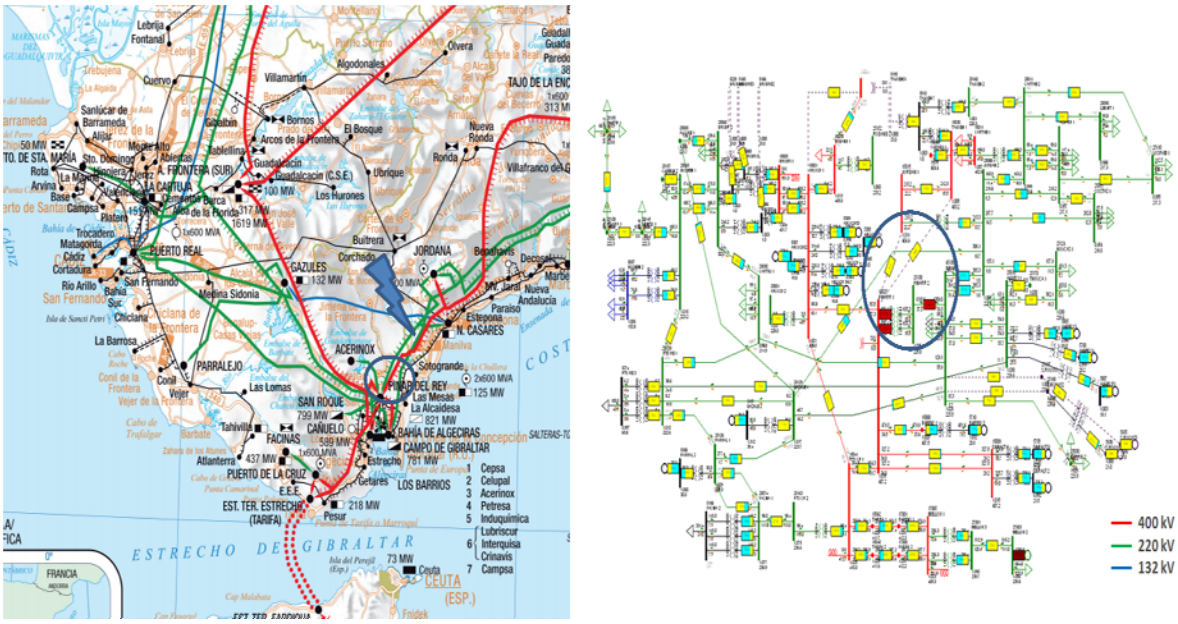

Figure 2.5: Selection of FACTS device location

During the whole year, the device allows importing additional RES power during 1,121 hours (i.e. 37% of the hours when Spain would be importing power from Morocco). In total, 372 GWh of additional RES energy could be imported due to the installation of the FACTS device. This amount corresponds to 0.4% of the total 2020 estimated renewable generation output in Spain.

Table 2.2: Additional RES imports due to the installation of the FACTS device

Situations (only for hours where RES energy is imported by Spain = 3,013)			Results
Demand in Andalusia	**RES generation in Andalusia**	**Number of hours**	**Additional hourly RES imports (MW)**
Peak (>0.85 p.u.)	High (0.4-0.7 p.u.)	10	0
Peak	Average (0.2-0.4 p.u.)	7	0-100
Peak	Low (0.13-0.2 p.u.)	194	100-200
Plateau (0.65-0.85 p.u.)	High	47	200-400

Plateau	Average	284	400-500
Plateau	Low	589	500-600
Valley (<0.65 p.u.)	Low/Average	1,882	0

Figure 2.6 presents Andalusia's augmented RES generation curve (considering imports from Morocco) with and without considering the installation of the FACTS device.

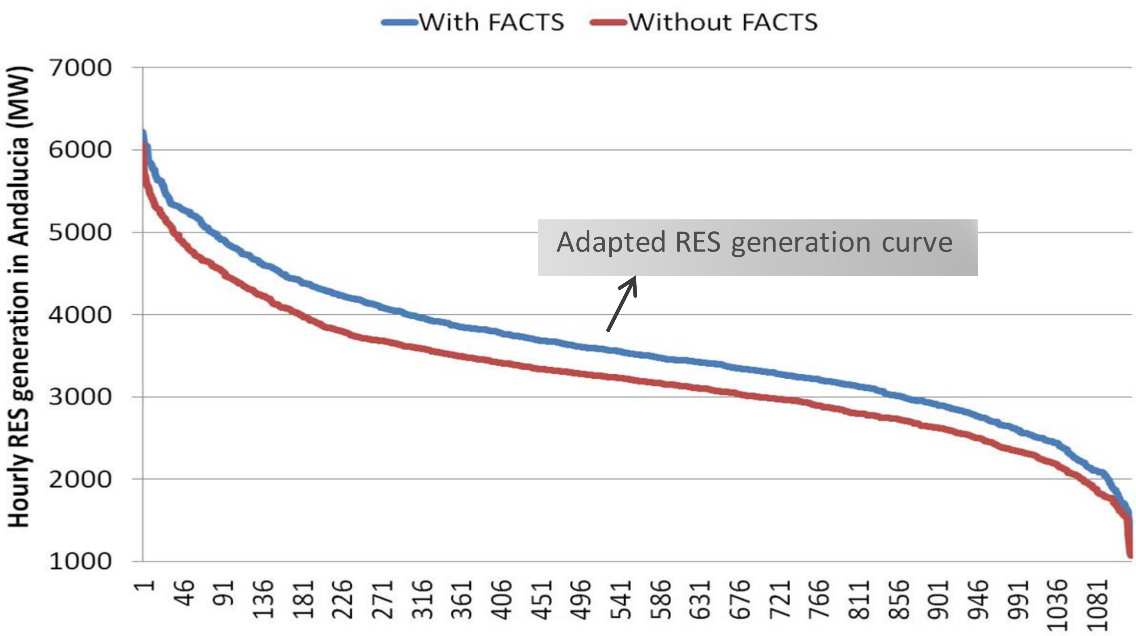

Figure 2.6: Adapted Andalusia's RES generation curve

3) *Impact of the additional RES generation on the Spanish power system operation*

As explained in Section 2.2, the ROM model was run for the base scenario, i.e. the case without considering the effect of the FACTS device on the augmented RES generation curve, and for the FACTS scenario, i.e. the case where the RES generation curve has been adapted to include additional imports allowed by this device. Figure 2.7 presents the total annual changes in the power system operation in the FACTS scenario with respect to the base case.

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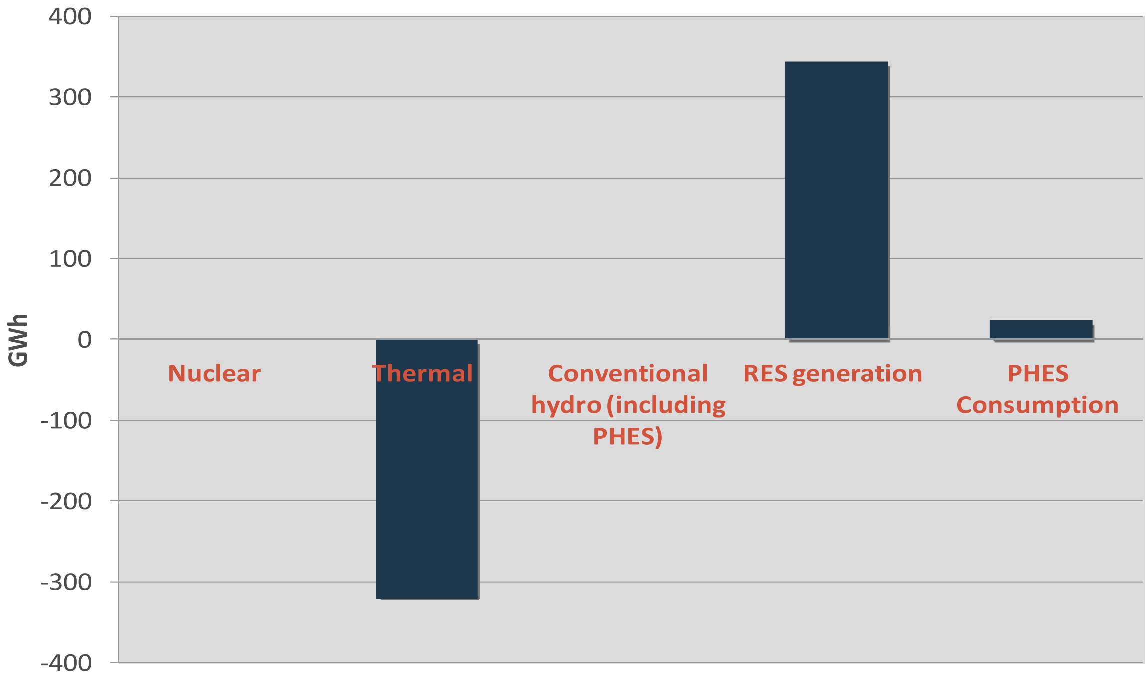

Figure 2.7: Impact of the FACTS device on the Spanish power system operation: total annual differences in system variables with respect to the base case scenario

As it can be observed in the figure, the additional RES energy imported from Morocco thanks to the use of the FACTS device replaces mainly electric energy produced by thermal generation in Spain. Comparing the base and the FACTS scenarios, one can see that the additional RES energy injected into the Spanish system corresponds to 0.4% of the total RES production in the base case and the reduction in the thermal production corresponds to 0.3% of the total thermal production in the base case. This additional RES production injected results in an increase in the use of pumped-storage units (1.1% increase in relation to the base scenario), which, nevertheless, does not avoid some RES curtailment.

2.5 Discussion of results

According to the ROM model results, the increase of the amount of RES energy imported thanks to the FACTS device results in a reduction in operation costs of approximately 30M€/year. The investment cost of the FACTS device installed under the Twenties project framework in Spain was estimated at, approximately, 4.3 M€ (García-González, 2013). According to these values, the device's cost is more than compensated by the operation costs savings achieved. In this respect, it is worth mentioning that, in this analysis, it is assumed that RES generators have zero operation costs. Therefore, it is assumed that Spain imports RES energy from Morocco at 0 €/MWh because marginal production costs in Morocco in the corresponding hours are zero (this implies that Spain is controlling the interconnection). However, a different price may be agreed between the two systems for imports. In this sense, operation costs savings actually achieved may be overestimated in this study.

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FACTS devices may have some advantages over other infrastructure equipment. Thus, the construction time of the former is much shorter than that of new transmission line. In this respect, FACTS can reduce or avoid transmission constraints in highly congested areas when permitting procedures are delayed and construction times of new transmission lines become quite long. In areas where building lines is not so difficult, FACTS devices can be an economic option to avoid congestion, and consequently also the application of redispatch measures and/or RES energy curtailment.

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3 2030 Analysis

3.1 Case study description

The 2030 analysis focuses on the use of innovative technologies to integrate higher amounts of intermittent RES generation. Technologies considered are demand-side management (DSM), with direct load control, and Compressed Air Energy Storage (CAES). The main objective of the study is to analyze the impact of these technologies on the operation of the Spanish power system and on the power flows in the Spain-France interconnection. For this purpose, the mid-term operation model ROM is used to jointly optimize the unit commitment and generation dispatch of both systems (Spain and France). Figure 3.1 shows the area of study in 2030 analysis.

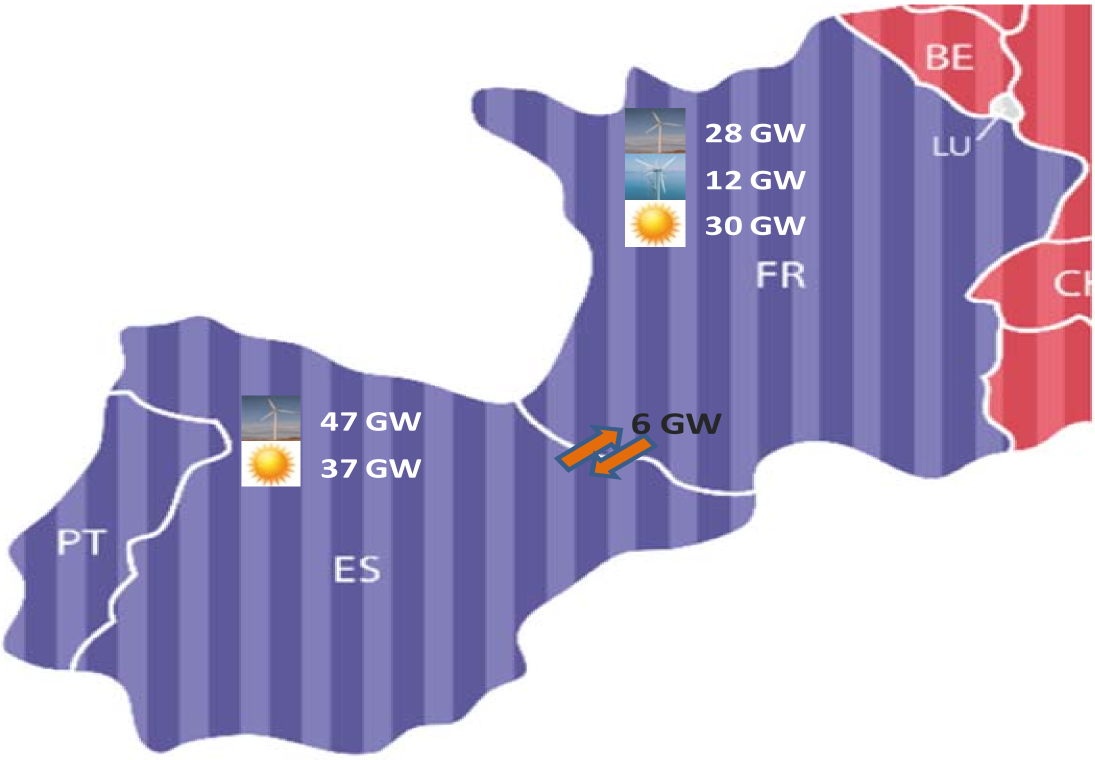

Figure 3.1: Area of study in the 2030 horizon

The analyses are carried out separately for each innovative technology considered. Regarding DSM, only load shifting is studied. It is assumed that an aggregator manages controllable loads of small consumers and optimizes, from the system operation perspective, the aggregate shifting of the load of these consumers. In this case, load is shifted from hours when marginal operation costs are higher (i.e. peak hours or hours with low renewable generation output) to hours when marginal operation costs are lower (i.e. valley hours or hours with high renewable generation output). Realistic limitations to the amount of demand that can be shifted and the periods during which load shifting can be

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performed are taken into account. The detail modeling made of DSM is described in Dietrich et al. (2012).

