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alysis of different storage technologies in the Spain NECP for 2030

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Abstract

In the paper, we have proposed three dimensions relevant to the flexibility assessment: power gradient, power, and energy. A two-phase procedure is projected to analyze an electric system's flexibility to cope with renewables' integration. The first step determines the margin on any dimension. The second one runs a cost-based operation model to determine how these dimensions are covered.

The ramp margin computed shows that a critical net demand ramp happens when solar power reduces its generation, but the system can still cope with this upward ramp.

Different flexible technologies cover the weekly energy variation of the net demand. It shows the high contribution of storage hydro and open-loop pumped-hydro storage to this variation. Flexible technologies supply upward and downward ramps of the net demand. Batteries and new closed-loop pumped-hydro storage are the storage technologies that contribute the most to these net-demand ramps. We also show that existing and new closed-loop pump-hydro storage participate more in the critical net-demand hours, having a high capacity factor, almost double the batteries.

1 Introduction

Nowadays, power systems are under tremendous pressure to be decarbonized to reach different targets imposed by clean energy policies. For example, in the European Green Deal (European Commission 2019) and Fit for 55 legislative packages, the EU and its member states are committed to cutting net greenhouse gas emissions in the EU by at least 55% by 2030, compared to 1990 levels[1]. In 2030 40% of the total energy consumption must be generated by renewable energy[2]. One key element for achieving these goals is to increase the share of renewable generation (mainly solar photovoltaics (PV) and wind) for producing electricity. These types of renewables are, in essence, not controllable or inflexible. Their integration requires other flexible technologies such as combined cycle gas turbines (CCGT), storage hydro, pumped-storage hydro, battery, solar thermal (or concentrated solar power CSP), demand side response (DSR), electric vehicle (EV) with or without vehicle to grid (V2G) possibility, and power to hydrogen.

The phasing out of fossil fuel power plant coupled with the increasing share of renewable energy stand as a challenge for the System Operator according to the security of supply during peak hours [Denholm et al 2020]. Indeed, firm capacity was traditionally provided by thermal and hydroelectric technologies. Given that the energy mix will introduce new technologies such as battery, it is necessary to know how the different technologies will respond to the several needs of the power system.

Although firmness assessment methods already exist [], they should be adapted since they are based on the availability of thermal and hydropower technologies. Additionally, authors in [ACER 2020, CNMC 2021] argue that firm capacity should be assessed jointly with the operational flexibility of power systems.

In this paper, we analyze how the different generating (e.g., CCGT) and storage technologies (in 2030, realistically, they will be pumped-storage hydro, battery, or solar thermal) play a role in integrating renewables by providing firmness and operational flexibility.

The main contributions of the paper are:

- Propose a flexibility assessment method in two phases: the first to analyze ex-ante the margin of the different flexibility dimensions and the second to determine how flexibility dimensions are covered with the various technologies
- Flexibility assessment and analysis of the contribution of each type of storage
- Application to the Spanish power system for 2030, where a high share of wind and solar generation is expected
- Sensitivity analysis to reduced hydro inflows

The paper is organized as follows. xxx

2 Flexibility assessment

To analyze the contribution of the storage technologies to the system operation we must first introduce the definition of operational flexibility as the ability of the system to withstand the uncertainty and variability in generation and electricity demand while maintaining the desired reliability at an

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[1] https://www.consilium.europa.eu/en/infographics/fit-for-55-eu-emissions-trading-system/

[2] https://www.consilium.europa.eu/en/infographics/fit-for-55-how-the-eu-plans-to-boost-renewable-energy/

affordable cost ("Challenges of Renewable Energy Penetration on Power System Flexibility: A Survey | Elsevier Enhanced Reader" n.d.).

Once assumed this definition, the next question to address is: which dimensions of operational flexibility can be defined or how to measure it? Since power systems will be mostly composed of inflexible technologies, the requirements of the power system, the abilities, and the contributions of technologies to the operational flexibility of the power system are assessed respectively to the net demand [Heggarty et al 2020]. Flexibility assessment in power systems is essentially based on these three main dimensions:

a) **Power gradient** [MW/h]
It corresponds to the power variation per unit of time. In systems with enough quick-response generation (e.g., hydropower), the time interval to analyze this metric can be one hour. Only systems with no generation of this type may need to deal with shorter time intervals of minutes or seconds. The primary metrics are upward and downward hourly (bi-hourly, tri-hourly) ramps of the net power demand[3].

b) **Power** [MW]
In the short-term, this metric deals with the demand-supply balance at any point in time, with the procurement of operating reserves for balancing the short-term uncertainty due to forecast errors in generation or demand. In the medium-term, the availability of enough generation to supply the demand is defined by the unit firmness, which is the contribution of each unit during the critical peak (net) demand hours. In the long-term, this is the system adequacy, usually measured by the reserve margin and expected energy not served (EENS), and loss of load probability (LOLP).

c) **Energy** [MWh]
Integrating the demand along different time intervals (e.g., day, week, season) defines the system requirements. The energy variation for those intervals is linked to the system storage needs.

Other papers have also found similar metrics ("Challenges of Renewable Energy Penetration on Power System Flexibility: A Survey | Elsevier Enhanced Reader" n.d.).

