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Exploring the roles of storage technologies in the Spanish electricity system with high share of renewable energy

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A B S T R A C T

At operational level, fossil fuel phase-out and high shares of non-dispatchable renewable energy resources (RES) will challenge the system operator's (SO) ability to balance generation, and the demand at any time. The variability of RES output ranges from one hour to a season, and critical events such as low supply and high demand might occur more frequently and for more extended periods. When evaluating the role of Energy Storage Systems (ESSs) in this context, the need for a long time scope to capture the different RES variabilities must be reconciled with the need for modeling the hourly chronology. This paper presents a medium-term operation planning model, addressing both the energy dispatch and the balancing services. This study shows that representing the combined chronological variability of demand and RES production is essential to properly assess the roles of different kinds of ESSs in the future 2030 electricity mix. Otherwise, it would not be possible to appropriately capture the frequency, depth, and length of events for which ESSs are activated. The analysis also highlights the importance of considering balancing services, given the significant contribution of batteries to the reserve market. Finally, the results show that batteries and Pumped Storage Hydro (PSH) have different roles in the Spanish electricity system with a high renewable penetration. While PSH is mainly used to provide energy during critical periods, batteries mostly provide balancing services.

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Abbreviations

BC	Base case
CCGT	Combined Cycle Gas Turbine
CLPSH	Closed-Loop Pumped Storage Hydro
ESS	Energy Storage System
MIP	Mixed Integer Linear Programming
NECP	National Energy and Climate Plan
OLPSH	Open-Loop Pumped Storage Hydro
PCI	Project of Common Interest
PSH	Pumped Storage Hydro
REE	Red Eléctrica de España (Spanish system operator)
RES	Renewable Energy Sources
RoR	Run-of-River hydro power plant
SO	System Operator
Solar PV	Solar photovoltaic
UGH	Hydropower Programming Unit (Unidad de Gestion Hidráulica in Spanish)

Nomenclature

Indices

ω	Scenario
n	Load Level
g	All kind of generating unit (thermal, hydro, RES and ESS unit)
t	Thermal unit
h	Hydro unit
or	Unit able to provide operating reserve
s	Energy Storage System (ESS)
r	Energy reservoir associated with an ESS

Parameters

$D_{\omega,n}$	Hourly load demand [MW]
DUR_n	Duration of each load level [h]
$CENS$	Cost of Energy Non-Served [€/MWh]
P_ω	Probability of each scenario [p.u.]
EF_s	Roundtrip efficiency for ESS unit (i.e., percentage of electricity put into storage that is latter retrieved) [p.u.]
$EI_{\omega,n,s}$	Weekly energy inflow for ESS unit [MWh]
$IUC_{\omega,g}$	Initial unit commitment status for the first hour of the year {0–1}
$\overline{P_g}, \underline{P_g}$	Maximum and minimum output of generating unit [MW]
$\overline{C_s}$	Maximum pumping of ESS unit [MW]
CV_g	Total variable cost of generating unit (includes fuel, variable O&M and emission costs) [€/MWh]
CV_s	Variable cost of ESS unit [€/MWh]
$R_{\omega,n}$	Ratio between upward reserves and total operating reserves set by the SO [p.u.]
I_s	Energy capacity of ESS unit [MWh]
τ_s	Duration of ESS discharge cycle (e.g., 24, 168, 672 for daily, weekly, monthly) [h]
CD, CU	Percentage use of energy concerning the balancing capacity for generating unit providing downward/upward operating reserves [%]
$DR_{\omega,n}, UR_{\omega,n}$	Hourly downward and upward operating reserve [MW]
RD_t, RU_t	Ramp down and ramp up limits of thermal unit [MW/h]
TD_t, TU_t	Minimum downtime and uptime of thermal unit [h]
CSD_g, CSU_g	Shutdown and start-up and costs of committed unit [M€]

Variables

$ens_{\omega,n}$	Energy non-served [MWh]
$gp_{\omega,n,g}, gc_{\omega,n,g}$	Generator output and consumption (discharge if ESS) [MW]
$p_{\omega.n,g}$	Production of unit above minimum output [MW]
$c_{\omega,n,s}$	Consumption of ESS unit above minimum output [MW]
$uc_{\omega,n,g}$	Commitment of a generation unit per load level {0,1}
$sd_{\omega,n,g}, su_{\omega,n,g}$	Shutdown, and start-up event of generating unit {0,1}
$\varphi_{\omega,n,or}$	Commitment in activating balancing energy from balancing capacity provided {0,1}
$SoC_{\omega,n,s}$	State of Charge (SoC) of the energy reservoir for ESS unit [MWh]
$s_{\omega,n,s}$	Spilled energy of the energy reservoir for ESS unit [MWh]
$dr_{\omega,n,or}, ur_{\omega,n,or}$	Provision of upward and downward operating reserves for generating unit [MW]
$dr'_{\omega,n,s}, ur'_{\omega,n,s}$	Provision of upward and downward operating reserves for ESS [MW]
$ad_{\omega,n,or}, au_{\omega,n,or}$	Activated energy associated to the provision of upward and downward operating reserves for generating unit [MWh]
$ad'_{\omega,n,s}, au'_{\omega,n,s}$	Activated energy associated to the provision of upward and downward operating reserves for ESS [MWh]

1. Introduction

The fossil fuel phase-out and high shares of non-dispatchable renewable energy resources (RES) such as solar and wind will challenge the operation of power systems (MITECO, 2021). The variability and the non-dispatchable nature of RES may jeopardize the security of supply and the provision of operating reserves. Energy Storage Systems (ESSs) such as Pumped Storage Hydro units (PSHs) and batteries are technologies that can shift energy at different timeframes to cope with the high variability of RES production. Thus, ESS could help reduce renewable curtailment and provide security of supply in renewable-dominated power systems (Qadir et al., 2021).

Although PSHs have operated for a long time in power systems, the current existing installed capacity is insufficient, and installing new ESSs, such as batteries, could help meet renewable targets by 2030. Since batteries differ from PSHs in their technical and economic parameters (Shaqsi et al., 2020), it is helpful to know how complementary and competitive they are in operational terms. For instance, batteries have shorter charge cycles and higher roundtrip efficiency than PSHs (Mongird et al., 2019).

In the context of the energy transition, Spain is an interesting real-case to study the challenges of integrating non-dispatchable RESs with battery and PSH technologies since the Spanish National Energy and Climate Plan (NECP) (MITECO, 2021) aims for a minimum of 74% of its electricity to be produced by renewables by 2030. Between 2020 and 2030, the Spanish NECP foresees a significant installed capacity increase of 70% for solar photovoltaic (Solar PV), 40% for wind, and 64% for ESS — i.e., PSH and batteries. The future ESS mix in Spain will consist of batteries and new and existing PSHs (BOE, 2021). Additionally, the Climate Change and Energy Transition Project Law foresees that the operation of all available ESS will contribute to the security and continuity of the electricity system at all times (BOE, 2021). Indeed, battery participation in energy and ancillary services was included in December 2020 in the Spanish System Operator (SO) operating procedures (BOE, 2020).

Traditionally, hydrothermal scheduling, considering energy and operating reserves, has been studied through models that reproduce the yearly operation on an hourly basis and minimize the system's total cost under different operational constraints (Ventosa et al., 2005). Such models need to be adapted to address lower thermal generation scenarios, and to represent other storage units with different characteristics, and charge and discharge timeframes. Indeed, the variability of RES production and water inflows requires considering a wide range of timeframes to account for the hourly, daily, weekly, and even seasonal variability of these resources.

In power systems with large share of non-dispatchable RES, periods with low non-dispatchable RES production are becoming significantly challenging. In the Ten-Year Network Development Plan (TYNDP) 2022 Scenario Building Guidelines (ENTSO-E, 2021a), ENTSO-E defines 'DunkelFlaute' scenarios as the two weeks of the year with high demand combined with low solar and wind generation. Although critical events often refer to high load demand and low non-dispatchable RES production, critical events should also be defined according to thermal unit unavailability. Since non-dispatchable RES production shares will increase, the frequency and duration of critical events are also expected to grow. Therefore, a medium-term scope – i.e., considering intertemporal constraints from months to hours – respecting the chronology of events seems necessary when studying the operating behavior of the different ESSs in RES-dominated power systems. Furthermore, future RES-dominated power systems with a high impact of forecast errors require analysis of the effects of the future ESS mix on system operation, including their role in energy arbitrage and the provision of auxiliary services. This paper specifically analyzes operating reserves.

The method must be technology-neutral when comparing ESS with different charge cycles. According to the time dimension, analysis of the roles of different ESSs requires a sufficiently long time scope and a time scope short enough to represent the operation of batteries and PSH accurately. Too short a time scope (<1 year) would not allow consideration of the seasonal variability of water inflows. While too long a time scope (>1 h) would not allow a correct picture of the operation of the batteries, given that the latter presents a storage capacity equivalent to a few hours. Additionally, the methodology must consider operating reserve since battery technology is authorized to provide balancing services in the context of the security of supply.

This paper aims to analyze the role of batteries and PSHs in the future ESS mix by exploring the 2030 Spanish NECP scenario. Due to its relevance for this study, the annual operation of the whole system is modeled in detail, with hourly temporal granularity. The model also optimizes the unit commitment of the thermal generating units and considers RES hourly data sets that allow accounting for the variability of wind, solar, and hydropower inflows. For hydropower units, the model considers weekly inflows for market-cleared generating units. The model maintains consistency and chronology between all input data. Particular attention is given to the representation of different ESS units with different storage timeframes in a medium-term operation planning model. The system operation is formulated as a large-scale mixed-integer programming problem (MIP).

Additionally, the model considers both the supply of energy and balancing services, including operating reserve capacity – i.e., balancing capacity – and activating such capacity -i.e., balancing energy-. The study explores different scenarios and sensitivities to account for the effects of critical parameters in the system operation. Under these different scenarios, the competition, and complementarities in operational terms among different ESSs are studied. The results also show how ESS technologies behave during critical hours of power systems.

This article is structured as follows: Section 2 reviews the modeling of ESS impacts in the electricity system and highlights the main challenges to be considered. Section 3 describes the methodology applied and the model considered. Section 4 presents the case study considered. Section 5 details the scenarios explored, and results are provided and analyzed in Section 6. Section 7 summarizes the main conclusions.

2. State of the art

Maintaining the security and continuity of the electricity supply is a fundamental task for the SO, and it has several mechanisms at its disposal, including balancing services (The European Commission, 2017). Frequency regulation services allow the SO to maintain frequency stability and energy balance. These services, also known as operating reserves, have different activation time horizons, ranging from a few seconds to two hours. These services adjust energy injections and withdrawals, upwards and downwards respectively, to cope with forecast errors from generation and demand (The European Commission, 2017), contingencies and forced outages from generation and network assets. Generally, there are two secondary and tertiary frequency regulation products: availability and activation (The European Commission, 2017). In other words, these services are offered firstly in terms of capacity (i.e., MW) and secondly in terms of energy (i.e., MWh).