The CAES technology functions in a similar way to pumped-hydro plants, but instead of pumping water from a lower to an upper reservoir, during periods of power surpluses, it compresses air and stores it under high pressure in underground caverns or vessels. When power is required, the pressurized air is heated and expanded and passes through a turbine driving a generator for power production. Storage is generally used to shift electricity production from low price hours to high price hours. In this study, it is assumed that the system operator owns the storage plant and uses it to transfer electricity production from hours of lower marginal operation costs to hours of higher marginal operation costs. The assumptions made regarding the simulation of the CAES operation are based on (Dollinger and Dietrich, 2013).

Given that both technologies analyzed in the 2030 study play a similar roll in system operation, they may have a similar impact on it. Of course, this impact will depend on the assumptions made and on the limitations of each technology.

3.2 Brief Methodology overview and assumptions

As previously explained, the impact of DSM and CAES on power system operation is analyzed separately for each technology. The ROM model is the tool used to determine the optimal generation dispatch in each case, minimizing system operation costs, taking into account that (i) DSM is applied to the Spanish load, and (ii) CAES is installed in the Spanish system. This model optimizes the joint (Spain and France) generation dispatch over a whole year, considering daily and hourly sub-periods. The impact of these technologies is assessed by comparing the operation results for a base case scenario, i.e. a case without DSM or CAES, and the results computed for the technology scenarios where either one or the other technology is used. For the 2030 analyses, the following assumptions have been made:

1) DSM

- Two levels/scenarios of load-shifting are considered: 2% and 4% (DSM 2% and DSM 4% scenarios, respectively), which means that in an hour a maximum of 2% and 4% of the total system hourly load can be shifted, respectively. Load shifting is only applied to the Spanish demand.
- Load shifting does not modify the total daily demand, i.e. during a specific day total upward demand shifting (load increases) is equal to total downward demand shifting (load reductions).
- A third-party (aggregator) manages controllable loads of small consumers (direct load control) and shifts their load only if an economic benefit can be obtained out of this, i.e. if, by moving load from one hour to another, system operation costs can be reduced. In the daily time horizon, the aggregator can shift demand in a same direction (i.e. upward or downward) during a maximum consecutive period of eight hours. Since the sum of load shifts in one direction must equal the sum of load shifts in the opposite direction, in most cases the maximum number of load shits in one direction in the daily time frame is equal to 8 hours.

2) CAES

- Two scenarios of CAES storage are analyzed: one where 2 GW of CAES are installed capacity in the Spanish power system and another one where 5 GW are installed.
- The CAES technology is modeled analogously to a pumped-hydro storage unit with an efficiency of 65%.
- The storage capacity of CAES devices in both scenarios is assumed to be equal to 4 hours at full injection rate, which results in a total maximum storage capacity of CAES of 8 GWh and 20 GWh for the scenarios of 2 GW and 5 GW of CAES installed, respectively.

3) Interconnection capacity

- A sensitivity analysis is also performed to assess the impact of the level of interconnection capacity between Spain and France on operation results. The above-mentioned scenarios for DSM and CAES have been run considering the base case interconnection capacity between both systems (6 GW) and also considering a scenario with lower interconnection capacity between Spain and France: only 3 GW.

3.3 Input data

Figure 3.2 shows the main input data used in this case study: installed generation capacities in Spain and France, Spanish and French peak loads, as well as total annual demand (in TWh) considered for the 2030 horizon. Other data used are the same as in the 2020 case study.

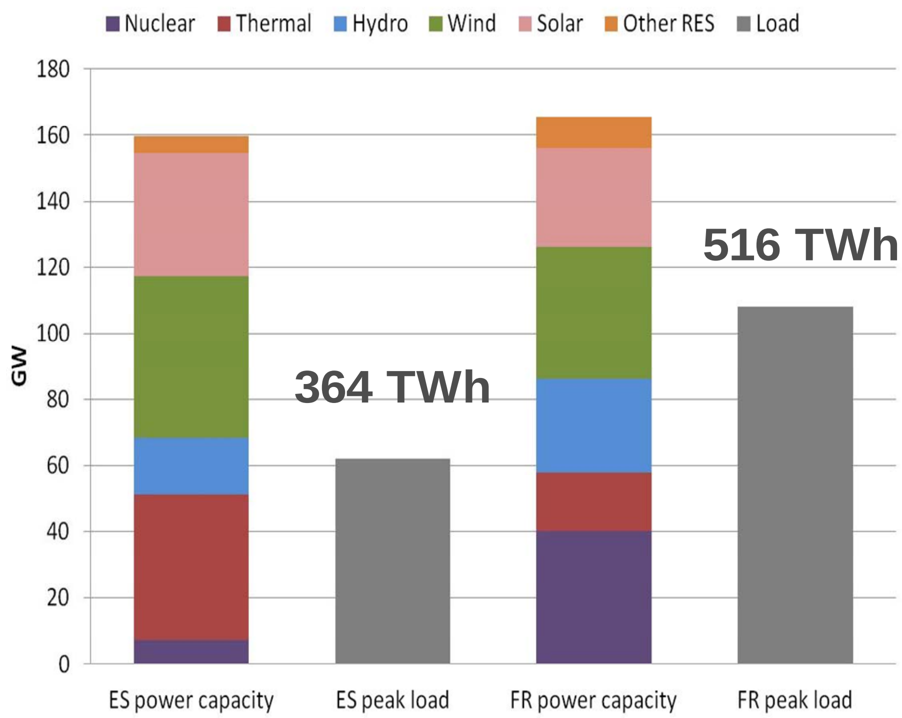

Figure 3.2: Demand and generation capacity mix in Spain and France in the 2030 horizon

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3.4 Results and sensitivities

In the following, the main results obtained from the ROM model when analyzing the impact of DSM and CAES on power system operation in the year 2030 are presented separately for DSM and CAES. After that, the impact of both technologies on system operation costs is discussed and results obtained in these scenarios are compared with those computed for the interconnection capacity sensitivity scenario. Finally, the costs of implementing DSM and installing CAES are briefly discussed.

1) Impact of DSM on power system operation

Figure 3.4 presents the hourly net load (i.e. hourly demand less the RES generation output) in Spain, with and without implementing DSM. It can be observed that load is reduced most in peak hours, when thermal generation is high, and increased mainly in valley hours, whenever there are generation surpluses in the system, but also during morning/afternoon hours when solar production is high. The total annual Spanish demand shifted by DSM corresponds to 0.85% (3.3 TWh/year) and 1.65% (6.4 TWh/year) of the total yearly demand in the DSM 2% and DSM 4% scenarios, respectively. It is worth emphasizing that, in this analysis, DSM is modeled in a similar way to storage capacity with a daily efficiency of 100%, i.e. total daily demand increase is equal to total daily demand reduction.

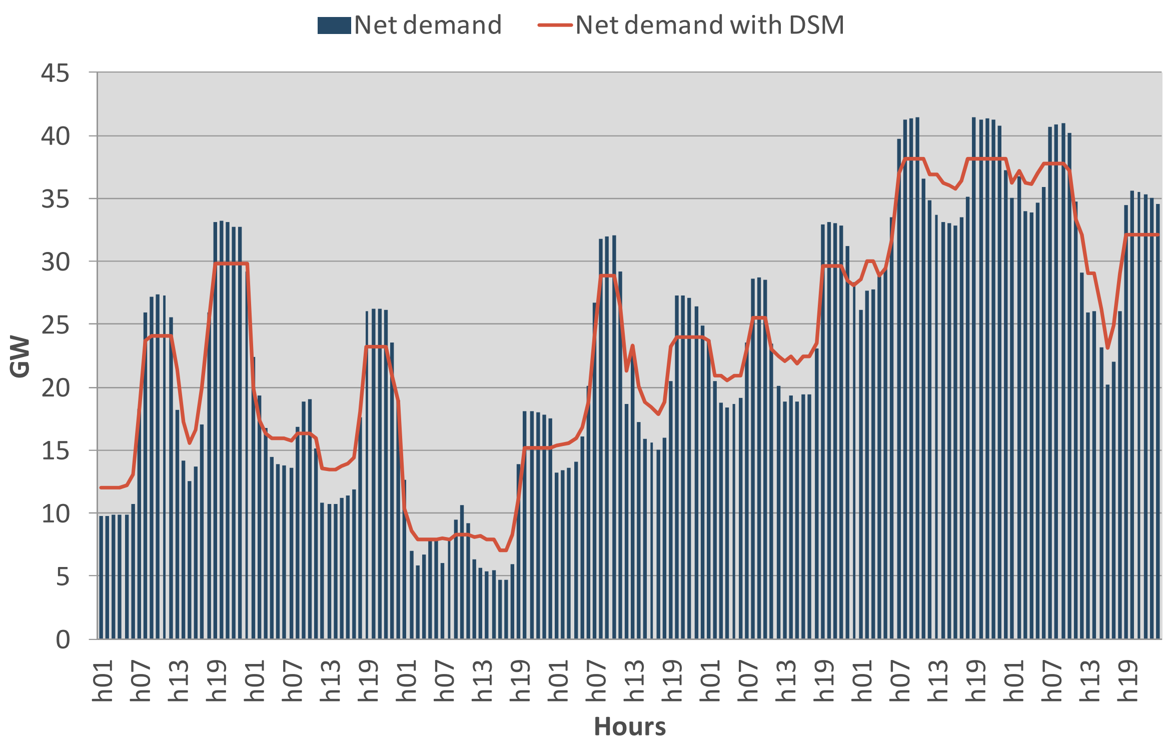
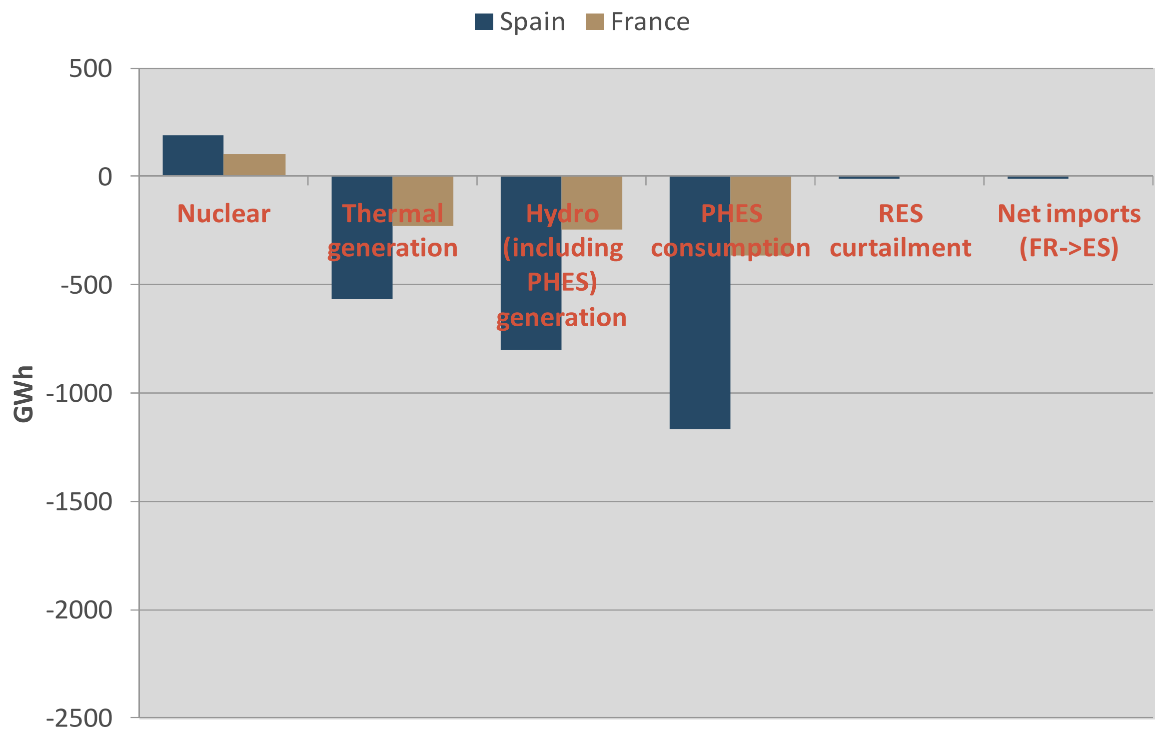
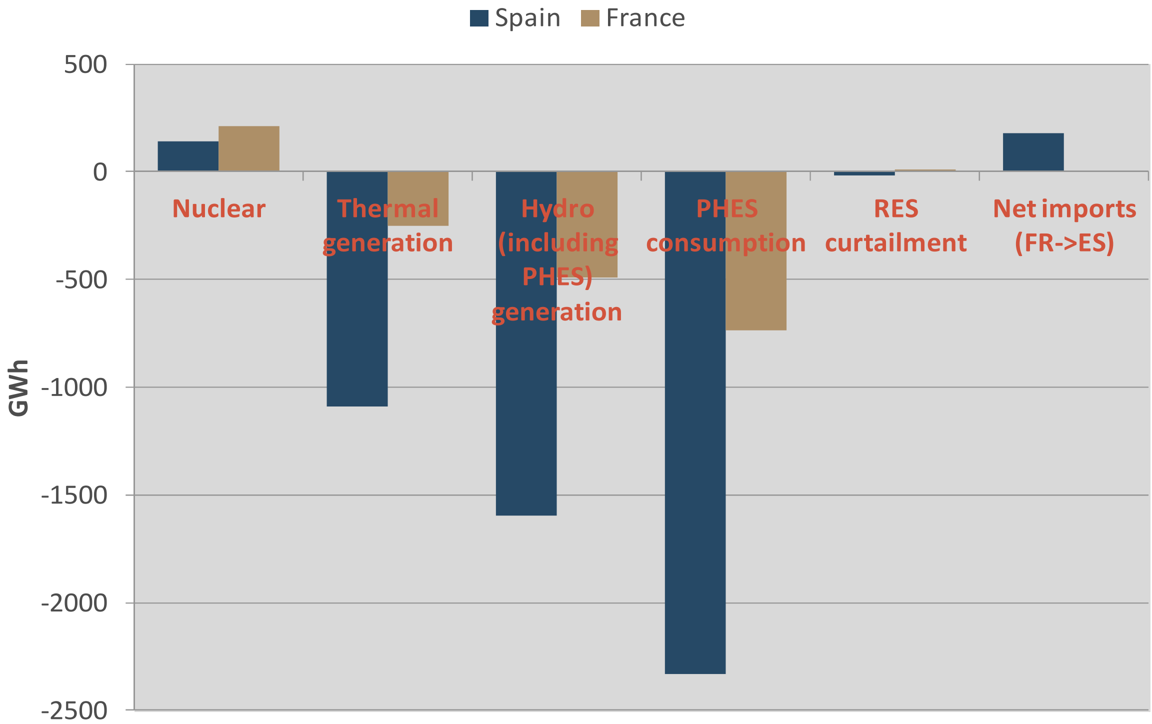