ENTSO-e (European Network of Transmission System and Operators for Electricity 2021) suggests two flexibility metrics (ramps and scarcity periods) as the starting point to analyze at a European scale. They mention that ramps can be especially critical at sunset in regions with large PV generation and simultaneous demand increases. Besides, they also propose the analysis of 5-day scarcity periods (e.g., dunkelflaute, an anticyclonic gloom where almost no wind and solar energy is generated) to analyze extended periods with low weather-dependent generation.

(Huclin, Ramos, et al. 2022) proposes a conceptual framework for jointly analyzing the firmness and operational flexibility of power systems. They split the analysis among system requirements (which flexibilities the system needs?), abilities (How much operational flexibility does the system have?), and contributions Who and in what dimensions is the flexibility provided?). Applying the discrete Fourier transform to the net demand, authors found that half a day, a day, and a week are the relevant time scopes for analyzing the operational flexibility dimensions in several European countries. The results obtained in (Huclin, Ramos, et al. 2022) are in line with similar studies focused on power system operational flexibility [Heggarty et al 2020, Saarinen et al 2021].

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[3] Net demand is the demand minus the inflexible (non-dispatchable) generation (e.g., solar PV, wind, small, or run-of-the-river hydro).

Other potential flexibility metrics associated with real-time system operation (e.g., inertia, rate of change of frequency ROCF, area control error, etc.) or related to transfer capacities and congestion management among areas, voltage control, and power quality are out of the scope of this paper.

In this paper, we propose these two phases for assessing the operational flexibility in an electric system:

a) **Margin analysis**
This phase answers the question: Does the system have enough operational flexibility? For that purpose and any dimension, a margin based on the system availability of the product (i.e., net ramp, net load, net energy) and the system requirements is computed

$$\boldsymbol{dimension\,margin = \frac{availability}{requirement}}$$

For example, the upward ramp margin will be the ratio between the sum of the available upward ramps of the flexible technologies and the maximum upward ramp of the net demand.

b) **Flexibility in system operation**
How much is the contribution of each technology to each flexibility product? The system operation is simulated by a market-based operation model that determines the optimal operation of the system, i.e., the use of the generation and storage resources to satisfy the demand considering all the operating constraints. The model considers the limitations of thermal units (ramp up/down, minimum up/down time, minimum load, must run, etc.), hydro scheduling of hydropower plants and reservoirs, battery management constraints (e.g., state of charge and charging and discharging processes), and operating reserve requirements. It is very relevant to consider all these constraints, given that the model must represent the system operation as realistically as possible.

3 Spanish case study

The Spanish National and Climate Plan NECP (Ministerio para la Transición Ecológica y el Reto Demográfico 2020) proposes the pathway to reach the emission reduction and increase in renewable production required for achieving the European energy policies. A similar consistent exercise is done in the National Trends scenario of the Ten-Year Network Development Plan 2022 by ENTSO-e (European Network of Transmission System and Operators for Electricity 2022a). These studies analyze horizons 2030, 2040, and 2050. For the paper's case study, we have selected the first horizon 2030 as the more realistic. The case study's wind, solar, and demand data have been taken from the TYNDP 2022 (European Network of Transmission System and Operators for Electricity 2022a). We have updated the CO2 price to 140 €/tCO2 according to the last estimations made by ENTSO-e in July 2022 (European Network of Transmission System and Operators for Electricity 2022b).

In **Table 1**, we present a summary of the installed capacity and production for the different technologies according to the TYNDP 2022 and the objective scenario of the NECP. The operation in the TYNDP is represented for three scenarios (called climate years). The last row of the table shows the peak demand and the year's demand.

We have considered for the Spanish power system 3 nuclear power plants, 50 CCGTs, 50 storage hydro programming units, three open-loop pumped-hydro storage (OL-PHS), and ten closed-loop pumped-hydro storage (CL-PHS). Solar PV and thermal and wind are considered aggregated technologies.

Table 1: Installed capacity and energy produced for the objective scenario 2030 for the Spanish system[4].

	TYNDP	NECP	TYNDP	TYNDP	TYNDP	NECP
			CY1995[5]	CY2008	CY2009	
	MW	MW	GWh	GWh	GWh	GWh
Nuclear	3,041	3,050	21,261	21,261	21,261	22,034
Gas	24,499	24,560	18,178	17,985	18,395	27,617
Hydro[6]	14,612	24,140	34,260	34,448	36,479	32,376
Open-loop pumped-hydro storage	2,683	-	-	-	-	-
Closed-loop pumped-hydro storage [7]	6,866	-	-	-	-	-
Wind Offshore	200	-	952	854	935	-
Wind Onshore[8]	48,350	48,550	118,058	110,686	114,893	109,464
Solar[9]	45,704	45,704	75,784	74,114	76,179	84,965
Other RES[10]	1,730	1,730	7,659	7,659	7,659	12,088
Other Non-RES[11]	3,980	3,980	18,887	18,887	18,887	18,399
Battery	2,500	2,500	-	-	-	-
	154,165	154,214	295,039	285,894	294,688	306,943
Peak demand	47,768	47,768				263,000

3.1 Ramp margin

As mentioned in the introduction, one of the critical issues in power systems with large-scale solar PV penetration is the upward ramp of the net demand due to the sharp decrease of solar production at sunset. In this section, we compute the margin for the upward and downward hourly ramps as an example of the ex-ante margin analysis. In **Table 2**, we present the maximum upward and downward ramps for 2019 as the latest year with regular electrical demand. The estimated ramps for the demand, wind, solar PV, and run-of-the-river hydro are taken from the TYNDP 2022 climate year 1995. The ramps for solar thermal assume a generation profile corresponding to a mean solar year. The ramps for the net demand for 2030 are computed based on the hourly profile of this net demand subtracting from the demand hour by hour the non-dispatchable renewable generation (i.e., wind, solar PV, and run-of-the-river hydro).