According to Heuberger et al. (2017), as non-dispatchable RES integration increases, the amount of required operating reserves will increase, too. Furthermore, in REE (2009) the Spanish SO details the role of PSH in electricity generation and shows that hydropower technology (i.e., dams and PSHs) is dominant in the supply of operating reserves. Moreover, Diaz et al. (2014) informs us that the integration of non-dispatchable RESs and the value of the PSH are even more critical when the PSH participates strongly in the provision of operating reserves.

In Oyler and Parsons (2020), the authors focused on how investments in PSH improve greenhouse gas mitigation in scenarios with a high share of non-dispatchable RES according to Distributed Generation scenario 2030 of the TYNDP (ENTSO-E, 0000a). They use a hydrothermal linear medium-term operation planning model with hourly operation details for representing the Spanish electricity system. The authors demonstrated the important role that PSH will have when increasing non-dispatchable RES shares. Nevertheless, the methodology used in Oyler and Parsons (2020) does not consider operating reserves. Furthermore, the scenarios analyzed in Oyler and Parsons (2020) do not consider the projection of the Spanish National Energy and Climate Plan (NECP) (MITECO, 2021) in terms of the increase of PSHs in

Spain for 2030, which is expected to increase 50%. As a result, the replicated system does not have the same generation flexibility as the one foreseen by the NECP scenario. Therefore, although the analysis provided in Oyler and Parsons (2020) brings essential insights around the interactions between investment in PSHs and the share of non-dispatchable RES, according to Heuberger et al. (2017), REE (2009) and Diaz et al. (2014), the assessment of the role of ESSs in scenarios with high RES is not explored since the applied methodology is not technology-neutral.

Similar to Oyler and Parsons (2020), the authors in Dollinger and Dietrich (2013) focused on how ESS can help increase wind and solar energy shares in the Spanish electricity mix by exploring 2020 scenarios. Authors have used a hydrothermal medium-term operation planning model with hourly operation details accounting for energy and operating reserves detailed in Dietrich et al. (2012). Authors have maintained chronology between input parameters in line with storage (i.e., temporal consistency of between input parameters regarding hourly load and RES generation profiles). Authors have also considered different ESSs with different timeframes (i.e., batteries, PSH, Electric Vehicle, Compressed Air Energy Storage, and Concentrated Solar Power). They concluded that ESSs improve the integration of renewables by flattening peak load. However, the case study explored can no longer be considered a highly renewable scenario since it was based on 2020 scenario forecasts and assumed that 20% of the total installed capacity would be renewable. Although operating reserves are considered in the study, the authors do not highlight the challenge that SO will face to ensure the security and continuity of supply of the power system when RES are the largest generation in the mix. As pointed out by BOE (2021) and ENTSO-E (2021b), the frequency of occurrence of critical events should increase; detailed characterization of critical events would provide a rigorous analysis of the complementary and competitive role of the different ESSs. This last aspect is missing in the study presented in Dollinger and Dietrich (2013).

Energy landscapes change with the installation of new non-dispatchable RES capacity, and this brings challenges across several dimensions of power systems (i.e., generation, transmission, and distribution). Refs. MITECO (2021, 2020) and BOE (2021) have already assessed the need to increase ESS capacity, mainly with battery and PSH technologies, to balance non-dispatchable RES output. Battery technology, almost mature at the generation level of power systems, lacks operational background. Therefore, comparing the roles of PSH and batteries for optimizing the energy mix is a topic of interest.

When evaluating the impact of energy storage on electricity system operation, the technical characteristics of ESSs need to be modeled. Refs. ENTSO-E (2021b) and ACER (2020) established a list of hypotheses around the methodology to follow to model a hydropower plant. These studies address the aggregation of hydraulic power plants and water reservoirs according to their nature and water inflows' inputs. Both references emphasized the distinction between Closed- and Open-Loop Pumped Storage Hydro (CLPSH and OLPSH). Since CLPSH shows different technical parameters than OLPSH, such as energy reservoir capacity and energy inflows, mixing two sub-technologies can lead to misestimating the role of each of them. In the remainder of this article, ESS refers only to PSH installations (i.e., OLPSH and CLPSH) and batteries, unless otherwise specified.

In Chazarra et al. (2016), the authors presented a hydrothermal operation planning model considering the energy and reserve market. Although their contribution, which was also listed in the review of Gonzalez et al. (2014), lies in modeling the use of operating reserves in a deterministic way based on historical data, their analysis does not account for high non-dispatchable RES penetration. Additionally, the explored scenarios do not consider batteries nor distinguish the subcategories belonging to the PSH (i.e., OLPSH and CLPSH). In Denholm et al. (2020), the authors have analyzed the role of batteries as a peaker capacity in several US regions in scenarios with a high share of non-dispatchable RES. Using a firm capacity approximation based-method similar to the Effective Load Carrying Capability (ELCC) (Madaeni et al., 2013), their research concludes that battery technology has the potential to behave as a peaker capacity, and this role will increase as the share of solar PV increases. Despite the relevant conclusion, the studies presented in Chazarra et al. (2016) and Denholm et al. (2020) lack consistency in comparing the roles of different ESS. Firstly in Denholm et al. (2020), the authors assume a perfect forecast and therefore neglect the operating reserves. Secondly, the technical differences of the different ESSs are not considered either in Chazarra et al. (2016) or Denholm et al. (2020). Thus, according to insights from Refs. Heuberger et al. (2017), REE (2009), Diaz et al. (2014), ENTSO-E (2021b) and ACER (2020), applied methodologies in Chazarra et al. (2016) and Denholm et al. (2020) are not technology-neutral.

Assessing operating roles of different ESS with different timeframes requires considering a time scale long enough to take into account the variability of the RES with a resolution small enough to best accommodate the operating reserves. In addition, the temporal consistency between the data in line with storage timeframes goes along with the study of how hydro storage technologies and batteries can alleviate variability and non-dispatchability of solar and wind resources (ENTSO-E, 2021b; ACER, 2020). Thus, input data must retain the chronological consistency between the variables (solar, wind, water inflows, and load demand) and the model must consider every hour of the year and not representative periods. This feature is particularly relevant since critical events such as high demand, low renewable production, and low hydro inflows, and unavailability of thermal units can range from a minute to several weeks. Their characterization within the model should be sufficiently precise to analyze the role of storage during these periods.

In Werlang et al. (2021), the authors jointly used an expansion and operation optimization model with other simulation modules to highlight the impacts of regulation on the use of ESSs in two case studies: Brazil and Mexico. One of their conclusion is that the roles of ESSs change depending on the power system considered. According to the authors' conclusions, batteries would have a more critical operational role in Mexico than in Brazil due to the diversity of the energy mix and the flexibility requirements that the power system may have. On the one hand, being energetically dependent on hydropower generation, Brazil presents energy flexibility requirements that batteries cannot meet due to their low energy capacity. On the other hand, Mexico, where the mix is more diversified than in Brazil, shows power flexibilities requirements, leaving battery technology a role to play. Although their study yields significant findings, the methodology used in Werlang et al. (2021) does not follow modeling guidelines brought in ENTSO-E (2021b) and ACER (2020). Indeed, by using representative days, the authors no longer maintain the chronology and consistency between the different time series.

This article proposes a comparison between ESSs with different timeframes that will be part of the future ESS mix, using a medium-term operation planning model. Contributions of this paper include:

- Jointly considering energy and balancing services accounting for the proper distinction between balancing capacity and balancing energy
- A medium-term operation optimization model preserving the chronology and consistency of input data time series

- The proper modeling of different ESS with different storage timeframes and quantification of ESS impact on the operation of power systems
- A detailed hydrothermal operation planning modeling according to market-cleared units for storage hydro and physical individual plants for PSH.

3. Methodology

Analyzing the operational competition between a mix of different ESSs requires an hourly resolution at the operation level and keeping the chronology of events (in terms of demand and non-dispatchable RES production) over a medium-term scope. When it comes to model details of the electricity system operation, linear optimization models are often used because of high algorithm efficiency, ensuring users find an optimal solution (Ventosa et al., 2005).

SEED (Spanish Electricity Economic Dispatch), the model presented in this paper, is an optimization medium-term operation support tool for carrying out different case studies or sensitivity analysis that can help representing the generation system operation in the future, for example, 2030. It reproduces the centralized operation of an electricity system on an hourly basis over a time scope of one year (i.e., 8760 h). The model is based on constraints whose main ones are explicitly included in the paper. The SEED model formulation is based on a publicly available open-access model named open TEPES (Ramos et al., 2022).

The model considers hourly demand with provision for balancing services (i.e., balancing capacity and balancing energy) as in Naversen et al. (2020). Although operating reserves occur over short time horizons, hourly approximation within medium-term models is acceptable. However, distinguishing between the power availability of the unit and the energy delivered remains preferable. Some references link availability and energy stochastically, and others deterministically. One deterministic method links balancing capacity and energy by an activation coefficient based on historical values (Gonzalez et al., 2014). Besides providing information on the management of the different ESSs, it is possible to measure how each technology contributes to providing hourly operating reserves and energy generation since the model preserves input data chronology.

SEED is a hydrothermal medium-term operation planning model that allows splitting hydroelectric power plants according to ACER (2020) and ENTSO-E (0000b). SEED represents storage hydro, CLPSH, OLPSH, and run-of-river. Run-of-river hydro can be considered non-dispatchable RES since it does not have storage capacity. In addition, the model defines different ESSs regarding their efficiency, installed capacity, and maximum and minimum energy capacity reservoirs. Internally, according to those parameters and the ratio of the installed power on the maximum reservoir capacity, the model decides how and which ESS should generate, store, pump, or spill water.

Another input parameter is defined to constrain the operation of CLPSHs and batteries to distinguish between daily operating storage (Daily ESS) and weekly operating storage (Weekly ESS). Weekly ESS can charge at weekends and discharge at every weekday peak hour. The Daily ESS can charge during off-peak hours and discharge at peak hours. All ESSs with a maximum discharge time of 6 h or less are considered as daily storage. SEED models hydro market units, and OLPSHs as seasonal storage. Maximum time discharge for market-cleared hydro units and OLPSHs is set to one week.

Installed capacity, variable costs, weekly energy inflows, and hourly profile of demand and non-dispatchable generation are introduced as data input according to MITECO (2021), ENTSO-E (0000a), ACER (2020), ENTSO-E (0000b) and ENTSO-E (0000b). Similarly to Refs. Dollinger and Dietrich (2013), Dietrich et al. (2012) and ENTSO-E (0000c), SEED considers the hourly supply of upward and downward operating reserves. Since providing operating reserves ensures electricity system continuity, only dispatchable technologies can participate in, such as thermal, ESS facilities and storage hydro (i.e., dams).

