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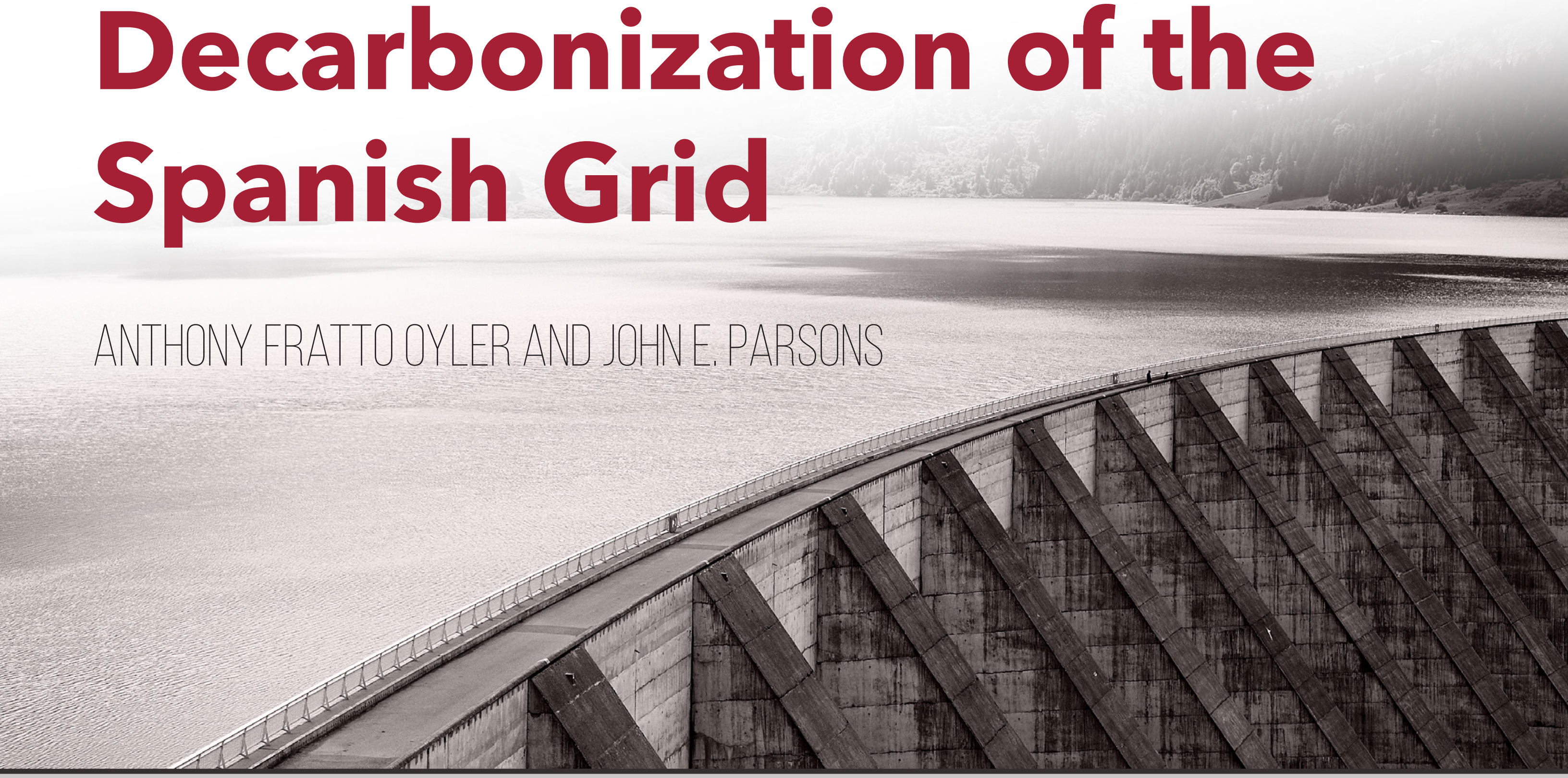
The Value of Pumped Hydro Storage for Deep Decarbonization of the Spanish Grid



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The Value of Pumped Hydro Storage for Deep Decarbonization of the Spanish Grid