In the ramp margin assessment, we ignore the potential support from the neighbor systems (i.e., Interconnections), France and Portugal, to be conservative in the analysis.

Table 2: Upward and downward ramps.

			Requirement	Requirement	Availability	Availability
	Downward	Upward	Downward	Upward	Downward	Upward

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[4] The reference scenario in the TYNDP is the mainland Spanish system, while the NECP deals with the national Spanish system (including Balearic and Canary Islands). That's the reason for the small discrepancies.

[5] The TYNDP 2022 considers three climate years that affect the demand, hydro, wind, and solar generation.

[6] Includes storage (10,972 MW) and run-of-the-river (3,640 MW) hydro.

[7] Includes existing (3,300 MW) and foreseen (3,566 MW) closed-loop pumped-hydro storage.

[8] Includes existing (27,370 MW) and foreseen (21,180 MW) onshore wind power.

[9] Includes existing and foreseen solar PV (15,550 and 22,854 MW respectively) and solar thermal (2,300 and 5,500 MW respectively).

[10] Other RES corresponds to biomass.

[11] Other Non-RES corresponds to cogeneration.

	2019	2019	2030	2030	2030	2030
	MW	MW	MW	MW	MW	MW
Demand	-3,659	5,389	-6,818	3,996		
Wind	-1,882	2,069	-4,131	4,541		
Solar PV	-1,610	1,618	-11,880	11,941		
Existing solar thermal	-840	1,321	-629	1,111		
Run-of-the-river hydro	-468	292	-154	189		
Net demand	-4,203	5,633	-10,745	12,701		
CCGT	-3,369	3,180			-6,343	5,704
Storage hydro	-1,425	1,430			-2,885	2,963
Exist. PS hydro (pumping)	-1,804	2,326			-3,613	0
Exist. PS hydro (turbining)	-972	1,373			0	2,186
New PS hydro (pumping)					-3,904	0
New PS hydro (turbining)					0	2,362
Battery					-2500	2500
Total [MW]					-19,245	15,715
Ramp margin [p.u.]					1.79	1.24

The ramp requirements are computed based on the net demand ramps, which in 2030 will reach similar values to solar PV ramps, see **Table 2**. Figure 1 shows that comparable ramps appear during several-year periods. Positive values are upward ramps (i.e., demand increase) and negative ramps are the opposite. However, the maximum positive ramp happens at 17 h and the minimum negative ramp at 9 h, both in fall. These extreme ramps are due to a decrease (increase) in solar PV and, consequently, a sharp increase (decrease) in net demand.

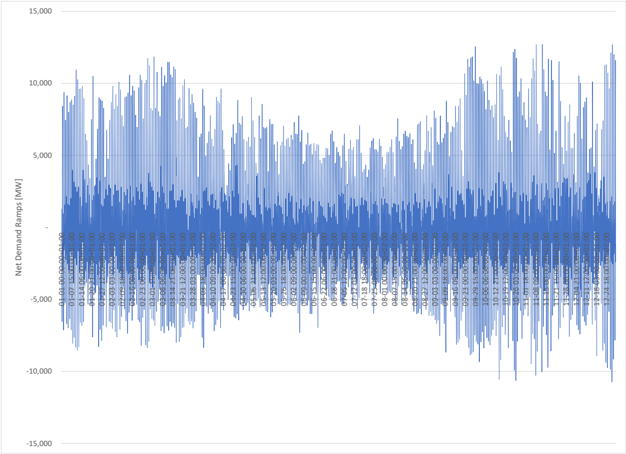

Figure 1. Estimated hourly ramps of the net demand for 2030.

For the ramp availability, we review the reasonable maximum contribution of each technology. The maximum historical downward and upward ramps of the CCGT (data taken from (Red Eléctrica de España 2022) for 2014 up to 2022) have been -5,083 and 4,571 MW, respectively, with a maximum historical production of 17,669 MW. Given that the CCGT installed capacity is 24,500 MW, assuming a 10% derate due to forced outages, we may think that 22,050 MW will be constantly available and, applying the same proportion of the ramps to the maximum historical production, we can conservatively estimate the CCGT ramp availability as -6,343 and 5,704 MW.

For the storage hydro ramps, whose data have been taken from (Red Eléctrica de España 2022) for 2011 up to 2019, we are assuming the quantiles 0.5 and 99.5% of downward and upward historical hourly ramps, which implies that they can be provided in any type of hydrologic year.

The maximum historical downward and upward ramps of the existing pumped-storage hydro, whose data have been taken from (Red Eléctrica de España 2022) for 2011 up to 2019, have been -2,233 and 3,613 MW ramps when pumping and -2,181 and 2,186 MW ramps when turbining, with a maximum historical consumption of 4,538 MW out of 5,983 MW installed and production of 4,215 MW.

New pumped-storage hydropower plants are scheduled before 2030. Applying the same proportion of the old ones, we can estimate the downward and upward ramps as -2,233 and 3,613 MW ramps when pumping as -3,904 MW and 2,362 MW when turbining.