Figure 3.3: Impact of DSM on hourly Spanish load

Figure 3.4 shows the total annual impact of DSM on power system operation, as differences between the level of aggregated annual operation variables for the DSM scenarios and for the base case scenario. As it can be observed in Figure 3.4a and Figure 3.4b, DSM partially replaces the use of pumped-hydro (PHES) units, since it provides flexibility to the system. In energy terms, the total reduction of PHES consumption in Spain and France in the DSM 2% scenario corresponds to 6% of the total PHES consumption in the base case scenario. The reduction of PHES consumption represents 50% of the total demand shifted in the DSM 2% scenario. The increased in flexibility of Spanish system provided by DSM also contributes to increasing nuclear power generated not only in Spain but also in France. In the base case scenario, the production by nuclear power plants has to be reduced during hyper valley hours. Comparing the base scenario and the DSM 2% scenario, total net imports from France are slightly reduced from 7,191 to 7,178 GWh in the second one. This is probably related to the increased nuclear production in Spain when DSM takes place.



(a) DSM 2% scenario: total annual differences with respect to the base case scenario



(b) DSM 4% scenario: total annual differences with respect to the base case scenario

Figure 3.4: Impact of DSM on the annual Spanish and French systems' operation

Changes in power system operation in the DSM 4% scenario are similar to the ones observed in the DSM 2% scenario. PHES consumption reduction in the DSM 4% scenario corresponds to 13% of total PHES consumption in the base case scenario. In the DSM 4% scenario, nuclear generation increase in France is higher than the one observed in Spain. As a consequence of this, net imports from France increase from 7,191 GWh in the base case scenario to 7,372 in the DSM 4% scenario. Finally, it is worth mentioning that RES curtailment does not significantly change when DSM is introduced. The main reason for this is that in the base case scenario curtailment already represents a very low share of RES feed-in (0.1%).

2) Impact of CAES on power system operation

Figure 3.5 shows the hourly net load curve (i.e. hourly demand less RES generation output) in Spain, with and without having CAES in the system. The figure shows that electricity is normally stored in CAES in hours of low net demand (i.e. valley hours or hours with high RES generation) and injected back by CAES into the grid in peak hours and hours with low RES generation. One main difference between the operation of CAES and the management of demand is that, in this analysis, DSM is assumed to have an efficiency of 100%, i.e. total daily demand increases and reductions are equal, while CAES is assumed to have an efficiency of 65%, i.e. total daily electricity produced by CAES storage amounts to 65% of the total daily stored energy. Therefore, in the latter case, there is a net demand increase. Besides this, different constraints apply to DSM and storage regarding the timing and amount of the load shifts they achieve.

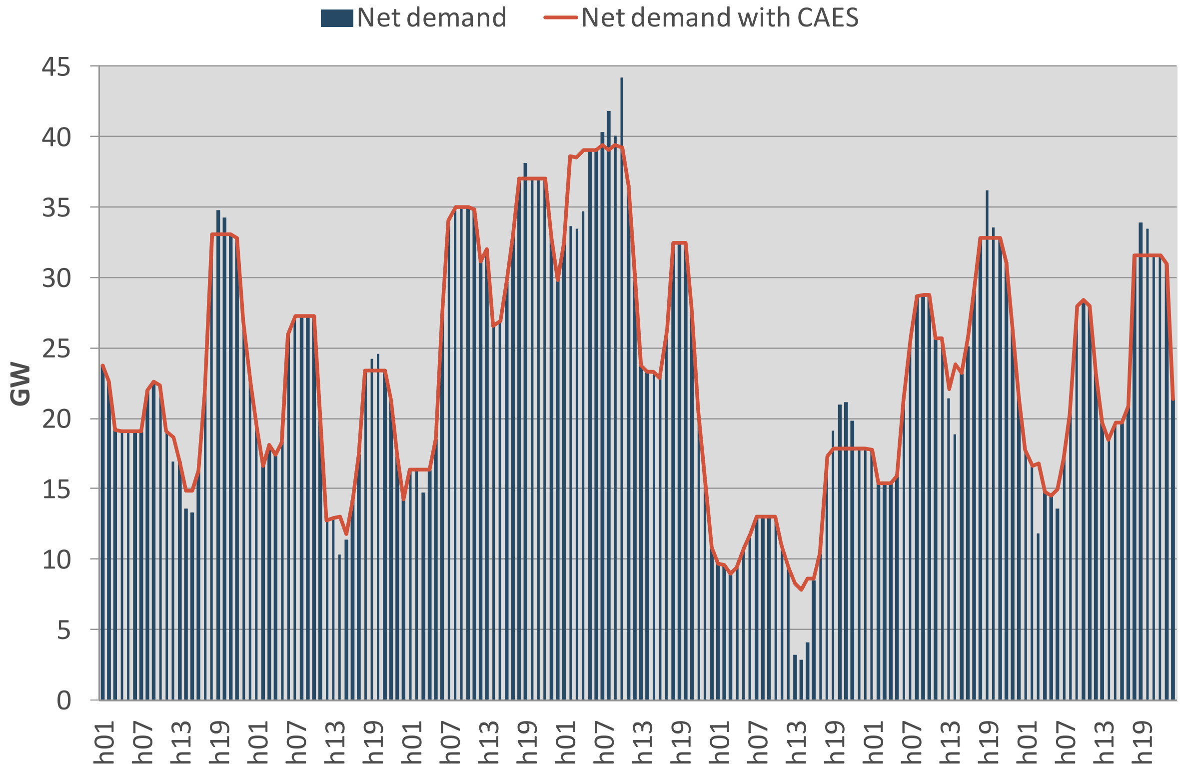


Figure 3.5: Impact of CAES on hourly Spanish load

As mentioned in Section 3.2, in this analysis, the capacity of CAES are 8 GWh and 20 GWh in the 2 GW and 5 GW scenarios, respectively. Consequently, the maximum amounts of energy that could be stored in one year (maximum energy capacity) are 2.9 TWh and 7.3 TWh (corresponding to the sum of energy stored on all days of the year in the situation in which the storage is completely filled and emptied every day), respectively. According to the results obtained from the ROM model, total energy stored and generated by CAES amounts to 1.2 TWh and 0.8 TWh/year, respectively, in the 2 GW scenario, and 2 TWh and 1.3 TWh/year in the 5 GW scenario. In the 2 GW scenario, the total annual energy stored by CAES corresponds to 41% of the yearly energy maximum capacity. In the 5 GW scenario, this value drops to 27%.

In the case of DSM, the maximum hourly load shifted is 1.3 GW in the 2% scenario (i.e. 2% of peak load) and 2.6 GW in the 4% scenario (i.e. 4% of peak load), respectively. Taking into account the constraint that in the daily time frame load can be shifted over a maximum period of 8 consecutive hours in the same direction (see Section 3.2), it can be considered that the maximum total annual amounts of energy that can be shifted are 3.8 TWh and 7.6 TWh in the 2% and the 4% scenarios, respectively. These values correspond to 2% and 4% of the annual peak demand multiplied by 8 hours per day during a whole year, respectively. Considering these values, the total annual shifted demand would correspond to

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87% and 84% of the maximum yearly energy that can be shifted in the 2% and the 4% scenarios, respectively.

The much lower utilization percentages of storage observed in the CAES scenarios in comparison with the DSM ones can be explained by the lower efficiency of CAES, which needs to be compensated by higher differences in marginal production costs between hours when power is injected and those when it is stored (i.e. CAES will be used when the 35% of energy “loss” in the storage cycle is compensated by the difference between the (low) marginal cost of production of energy stored and the (high) marginal cost of energy produced in those hours when it is injected by CAES. It is important to point out that this analysis is based on operation costs rather than market prices. In practice, the use of commercial storage will depend on market price differences. Therefore, the utilization of CAES can be higher than the one computed in this analysis.

Figure 3.6 shows the total annual impact of CAES on power system operation, as differences between the level of aggregated annual operation variables in the CAES scenarios and those in the base case scenario. As it can be observed in Figure 3.6a and Figure 3.6b, differently from what occurs in the DSM scenario, PHES consumption increases when CAES exists. It is important to notice that CAES storage introduces higher flexibility than DSM and a net demand increase. Both factors contribute to increasing the amount of nuclear power production that can be integrated into the system, part of which is replaced by RES generation in the base case scenario. The increase in the amount of nuclear power production, which is not flexible, in turn, increases the need for system flexibility. The net demand increase produced by CAES contributes to an increase in thermal generation but also reduces RES curtailment. In the 2 GW scenario, the higher nuclear power production in Spain causes a reduction in total net imports from France, which change from 7,191 GWh/year (base case scenario) to 7,122 GWh/year. In the 5 GW scenario, the higher production by nuclear power plants in France compared to the 2 GW scenario results in an increase in net imports from France, which changes from 7,191 GWh/year (base scenario) to 7351 GWh in the 5 GW scenario.