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Abstract

This paper addresses the role of pumped hydro storage (PHS) to decarbonization of the electricity sector using Spain's power system as a case study. Spain has an ambitious decarbonization target and a large installed base of pumped hydro. We conduct our analysis looking out to the projected load in 2030 and alternative portfolios of low-carbon generation capacity operated to meet that load. Our analysis will show how the existing capacity of pumped hydro improves the utilization of all low-carbon generation sources, including solar PV, wind, and also nuclear, while decreasing the dispatch of natural gas-fired generation and therefore greenhouse gas emissions. We then evaluate the impact of additional investment in pumped hydro storage and how this impact varies as low-carbon sources become an even larger share of the system. Our results demonstrate that the expanding scale of low-carbon generation warrants additional investments in pumped hydro.

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1 Introduction

This paper addresses the role of pumped hydro storage (PHS) to decarbonization of the electricity sector. Strategies for decarbonization generally look to expanded penetration of renewable generation, especially wind and solar PV. The variability in the renewable resource is a major challenge that must be managed. Electricity storage of some form or another is one important management tool. Pumped hydro is a mature storage technology, and—aside from reservoir hydro–accounts for the vast majority of storage installed on power systems across the world.

To conduct our analysis, we use Spain's power system as a case study. Spain has an ambitious decarbonization target—a 100% renewable electricity grid by 2050 [20]. Spain also has a large installed base of pumped hydro storage—-the highest capacity in Europe, and the fourth highest in the world, following the U.S., China and Japan [8]. Our analysis will show how this existing capacity improves the utilization of all low-carbon generation sources, including solar PV, wind, and also nuclear, while decreasing the dispatch of natural gas-fired generation. Therefore, investments in pumped hydro reduce greenhouse gas (GHG) emissions. We then evaluate the impact of additional investment in pumped hydro and how this impact varies as low-carbon sources become an even larger share of the system. Our results demonstrate that even in the Spanish case, with a high installed base of pumped hydro storage, additional investments become warranted as low-carbon generation expands.

We conduct our analysis looking out to 2030 and projections for installed capacity and for load. As a reference point, we take the Distributed Generation scenario detailed in the Ten-Year Network Development Plans 2018 developed by the European Network of Transmission System Operators for Electricity (ENTSO-E) in collaboration with their sister organization responsible for natural gas transmission systems [21]. This scenario was used as one base case scenario in the report by Spain's Commission of Experts tasked in 2017 with informing Spain's Inter-ministerial Working Group's development of a future Law on Climate Change and the Energy Transition [4]. This is our Base Case scenario. We then analyze three deeper decarbonization scenarios–each one utilizing expanded investments in one low-carbon technology, including nuclear (preserving Spain's existing nuclear plants), wind, and solar PV. In each of these deeper decarbonization portfolios, incremental investment in pumped hydro capacity is a cheaper source of carbon abatement than further investments in either wind or solar PV capacity.

The focus in this paper is on pumped hydro storage's use as a balancing resource to complement the hourly dispatch of other generation, whether as a peaking resource to complement baseload and load-following generation or as a flexible resource to firm up wind or solar generation. Pumped hydro can provide a variety of other services as well, including frequency regulation and operating reserves, but they are not included in our valuation. If they were, they would strengthen the case for further investments.

The next section analyzes the role of pumped hydro in the current Spanish electricity system. Then, section 3 presents our modeling approach for analyzing its role in a future, deeply decarbonized system. In subsections 3.2 and 3.3, we use the model to present results organized around two different questions. First, what is the impact of the existing base

Table 1: Installed Capacity and Generation in 2018

		Installed Capacity (MW) [A]	Share [B]	Generation and Demand (GWh) [C]	Share [D]	Capacity Factors [F]
	Spanish Generation (Peninsula)					
[1]	Hydro	20,376	21%	36,112	14%	20%
	of which PHS = 6,491					
[2]	Nuclear	7,117	7%	53,198	21%	85%
[3]	Coal	9,562	10%	34,882	14%	42%
[4]	Combined cycle	24,562	25%	26,403	10%	12%
[5]	Wind	23,091	23%	48,946	19%	24%
[6]	Solar PV	4,466	5%	7,374	3%	19%
[7]	Solar Thermal	2,304	2%	4,424	2%	22%
[8]	Other Renewable	983	1%	4,279	2%	50%
[9]	Cogeneration and Other Non-Renew	6,183	6%	31,275	12%	58%
[10]	Total	98,643		246,893		
[11]	Pumped hydro consumption			-3,198	-1%	
[12]	Balearic Islands' HVDC link			-1,233	0%	
[13]	Interconnection Balance			11,102	4%	
[14]	Demand			253,563		