The maximum historical downward and upward ramps of the existing solar thermal (data taken from (Red Eléctrica de España 2022) for 2014 up to 2022) have been -1,228 and 1,391 MW, respectively, with a maximum historical production of 2,222 MW out of 2,300 MW installed. However, it can be seen from Figure 2 that existing solar thermal is partially dispatchable, i.e., able to store energy even during the night, and consequently smoothing its output ramps. This figure represents six centroids obtained by the k-means algorithm that condense all the days of a year. Ramps at sunrise are higher than at sunset due to existing solar thermal storage capacity. We consider that newly installed solar thermal with 9 h of storage capacity will be able to move its output out of the critical upward ramping hours of the net demand. Consequently, we have not considered this ex-ante margin analysis.

Considering the system availability and requirements, the ramp margin is 179% for downward ramps and 124% for upward ones, which means that in 2030 the system can be stressed for the upward ramp but not with scarcity.

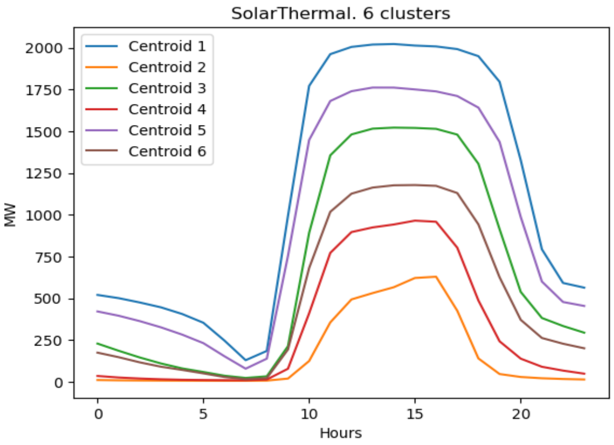

Figure 2. Six centroids for historical solar thermal output for 2014-2022.

3.2 Flexibility in system operation

Now, we assess the deployment of the system flexibility by simulating the system operation from an economic point of view. We use the openTEPES model (Ramos, Quispe, and Lumbreras 2022), an optimization-based model that determines the hourly dispatch of the different generating units with all the detailed operating constraints to minimize the total system variable cost.

The output of each technology for the year 2030 is summarized in **Table 3** and Figure 3. Wind generation has the highest energy share, followed by solar PV, CCGT, and nuclear. Then, several storage technologies such as storage hydro, pumped-hydro storage, and solar thermal, also have essential production. According to these numbers, the hydro, wind and solar renewable generation satisfies 75% of the demand.

Table 3: Energy output for each technology.

		Generation GWh	Consumption GWh	Spillage GWh
Nuclear	Nuclear	22,046		
CCGT	CCGT	23,346		
Run-of-the-river Hydro	Hydro_NonUGH	6,606		
Storage Hydro	Hydro_UGH	14,768		26
Open-loop Pumped-hydro Storage	OL_PHS	14,975	-8,274	373
Closed-loop Pumped-hydro Storage	CL_PHS	8,072	-12,918	971
Closed-loop Pumped-hydro Storage New	CL_PHS_New	9,302	-13,298	671
Wind Offshore	Wind_Offshore	816		136
Wind Onshore	Wind_Onshore	113,454		4,605
Solar PV	Solar_PV	57,680		4,384
Solar Thermal	Solar_Thermal	4,063		563
Solar Thermal New	Solar_Thermal_New	13,159		1,995
Biomass	Biomass	12,088		
Cogeneration	Cogeneration	18,399		
Battery	Battery	5,243	-6,888	
Total		324,017	-41,378	13,724

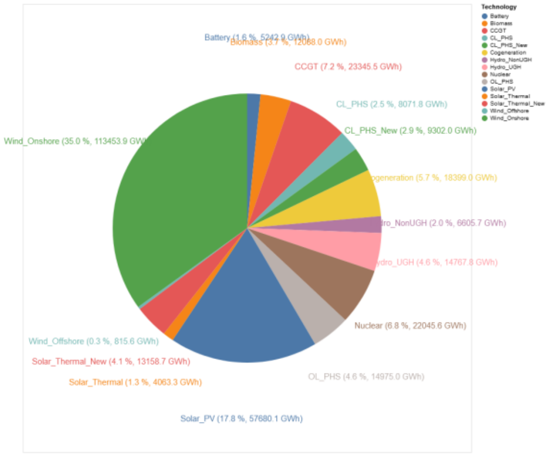

Figure 3. Energy output and corresponding share for each technology.

In Figure 4, we can observe the capacity factor of each technology, which is the energy produced divided by the installed capacity time and the hours of a year. It is relevant to analyze the capacity of the different storage technologies, e.g., CL-PHS and batteries. The capacity factor of PHS is higher than that of the battery, which means that the significant storage capability[12] of the PHS overcomes the higher efficiency of the battery[13]. Similar observations were made in (Huclin et al 2022).

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[12] Batteries have 2 h of energy storage (clearly daily storage), while the energy storage of CL-PHS ranges from 5 to 125 h (from daily to weekly storage), depending on the unit.

[13] We have considered a charge/discharge efficiency of 90% for the battery, 70% for the existing CL-PHS, and 75% for the new CL-PHS.