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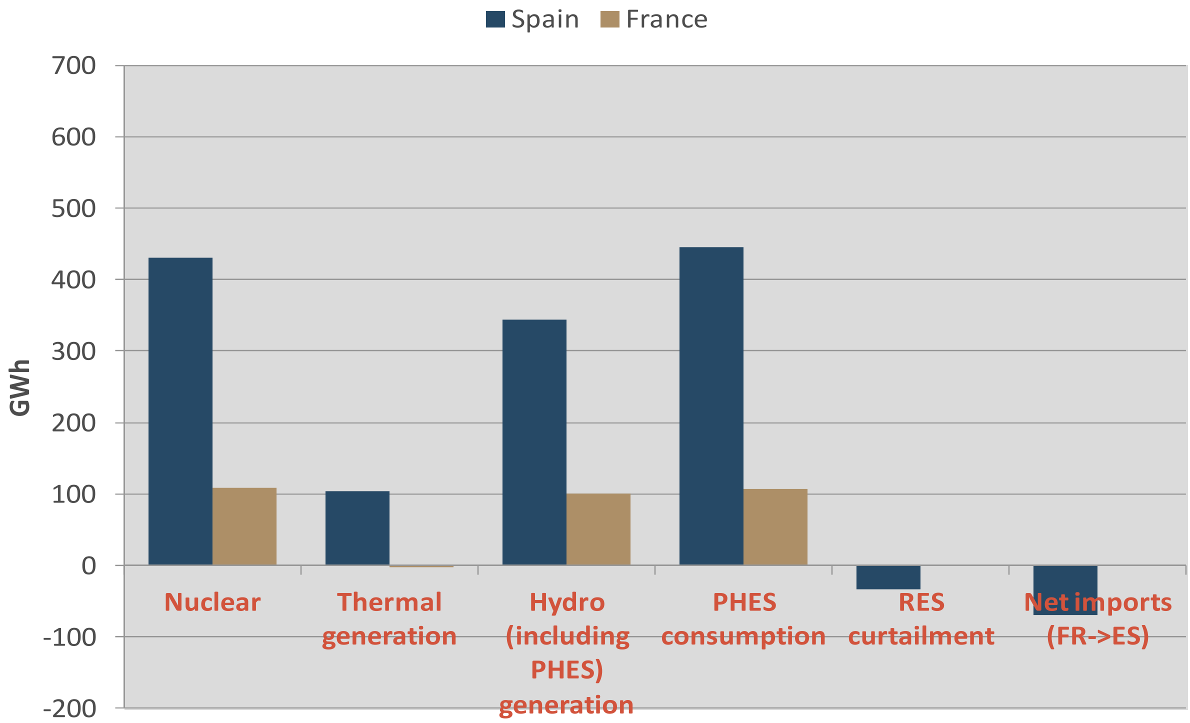
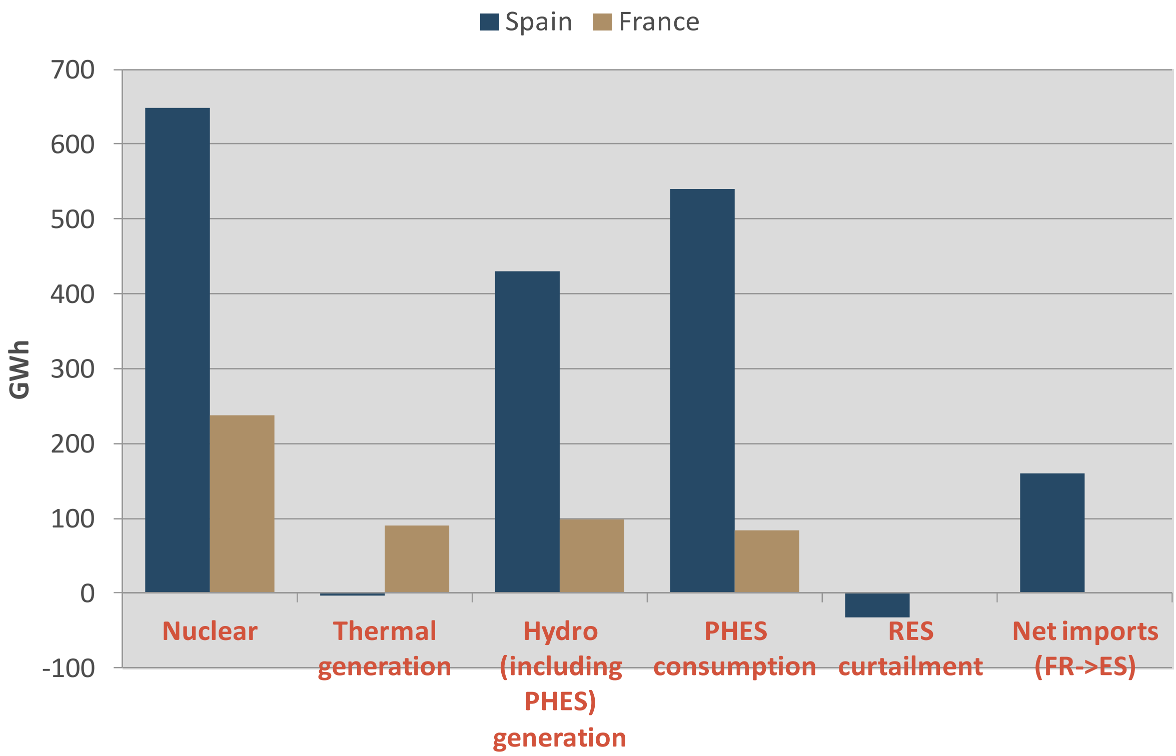


(a) CAES 2 GW scenario: total annual differences with respect to the base case scenario



(b) CAES 5 GW scenario: total annual differences with respect to the base case scenario

Figure 3.6: Impact of CAES on the annual Spanish and French systems' operation

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3) *Impact of DSM and CAES on system operation costs, including the interconnection capacity sensitivity analysis*

Figure 3.7 shows the differences between total annual (Spanish and French) system operation costs in several scenarios of use of DSM and for several levels of interconnection capacity, with respect to the base case scenario, where there is no DSM and the ES-FR interconnection capacity is equal to 3 GW. The "DSM 2% (3GW IC)" and the "DSM 4% (3GW IC)" scenarios correspond to the cases in which DSM is applied to the above-mentioned base case scenario. The scenario "+3GW IC" corresponds to the original base case scenario where no DSM takes place and where the ES-FR interconnection capacity is equal to 6 GW. Finally, the "DSM 2% (6GW IC)" and the "DSM 4% (6GW IC)" scenarios correspond to the scenarios of implementation of DSM that have already been presented.

Comparing the base case scenario (3GW IC) with the DSM scenarios "DSM 2% (3GW IC)" and "DSM 4% (3GW IC)", one can see that total annual system operation cost reductions achieved in the latter correspond to 0.4% and 1% of the total operation costs in the base case scenario, respectively. It is observed that increasing the level of maximum hourly load shifting from 2% to 4% allows operation cost savings to increase by more than two times. When the "extra" 3 GW of interconnection capacity is added to the system ("+3GW IC" scenario), total operations cost savings reach 2.6% of the total operation costs in the base case scenario. Considering the "+3GW IC" scenario as the base case scenario, the introduction of DSM in the 2% and the 4% scenarios produces operation cost savings corresponding to 0.6% (≈130 M€) and 0.9% (≈182 M€) of the total operation costs in the base case scenario, respectively. This means that, even after increasing interconnection capacity, DSM contributes further operation cost savings.

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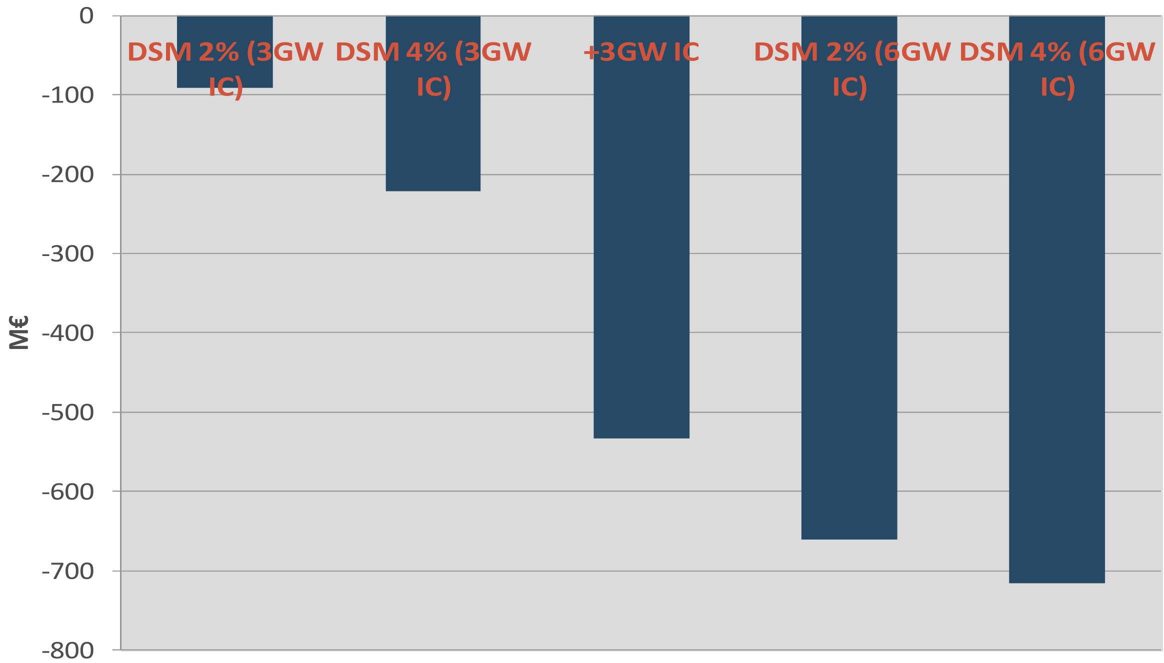

Figure 3.7: Impact of DSM on the total annual system operation costs: total annual differences with respect to the base case scenario with 3GW of interconnection capacity

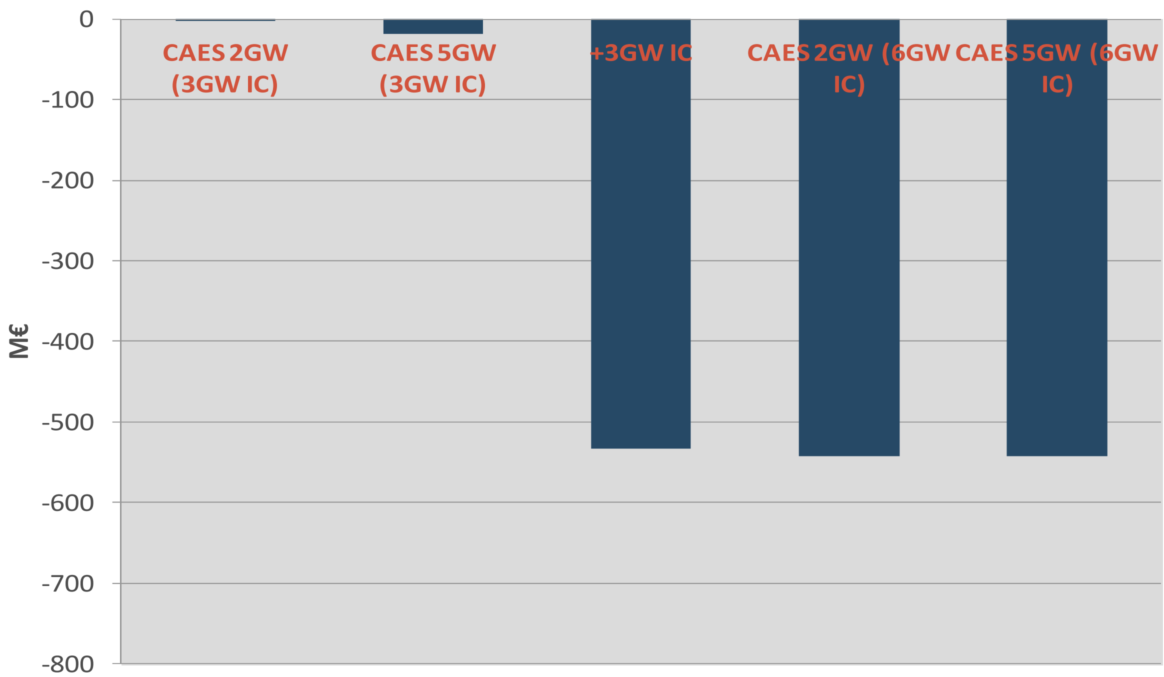

Figure 3.8: Impact of CAES on the total annual system operation costs: total annual differences with respect to the base case scenario with 3GW of interconnection capacity

Figure 3.8 presents the differences between total annual system operation costs in different scenarios of CAES and interconnection capacity deployment, with respect to the base case scenario without CAES and with an ES-FR interconnection capacity equal to 3 GW. It can be observed that, compared to DSM, operation cost savings achieved by CAES are much lower. As previously explained, this is due to the much lower efficiency of CAES compared to that of DSM (assumed to be 100% in this study).

According to the results computed, in the “CAES 2GW (3GW IC)” scenario, operation cost savings obtained are approximately 3 M€ with respect to the base case (3GW IC) scenario. If CAES capacity is increased to 5GW, cost savings increase to 19 M€. When higher interconnection capacity is considered, i.e. an increase of + 3GW is implemented, cost savings achieved with respect to the base case (+ 3GW IC) scenario are 8.8 M€ and 9 M€ in the 2 GW and the 5 GW scenarios, respectively.

4) *Technology costs*

The costs of implementing DSM for small consumers in Spain have been estimated in the GAD project[6]. These include the costs of smart meters, energy boxes (i.e. load controllers) and the adaptation of electric appliances, as well as the cost of communication and control equipment at the TSO, DSO and retailer levels. These costs were estimated considering three levels of participation of small consumers in DSM: 25%, 50% and 100%. Taking into account that there are around 22,000,000 small consumers in Spain, and that they consume approximately 42% of the total electric load in Spain, the participation level of small consumers assumed in this analysis is, approximately, 5% in the DSM 2% scenario (i.e. 1,100,000 customers) and 10% in the DSM 4% scenario (2,200,000 customers). Table 3.1 presents the costs estimated for the implementation of DSM in the 2% and 4% scenarios, based on the costs assessed in the GAD project (Conchado and Linares, 2010).

Table 3.1: Estimated costs of implementing DSM for small customers (5% and 10% of participation level)

	Unitary cost (€) (GAD project)	Total cost (M€) – DSM 2%	Total cost (M€) – DSM 4%
Communication & control equipment	3,000,000	92*	92*
Smart meter	160	176	352
Energy box (load controller)	160	176	352
Customer interface	20	22	44
Adaptation of appliances	220	242	484
Total		**708**	**1,324**

* Assumed to be the same as the communication & control cost computed for the GAD-25% scenario

[6] The GAD (Gestión Activa de la Demanda) project was financed by the Spanish government. For more details see (in Spanish): http://gad.ite.es/index_es.html

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According to the data provided by Lund & Salgi (2009), the investment cost of CAES storage is about 500 €/kW. Using this value, the total investment costs in the scenarios of 2 GW and 5 GW of storage capacity have been estimated at 1,000 M€ and 2,500 M€, respectively. Considering that the lifetime of the CAES storage is 30 years and using a fixed charge rate of 7%, the annualized investment costs of the CAES storage considered is approximately 80 M€ and 200 M€ in the scenarios 2 GW and 5 GW, respectively. According to publicly available data concerning the costs of the assessed technologies, the application of DSM for small consumers through the implementation of direct load control and the installation of the required infrastructure would require investments in the same range as those required for the construction of CAES.

Considering these cost values and the economic benefits obtained through the use of the technologies in terms of thermal cost savings, it can be expected that the annualized investments required for the implementation of load-shifting or storage solutions with very high efficiency levels could be more than compensated by savings in operation costs. Nevertheless, to obtain conclusive results related to the cost-benefit analysis, one will need to consider all possible benefits of these technologies when efficiency levels considered for DSM and CAES are lower.