The model formulation is detailed below. All parameters and variables presented are written in upper and lower-case letters, respectively.

The objective function (1) to be minimized is the total system operation cost over the full-time scope (one year). The total system operation cost consists of generation production costs CV_g (i.e., fuel, variable O&M, emissions costs), cost of charging ESSs, CV_s , and non-served energy cost ($CENS$). The parameter DUR_n represents the duration of each load level n considered, in this case, $DUR_n = 1$. The set g refers to all installed generating units, while the set ess, relates only to generating units able to consume by charging or pumping.

$$\min \left(\sum_{\omega,n,g} P_\omega DUR_n (CV_g gp_{\omega,n,g} + CV_s gc_{\omega,n,s} + CENSens_{\omega,n}) \right) \tag{1}$$

Eq. (2) shows the balance between generation and demand. The equation applies simultaneously for all the considered load levels over the time scope.

$$\sum_g \left(gp_{\omega,n,g} - gc_{\omega,n,s} \right) + ens_{\omega,n} = D_{\omega,n} \qquad \forall \omega, n \tag{2}$$

Generation output variable of generation units $gp_{\omega,n,g}$ is defined in (3) and considers both the unit energy generation and the unit energy usage – i.e., energy activation – related to the provision of upward and downward operating reserves. The model considers the energy activation for providing upward and downward operating reserves in a deterministic way as in Dollinger and Dietrich (2013), Chazarra et al. (2016) and Pérez-Díaz et al. (2015). Energy activation (i.e., energy usage $ad_{\omega,n,or}, au_{\omega,n,or}$) is modeled using deterministic activation coefficients (CD, CU) applied to the value of the operating reserve provided ($dr_{\omega,n,or}$, $ur_{\omega,n,or}$) as shown in Eq. (19). Eq. (3) does not consider non-dispatchable technologies.

$$gp_{\omega,n,g} = \underline{P_g} uc_{\omega,n,g} + p_{\omega,n,g} + au_{\omega,n,or} - ad_{\omega,n,or} \qquad \forall \omega, n, g \tag{3}$$

The consumption output variable of installed ESS units $gc_{\omega,n,s}$ is defined in (4). It includes the unit energy consumption and the unit energy activation related to the provision of upward and downward operating reserves. Variables that account for ESS participation in operating reserves $\left(dr'_{\omega,n,s}, ur'_{\omega,n,s}\right)$ when they are consuming (charging) are different from the ones used in Eq. (3) which refers to them being producing. Since ESSs can generate and pump whereas thermal units do not, the model needs to differentiate the upward and downward operating reserves provided by ESS when pumping (Eq. (3)) than when producing (Eq. (2)). Therefore, the model distinguishes ESS from non-ESS technologies according to the supply of operating reserves.

$$gc_{\omega,n,s} = c_{\omega,n,s} + au'_{\omega,n,s} - ad'_{\omega,n,s} \qquad \forall \omega, n, s \tag{4}$$

The logical relationship between commitment, start-up, and shutdown status of a committed unit is presented in (5) based on Tejada-Arango et al. (2020). Eq. (5) takes into account for the first load level of the first period an initial commitment status for all units, based on merit order loading, including non-dispatchable RES and ESS units. ($n - 1$) is used for the previous load level.

$$uc_{\omega,n,g} - uc_{\omega,n-1,g} = su_{\omega,n,g} - sd_{\omega,n,g} \qquad \forall \omega, n, g \tag{5}$$

Maximum ramp-up and ramp-down for both thermal and ESS units are respectively formulated in the Eqs. (5a) and (5b) according to Ref. Damci-Kurt et al. (2016). Eqs. (5a) and (5b) reflect the capacity $p_{\omega,n,g}$ and balancing capacity $ur_{\omega,n,g}$ delivered in the hour under consideration, as well as the capacity $p_{\omega,n-1,g}$ and balancing capacity services $ur_{\omega,n-1,g}$ provided in the previous hour.

$$\frac{p_{\omega,n,g} + ur_{\omega,n,g} - \left(p_{\omega,n-1,g} + dr_{\omega,n-1,g}\right)}{RU_g DUR_n} \leq uc_{\omega,n,g} - su_{\omega,n,g} \qquad \forall \omega, n, g \tag{5a}$$

$$\frac{p_{\omega,n,g} - dr_{\omega,n,g} - \left(p_{\omega,n-1,g} + ur_{\omega,n-1,g}\right)}{RD_g DUR_n} \leq -uc_{\omega,n,g} + sd_{\omega,n,g} \qquad \forall \omega, n, g \tag{5b}$$

Eq. (6) defines the state of charge of energy reservoir for all ESS units. The model considers roundtrip efficiency EF_g for the consumption $gc_{\omega,n,s}$ of an ESS unit. Although hydropower production output actually changes according to the level of energy capacity reservoirs, the model assumes that the production output of ESS $gp_{\omega,n,s}$ (i.e., storage hydro and PSH) do not have water head dependency. In other words, generating and pumping actions are reflected in the state of charge of different energy reservoirs. At the same time, the available power capacity is assumed to be constant regardless of the level of energy reservoir. That means the power output does not vary according to the state of charge of the energy reservoir. Energy inflows $EI_{\omega,n,s}$ are assumed to be determined weekly. ESS state of charge is formulated according to the duration of the ESS discharge parameter τ_s and therefore limits the use of the ESSs according to their maximum discharge time. For example, in case ESS has $\tau_s = 24$ or 168 Eq. (6) will set the ESS state of charge variable one time per day or per week, respectively, over the year (i.e., 360 times or 52 times in a year). Therefore, different levels of flexibility brought by ESSs with different timeframes according to their discharge time are accounted for. State of charge of energy reservoir for ESS also considers the possible spillages $s_{\omega,n,s}$ and the energy usage from providing operating reserves as set in (3) and (4).

$$SoC_{\omega,n-\tau_s,s} - SoC_{\omega,n,s} - s_{\omega,n,s} + \sum_{n'=n+1-\tau_s}^{n} \times \left(EI_{\omega,n,s} - gp_{\omega,n,s} + EF_g gc_{\omega,n,s}\right) = 0 \qquad \forall \omega, n, s \tag{6}$$

Upward and downward operating reserves provided by dispatchable units, such as thermal and ESS units, are shown in Eqs. (7) and (8). Considering that ESS can provide auxiliary services while pumping, variables for representing the supply of operating reserves are differentiated for thermal and ESS units when producing $\left(dr_{\omega,n,or}, ur_{\omega,n,or}\right)$ and ESS units when charging $\left(dr'_{\omega,n,or}, ur'_{\omega,n,or}\right)$. The restrictions (7) and (8) are such that the operating reserves to supply at each load level must be greater or equal to the input parameters $\left(DR_{\omega,n}, UR_{\omega,n}\right)$. Thus, the model accounts for operating reserves as an additional load to supply and provides a safety margin in case of critical events (Dollinger and Dietrich, 2013; Dietrich et al., 2012; ENTSO-E, 0000c; Dietrich et al., 2010).

$$\sum_{or} ur_{\omega,n,or} + \sum_{s} ur'_{\omega,n,s} \geq UR_{\omega,n} \qquad \forall \omega, n \tag{7}$$

$$\sum_{or} dr_{\omega,n,or} + \sum_{s} dr'_{\omega,n,s} \geq DR_{\omega,n} \qquad \forall \omega, n \tag{8}$$

Eqs. (9) and (10) below define the maximum and minimum output of the second block of a committed unit. Eqs. (9) and (10) consider providing downward and upward operating reserves $\left(dr_{\omega,n,or}, ur_{\omega,n,or}\right)$. Eqs. (9) and (10) are formulated for thermal units and ESS units only in the case of generating (i.e., discharging).

$$\frac{p_{\omega,n,or} + ur_{\omega,n,or}}{\overline{P_{or}} - \underline{P_{or}}} \leq uc_{\omega,n,or} \qquad \forall \omega, n, or \tag{9}$$

$$\frac{p_{\omega,n,or} - dr_{\omega,n,or}}{\overline{P_{or}} - \underline{P_{or}}} \geq 0 \qquad \forall \omega, n, or \tag{10}$$

Eqs. (11) and (12) define ESS unit consumption by considering supplying upward and downward operating reserves from ESS $\left(ur'_{\omega,n,s}, dr'_{\omega,n,s}\right)$ while the unit is consuming (i.e., charging). Eqs. (9)–(12) were adapted from Tejada-Arango et al. (2020), Gentile et al. (2017), Morales-Espana et al. (2014) and Morales-Espana et al. (2013).

$$\frac{c_{\omega,n,s} + dr'_{\omega,n,s}}{\overline{c}_s} \leq 1 \qquad \forall \omega, n, s \tag{11}$$

$$\frac{c_{\omega,n,s} - ur'_{\omega,n,s}}{\overline{c}_s} \geq 0 \qquad \forall \omega, n, s \tag{12}$$

Eq. (13) prevents the ESS units from charging and discharging simultaneously using their full installed capacity. As it can be noted, Eq. (13) is consistent with Eqs. (9) and (11).

$$\frac{p_{\omega,n,s} + ur_{\omega,n,s}}{\overline{P_s} - \underline{P_s}} + \frac{c_{\omega,n,s} + dr'_{\omega,n,s}}{\overline{c}_s} \leq 1 \qquad \forall \omega, n, s \tag{13}$$

Eqs. (14) and (15) prevent ESS units while producing for providing operating reserves (i.e., upward and downward, respectively) if their energy reservoir is empty.

$$ur_{\omega,n,s} \leq \frac{SoC_{\omega,n,s}}{DUR_n} \qquad \forall \omega, n, s \tag{14}$$

$$dr_{\omega,n,s} \leq \frac{I_s - SoC_{\omega,n,s}}{DUR_n} \qquad \forall \omega, n, s \tag{15}$$

Eq. (16) is employed to respect the ratio between the upward and the total reserves provided set by the SO for all units. Although this restriction also applies to ESSs when charging and discharging $(dr'_{\omega,n,s}, ur'_{\omega,n,s})$, for the sake of simplicity, it is not shown here.

$$ur_{\omega,n,g} = R_{\omega,n}\left(\frac{ur_{\omega,n,g} + dr_{\omega,n,g}}{DUR_n}\right) \qquad \forall \omega, n, g \in or \tag{16}$$