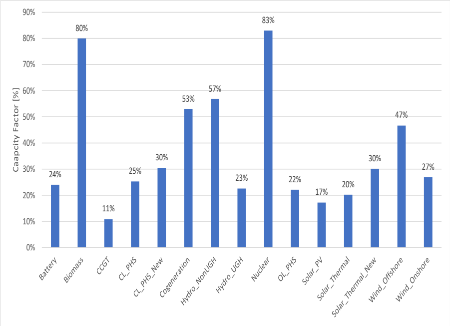


Figure 4. The capacity factor for each technology.

3.2.1 Power gradient. Ramps

In Figure 5, we show the contribution of each technology to the downward and upward ramps and the ramps of the net demand. As shown in the figure, the battery absorbs on average (for all the hours of a year) 700 MW of the upward and downward ramps, the new OL-PHS captures around 750 MW and the existing OL-PHS around 550 MW of each one. We can say that batteries can quickly adapt its production to the change in the net demand. OL-PHS can also play an important role in the net demand variability but at a lesser extent.

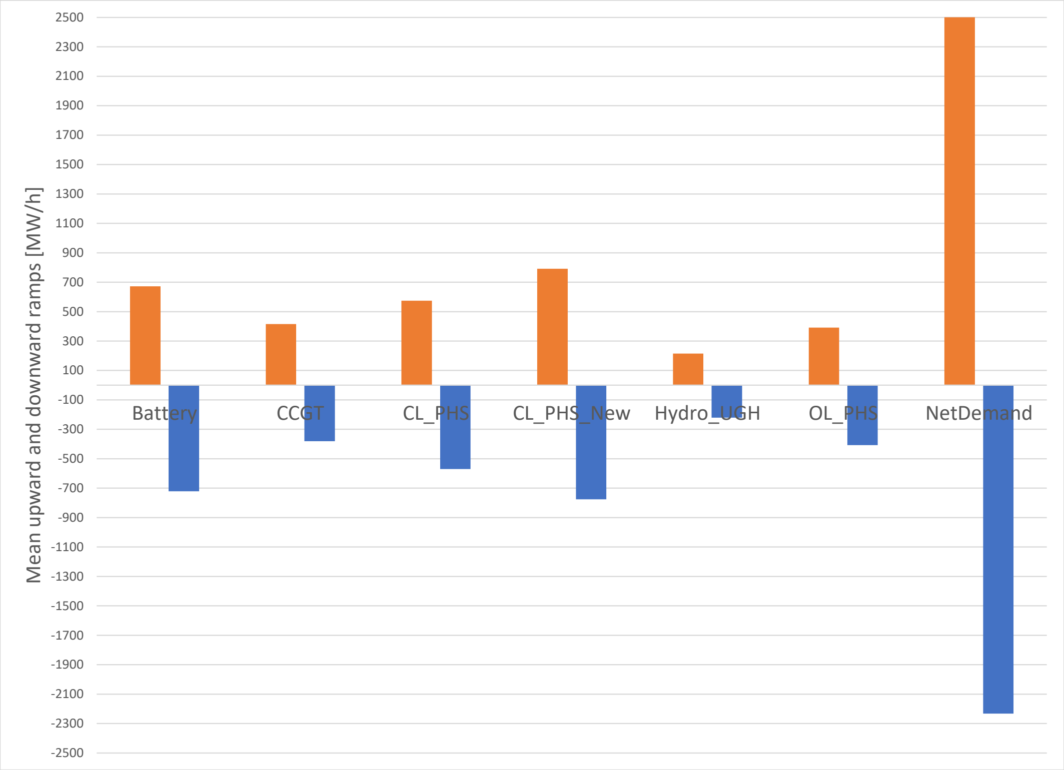
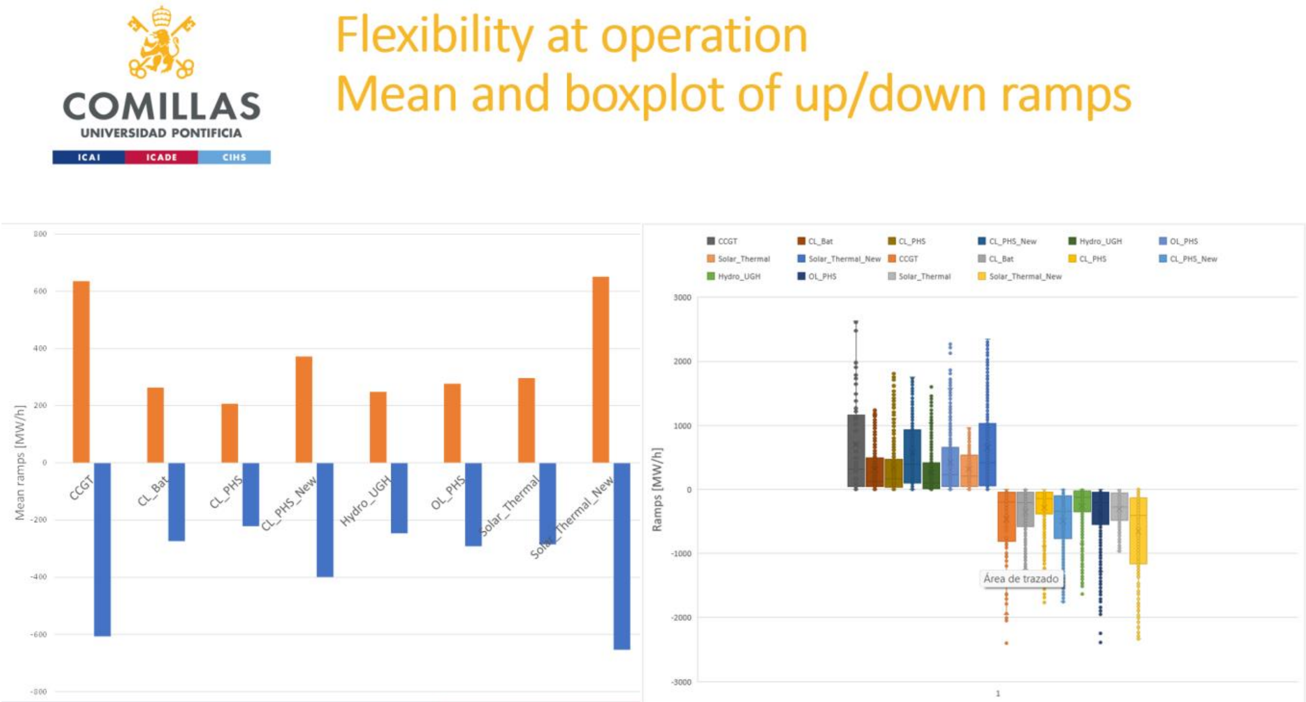