Source: Red Eléctrica de España, Statistical series of the Spanish electricity system. Installed power capacity and Balance. https://www.ree.es/en/statistical-data-of-spanish-electrical-system/statistical-series/national-statistical-series. Values shown are for Peninsular Spain only.

Notes:
Hydro includes all forms of hydro, including pure pumped hydro and small river hydro.

of pumped hydro capacity on the operation of low-carbon generation and on emissions? Second, what is the value of further investments, and how does it compare against the value of alternative investments in low-carbon generation?

2 Hydro and Pumped Hydro Storage in Spain Today

2.1 Hydro

Table 1 shows a summary profile of Spain's installed generation capacity in 2018, sorted by technology. It also shows the respective shares of annual generation and the average capacity factor for each technology class.

Hydro capacity–including reservoir hydro, run-of-river hydro and pumped hydro storage–totaled more than 20 GW, or a little over 20 percent of total capacity [10]. This is a mix of very large and very small units. The table shows that in 2018 combined hydro generation totaled 36 TWh, or 14 percent of demand.

Spain's reservoirs have a combined maximum reserve of 18,556 GWh distributed across the six major river basins [12].[1,2] They provide some inter-annual storage to cushion variation in annual rainfall. From 2014 through 2018, the reserve in place has ranged between 4,000 and 14,000 GWh. Nevertheless, annual hydro generation fluctuates with annual inflows. The year 2017 was a historically dry year for Spain, with a hydroelectric index of 0.5, and hydro generation accounted for only 7 percent of total generation.[3] In contrast, 2018 was a historically wet year, with a hydroelectric index of 1.3 which enabled hydro to account for 14 percent of total generation [10, 12]. In general, hydro provides 5-15 percent (20-40 TWh) of total demand.

Hydro generation fluctuates seasonally, too, with the seasonal pattern of rainfall and snow melt. Figure 1 shows the aggregate generation of all hydro resources by month for the last five years [11, 10]. Regardless of the year's hydroelectric index, which is reported in the figure's legend, hydro generation is greatest in the winter and spring.

2.2 Pumped Hydro Storage

Table 2 shows the eight pure pumped hydro (bombeo puro) and six pump-back (bombeo mixto) units as defined for bidding into the Spanish electricity market.

Pure pumped hydro units are those for which the upper reservoir has no natural inflows. They depend entirely on water that has been pumped to the upper reservoir from the lower reservoir, which sits on a stream or other body of water [7, 9]. The total generation capacity at these pure pumped hydro units is 3,418 MW. Pump-back units use an upper reservoir that is otherwise fed from natural inflows. It is in the nature of a pump-back unit that the generation capacity cannot be uniquely attributed to pumped hydro as opposed to reservoir hydro. However, we can use pumping capacity as a benchmark for scale, and note that the pump-back capacity is 70 percent of the pure pumping capacity.

Pumped hydro can provide a number of different services, including ancillary services such as frequency regulation, reserves, fast-ramping capability, capacity, and intraday or seasonal balancing of generation with load. These function at different levels of time granularity,

[1] Per Red Eléctrica de España (REE, the system operator), "The hydroelectric reserve of a reservoir is the quantity of electricity that could be produced in the reservoirs own power station and in all the power stations situated downstream, with the total drainage of its current usable water reserves at that time and providing that drainage occurs without natural contributions." This capacity is split roughly in half between annual regime reservoirs–those in which the fill and drainage cycle occurs over a one-year period–and hyper-annual regime reservoirs–those which allow the variations in rainfall to be offset in cycles of more than one year. The capacity reported here does not include reservoirs of the pure pumped hydro units.