Eqs. (17)–(19) handle the relation between balancing capacity and balancing energy provided for generation plants allowed to participate in operating reserves. Eqs. (20)–(22) handle the same relation as (17)–(19) respectively to ESS in pumping mode. Eqs. (17), (18) and (20), (21) include binary variable $\varphi_{\omega,n,or}$ to account for the activation of the balancing capacity provided by thermal and ESS units. Eqs. (19) and (22) prevent units from supplying upward and downward balancing energy simultaneously. Eqs. (17)–(22) are inspired from Naversen et al. (2020) and Pérez-Díaz et al. (2020).

$$au_{\omega,n,or} \leq \left(\overline{P_{or}} - \underline{P_{or}}\right)\varphi_{\omega,n,or} \qquad \forall \omega, n, or \tag{17}$$

$$ad_{\omega,n,or} \leq \left(\overline{P_{or}} - \underline{P_{or}}\right)\left(1 - \varphi_{\omega,n,or}\right) \qquad \forall \omega, n, or \tag{18}$$

$$au_{\omega,n,or} - ad_{\omega,n,or} = CU \cdot ur_{\omega,n,or} - CD \cdot dr_{\omega,n,or} \qquad \forall \omega, n, or \tag{19}$$

$$au'_{\omega,n,s} \leq \left(\overline{C_{or}} - \underline{C_{or}}\right)\varphi_{\omega,n,s} \qquad \forall \omega, n, s \tag{20}$$

$$ad'_{\omega,n,s} \leq \left(\overline{C_{or}} - \underline{C_{or}}\right)\left(1 - \varphi_{\omega,n,s}\right) \qquad \forall \omega, n, s \tag{21}$$

$$au'_{\omega,n,s} - ad'_{\omega,n,s} = CU \cdot dr'_{\omega,n,s} - CD \cdot ur'_{\omega,n,s} \qquad \forall \omega, n, s \tag{22}$$

Eqs. (23)–(24) prevent ESS units while charging for providing operating reserves (i.e., upward and downward, respectively) if their energy reservoir is empty.

$$ur'_{\omega,n,s} \leq \frac{I_s - SoC_{\omega,n,s}}{DUR_n} \qquad \forall \omega, n, s \tag{23}$$

Table 1
Representation in SEED of electricity system of the Spanish peninsula in 2030 according to MITECO (2021), Diaz et al. (2014) and Morales-Espana et al. (2014).

Technologies	Installed capacity (# programming units considered) [MW]	Installed pump capacity [MW]	Energy reservoirs [GWh]	Cycle discharge [Seasonal/Weekly/Daily]	Roundtrip efficiency [%]	Variable cost [€/MWh]	Emission rate [€/MWh]	O&M Variable cost [€/MWh]
Nuclear	3050 (3)	na	na	na	na	23	0	0
CCGT	24 560 (50)	na	na	na	na	40	0,33	2
Cogeneration	3980 (1)	na	na	na	na	0	0,575	0
Solar PV	38 404 (122)	na	na	na	na	0	0	0
Solar Thermal	7300 (1)	na	na	na	na	0	0	0,46
Wind Onshore	48 550 (70)	na	na	na	na	0	0	0
UGH	7500 (53)	na	9780	Seasonal	na	0	0	0
No UGH (RoR)	1303 (1)	na	na	na	na	0	0	0
OLPSH	7750 (4)	2114	6208	Seasonal	0,75	0	0	0
Existing CLPSH	3648 (10)	3552	120	Weekly/Daily	0,75	0	0	0
PCI I	235	235	1,5	Daily	0,79	0	0	0
PCI II	3400	3400	27,2	Weekly	0,79	0	0	0
PCI III	552	548	3,67	Daily	0,78	0	0	0
Batteries	2500 (1)	2500	10	Daily	0,9	0	0	0
Others RES	1730 (1)	na	na	na	na	0	0	0

$$dr'_{\omega,n,s} \leq \frac{I_s - SoC_{\omega,n,s}}{DUR_n} \qquad \forall \omega, n, s \tag{24}$$

Eqs. (25)–(35) detail variable bounds.

$$0 \leq gp_{\omega,n,g} \leq \overline{P_g} \qquad \forall \omega, n, g \tag{25}$$

$$0 \leq gc_{\omega,n,g} \leq \overline{C_g} \qquad \forall \omega, n, g \tag{26}$$

$$0 \leq ur_{\omega,n,g} \leq \overline{P_g} - \underline{P_g} \qquad \forall \omega, n, g \tag{27}$$

$$0 \leq ur'_{\omega,n,s} \leq \overline{C_s} \qquad \forall \omega, n, s \tag{28}$$

$$0 \leq dr_{\omega,n,g} \leq \overline{P_g} - \underline{P_g} \qquad \forall \omega, n, g \tag{29}$$

$$0 \leq dr'_{\omega,n,s} \leq \overline{C_s} \qquad \forall \omega, n, s \tag{30}$$

$$0 \leq p_{\omega,n,g} \leq \overline{P_g} - \underline{P_g} \qquad \forall \omega, n, g \tag{31}$$

$$0 \leq c_{\omega,n,g} \leq \overline{C_s} \qquad \forall \omega, n, s \tag{32}$$

$$0 \leq s_{\omega,n,s} \qquad \forall \omega, n, s \tag{33}$$

$$0 \leq SoC_{\omega,n,s} \leq I_s \qquad \forall \omega, n, s \tag{34}$$

$$0 \leq ens_{\omega,n} \leq D_{\omega,n} \qquad \forall \omega, n \tag{35}$$

The contribution of the model lies in the fact that it is a medium-term model with hourly operation details that simultaneously differentiates between different ESS, according to their time frames, and considers the energy used by ESS and thermal units in providing energy and operating reserves.

4. Case study: The Spanish electricity system in 2030

The Spanish mainland's electricity system will be used as a case study given non-dispatchable RES shares are expected to reach 74% of total electricity consumption by 2030 according to NECP (MITECO, 2021). Based on Spanish NECP 2030, Table 1 summarizes parameters of installed generation capacity per technology in Spain by 2030. This study does not consider the effect of cross-border interconnections.

According to MITECO (2021, 2020) and BOE (2021), ESSs are identified as necessary in integrating non-dispatchable RES. The available storage will be a mix of ESS technologies responding to different technical and economic characteristics. Therefore, it is essential to consider the features of all ESSs considered to evaluate their operation in the future mix at a programming unit[1] level.

[1] Spanish SO defines Programming units as "thermal unit, pumping unit, management unit of hydroelectric power plants or management unit of a set of wind turbines in a wind farm which evacuate energy in the same grid node" (Glossary, 2021).

When representing the system's operation to assess the ESS role in high shares' scenario of non-dispatchable RES, it would be preferable to define the ESS mix in the model as suggested in Ref. Ventosa et al. (2005). Therefore, the model can effectively evaluate the flexibility provided by each of the available ESS and their impact on the system's operation when the electricity system faces high shares of non-dispatchable energies (ENTSO-E, 2021a).

According to NECP, in 2030, the Spanish electricity system will dispose of 12 GW of ESS composed of 9.5 GW of PSH and 2.5 GW of batteries. In 2020, Spain counted 5.6 GW of existing PSH installed capacity. Therefore, almost 3.9 GW of CLPSH should be installed up to 2030 (MITECO, 2021; ENTSO-E, 0000a).

Existing installed CLPSH programming units range from 100 MW to almost 1400 MW. Moreover, the maximum water energy reservoir capacity for CLPSH currently installed in Spain varies from approximately from 1 GWh to 31 GWh (REE – activities, 2020). As a result, the maximum consecutive discharge time when the reservoir is at maximum capacity can range from five hours to more than one week. Therefore, to study the complementarity roles and operational competition of ESSs for Spain in the horizon of 2030, energy capacity reservoir and roundtrip efficiency for projected ESSs (i.e., PSH and batteries) remain sensible parameters to be defined.

ESSs such as batteries and PSH are characterized by their installed power, maximum discharge time when the reservoir is full (i.e., or maximum energy reservoir capacity), and roundtrip efficiency such as defined by ENTSO-E (2019). Refs. MITECO (2021) and ENTSO-E (0000a) specify that installed batteries will have a minimum of two hours of discharge with an installed power of 2.5 GW. Given the roundtrip efficiency of batteries is not specified in MITECO (2021) or ENTSO-E (0000a), this parameter is taken from Mongird et al. (2019). Regarding the new CLPSHs projected to be installed, only the total installed power is specified in MITECO (2021) and ENTSO-E (0000a). According to the technical parameters of batteries and new CLPSHs, the following assumptions are formulated:

- The roundtrip efficiency of the batteries is based on Mongird et al. (2019). MITECO (2021) and ENTSO-E (0000a) mention that discharge time at maximum capacity of batteries must be at least 2 h, suggesting that it could be higher. Since various references represent Lithium-Ion battery technology with a discharge time of 4 h, a discharge time of 4 h has been adopted in the model as an average value of maximum discharge time for battery energy storage.

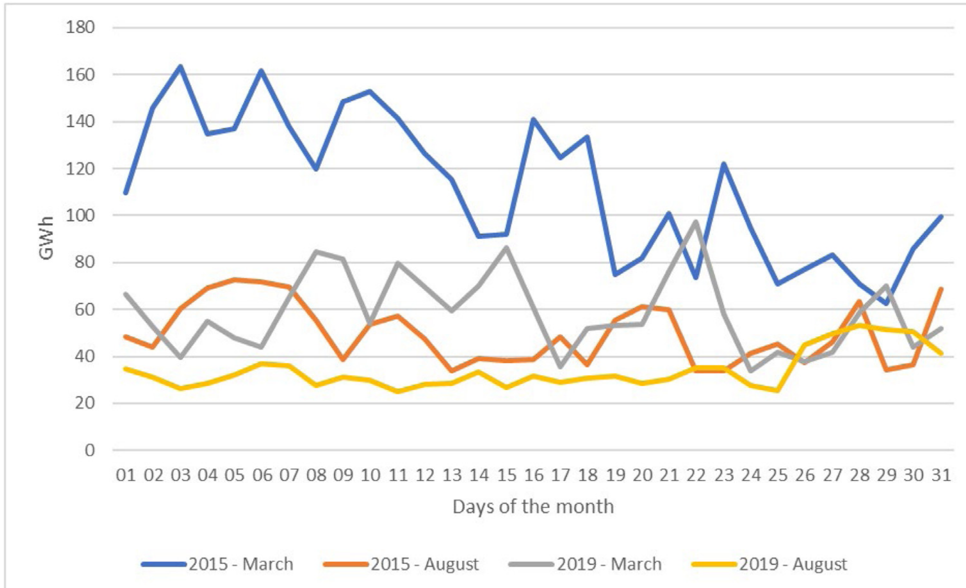

Fig. 1. Daily hydropower production data over February and August in 2015 and 2019 according to available data (Pérez-Díaz et al., 2020).