3.5 Discussion of results

The 2030 horizon study focuses on the application of innovative technologies expected to be available in 2030 such as DSM and CAES storage, to integrate higher shares of intermittent RES generation. In this study, the type of DSM considered has been load shifting, assuming that, during a certain day, all load increases must be equal to the sum of load reductions. Load shifting has been modeled as a storage device with an efficiency of 100% and with certain constraints on the amount and timing of load that can be shifted. CAES is simulated as a PHES unit with an efficiency of 65%. Due to differences in the efficiency levels considered, DSM achieves better results than CAES, although both technologies contribute to a higher integration of RES production and render operation cost savings. It was observed that the lower the efficiency level of the storage device, the higher the net demand in the system. This may lead to higher thermal power production in some hours, reducing thermal costs savings.

In practice, from a social welfare perspective, both technologies (i.e. DSM and CAES) should have a similar impact on power system operation. Nevertheless, the distribution of benefits among market participants will probably be not the same in the two cases. In the case of CAES, the agent who may more directly benefit from it is the storage owner. Depending on the impact of CAES (or storage in general) on the electricity market outcome, consumers could be indirectly beneficiated by being faced with lower and/or flatter market prices. In the case of DSM, consumers are directly benefitted by it. However, small consumers may not obtain high enough benefits from DSM to decide to participate in these types of solutions. In general, consumers may only participate in DSM if economic benefits are higher than implementation costs (including the costs associated with the customers' comfort deterioration).

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Achieving an equivalent "efficiency" of 100% in load shifting (i.e. getting to a situation where the daily sum of load increases are equal to the sum of load reductions) could be difficult, since the potential for load reduction in peak hours is generally higher than the potential for load increase in valley hours. In this analysis, however, it has been assumed that a third party is responsible for the management of small consumers' loads, and that the necessary smart grids infrastructure is installed. If this occurs and direct load control is implemented, the potential benefits of DSM for small consumers could be much more easily achieved. It is also relevant to point out that other types of DSM programs could be implemented at lower costs, such as price-based incentive programs through which consumers respond to price incentives. However, while this latter type of DSM program could be more easily implemented, the potential benefits obtained from it, at least by small consumers, would be probably lower[7].

Finally, it is worth mentioning that the economic benefits produced by the technologies assessed in this analysis do not include all the possible benefits that these solutions may bring about to power systems. Benefits not considered here include the decrease in the amount of network infrastructure expansion needed and that in the environmental impact of the power system. Carrying out a complete cost-benefit analysis would require the assessment of all possible benefits.

[7] For more details on potential benefits and costs of DSM programs, see Olmos et al. (2011)

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4 2050 analysis

4.1 Case study description

The 2050 analysis focuses on the deployment of two types of innovative solutions to integrate massive amounts of RES generation in Europe: the first one is a European-wide solution based on the development of a supergrid, similar to the one promoted through several projects like DESERTEC or MEDGRID, i.e. connecting RES generation (mainly wind and solar power) in North Africa to main load centers in Europe; the second one focuses on local (i.e. country level) approaches, like the massive use of electric vehicles (EVs) and DSM. Local solutions considered are applied only to the Spanish system.

Since our analysis focuses on the Spanish system, the interconnection between Europe and the North African system considered is the Spain-Morocco one. Therefore, apart from the Spanish system, the Moroccan power system is also modeled. In order to assess the impact of power flows coming from Africa on the operation of the Spanish system, other two important European demand centers are modeled: France and Germany. Figure 4.1 presents the systems modeled and the interconnections studied in the 2050 horizon.

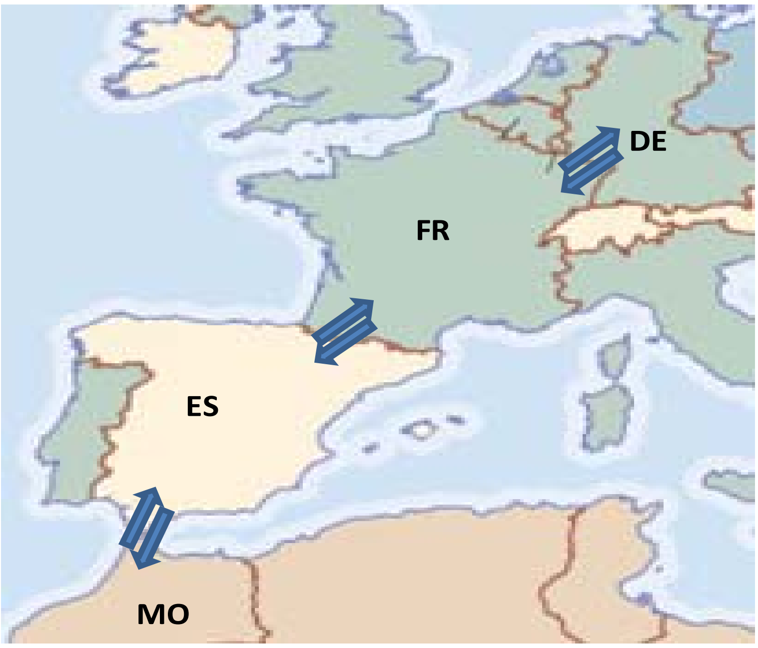

Figure 4.1: Area of study in the 2050 horizon

The analyses are carried out separately for the two case studies:, (a) HVDC supergrid and (b) the massive use of EVs & DSM. In our analysis, the existence of a supergrid is modeled by considering larger interconnection capacities than the ones existing in the base case scenario. EVs deployed increase the net load because charging is required for transportation use. However, they can also store electricity at certain time to inject it back into the grid at a later time (vehicle-to-grid or V2G) when there is an economic benefit (from the system operation perspective) in doing so. The detailed modeling of EVs is described in (Fernandes et al., 2012).

As for DSM, as in the 2030 horizon study only load shifting is analyzed. A higher level of DSM penetration is assumed in the 2050 horizon, though. In order to assess the impact of these technologies on operation costs, system operation is simulated using the ROM model for four case studies: (i) base case scenario, without DSM, without EVs and considering lower values of interconnection capacities; (ii) considering only the addition of HVDC interconnection capacity among systems to that in the base case; (iii) considering only the existence of a certain amount of EVs on top of the situation on the base case; and (iv) considering together the deployment of EVs and DSM. Economic benefits produced by these technologies are computed as the difference between operation costs in the base case scenario and costs in those cases where each of these technologies is considered.

4.2 Brief Methodology overview and assumptions

As previously mentioned, the ROM model is used to simulate power system operation during a whole year. The unit commitment and generation dispatch is jointly optimized for Morocco, Spain, France and Germany, taking into account the conventional generation capacity mix, RES generation profiles, interconnection capacities, and demand in each country. Each system (country) is modeled as a single node, i.e. local network constraints are not taken into account in this analysis. The following main hypotheses are considered for each studied technology:

1) HVDC supergrid

- The existence of the HVDC supergrid is modeled by increasing interconnection capacities among countries with respect to the base case scenario. Also, it is assumed a massive deployment of RES generation in North Africa. The level of interconnection capacities and RES deployment considered are based on the study published in (Zickfeld and Wieland, 2012).
- The same generation capacity mix (including RES installed capacity) is considered in both the base case and the supergrid scenarios in all systems.

2) EVs

- It is assumed that EVs charging is managed by a third-party (aggregator), which minimizes system operation costs, constrained by users' driving and plug-in patterns. It is also assumed that by 2050 all EVs have V2G capability. Therefore, EVs are charged not only for transportation purposes but also for storing electricity when an economic benefit can be obtained from it (i.e. when system operation costs are reduced when electricity is moved from hours with excess of generation to peak hours);
- The number of EVs assumed to be integrated into the Spanish system by 2050 is 1,000,000. The parameters of EVs and batteries considered to model them follow: specific consumption (in kWh/km), maximum battery storage capacity (in kWh), grid-to-battery, battery-to-wheel and battery-to-grid efficiencies, and charging and

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discharging rates. For simplification purposes, only one type of EV user is considered (whose transportation needs are represented by the daily distance range, and driving and plug-in patterns).

3) DSM

➢ The same hypotheses considered in the 2030 horizon study are used in the 2050 analysis: i.e. load shifting does not modify total daily demand and it is managed by a third-party aggregator. In the 2050 horizon study the maximum hourly load than can be shifted is equal to 8% of the total hourly demand.

4) Priority dispatch of RES

➢ For the 2050 horizon it is assumed that there is no explicit priority dispatch for RES production. There is an implicit priority dispatch related to the much lower costs associated with RES generation. For simplification purposes, it is considered that RES producers have operation costs equal to 10 €/MWh.

4.3 Input data

Main input data used in the 2050 horizon study include demand, generation and interconnection capacities for each analyzed system (i.e. Spain, France, Germany, and Morocco), and parameters related to the modeling of EVs. Figure 4.2 shows the peak load (in GW), total yearly demand (in TWh), and generation capacities for each system considered in the 2050 horizon study for all scenarios (base case and technology scenarios).

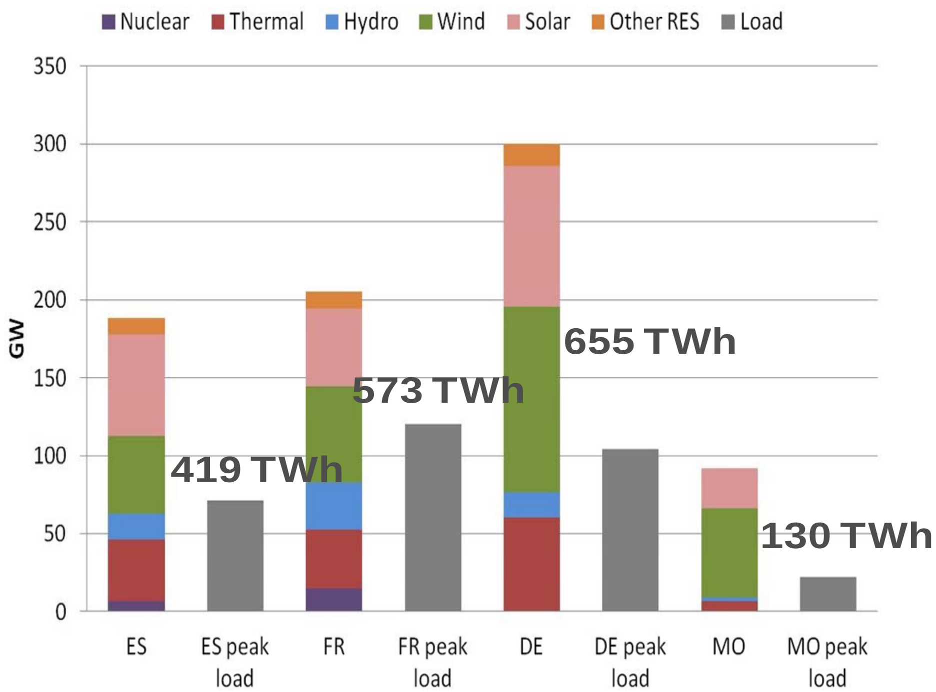

Figure 4.2: Demand and generation capacity mix in Spain, France, Germany and Morocco in the 2050 horizon

Table 4.1 presents the interconnection capacities considered in the base case scenario (which are the same as those in the scenarios with EVs and DSM) and the capacities assumed in the supergrid scenario.

Table 4.1: Interconnection capacities in the base case and in the HVDC supergrid scenarios

	Interconnection capacity (GW)	
	Base case	HVDC supergrid
MO - ES	2	20
ES - FR	12	20
FR - DE	8	15

Figure 4.3 presents daily plug-in and driving patterns of EVs considered in the analysis. For simplification purposes, only one type of EV user is considered. The type chosen is the commuter one. For simplification purposes, it is assumed that during weekends plug-in and driving patterns are the same as those during the weekdays. Other parameters related to EVs include: specific vehicle consumption of 0.20 KWh/km, total annual distance covered of 18,250 km/vehicle, battery maximum storage capacity of 40 KWh, grid-to-battery, battery-to-wheel and battery-to-grid efficiencies of 95% each, and charging and discharging ramps of 6.7 and 10 kW/h, respectively.