Figure 5. Mean value of downward and upward ramps of several technologies and for the net demand.



Flexibility at operation
Mean and boxplot of up/down ramps

3.2.2 Power. Firmness

In this section, we analyze the contribution of each technology to the net load demand, especially in the potentially critical hours of the net demand. On the left side of Figure 6, we present the ratio between the net demand and the peak demand. The net demand exceeds 60% of the peak demand in a few hours, and it is negative in almost 2000 hours, allowing storing of energy on a daily/weekly cycle. The Figure 6. (right) shows the capacity factor of technologies based on a reduced number of critical hours (The blue bars show the capacity factor based on the highest 300 hours, orange bars shows the same metrics based on the 600 highest hours of the net demand, and grey bars show the annual capacity factor based on 8760 hours) with the most significant values of the net demand. This method is a capacity credit approximation based method called the capacity factor-based approximation method (Madaeni et al, 2012). As it can be observed, the existing and new PHS (i.e., CL-PHS and OL-PHS) have a capacity factor of 50-60%, while the battery holds a 25% capacity factor. This operation indicates that the contribution of the PHS is strongly oriented to produce at the critical net demand hours, given their flexibility and storage capability. Additionally, the capacity factor of PHS decreases significantly as the number of hours considered increases while for the Battery it is almost constant.

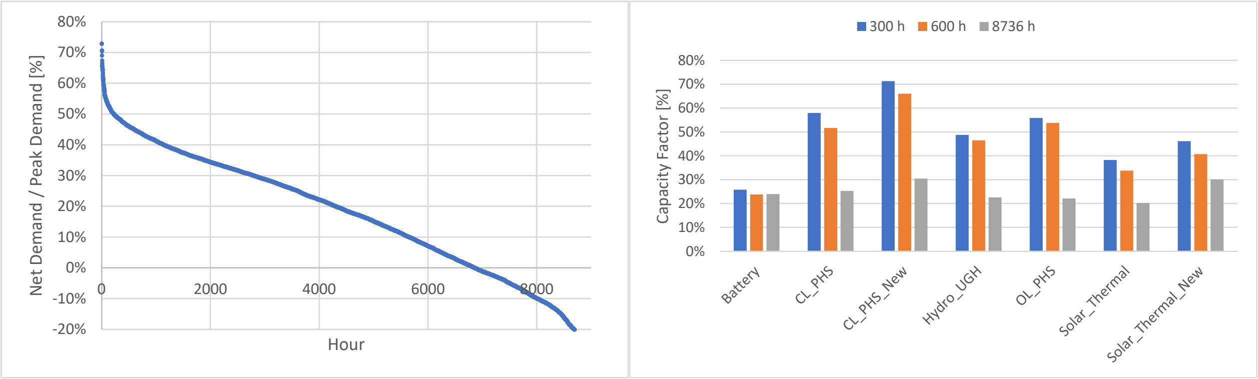


Figure 6. (left)Ordered net demand capacity factor and (right) capacity factor for each storage technology in the 300 or 600 peak hours of the net demand.

A similar conclusion is obtained in (Huclin, Pablo Chaves, et al. 2022), which determines the contribution of each storage technology to the system firmness.

3.2.3 Weekly energy

The energy demanded every week changes throughout the year. We can observe higher demands in winter weeks and summer weeks and moderate values in spring and fall. If we include the non-dispatchable technologies (run-of-the-river hydro, solar PV, and wind), we can observe that the resulting net demand also changes over the year, but then the previous pattern is no longer valid because of the variation of each non-dispatchable technology.

An interesting way to analyze this variation of energy needed and how each technology contributes to it is by taking the difference between the energy of any period (e.g., one week) and the mean yearly energy of a week. Higher values with respect to the mean value reach 4000 MW (672 GWh in a week, approximately 10% of the weekly demand), while lower values are -3000 MW (-504 GWh in a week). Figure 7 presents how this variation of the net demand with respect to its mean annual value along the 52 weeks is satisfied with variations of the different flexible technologies for their mean yearly production. For example, in the Figure 7, there is a high contribution of the open-loop pumped-hydro storage (OL-PHS) over many weeks. Besides, the storage hydro (Hydro-UGH) absorbs negative variations in the year's first half and primarily positive variations in the second half, in grey in the figure. The opposite happens with the battery and the existing and new closed-loop pumped-hydro storage (CL-PHS).