- Technical and economic parameters for new CLPSHs are based on current ongoing projects, named Project of Common Interest (PCI) (PCI, 2021), aimed to be finished and operating by 2030. Table 1 shows three projects of new CLPSH, namely PCI I, PCI II, and PCI III, and their technical features, which are included in the analysis.

Apart from the heterogeneous size of the future ESS mix, Spain has the same installed capacity in Combined Cycle Gas Turbine (CCGT) as storage hydro, i.e., around 16% of its total installed generation mix. According to ten years of historical data (REE — Activities, 2020), annual hydropower production ranged between 13 GWh in 2005 and 40 GWh in 2013. Even though a similar pattern is repeated every year for the hydropower production of the Spanish peninsular system, there is a change in magnitude from year to year, resulting in an annual variability. In addition to a yearly variability, the water inflows data also show seasonal variability. For illustrating hydropower seasonality dependence, Fig. 1 represents the daily productions during February and August for 2015 and 2019 for Spain based on hourly values from ESIOS (2020).

Fig. 1 shows how much the trend for the same month from one year to another can vary (e.g., March 2015 and 2019 have different trends according to Fig. 1). In addition, Fig. 1 allows seeing the changes in the order of magnitude of daily output for the same month in two different years. Therefore, representing hydropower technology in the Spanish electricity system must consider annual and seasonal water inflow variations. The representation of the hydrothermal system operations at an hourly level over one year and having a large historical database to explore the most extreme scenarios is validated by MITECO (2021), ENTSO-E (2021b), ACER (2020) and ENTSO-E (0000c).

Load demand and generation hourly profiles introduced in the model are based on 2015 data (REE — Activities, 2020). Hourly generation profiles of solar PV and wind generation are introduced for each programming unit considered by SEED. As wind and sun are not blowing and shining in the same way at different places, SEED can maintain differences in production according to programming unit sites. However, for this study, Solar PV and wind turbine programming units were aggregated according to the company they belong to. The same treatment is given to water inflow profiles according to hydro programming unit and OLPSH. Water inflows between two different hydro basins are not totally correlated because of their various sites. (e.g., in the Spanish peninsula, the Ebro basin experiences a late winter snowfall that the Duero basin does not have.)

Thermal power plants are defined by the installed capacity, Equivalent Forced Outage Rate (EFOR) based on historical values, emission rate, and variable costs parameters. Renewable non-dispatchable technologies (Wind and Solar PV) do not have variable costs, and they follow hourly generation profiles.[2] Hydropower plants are defined by installed capacity (MW), EFOR[3] (%), reservoir capacity (MWh), maximum time discharge cycle (hours), and roundtrip efficiency (%).

The hourly operating reserve requirements are based on three parameters according to demand and forecasting errors of wind generation (3% and 10% respectively as in Dietrich et al. (2010)) and the failure of the biggest generation unit.[4] The energy provided by the committed power reserve capacity is based on historical data (REE — Activities, 2020). In Spain, balancing energy represents 25% and 30% (i.e., *CD* and *CU*) of downward and upward operating reserves to be provided, respectively, according to Chazarra et al. (2016).

Table 1 resumes the main input parameters for representing the Spanish electricity system regarding the NECP objective (MITECO, 2021) based on scenarios presented in ENTSO-E (0000a). Table 1 shows variable costs (i.e., fuel costs), O&M variable cost and emission rate according to IEA (2019) considered, and technical parameters of generating units present in the system studied. Table 1 also presents the required parameters for

2 Other sources such as biomass and cogeneration are considered also with generation profiles and are non-dispatchable. Future research should consider the modeling of these resources considering the constraints associated with them.

3 In the case of hydropower, EFOR is used to consider the capacity limit due to not enough water at the reservoir and it is based on a historical series of hourly production over 10 years. It allows us to consider the capacity reduction due to water-head effect. However, it does not apply to the CLPSH, as the historical data have shown that they have operated at maximum installed capacity.

4 For upward operating reserves it is based on the failure of a biggest plant and for the downward operating reserves it is based on the failure of the biggest pump physical unit, in Spain 1100 and, 200 MW, respectively according to REE — Activities (2020) and ESIOS UP (2020).

Table 2
Base case (*BC*) and scenarios sensitive regarding water inflows (*BCdry*, *BCwet*) and the modeling of balancing services (*BC no balancing energy*, *BC no balancing capacity*).

	BC	*BCdry*	*BCwet*	*BC no balancing energy*	*BC no balancing capacity*
Energy activation	x	x	x		
Unit power reserve	x	x	x	x	
Water inflows	Medium	Low	High	Medium	Medium

defining ESS according to MITECO (2021) and ENTSO-E (0000c), such as installed power capacity, energy reservoirs associated with ESS technologies, roundtrip efficiency.

Table 1 shows that the ESS mix can be heterogeneous in terms of maximum energy reservoir capacity, storage duration cycle, and installed capacity. Table 1 details how SEED disaggregates hydropower technologies into four technologies (i.e., programming unit -UGH-, Run of the river,[5] OLPSH, and CLPSH). Energy reserves capacity (GWh) associated with UGHs and OLPSH are considered similarly as REE — Activities (2020). As mentioned in Oyler and Parsons (2020), the total energy reservoir capacity of 18 538 GWh available in Spain does not include the energy reservoir capacity of CLPSH.[6] Different methods exist to calculate the maximum energy reservoir capacity of CLPSH according to the net waterfall (Latorre et al., 2005). In this paper energy reservoir capacity of each existing CLPSH is based on the maximum consecutive working hours multiplied by the capacity installed.[7] Pumping efficiency considered for OLSPH and existing CLPSH is set according to Oyler and Parsons (2020), Kougias and Szabó (2017), and for new CLPSH according to PCI (2021). The collection of data in line with hourly generation profiles and the aggregation considered for hydropower programming units have both followed the recommendations of BOE (2020), Ventosa et al. (2005) and ACER (2020) according to temporal consistency between input data and programming units.

Until now, Spain has relied on the flexibility provided by fossil-fuel generation and hydropower technologies. Although the storage capacity will increase, it is important to know how the different ESSs will ensure the system's continuity of supply by increasing its flexibility.

What is more, given the high variability introduced by non-dispatchable RESs, critical events, where ESSs are expected to play a key role, are likely to increase. Hence, critical events must be tracked and analyzed. Analyzing the role of storage in Spain in 2030 through an operation model must be done with the following considerations:

- Medium-term scope to consider hydropower seasonal variability over a year.
- Maintaining chronology of events for analyzing ESS role during critical events.
- Representing different ESSs with different timeframes and technical parameters to characterize rigorously ESS roles in future Spain 2030 mix.
- Since electricity system security became challenging due to the penetration of non-dispatchable RESs, it is necessary to consider balancing services through operating reserves' modeling is necessary. Also, given hydropower technologies strongly participate in providing operating reserves, balancing services must taken into account when evaluating the role of ESS.

[5] Non-UGH includes non-dispatchable hydropower technology, also known as Run-of-River.

[6] This value represents the maximum physical value. However, historically the maximum reservoir level reached in Spain was around 14 TWh in 2016 (ESIOS, 2020).

[7] The energy reservoir capacities are obtained from a 10-year database providing hourly data for each existing CLPSH.

Table 3
Problem size of *BC* scenario.

Constraints	16.690.570
Variables	18.093.718
Non-zeros	56.888.301

5. Scenarios

Exploring the role of ESS in a 2030 scenario according to MITECO (2021) requires firstly building the base case (*BC*), which will be used as a reference case as represented in Table 1. A scenario of average water inflows – i.e., 25.1 TWh according to the year 2015 (ACER, 2020) – is used as a reference case. Two additional scenarios are defined and compared to the *BC* scenario according to water inflows. *BCwet* and *BCdry* are based on the annual weekly profile of 2016 and 2017, respectively, with 34.5 TWh and 15.9 TWh of energy hydro inflows.

In addition to scenarios exploring water inflows' influence on ESS operation, two more scenarios are designed to contrast the *BC* results based on different modeling assumptions of balancing services. Although modeling balancing services is approximated by hourly upward and downward operating reserves, the distinction between unit power reserve and energy activation is maintained. Therefore, balancing energy is not considered in the first scenario based on *BC* (*BC no balancing energy*). To complete exploring the consequences of including balancing services in a medium-term model, this study analyzes another scenario based on *BC* without considering the provision of balancing capacity (*BC no balancing capacity*). Table 2 resumes the five scenarios explored according to both parameter and constraint changes.

All scenarios were executed using GUROBI 9.1 under GAMS 35.0 with 32 GB of RAM. Table 3 presents the problem size:

6. Results and analysis

Given the possible operational roles of ESSs, such as PSHs and batteries, their operation may impact various indicators of system operation. Therefore, according to the focus of the study, this evaluation considers the impact on (1) changes in technologies generation and total operation cost according to different water inflows' scenarios, (2) the same changes according to different modeling assumptions of balancing services, (3) sensitivities analysis on ESS parameters, (4) technologies providing operating reserves, (4) behavior of ESSs during critical events.

6.1. Changes in technologies generation and total operation cost according to different water inflows' scenarios

In this section, the roles of ESS technologies are assessed according to different water inflows scenarios. Fig. 2 compares annual energy production per technology for two different years, 2019 according to available data in ESIOS (2020), and 2030 according to results of the BC scenario. As foresees by MITECO (2021), in 2030, non-dispatchable RESs represent most of the electricity generation. Given the energy produced, one might

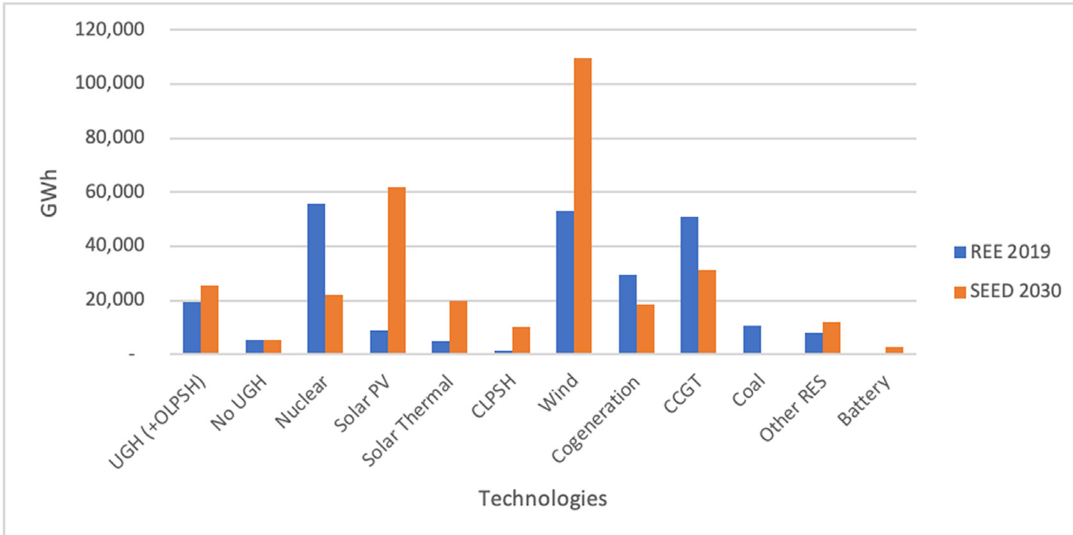

Fig. 2. Mix of electricity generation in GWh in Spain in 2019 according to Gentile et al. (2017) and 2030 according to *BC* scenario results obtained with SEED.