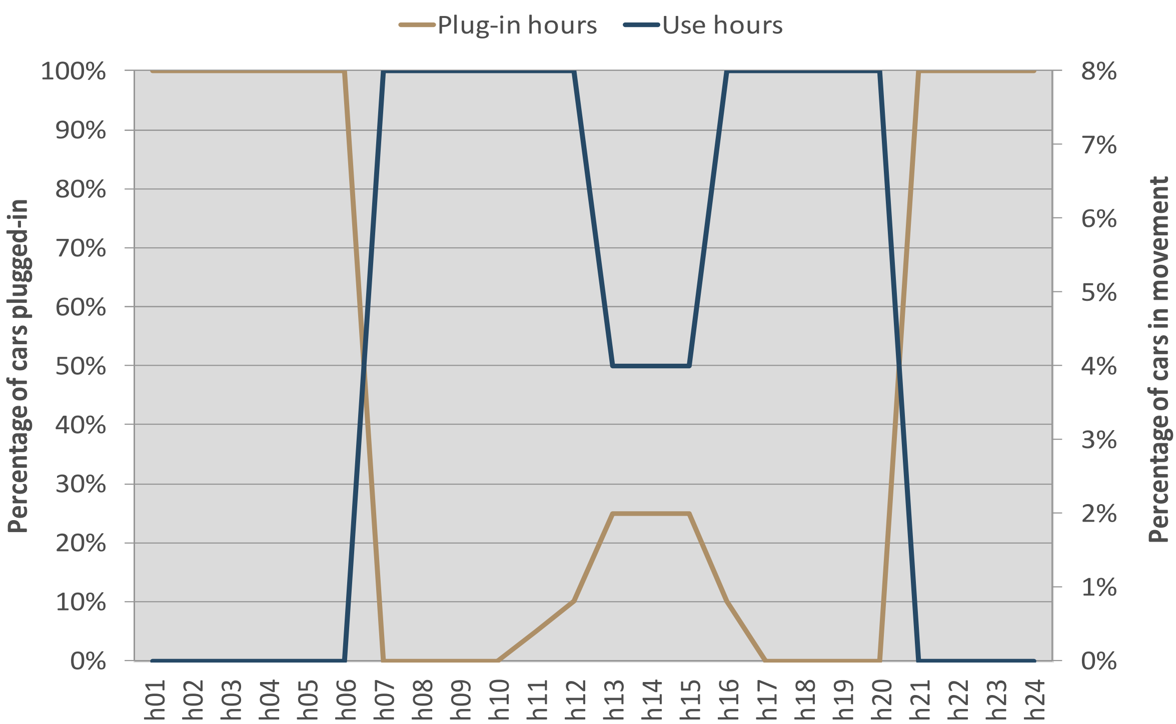

Figure 4.3: EVs daily plug-in and driving patterns

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4.4 Results and sensitivities

This section presents the main results produced by the ROM model on the impact on system operation of the development of a HVDC supergrid connecting North Africa and the rest of Europe, and the deployment of EVs and DSM in the Spanish power system. After that, the impact of these solutions on system operation costs is discussed.

1) HVDC supergrid

Figure 4.4 shows net power flows in the different studied interconnections in the base case and the supergrid scenarios. As it can be observed in the figure, an important share of RES generation power imported from North Africa "stays" in the Spanish system: net flows in the interconnection MO→ES increase by, approximately, 70 TWh in the supergrid scenario; while net flows in the ES→FR interconnection change direction, i.e. in the base case scenario Spain imports 20 TWh from France while in the supergrid scenario Spain exports 20 TWh to France. Therefore, in net terms, Spain exports to France about 56% of the additional energy imported from North Africa in the supergrid scenario. France in turn increases net exports to Germany by 11 TWh in this scenario, which represents 30% of the additional energy imported by the French system in this scenario (i.e. 40 TWh).

Figure 4.5 presents the total annual changes in power system operation in the supergrid scenario with respect to the base case scenario. It can be observed that electricity produced by RES generation located in North Africa replaces part of the power produced by thermal generation in Spain, France and Germany and also part of power produced by nuclear generation in France and Spain in the base case scenario. In this respect, the higher impact is observed in the Spanish system, since it is consuming a large part of the power imported from Morocco. In Spain, thermal and nuclear power production decrease by 40% and 14%, respectively, when compared to the base case scenario; in France, thermal and nuclear power plants reduce their production by 29% and 7%, respectively; finally Germany's thermal generation decreases its production by 6% with respect to the base case scenario. Regarding curtailment, it is important to point out that RES curtailment in Morocco in the base case scenario is very high. This is probably due to the fact that the same generation capacity mix (including RES installed capacity) is considered in both the base case and the supergrid scenarios in Morocco, which results in an icrease also in conventional generation capacity associated with that in RES generation capacity. If massive RES generation is deployed in North Africa, this deployment should be associated with the development of a supergrid to bring power surpluses to Europe unless very relevant load increases occur in the Moroccan system.

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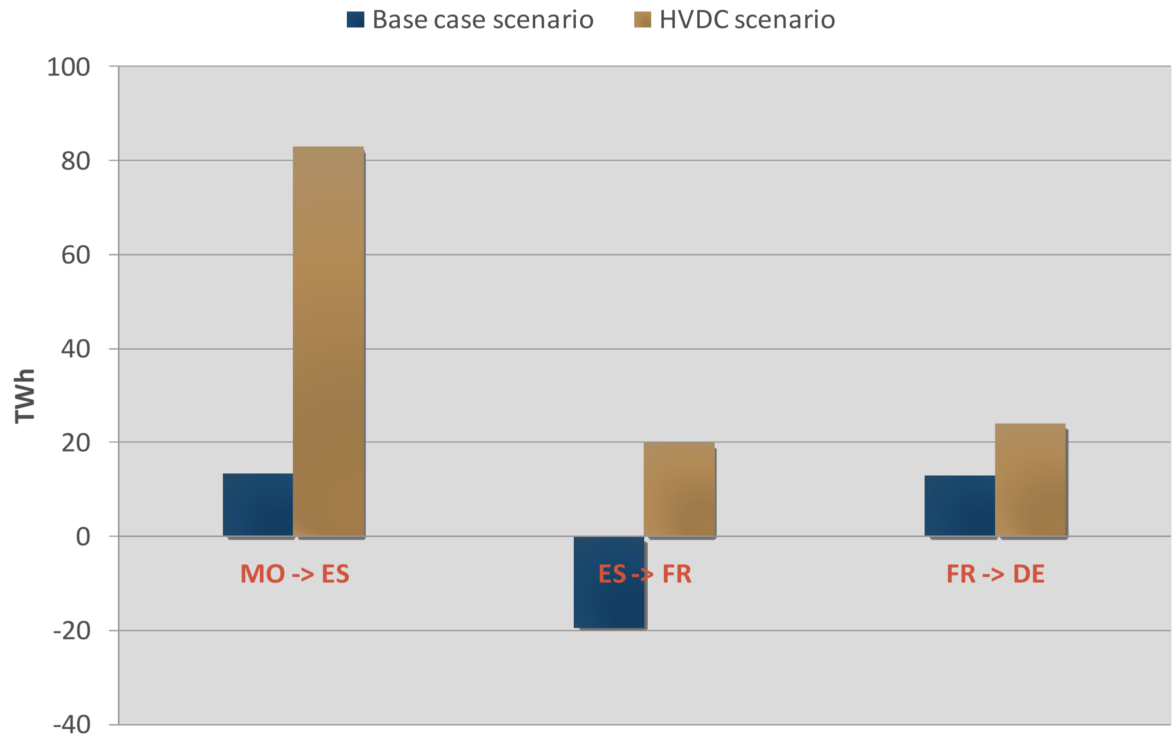

Figure 4.4: Total annual net power flows in the interconnections in the base case and the HVDC supergrid scenarios

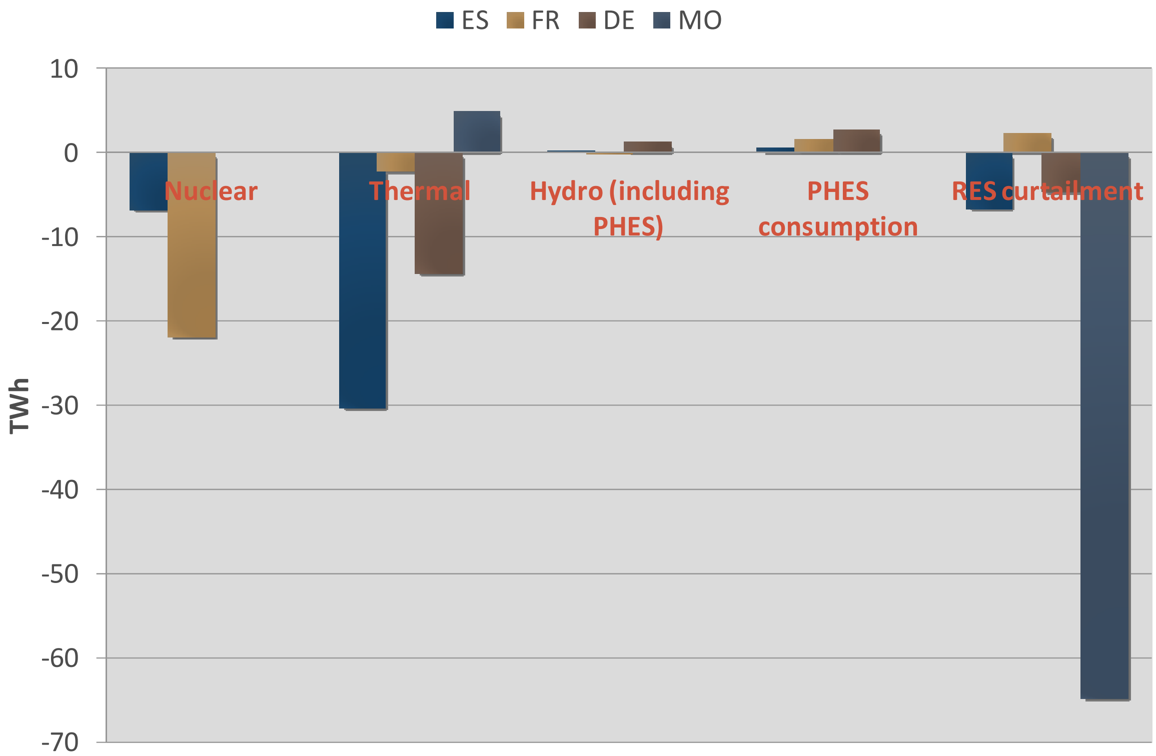

Figure 4.5: Impact of the supergrid on power system operation: total annual differences with respect to the base case scenario

2) *Electric vehicles and demand-side management*

As explained in Section 4.1, two scenarios including EVs have been run: one including only EVs and another one including EVs and DSM. In the following, the system operation results computed in both cases (compared with those in the base case scenario) are presented.

Figure 4.6 shows the original Spanish load duration curve (i.e. the curve in the base case scenario) and the load curve including EVs charging (in the EVs scenario). It can be observed that, as a result of the implementation of a smart charging strategy, EVs are charged mainly during periods with lower demand levels, although driving and plug-in patterns may require that some charging is carried out during hours with higher demand levels. Total EVs' energy requirements for transportation purposes amount to 3.7 TWh/year. Another 6.0 TWh/year of electric energy are injected back into the grid by EVs after having been stored for some hours. Since there are efficiency losses in the process of charging, and discharging, EVS, in total, annual EVs' consumption is equal to 10.7 TWh. Therefore, EVs cause a net demand increase of 4.7 TWh/year (i.e. total EVs consumption less the energy re-injected into grid). Figure 4.7 shows the impact of EVs on power system operation. This is represented as total annual differences in the level of power production by the several generation technologies with respect to the base case scenario.

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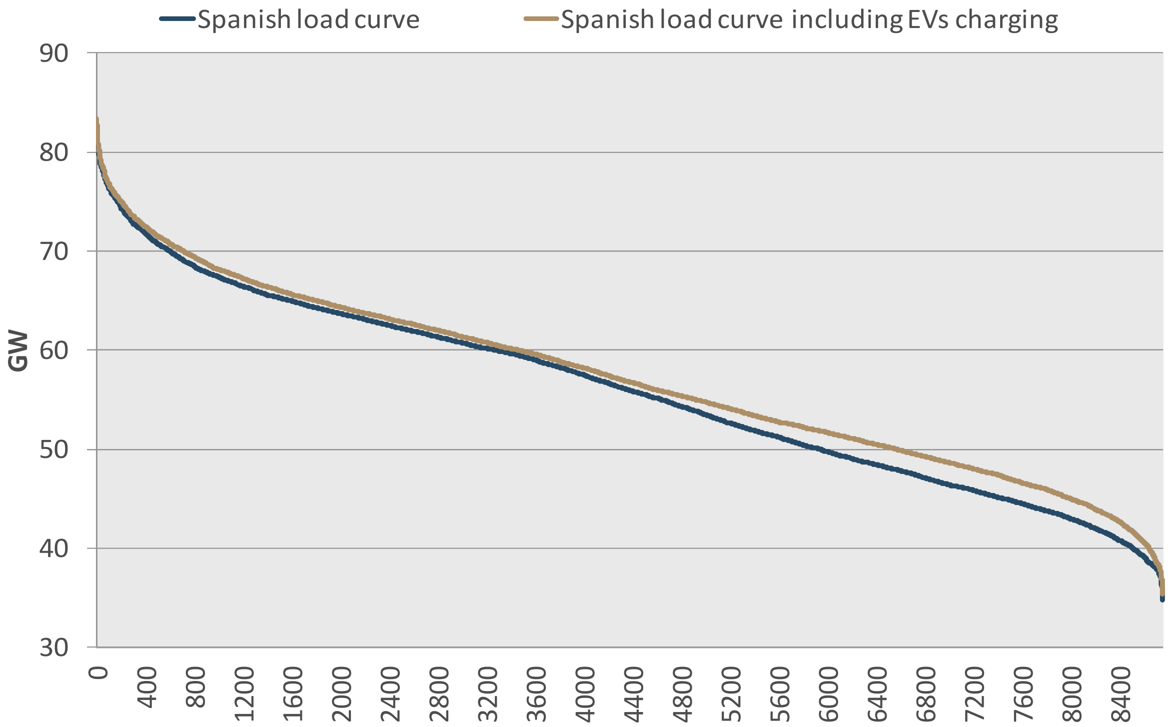

Figure 4.6: Spanish load duration curve with and without considering EVs charging

Figure 4.7 shows that EVs with V2G capability represent an important source of flexibility to be used in power system operation, since they achieve the reduction of RES energy curtailment and replace, partially, the use of PHES units.