[2] There are many more individual river basins, but six aggregates are defined for administrative purposes. Royal Decrees 1/2001, 125/2007, and 29/2011 established the River Basin Districting and Territory for Spain.

[3] The Spanish system operator, Red Eléctrica de España (REE), reports a yearly hydroelectric index defined as the quotient between the producible energy that year and the historical average producible energy, so that an index of 1.0 constitutes an average year. Producible energy is defined by REE as maximum quantity of electricity that theoretically could be produced considering the water supplies registered during a specific period of time, and once the supplies used for irrigation or uses other than the generation of electricity have been subtracted.

Table 2: Pumped Hydro Storage Capacity in 2018

Pure Pumping Units

Name	UP Code	Generation Capacity (MW)	Pumping Capacity (MW)
Aguayo	AGUG/AGUB	360	360
Bolarque	UFBG/UFBB	215	208
Guillena	GUIG/GUIB	207	225
Ip	CHIPG/CHIPB	89	99
La Muela	MUEL/MUEB	1,512	1,390
Moralets	MLTG/MLTB	219	219
Sallente	SLTG/SLTB	439	400
Tajo Enc.	TJEG/TJEB	377	420
Subtotal		3,418	3,321

Pump-back Units

Name	UP Code	Pumping Capacity (MW)
Duero	DUEB	1,308
Endesa	ENDPRB	100
Guadalquivir	GDLQB	14
Sil	SILB	412
Tajo	TAJB	380
Tanes	TANB	110
Subtotal		2,324
Total		5,645

Source: Red Eléctrica de España, e-Sios database, Programming Units

Note: There are many more than 6 pump-back units which are grouped into 6 entities defined for bidding and dispatch.

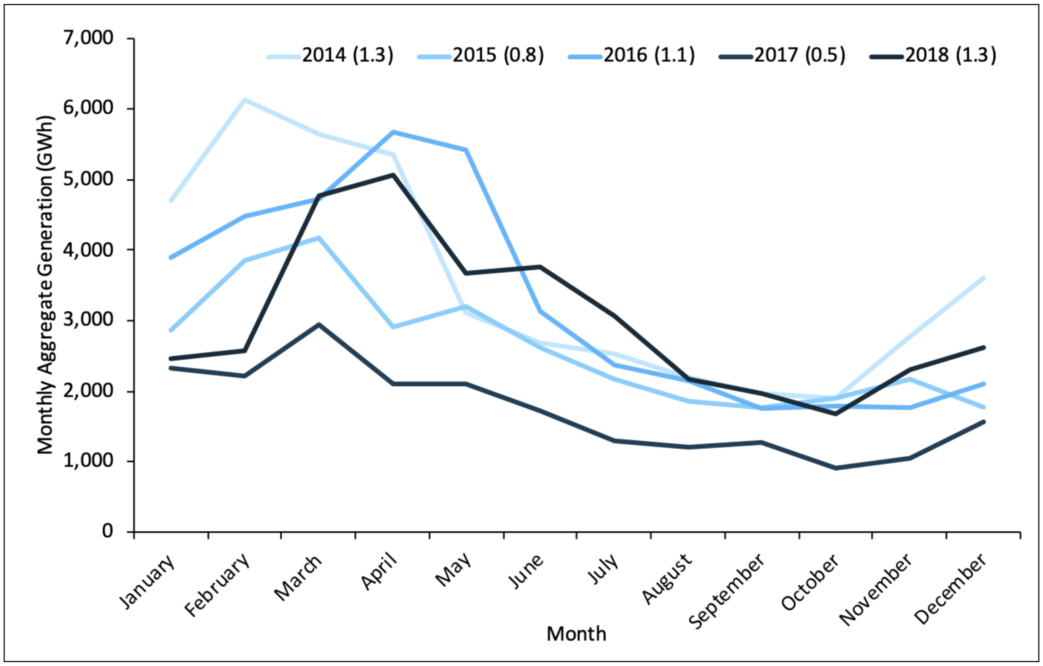

Figure 1: Monthly Generation of Aggregate Hydro Resources in Spain 2014-2018

with ancillary services being the shortest and capacity the longest. The value added by each service depends on the full portfolio of generation on the system and on the time structure of load and renewable resource factors.