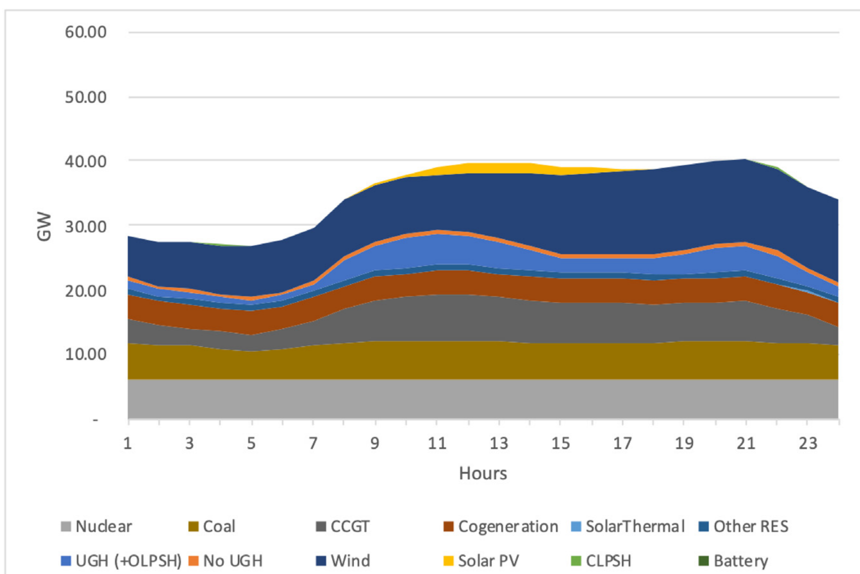

Fig. 3. Hourly economic dispatch for the Spanish electricity system during the day with the annual peak hour in 2019 according to Gentile et al. (2017).

think that CCGT and ESS have different behaviors. However, comparing these technologies in terms of hours of use is necessary as their installed capacity is different.

Figs. 3 and 4 represent the hourly operation during one day in 2019 according to available data from the SO (ESIOS, 2020) and 2030 according to the *BC* scenario, respectively. Note that figures represent the same day (i.e., the first day of the last week of January). Figs. 3 and 4 highlight operating changes in the economic dispatch of different technologies and changes in load patterns.

Comparing 2019 and 2030 economic dispatch allows one to observe the decreasing available baseload in the Spanish electricity system in 2030 (i.e., nuclear technology) by half, and no coal production is present. In addition, CCGT sees its output reduced and its scheduling changed. Moreover, the increase of the power requirement at peak hours is higher in 2030 than in 2019. Indeed, due to the non-dispatchable RES variability, the system requires more flexibility provided by thermal hydropower and ESS technologies.

Additionally, Tables 4 and 5 present results for the *BC*, *BCdry*, *BCwet* scenarios through annual full-time equivalent operation hours[8] and various electricity system indicators, respectively (i.e., total operation cost, total emission, RES curtailment).

The variations in total operation cost are mainly due to a change in CCGT generation since hydropower and ESS technologies have no variable cost. UGH, and OLPSH productions follow the annual water inflows scenario trend. Although it may seem counter-intuitive, batteries, existing and new CLPSH, increase their output in a wet scenario and outperform the CCGT in terms

[8] Annual full-time equivalent operation hours is commonly employed to point out and compare the use of different technology. It is defined for each technology by the ratio between the total energy produced and the installed capacity.

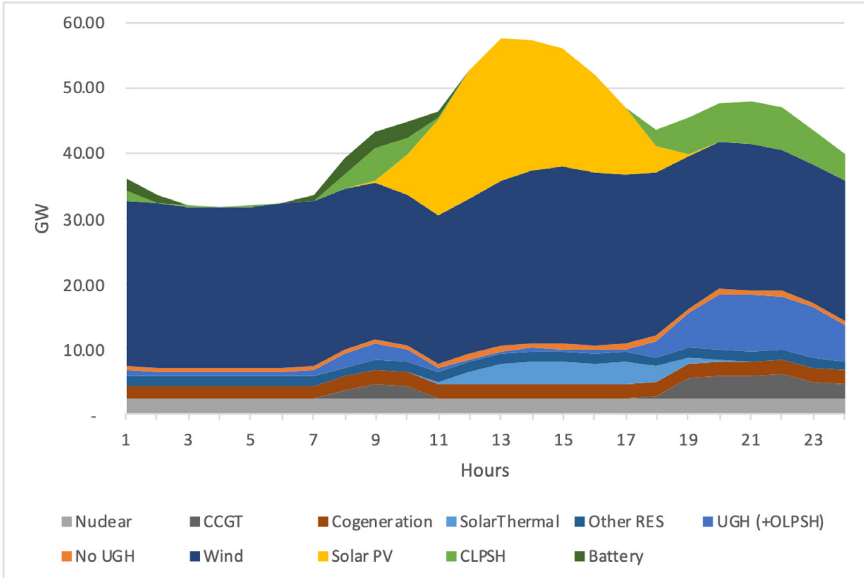

Fig. 4. Hourly economic dispatch for the Spanish electricity system during the day with the annual peak hour in 2030 according to the *BC* scenario. Results were obtained with SEED.

Table 4
Annual full-time equivalent operation hours for technologies according to different water inflows scenarios (BC, BCdry, and BCwet).

	BCdry [h]	*BCwet* [h]	*BC* [h]	*BCdry*/*BC* [%]	*BCwet*/*BC* [%]
Battery	1125	1115	1093	3%	2%
CCGT	1465	1041	1267	14%	−22%
CLPSH	1264	1296	1219	4%	6%
Cogeneration	4623	4623	4623	0%	0%
New CLPSH	1441	1439	1395	3%	3%
Nuclear	7224	7224	7224	0%	0%
OLPSH	1908	3395	2476	−30%	27%
Other RES	6987	6987	6987	0%	0%
No-UGH	4437	3039	4091	8%	−35%
Solar PV	1629	1585	1612	1%	−2%
Solar Thermal	2696	2696	2696	0%	0%
UGH	1641	3242	2381	−45%	27%
Wind Onshore	2285	2226	2257	1%	−1%

of annual working hours according to Table 4. When water inflows are abundant, the system prefers to rely on ESS rather than CCGT since for the former, the minimum technical output depends on the energy stored and do not have fuel cost. Furthermore, in extreme scenarios (i.e., wet and dry scenarios), the duration and frequency of the critical period change according to the based-case scenario. Even though the available mix is not dispatched in the same way in the different scenarios, Table 5 shows that the NECP RES goal of 74% is achieved for all scenarios, and no Energy Not Served (ENS) is observed.

According to Table 4, in a context of high non-dispatchable RES, CCGT, CLPSH (new and existing), and battery technologies work approximately the same duration of time in one year - e.g., below 1500 h. However, annual full-time equivalent operation hours may not be a sufficient indicator to affirm both technologies are used as peak capacity.

6.2. Changes in technologies generation and total operation cost according to different operating reserves' modeling considerations

The three scenarios presented in Table 6 may highlight why the medium-term operation planning model should consider balancing services when analyzing the future role of ESS in a context of high renewable penetration. Until now, medium-term operation planning models did not necessarily represent the correct use of the ESS mainly due to its economic use. Given the high shares of renewables in 2030, the medium-term models are led to consider more details at the operational level, such as balancing services, to allow adequate decision-making on the future operation of the electricity system (Pérez-Díaz et al., 2020).

Tables 6 and 7 presents results for *BC*, *BC no balancing energy*, *BC no balancing capacity* scenarios through annual full-time equivalent operation hours, and various electricity system indicators, respectively (i.e., total operation cost, total emission, RES curtailment).

According to Table 6, although not considering energy activation against not balancing services (i.e. neither balancing capacity nor balancing energy) has a small impact, it results in underestimating the contribution of batteries to provide services by 6% (energy and balancing services). Additionally, Table 7 shows that not considering balancing services underestimates annual total operating cost and RES curtailment.

Table 6 shows that battery technology is the most impacted by a change in accounting for balancing services. Considering balancing services increase full-time equivalent operation hours of batteries and CLPSH. Section 6.3 explains more in detail why the operating reserves consideration impacts more significantly batteries.

6.3. Sensitivity analysis for determining how relevant ESS factors impact electricity system dispatch

This section aims to analyze how modeling operating reserves most impact different ESSs. Two additional scenarios, *BC weekly cycle* and *BC roundtrip* are built to isolate parameters that describe batteries. *BC weekly cycle* differs from *BC* according to the cycle discharge of batteries. While in the *BC* scenario, battery technology must be filled up at the end of the day, in the *BC weekly cycle*, batteries must meet their maximum reserve at the end of the week. *BC roundtrip* differs from *BC* according to the roundtrip efficiency of battery technology. In the *BC roundtrip*, the roundtrip efficiency of batteries is similar to the one of the new CLPSHs (i.e., 79%). Table 8 resumes sensitivy scenarios. Table 9 presents results for sensitivity scenarios according to the annual full-time equivalent operation hours for technologies.

Table 5
Indicators of electricity system operation for three different water inflows scenarios (BC, BCdry, BCwet).

		BCdry	*BCwet*	*BC*	*BCdry/BC*	*BCwet/BC*
Total operation cost	M€	3.862	3.166	3.536	8%	−12%
Emission	MtCO2	22,5	19,0	20,9	7%	−10%
RES curtailment	%	17%	22%	19%	−12%	12%
%RES	%	75%	78%	77%	−2%	2%
SRMC	€/MWh	45	39	44	3%	−11%
ENS	MWh	0	0	0	0%	0%

Table 6
Annual full-time equivalent operation hours for technologies according to different scenarios based on the modeling of operating reserves (BC, BC no balancing capacity, and BC no balancing energy).