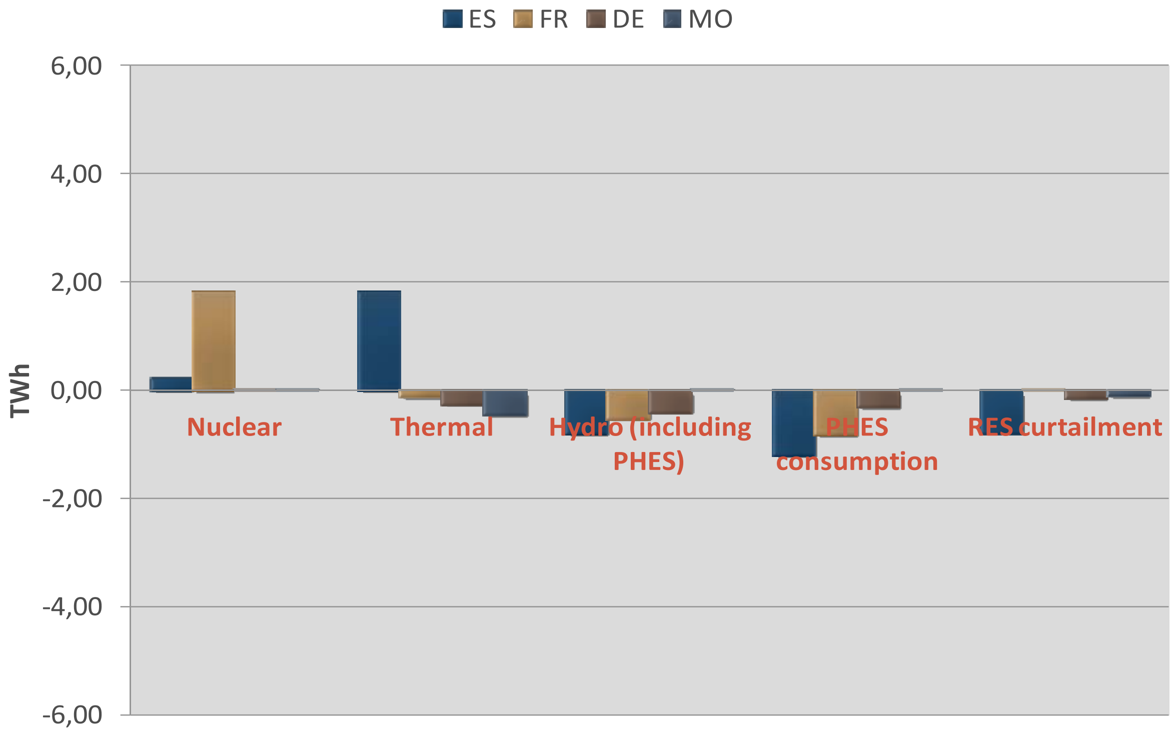

Figure 4.7: Impact of EVs on power system operation: total annual differences with respect to the base case scenario in the amount of power produced by each technology

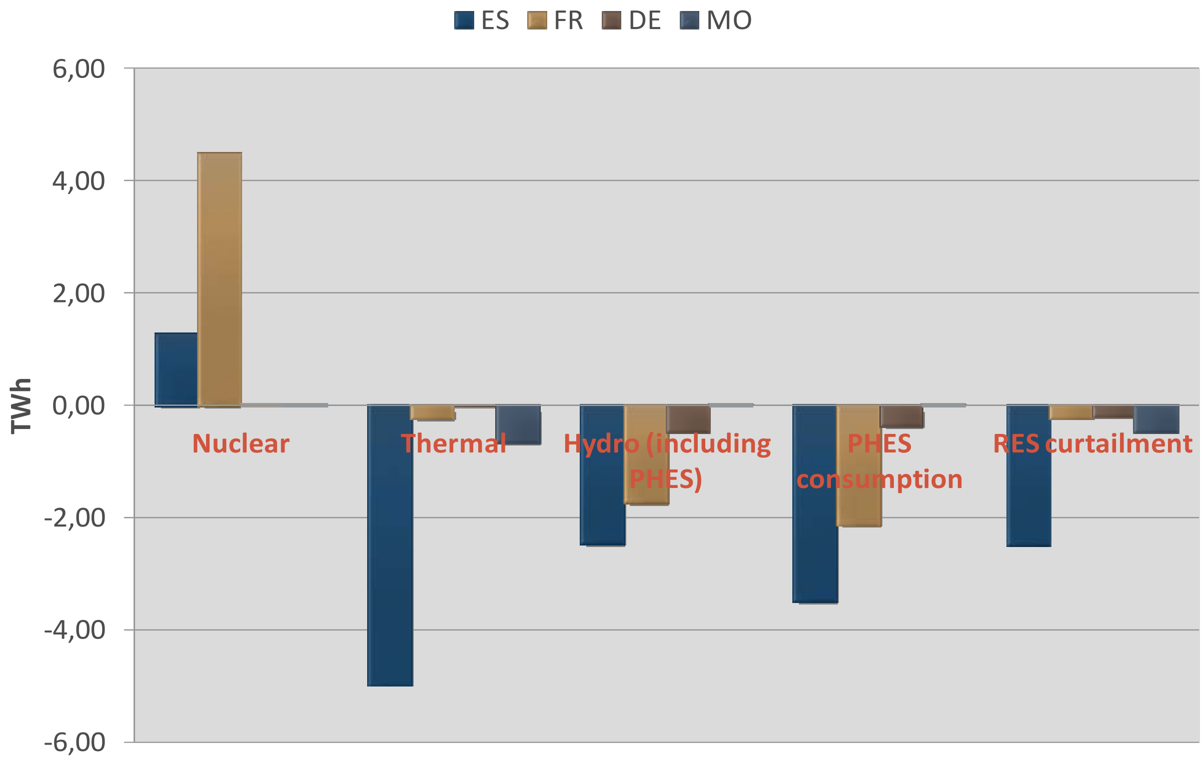

Figure 4.8: Impact of EVs and DSM on power system operation: total annual differences in the energy production level by main generation technologies with respect to the base case scenario

The most important differences in the level of power production by generation technologies that result from the consumption of power by EVS and the injection into the grid of part of this afterwards are listed next: increase of nuclear power production (25% of total absolute changes), decrease of PHES consumption and generation (29% and 21%, respectively), increase of RES feed-in (13%), i.e. reduction of RES energy spillages, and, increase of thermal generation (12%). Figure 4.8 shows the joint impact of EVs and DSM on power system operation as total annual differences in the energy production level by main generation technologies with respect to the base case scenario.

It can be observed that, added to EVs' flexibility, the high flexibility introduced by DSM results in an even further increase in the RES feed-in and nuclear power production, and a reduction in the use of PHES units and thermal generation. It is worth noticing that, in this case, thermal generation production is reduced in comparison with the only EVs and the base case scenarios. This can be explained by the fact that the "extra" flexibility brought about by DSM allows a much higher increase in nuclear generation output compared to the EVs' only scenario, thus avoiding an increase in thermal power production.

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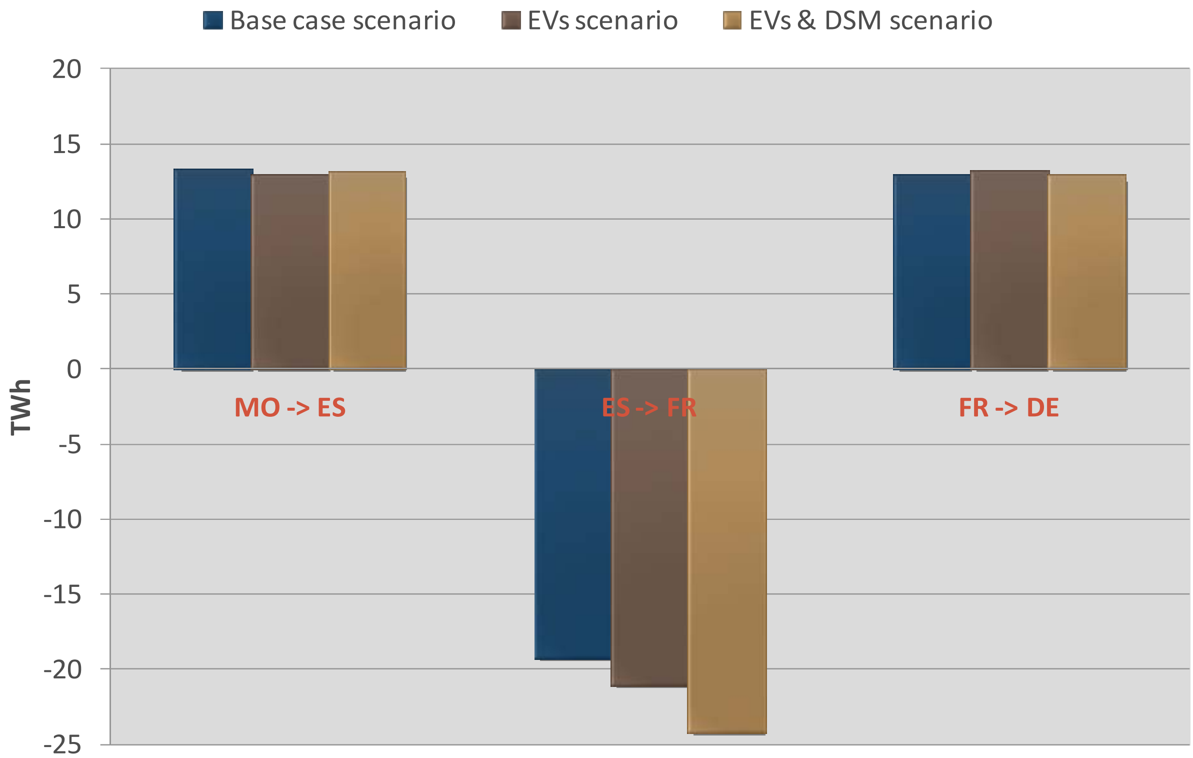

Figure 4.9: Total annual net power flows in the interconnections in the base case, the EVs and the EVs & DSM scenarios

Finally, Figure 4.9 shows the total annual net power flows in the studied interconnections in the several scenarios. It is observed in the figure that the most affected interconnection is the one connecting the Spanish and the French power systems both in the only EVs scenario and in the EVs & DSM scenario. This is a result of the fact that the higher flexibility, added to the higher demand, existing in the Spanish system in these scenarios allows nuclear power production in France to be increased. This, in turn, results in an increase in net exports from France to Spain.

3) Impact of the studied technologies on system operation costs

Figure 4.10 shows the total annual operation cost savings (negative values) for the four systems (i.e. Morocco, Spain, France and Germany) achieved in each case with respect to the base case scenario. It is clear that the development of the supergrid would bring about the higher benefits in terms of cost savings. According to the results computed, achieved cost savings in the HVDC scenario correspond to 8% (≈3,137 M€) of the total operation costs of the base case scenario. It must be noted that this reduction in operation costs is not only due to the deployment of a supergrid, but also, and largely, to the deployment of large amounts of RES generation in Morocco, which have a relevant investment cost. In the scenario where only EVs are added, operation costs increase with respect to the base case, since the total system demand is higher. However, it is important to point out that while the introduction the EVs increases costs in the power sector, due to the higher electricity

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demand existing in this case, EVS produce benefits to the transport sector, like the large reduction occurring in the use of fossil fuels and carbon emissions. In the EVs scenario, the increase in operation costs with respect to the base case represents 0.5% of the total costs in the base case scenario. Finally, in the scenario where both EVs and DSM are considered, cost savings correspond to 1.3% (≈515 M€) of the total operation costs in the base case scenario.

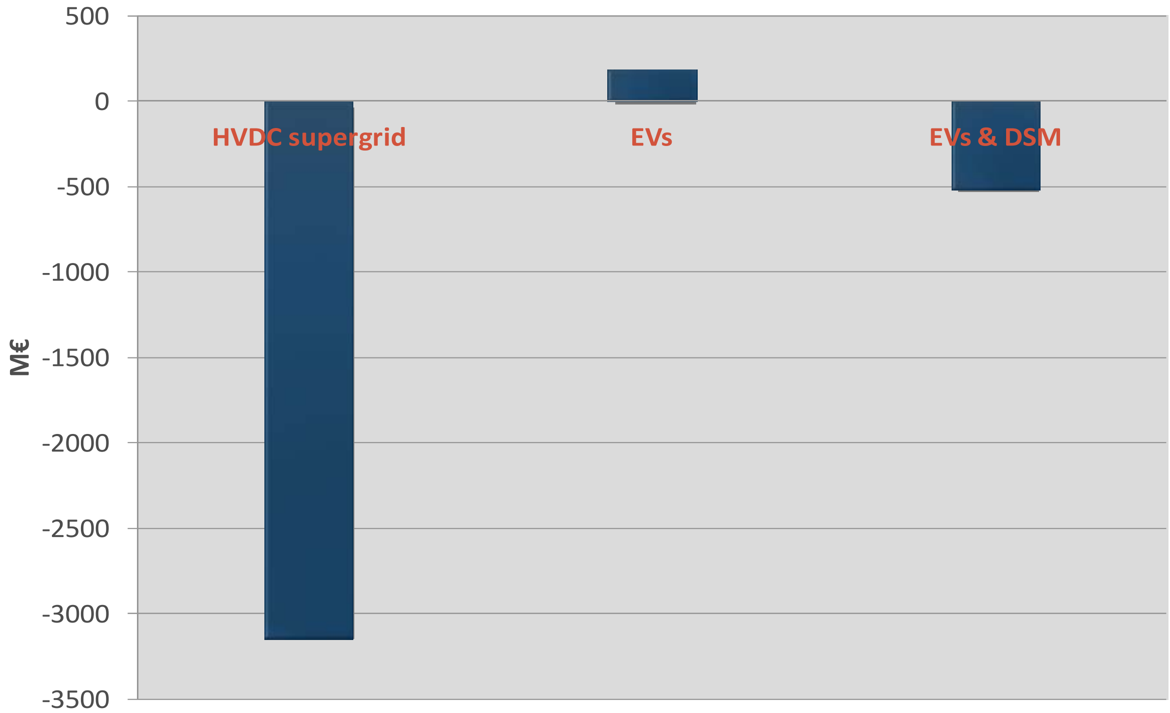

Figure 4.10: Impact of the 2050 horizon studied technologies on total system operation costs: total annual differences with respect to the base case scenario

4) *Technology costs*

Although the deployment of an HVDC supergrid can bring significant economic and environmental benefits to European power systems, it would also require huge investments both to deploy the nework itself and to build new generation in the north of Africa which would export part of its production to Europe. In this study, a rough estimate of the cost of the investments required for the development of the interconnections considered in the HVDC scenario is provided based on cost elements found in the works published by the Cigré Working Group B4 (2013), Godron et al. (2014), and Van Hertem and Ghandhari (2010). The main cost elements considered are shown in Table 4.2.