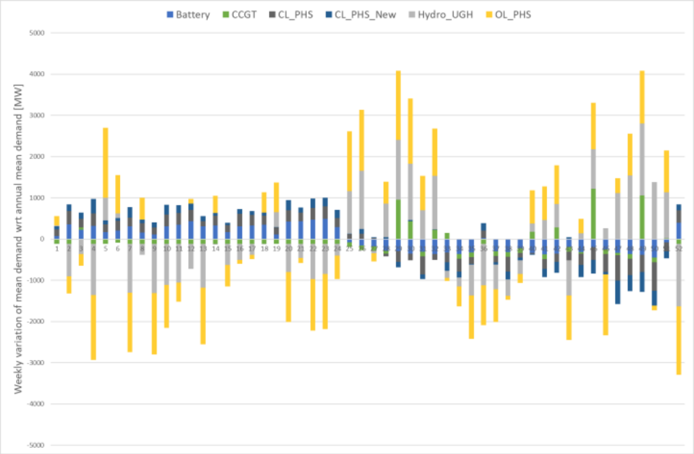


Figure 7. Contribution of each technology to the weekly variation of the net demand with respect to the mean annual net demand.

Figure 8 shows the box plot of the weekly variation over all the year of each technology to adapt its production to the variation of the net demand. Battery, CCGT, storage hydro, and OL-PHS have a slight negative median value while existing and new closed-loop pumped-hydro storage have a positive one. The whiskers of the OL-PHS are approximately ± 1700 MW, i.e., there is a week where the output of this technology is very high, 1700 MW above its annual mean, and another week where the output is meager, 1700 MW below its yearly mean. Storage hydro and OL-PHS absorb most of the weekly variation of the net demand, followed by the contribution of batteries and CL-PHS.

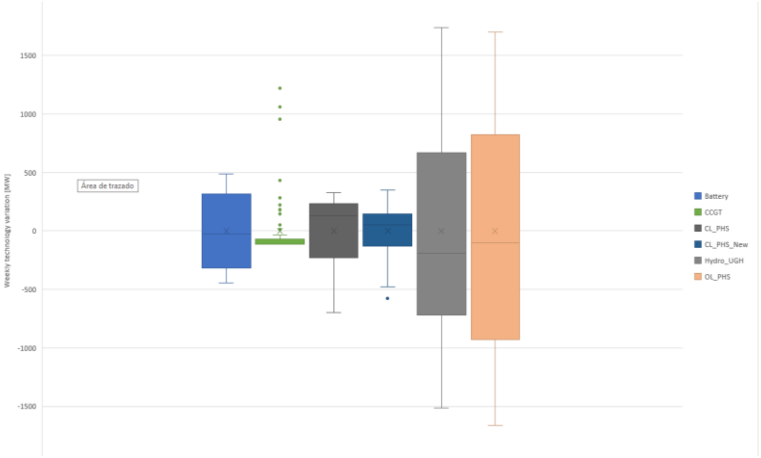


Figure 8. Weekly variation of each technology.

Figure 9 shows the ratio between the mean annual variation of each technology with respect to its installed capacity, i.e., how the weekly variation of the net demand imposes variation of flexible technologies and how much of the technology is used on an annual average (the bars) and minimum (yellow squares) and maximum (grey circles) weekly variations. It can be observed the maximum weekly variations are very high (reaching almost 80%) for battery and CL-PHS.

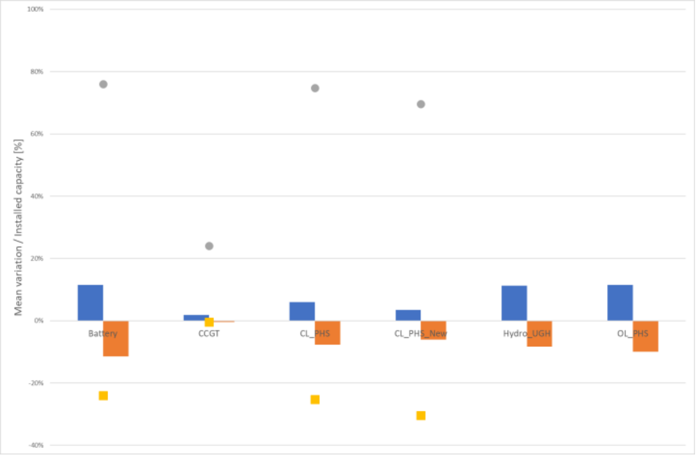


Figure 9. Mean variation of each technology with respect to its installed capacity.

3.3 Sensitivity analysis: lower hydro inflows

Hydro generation plays a crucial role in providing flexibility to the system in two dimensions: power gradient because it can quickly update its production to the hourly variation of the net demand and energy with the ability to store a large amount of energy. We have studied the case where the natural inflows have been reduced by 25%. Although in a very dry year in Spain, natural hydro inflows can be as small as half of the average year, this case study shows how the system behaves with a reduction in hydro generation.