Technologies	BC [h]	BC no balancing energy [h]	BC no balancing capacity. [h]	BC no balancing energy/BC [%]	BC no balancing capacity/BC [%]
Battery	1093	1033	1028	−6%	−6%
CCGT	1267	1266	1266	0%	0%
CLPSH	1219	1203	1205	−1%	−1%
New CLPSH	1395	1392	1392	0%	0%
OLPSH	2476	2536	2555	2%	3%
UGH	2381	2381	2379	0%	0%

Table 7
Indicators of electricity system operation for three scenarios (BC, BC no balancing capacity, BC no balancing energy).

		BC	BC no balancing energy	BC no balancing capacity	BC no balancing energy/BC [%]	BC no balancing capacity/BC [%]
Total operation cost	M€	3.536	3.533,2	3.533,3	−0,07%	−0,07%
Emission	MtCO2	20,9	20,8	20,8	−0,04%	−0,04%
RES curtailment	%	19,2%	19%	18,9%	−0,88%	−1,16%
%RES	%	76,7%	76,8%	76,8%	0,09%	0,11%
SRMC	€/MWh	44	44	44	0%	0%
ENS	MWh	0	0	0	0%	0%

Table 8
Sensitivity scenarios according to roundtrip efficiency (BC roundtrip) and cycle discharge of batteries (BC weekly cycle).

	BC	BC weekly cycle	BC roundtrip
Roundtrip efficiency	90%	90%	79%
Cycle discharge	Daily	Weekly	Daily

According to Table 9, switching from a daily to a weekly discharge cycle gives the batteries greater flexibility. This gain in flexibility increases the dispatch of the battery technology (i.e., + 39% respectively to the *BC* scenario). The technologies seeing their dispatch decreased are first the new CLPSH (i.e., −12%), then the existing CLPSH (i.e., −8%), and finally CCGT (i.e., −2%). Table 9 shows that the variation in the dispatch of the battery technology is higher for the *BC weekly cycle* than for the *BC roundtrip*, respectively, to the *BC* scenario.

To complete sensitivity analysis, Table 10 shows various electricity system indicators, respectively (i.e., total operation cost, total emission, RES curtailment) that are in line with results shown in Table 9. The change from a daily to a weekly discharge cycle of the batteries allows the system to reduce its total operating costs by 1.2%, according to Table 10. Therefore, a greater flexibility of the batteries helps to reduce the use of CCGTs and the RES curtailed (i.e., −3.3%).

From these sensitivities (i.e., *BC weekly cycle* and *BC roundtrip)*, it is possible to classify the ESS parameters that have the greatest impact on their dispatch and thus explain why battery technology is the most impacted by the consideration of operating reserves. Although closely related to the energy capacity of the reservoir, the longer the discharge cycle (i.e., seasonal), the more flexibility it gives to the technology. As batteries have a daily discharge cycle, they have reduced flexibility compared to CLPSH (i.e., weekly discharge cycle). Additionally, at equal roundtrip efficiency, the new CLPSH is the technology that absorbs the lack of capacity of batteries. Thus, the batteries would increase the availability of remaining ESS during critical events, participating vigorously in providing operating reserves, first because of their daily discharge cycle and then because of their high roundtrip efficiency.

6.4. Technologies providing energy and balancing services

Section 6.1 shows that CCGT, batteries, and CLPSH technologies work few hours per year. However, results provided in Section 6.2 show that those technologies are impacted differently according to different balancing services modeling assumptions. Therefore, this section focuses on how much technologies produce in both energy and balancing services.

Fig. 5 presents the results according to technology share in providing balancing capacity services. UGH and OLPSH represent 45% (24% and 22% respectively) of total balancing services provided, which is in line with REE (2009). Although other technologies participating in reserve markets provide less balancing services, it remains relevant to highlight CLPSH and batteries, and CCGT provide together an equivalent quantity of total balancing services than UGH and OLPSH (13%, 11%, and 16%, respectively).

Additionally, when assessing the roles of different ESS, a relevant indicator is to compare the total balancing services and the total energy provided by each technology. Fig. 6 shows the ratio between both services. If the ratio is close to 1, the technology produces same quantity in the energy market as in the reserve market. If the ratio tends to 0, the technology does not provide balancing services. Results according to the *BC* scenario are shown in Fig. 6.

Regarding results provided in this section, they show that technologies provide their services differently. Regarding Fig. 6, battery technology produces almost the same energy in the energy market as the balancing energy, making it sensitive to which

Table 9
Annual full-time equivalent operation hours for technologies according to different roundtrip efficiency and cycle discharge of batteries (BC, BC weekly cycle, and BC roundtrip).

Technologies	BC [h]	BC weekly cycle [h]	BC roundtrip [h]	BC weekly cycle/BC [%]	BC roundtrip/BC [%]
Battery	1093	1782	907	39%	−21%
CCGT	1267	1241	1274	−2%	1%
CLPSH	1219	1125	1209	−8%	−1%
New CLPSH	1395	1247	1456	−12%	4%
OLPSH	2476	2459	2433	−1%	−2%
UGH	2381	2381	2351	0%	−1%

Table 10
Indicators of electricity system operation for three scenarios (BC, BC weekly cycle, BC roundtrip).

		BC	BC weekly cycle	BC roundtrip	BC weekly cycle/BC	BC roundtrip/BC
Total operation cost	M€	3.536	3.494	3.548	−1,2%	0,3%
Emission	MtCO2	20,9	20,6	20,9	−1,1%	0,3%
RES curtailment	%	19,2%	18,6%	18,7%	−3,3%	−2,7%
%RES	%	76,7%	76,8%	76,8%	0,4%	0,1%
SRMC	€/MWh	44,3	45	44,3	1,5%	0,1%
ENS	MWh	0	0	0	0%	0%

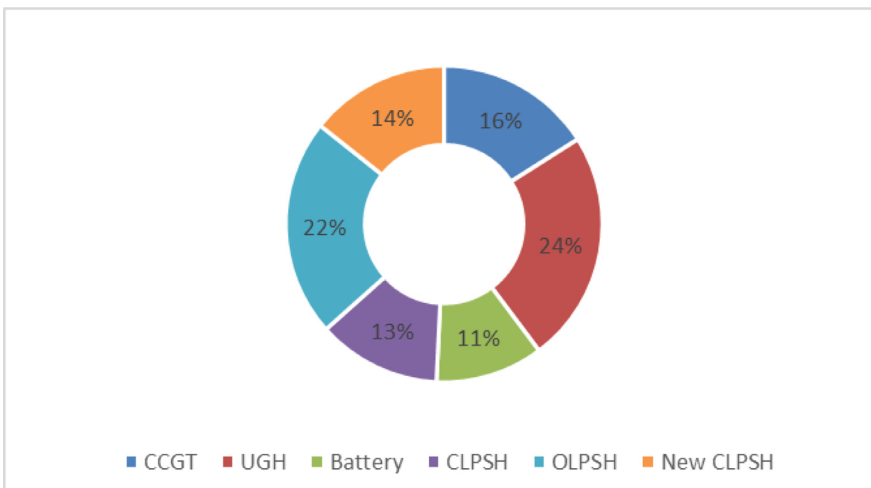

Fig. 5. Share in % of technologies competing in balancing services according to BC scenario.

modeling assumptions are applied on balancing services. This result reinforces the idea that analyzing the future role of ESS should be done, including both reserve and energy markets and ESS participation in both markets.

6.5. The behavior of ESS during critical events

An additional aspect to compare the role and operational competitiveness of the different available ESSs technologies is their contribution to the firm capacity required in the system to guarantee the supply. Capacity markets are designed to remunerate this very important service. Therefore, this service represents a relevant issue when comparing the competitiveness and role of generation technologies and ESSs. Although this should be properly addressed by using stochastic models, deterministic operation models such as the one described in this paper could be used to get insights into the comparative role of ESSs regarding this issue.

This issue is even more important in systems largely dominated by intermittent generation. A much higher frequency of critical events is to be expected, stressing the system and critical events of much larger duration that should be faced with the non-dispatchable resources in place. Thermal generation and ESSs will be the major players in this regard. In electricity systems dominated by thermal generation, critical hours are strongly related to the number of hours of very high demand. There may be sequences of many consecutive critical hours in electricity systems with a larger share of non-dispatchable RES generation. Analyzing the behavior of ESS technologies during critical events could help in assessing their roles. Therefore, this section evaluates the contribution of PSH units during the most critical hours regarding their production level.

Although several methods exist regarding for assessing peaking capacity resources (Denholm et al., 2020), they are not applicable in deterministic analysis using an operation model without considering investments. A different approach is applied in this analysis, where the average value of the capacity factor of the technology among critical periods is used to evaluate the peaking capacity of ESS technologies, that is their contribution to the firmness of the system (Madaeni et al., 2013). The larger they are present in those critical periods, the larger is their ability to contribute to the guarantee of supply of the system.

Regarding the obtained measure, the technology is considered reliable during peak hours of net demand when the measure tends to one. However, the number of critical hours to consider remains to be determined. Indeed, a high number of critical hours would make the measure to tend towards the average annual load factor for each technology since we are including in the analysis hours that are not so critical. On the other hand, a small

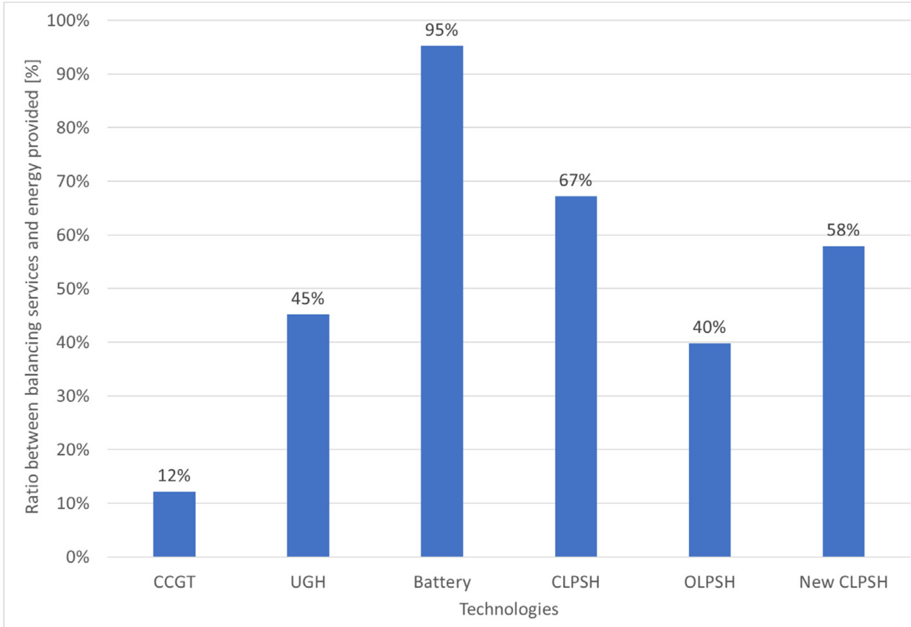

Fig. 6. Ratio between balancing energy and wholesale energy provided for each technology for BC scenario.

number of hours would not reflect critical events longer than two hours. It will not capture the risk of not having enough energy during longer close periods, resulting in some ESS being either over or under-evaluated in this regard. Therefore, a sensitivity analysis has been performed concerning the number of critical hours considered, adopting a range between 100 and 300 h. The hours selected are those with the highest net demand once the RES intermittent production is discounted.