Figure 2 highlights the combination of services pumped hydro currently provides by highlighting its dispatch through different components of the market. [4]

The dashed lines in the figure show the average hourly schedule from the PBF market, which is the day-ahead schedule before any adjustments for system constraints and operating reserves. It shows pumped hydro's planned role in balancing hourly generation and load. The solid lines show the hourly dispatch schedule for the P48 market, which is the final schedule after adjustment for system constraints and operating reserves, and after adjustments in the intraday markets. This nets pumped hydro's other roles, for example as a source of operating reserves. On average, the final schedule shows less generation in all hours than the original day-ahead schedule–30 percent less overall. In contrast, the final schedule shows more consumption in all hours than the original day-ahead schedule–on average, more than double the consumption.

In the modeling we do in Section 3 we will be examining the role of pumped hydro within an optimization of hourly dispatch, but our analysis abstracts from the intraday uncertainties and dynamics driving the demand for operating reserves and other shorter

[4] Our analysis of pumped hydro operation focuses only on pure pumped hydro due to the aforementioned fact that production data for pump-back storage is included in general hydro reservoir production. Both REE and the individual plants do not identify what production in a hydro reservoir plant is from natural water inputs or the operation of the pumping unit.

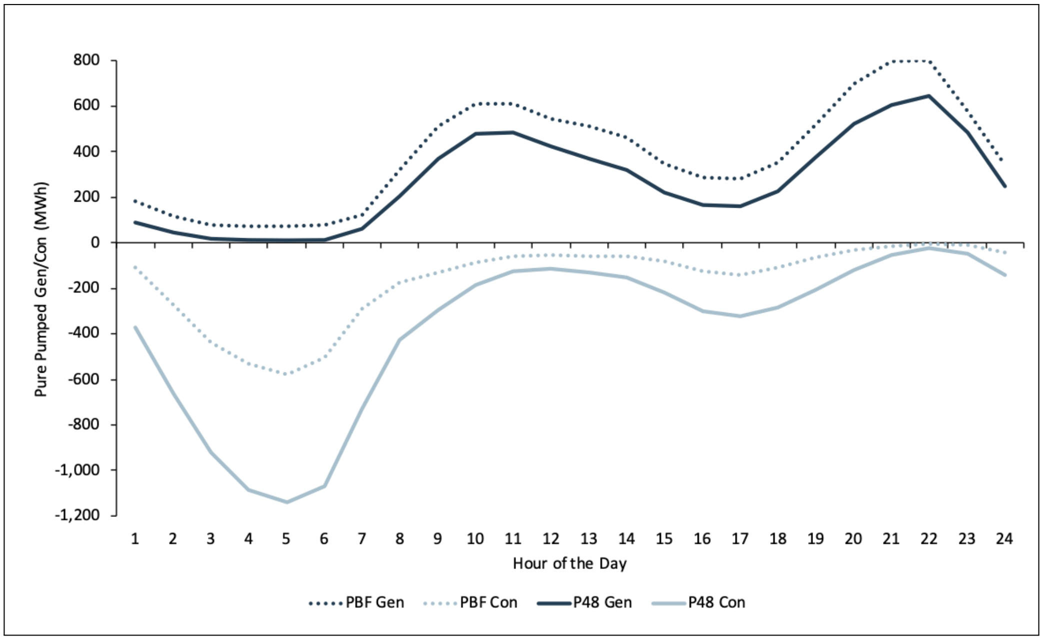

Figure 2: Contrasting the Hourly Average Generation and Consumption Scheduled in the Day-Ahead Market (PBF) Against the Final Schedule (P48), 2014-2017.

Source: REE, eSios, PBF and P48 Markets.

timescale contributions.

2.3 Daily Pattern of Energy

Figure 3 shows the average daily pattern of operation of the pure-pumped hydro units across 2014-2017.