Hydro production from run-of-the-river, storage hydro, and open-loop pumped-hydro storage in this dry year is reduced from 36,349 GWh of the average one to 28,693 GWh. Consumption in storage by hydro units and batteries decreases from 41,378 GWh to 35,377 GWh, 15%. At the same time, curtailment of RES and spillage from storage reduces from 13,724 GWh to 11,399 GWh, 17%. Variable operation cost increases by 209 M€.

Table 4: Energy output for each technology in a dry year.

		Generation	Consumption	Spillage
		GWh	GWh	GWh
Nuclear	Nuclear	22,046		
CCGT	CCGT	23,674		
Run-of-the-river Hydro	Hydro_NonUGH	4,954		
Storage Hydro	Hydro_UGH	11,090		
Open-loop Pumped-hydro Storage	OL_PHS	12,649	-7,832	
Closed-loop Pumped-hydro Storage	CL_PHS	7,036	-10,499	314
Closed-loop Pumped-hydro Storage New	CL_PHS_New	8,682	-12,139	422
Wind Offshore	Wind_Offshore	819		133
Wind Onshore	Wind_Onshore	113,872		4,186
Solar PV	Solar_PV	58,020		4,044
Solar Thermal	Solar_Thermal	4,162		464
Solar Thermal New	Solar_Thermal_New	13,318		1,836
Biomass	Biomass	12,088		
Cogeneration	Cogeneration	18,399		
Battery	Battery	3,775	-4,907	
Total		314,584	-35,377	11,399

Although there is a reduction in hydro inflows, the storage systems, and CCGT to the upward and downward ramps do not change dramatically, which means that these technologies are still responsible for absorbing the variations in net demand, as seen in Figure 10.

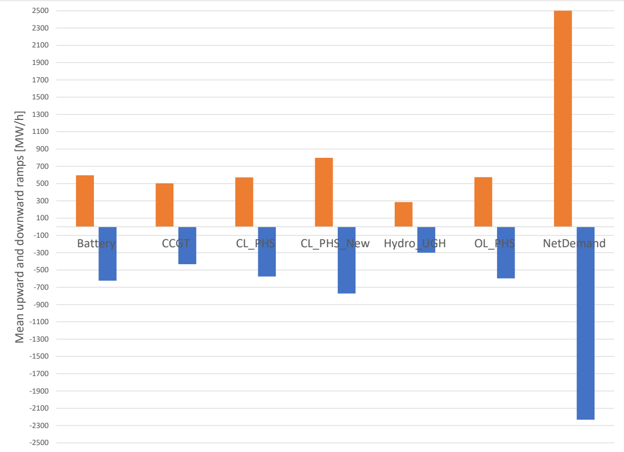


Figure 10. The mean value of downward and upward ramps for several technologies and the net demand.

We can also observe a similar behavior to before in Figure 11, where the contribution of each technology to the weekly variation of the net demand. OL-PHS (yellow bars) and storage hydro (grey bars) are the main contributors, as happened in the average hydro case study.

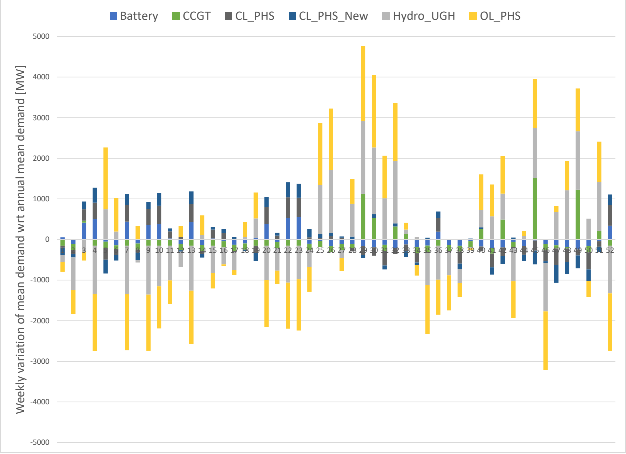


Figure 11. Contribution of each technology to the weekly variation of the demand with respect to the mean annual demand in a 25% drier year.

Both observations for the drier case reinforce the robustness of the flexible technologies in providing these variations for ramps and weekly net demand.

4 Conclusions

In the paper, we have proposed three dimensions relevant to the flexibility assessment: power gradient, power, and energy. A two-phase procedure is projected to analyze an electric system's flexibility to cope with renewables' integration. The first step, ex-ante, determines the margin on any dimension and the second runs a cost-based operation model to determine how these dimensions are covered.

Upward and downward ramps of the net demand increase dramatically in the Spanish system in 2030 due to high wind and solar share. These high ramps introduce new challenges to the operation of flexible technologies (CCGT, storage hydro, OL- and CL-PHS, and batteries). A ramp margin of 20% is enough to consider that the system will cope with the high ramp due to the decrease in solar PV generation at sunset.

Net demand ramps are approximately evenly provided by different flexible technologies, with batteries and new CL-PHS being the main contributors.

Although the annual capacity factors of the hydro storage technologies barely exceed 20%, they enormously increase to +50% in the critical net demand hours, showing their high contribution to the system firmness. On the contrary, batteries can only play a minor role in system firmness due to their limited storage capacity.

Storage hydro and OL-PHS mainly provide weekly variation of the net demand, while other technologies also contribute to a lower extent.

5 Conflict of Interest

The authors declare that the research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

6 Author Contributions

The first author has written the paper and made the model run. The second author has helped to develop the concept presented and review the manuscript. The third author has xxx.

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