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Table 4.2: Elements considered in the estimate of the cost of HVDC links

Cost elements of HVDC link	
Converter station (1 GW)	110 M€/station
Subsea cable 3 GW	3.4 M€/km
Underground cable 3 GW	3.7 M€/km
Converter losses	0.9%

Based on the unit costs shown in Table 4.2, it is estimated that the additional 18 GW of HVDC interconnection capacity built between Spain and Morocco in the HVDC scenario (difference between the supergrid scenario and the base case scenario) would cost approximately 8,256M€; the additional 8 GW of HVDC interconnection capacity between Spain and France would cost 3,709 M€; and, the additional 7 GW between France and Germany would cost 3,246 M€. In total, the additional interconnection capacity existing among these countries would cost, approximately, 15,210 M€. Considering a lifetime of transmission lines equal to 40 years and an interest rate of 7%, the annualized investment costs of this additional interconnection capacity would be 1,100 M€.

Table 4.3: Estimated costs of implementing DSM for small consumers (20% participation level)

	Unitary cost (€) (GAD project)	Total cost (M€) – DSM 20%
Communication & control equipment	3,000,000	92*
Smart meter	160	704
Energy box (load controller)	160	704
Customer interface	20	88
Adaptation of appliances	220	968
Total		**2,464**

* Assumed to be the same as the communication & control cost computed for the GAD-25% scenario

As previously explained (Section 3.4, point 4), the costs of implementing DSM for small consumers have been estimated based on information from the GAD project (Conchado and Linares, 2010). By 2050, it is assumed that the participation of small consumers in DSM programs could reach 20% (i.e. equivalent to a participation of 8% of the total Spanish demand). The corresponding costs are shown in Table 4.3.

4.5 Discussion of results

The 2050 horizon study focuses on two types of solutions to integrate massive amounts of RES generation in Europe: the development of a supergrid, which is an option that would require the participation of all European countries, and the massive deployment of EVs and DSM, which are alternatives that could be implemented at a local (country/region) level.

An HVDC supergrid could bring significant benefits in terms of the increase in the amount of RES energy integrated and, consequently, also in terms of the environmental impact of the sector at a European level. Nevertheless, the development of this supergrid would require huge investments, which would depend not only on one country/region but rather on agreements reached among all those in the region, which would require having a common European Policy and on European funds, and achieving a common understanding of the situation with North African authorities. On the other hand, DSM benefits in relation to RES integration would be much more limited than those produced by an HVDC supergrid, but would also have much lower implementation costs.

5 Conclusions and policy recommendations

5.1 Main techno-economic conclusions

The analyses performed for the Spanish system have focused on different innovative solutions to deal with RES integration issues in different time horizons: 2020, 2030 and 2050. The main objective of the analyses conducted for the Spanish case has been to assess the impact of these innovative solutions on power system operation and on system operation costs. In order to simulate power system operation during a whole year, a mid-term unit commitment model has been used. The impact of each technology in each time horizon was assessed by comparing the model system operation results in two scenarios: the base case (i.e. case without the studied technology) and the scenario in which the technology is deployed.

The 2020 analyses carried out for the Spanish case study have focused on the use of a power flow controlling device that re-directs power flows from congested lines to parallel corridors with available capacity to avoid/reduce local transmission grid congestion, thus contributing to RES integration. According to the results of our study, the total annual economic benefits, in terms of operation cost savings, achieved by the installation of this device are more than enough to cover its investment cost. It has been concluded that, at least in the short-term (i.e. for relative low levels of RES penetration and grid congestion), FACTS devices are a cost-efficient solution to integrate more RES generation.

The 2030 analyses have focused on innovative solutions that aim to safely and efficiently cope with an increase in the level of intermittency of power generation caused by larger amounts of RES generation being installed. This is needed to avoid significant RES generation curtailment. More specifically, the impact of DSM (load-shifting) and CAES on power system operation has been assessed. Although it has been considered in our analysis that these solutions are deployed only in Spain, simulations were jointly run for the Spanish and the French systems so that the impact of deploying these technologies in Spain on the Spain-France interconnector could be studied. The results of the analyses indicate that both solutions can contribute not only to increasing the Spanish system flexibility but also to achieving a more efficient dispatch in France (i.e. part of the flexibility could be benefiting the French system and, therefore, be “exported”). It has been observed that, although in principle both solutions should have a similar impact on power system operation, the level of efficiency of the processes involved in the two cases (i.e. load shifting, and storing and generating electricity) have an important impact on operation cost savings, which results in these savings differing significantly for both technologies.

Considering the estimated unit technology costs values and the potential economic benefits produced by these technologies in terms of thermal cost savings, the annualized investment required for the implementation of load-shifting or storage solutions with very high efficiency levels could be compensated by savings in operation costs achieved by them. However, for drawing conclusions, a complete cost-benefit analysis would be needed, which would require the assessment of all the possible benefits of these technologies, especially for lower efficiency levels of the former.

Finally, as uncertainties related to grid developments occurring and integration solutions deployed are significantly higher in the 2050 horizon, two alternative types of solutions have been studied for this target year: the first one involve the development of an HVDC supergrid to bring RES electricity from North Africa to Europe, i line with the DESERTEC and MEDGRID vision; and the second option involved the deployment of “local”/country level solutions to integrate RES generation, in this case EVs and DSM.

Results computed in the HVDC supergrid scenario showed that an important share of power produced by RES generation coming from North Africa would be consumed in the Spanish system, since only 56% of the additional energy imported from North Africa into Spain is exported to France in this scenario. Results computed have shown that RES power production imported from North Africa replaces a great share of thermal and nuclear power production, which allows important thermal cost savings in the HVDC scenario. On the other hand, the development of this supergrid and RES generation in North Africa would require huge investments, which would depend not only on one country/region but rather on the existence of a common European Policy on these issues, the availability of European funds, and the common willingness of authorities on both sides of the Mediterranean to go ahead with this ambitious project.

The potential economic benefits of local solutions would be much more limited compared to those of an HVDC supergrid. However, at the same time, the implementation of these solutions would require much smaller investments.

5.2 Policy recommendations

The analyses carried out within the GridTech project for the Spanish case study provide some policy insights for the different time horizons:

- In the short-term, innovative solutions to facilitate the use of the existing transmission capacity such as FACTS devices can be not only a cost-efficient solution to avoid grid congestion and integrate higher amounts of RES generation, but also the only feasible solution for highly congested areas if permitting procedures are delayed and construction times of new transmission lines become quite long. Therefore, providing adequate incentives for TSOs to invest in this type of solutions is recommended. In this sense, regulators should recognize efficient costs incurred by system operators due to the investment in new grid technologies.
- In the mid to long term, solutions to increase the system flexibility, such as DSM and storage, help to integrate larger amounts of RES production, contributing to the achievement of operation cost savings. It was observed that the level of efficiency of these solutions can affect operation in a significant way. If efficiency levels of both options studied are similar, under a social welfare perspective, both technologies (i.e. DSM and CAES) should have a similar impact on power system operation. Nevertheless, the distribution of benefits among market participants will probably be not the same in the two technology cases. In the case of CAES, the agent who perceives more directly its benefits is the storage owner. Depending on the impact of CAES (or storage in general) on the electricity market outcome, consumers could be indirectly benefitted

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by CAES by facing lower and/or flatter market prices. In the case of DSM, consumers would be directly beneficiated by its use. However, the benefits obtained by small consumers from DSM may not be high enough to encourage them to participate in its deployment process. Normally, consumers will participate in DSM deployment only if the economic benefits they perceive are larger than the implementation costs they face, including the costs associated with the deterioration affecting the consumers comfort when they are enrolled in DSM programs.

- Results computed point out that the development of a supergrid could bring significant economic benefits to power system operation. Nevertheless, if a European supergrid is to be developed, a high-level of coordination between involved countries will be required. Furthermore, building this supergrid would require reaching an agreement on long-term RES production targets to be achieved in each system, the harmonization of network infrastructure planning processes, the development of common funding schemes, and that of a fair and efficient methodology to allocate investment costs among the involved countries. Therefore, policy makers must take into account all infrastructure and generation investments and transaction costs, as well as all potential benefits from these network and generation developments (not only those concerning operation cost savings) when deciding whether to go for a EU-wide solution in cooperation with North Africa. We believe benefits from these could be larger than costs, but conclusions on the advisability of this solution should be robust to achieve the involvement of all relevant parties in this process.

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7 Appendix

7.1 The ROM model

The ROM model is a unit commitment model that has been developed at the Instituto de Investigación Tecnológica of Universidad Pontificia Comillas. This tool has been used in previous European projects such as SUSPLAN (Planning for Sustainability), MERGE (Mobile Energy Resources in Grids of Electricity) and TWENTIES (Transmitting wind), to perform power system operation analyses under the penetration of intermittent RES generation, integration of electric vehicles and implementation of demand-side management measures.

This mid-term operation model is formulated as a mixed-integer program (MIP) using the General Algebraic Modeling System (GAMS). This tool is a two-stage model whereby a daily deterministic optimization model (first stage) is followed by a sequential hourly simulation (second stage). The first stage solves the unit commitment problem for each day of the year minimizing operation costs. In the second stage, first unit commitment is revised and generators are re-dispatched depending on unit outages occurred after generation dispatch and on wind forecasting errors. In this stage, Monte Carlo method is used to simulate unit outages. After that, during real time operation corrective measures are applied to counteract possible unit outages and wind forecasting errors. In order to simulate system operation during a whole year, the model runs 365 daily unit commitment problems (each one of them with 24 hours time steps). The initial conditions of each day depend on the final schedule of the previous day. The operation model does not take into account internal network constraints, although interconnection between neighboring countries are included.

In the first stage, unit commitment and hourly dispatch of all thermal and hydro units, as well as the assignment of up and down reserves to these units, are decided. Operation costs for the whole system are minimized in the objective function. These costs include fixed and variable costs of thermal units (no-load, start-up, fuel, operation & maintenance costs, and CO2 emissions), penalty for shortcoming of up and down reserve, and non-supplied energy costs. Detailed operation constraints are also taken into account in the unit commitment model:

i) Demand and generation balance and, supply of operating reserves. Up and down reserve requirements are input data of the model and include two main components: the first is related to wind forecasting errors, and the second is related to unit outages. These reserve requirements can be compared to the supply of secondary and tertiary reserves in the ancillary services market.

ii) For thermal units: start-up/shutdown time, bound on power reserve and power output, up and down ramps and exponential start-up costs.

iii) For hydro units: bound on pumped storage up and down reserves, water inventory in hydro reservoirs and pumped storage, bounds on hydro power output and daily hydro output target. Decisions above the daily scope, as the weekly scheduling of pumped storage hydro plants, are done internally by the model respecting economic criteria. Yearly hydro scheduling of storage hydro plants is done by a longer term model (hydrothermal coordination) and has to be provided as input data to the operation model.

Series of distributed generation and wind generation are estimated and introduced in the model as input data. Distributed generation comprises small hydro, solar and biomass technologies. This series is estimated based on hourly generation profiles and installed capacity of each technology. Wind generation series is produced from real historical production profiles, which is extrapolated for the studied year. Average values are not used in order to avoid variability smoothing.

In the second stage, the model revises the previous schedule and re-dispatches generators at 12pm of “D-1” taking into account unit outages occurred after generation dispatch (2pm of “D-1”) and wind forecasting errors. Monte Carlo simulation is run to simulate unit outages. Regarding wind forecasting errors, two series are used in the model. The first one corresponds to the estimation of wind generation at the time of generation dispatch. The second one corresponds to a better estimation of wind generation when unit commitment is modified (re-dispatch). Wind generation series corresponds to real wind production (see Fig. 1). The second stage is divided in two parts:

a) At midnight, unit commitment is modified to account for better wind production estimation (wind forecasting error at 12pm), and unit outages (Monte Carlo simulation) occurred after generation dispatch is decided. This is assumed to be the last hour at which a thermal unit can be committed to reach the morning demand ramp. The objective is to reduce the difference between generation and demand to a safe margin.

b) Subsequently, the model simulates unit outages and takes into account real wind production (wind generation series). Corrective actions are applied for production deviations due to wind forecasting errors and unit outages. The order in which these actions are applied follows economic criteria: (1) hydro reserve deployment; (2) pumping units reserve deployment; (3) thermal reserve deployment; (4) commitment of gas turbines in real time. If generation and load balance is not achieved after reserve is deployed, two operating situations can happen: i) non-supplied energy, if generation is not able to cover demand and ii) energy curtailment (water and/or wind).

The main outcomes of the operation model are the hourly generation by technology, system marginal cost, CO_2 emissions, the use of reserves and energy curtailment.

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