For comparison purposes, the average hourly system demand is also shown using a second scale. As the figure shows, pure-pumped hydro follows a clear daily pattern on average: pumping occurs overnight–mostly in hours 1-7–and generation during the day has two peaks–one in the late morning, and the other in the late evening. Some pumping happens in the mid-afternoon and early evening–between hours 15-19–in preparation for the second evening peak load. The generation peaks roughly match the timing of system demand peaks, although the proportional change in pure-pumped generation is greater than the proportional change in system demand.

2.4 Seasonality

Figure 4 shows the seasonality in pumped hydro generation.

This graphs the average monthly P48 generation and consumption for 2014-2017. The secondary axis is the monthly average "producible hydroelectric energy", i.e. the maximum quantity of electricity that could theoretically be produced considering the water inflows. It

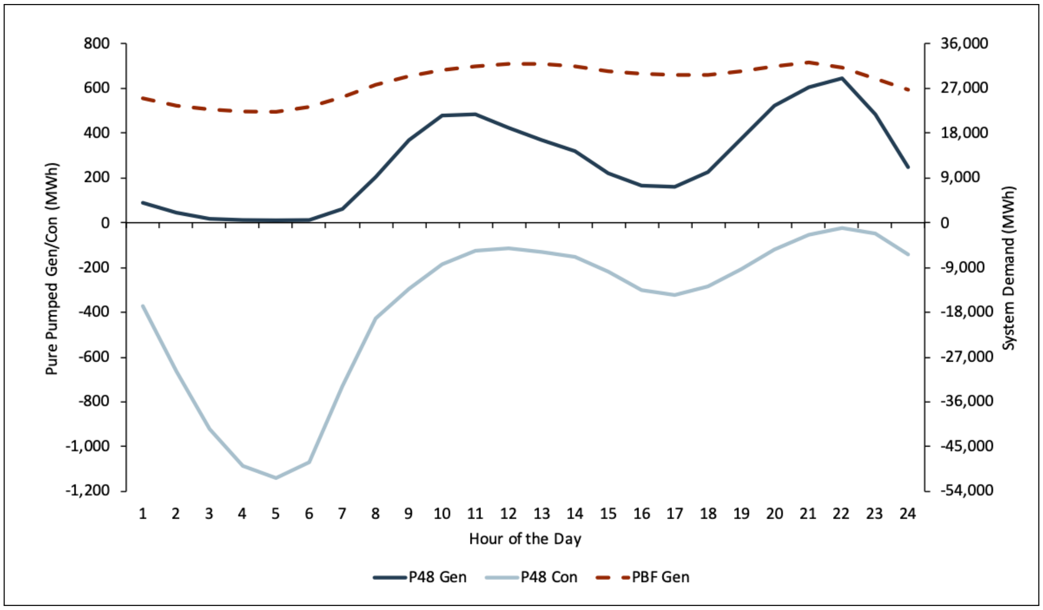

Figure 3: Hourly Average Generation and Consumption of the Pure-Pumped Hydro Units, 2014-2017.

Source: REE, eSios, P48 Market.