Fig. 7 shows capacity factors of ESS technologies based on annual demand (green line), on 100 h and 300 h of highest demand (blue bars), and on 100 h and 300 h of highest net demand (orange bars).

In Fig. 7, the values of the demand-based capacity factors (blue bars) tend to be close to the annual mean of capacity factor, especially for the critical 300 h rank. Furthermore, the net demand-based capacity factor (orange bar) is higher than the demand-based capacity factor, indicating a better availability of ESS when demand is high and non-dispatchable RES production is low. From these two observations, (1) the so-called critical hours of the system should be defined considering both the production of non-dispatchable RES and load demand; (2) a too large time window could lead to a misinterpretation of the results, as we would no longer talk about availability in critical periods of the considered technology but about the annual mean of the capacity factor.

Another observation in Fig. 7 is the possible relationship between the availability of ESSs and the capacity of their energy reservoirs. Indeed, the obtained ranking of ESS availability at peak hours is in line with the energy reservoir size of each ESS. Regarding results in Fig. 7, the larger the energy reservoir, the more available ESS is.

Changing the critical hours rank affects the availability of ESS technologies distinctly. OLPSH and existing CLPSH see their availability increased when the considered critical hours decrease, whereas the availability of new CLPSH and batteries diminish. As the observation range of critical hours is reduced, the net demand values are higher. In addition, batteries and new CLPSHs have a smaller energy storage capacity than the remaining ESS (OLPSH and existing CLPSH). Thus, the smaller the number of critical hours considered, the less ESS with small energy reservoirs are available.

Although batteries have a high roundtrip efficiency coefficient, Fig. 8 shows that, among all ESS technologies, batteries would not be available during critical events considering 100 h nor 300 h highest net demand values. This effect can be due because the batteries have a maximum discharge time of 4 h.

Fig. 8 shows that the most extended critical period measured is 7 h. In the case of the highest 100 h of net demand, the number of times 4 h and 5 h events occur is equivalent. In the highest 300 h of net demand, the occurrence of 5 h events is greater than that of 4 h. Although the periods may be of the same duration as the maximum battery discharge time, several periods are ranging from one to three critical hours in a row. In addition, the critical events appear before or after critical periods (e.g., even if they are not consecutive, they are close in time, for instance, during consecutive days). Therefore, due to their low storage capacity, batteries cannot make themselves available at the same level as the remaining ESS (e.g., not having had time to recharge to 100% before the next event).

The data used in this study are exclusive to the case study analyzed. Furthermore, the observations made from the results obtained may be subject to change depending on the case study considered.

7. Conclusions

This article presents a medium-term centralized operation planning model to reproduce the operation of the Spanish system in 2030. However, the proposed approach could be used for a case study involving a larger geographical area, including France, Spain, and Portugal. The medium-term modeling, including the hourly production of energy and operating reserves, highlighted the role of ESSs in ensuring the security and continuity of supply of the electricity system. Three groups of indicators (e.g., sequences of consecutive hours of highest net demand, total energy and operating reserves production, an average of capacity factor according to a range of peak hours of net demand) were used to assess the contribution of ESSs to the reliability of the electricity system during critical events and to analyze the competition and complementarity between different ESSs (namely, batteries and pumped storage hydro).

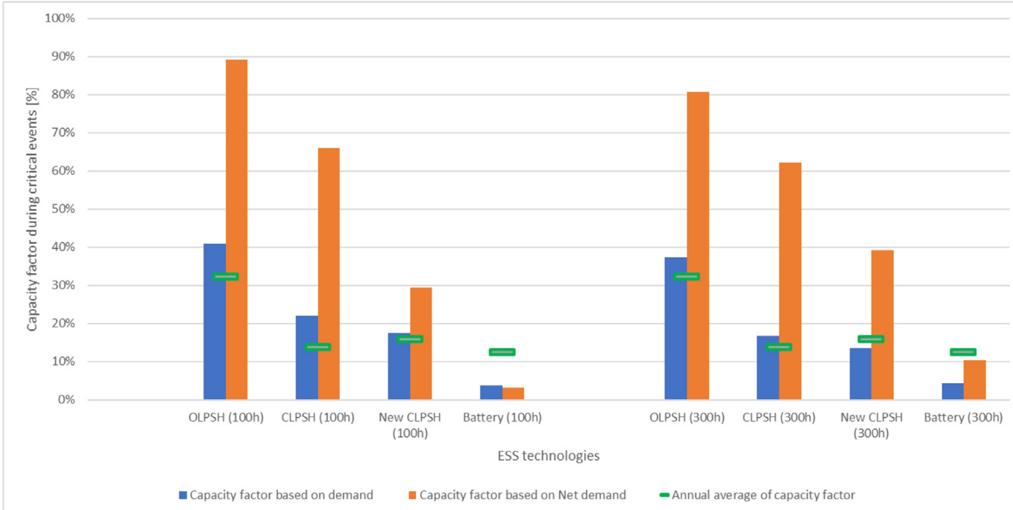

Fig. 7. Capacity factor of ESS technologies obtained for BC scenarios for a range of 100 (left-hand side) and 300 (right-hand side) critical hours according to demand (blue bars) and net demand (red bars). . (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

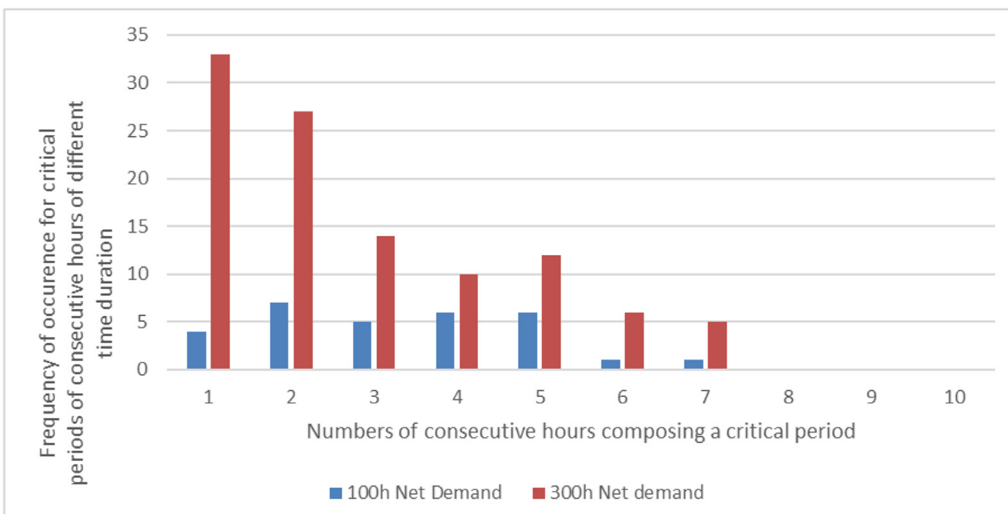

Fig. 8. Frequency of occurrence of critical events of different durations according to a range of 100 and 300 h of highest net demand for BC scenario.

According to the ESS availability during critical events, this study highlights that defining critical events should consider demand and non-dispatchable RES production. In addition, the range of peak hours of net demand is a sensitive parameter. It should be chosen cautiously to allow a fair analysis between ESS and the characterization of critical periods of different durations.

In addition, this paper explores the roles of different ESSs according to critical water inflow scenarios (i.e., dry and wet water hydro inflow scenarios). Although RES penetration relies on water hydro inflow scenario considered, impacts on CLPSHs and batteries productions are similar.

Moreover, it has been shown that considering balancing services in a medium-term operation model is relevant to evaluate storage technologies' role. Given that 4 h-batteries provide almost the same amount of energy in both energy and reserve markets, the analysis of their contribution to the electricity system's reliability is sensitive to considering balancing services. Although batteries seem to last to contribute to the system's reliability during critical periods, their production in the reserve market is equivalent to that injected from other ESSs. Therefore, the omission of balancing services might lead to misevaluate analyzing complementarity of different ESSs.

Regarding the generation of ESSs to the energy market, the higher the installed capacity, the higher the production in the reserve market. Besides, the complementarity of the ESSs is that the batteries would essentially be intended to participate in the reserve market and thus allow the larger capacity ESSs such as the CLPSHs to be available to contribute to maintaining the reliability of the system during the highest net-demand peak hours. These conclusions remain in the context of Spain in 2030 according to the planned electricity generation mix and were obtained through deterministic scenarios.

The authors found relevant enhancing operation details modeling within a medium-term operation model for completing this analysis. This change could lead to improving the representation of balancing services. The option of introducing stochasticity is also considered the next step to enhance the study of ESS availability during critical periods. An additional major improvement that could be envisaged is the consideration of demand response and interconnections in the model, as these features, if expected to be large enough, could significantly impact the results of the operational behavior of ESSs in the system. Since the proposed approach only considers the operation of power systems, the first limitation is the expansion of the generation.

The proposed approach does not include investment options. However, these could be included in future studies that focus on exploring the impacts of ESS operations on investment decisions and the evolution of the installed energy mix (Ramos et al., 2022). A second limitation relates to the consideration of the transmission network. However, it is not uncommon for the network to be ignored, and even less so for the Spanish case, where, when the study focuses exclusively on generation, the Iberian Peninsula is treated as a single node (i.e., generally referred to as the copper plate) (Morales-Espana et al., 2014; Barquin et al., 2004). A third limitation concerns the stochasticity of the scenarios analyzed. Although the model explores deterministic scenarios, it would be possible to integrate it into a Monte Carlo simulation. Monte Carlo simulation would aim to reproduce many times the different scenarios for demand or RES generation profiles. A fourth limitation is the technologies considered. Although the article proposes to compare different storage systems, some technologies, which are sometimes seen as storage systems, or at least as flexibility solutions, are not included, such as electric vehicles, interconnections, and demand-side management. It is conceivable to introduce these technologies in a future article where the comparison would extend to storage systems and all flexibility solutions available to the system operator. Although, several storage technologies (e.g., Flywheel, Compressed Air Energy Storage, Electric vehicles) are not considered in this study, it would be possible to represent them as long as their parameters (i.e., storage capacity, installed power, efficiency, and discharge time) can be used to model the annual operation. Thus, the proposed approach is scalable and replicable once the parameters are carefully determined.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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