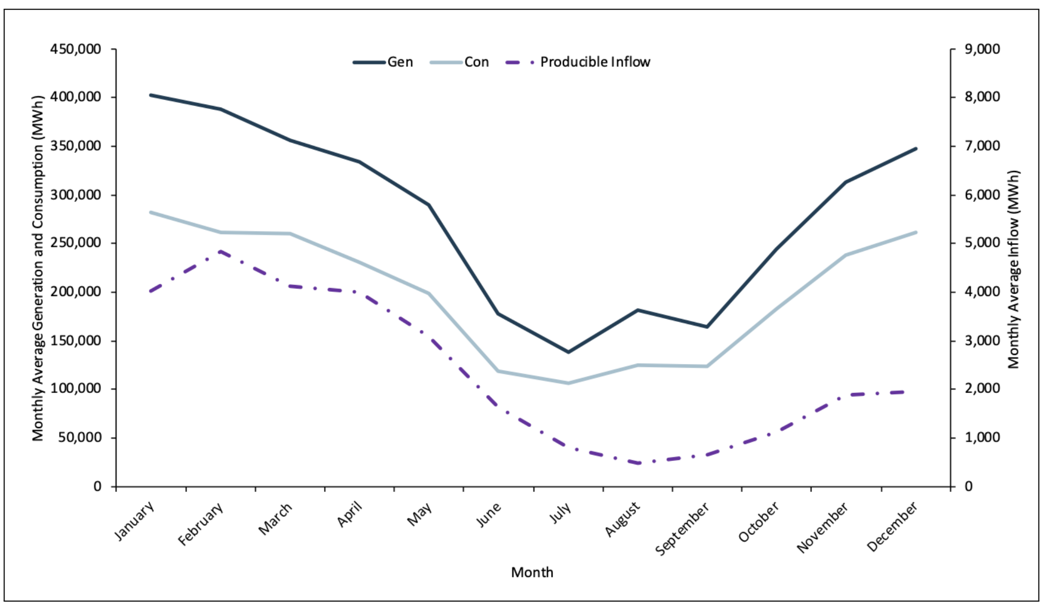

Figure 4: Average Monthly PHS Generation & Consumption versus Producible Hydroelectric Energy, 2014-2017

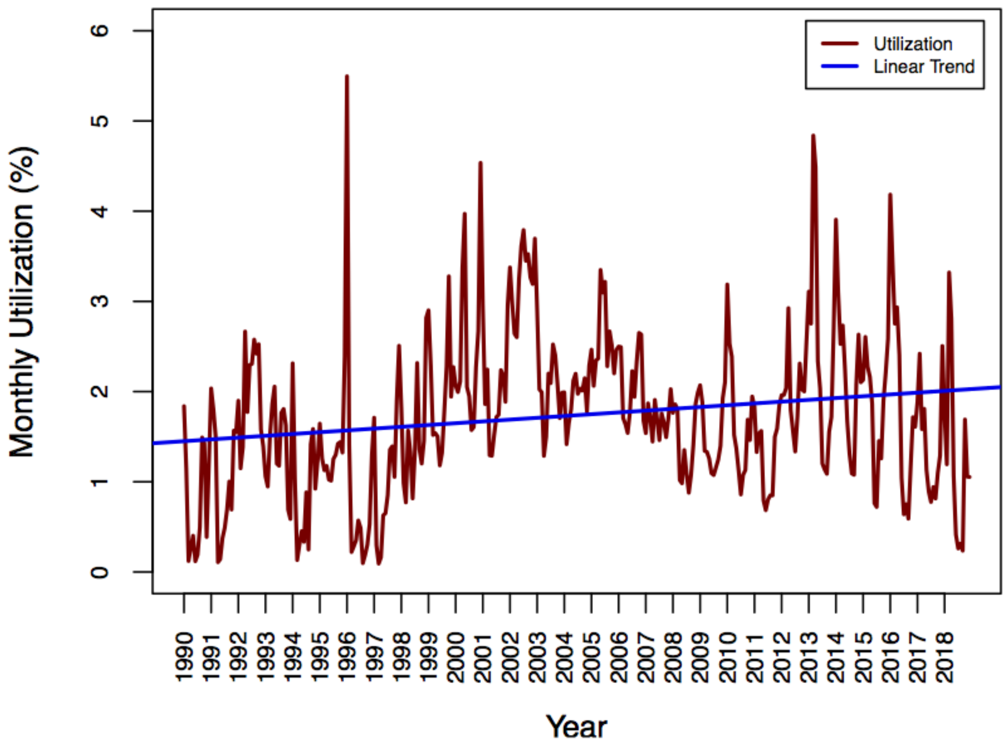

Figure 5: Monthly Utilization Rate for PHS, 1990-2018

demonstrates how pumped hydro utilization is tied to hydro flows. Maximum generation and consumption occur during the wet periods of winter and spring months, and minimums during the dry summer and early fall. The ratio of monthly generation to consumption is approximately constant at 72 percent, reflecting the average efficiency of pumped hydro generation. This tells us that their operation follows a seasonal trend but not seasonal arbitrage. If there were a pattern of seasonal arbitrage we'd expect high consumption seasons to translate into increased generation during low consumption seasons.

2.5 Utilization

Figure 5 shows the monthly utilization rate for pumped hydro storage from 1990-2018.

The utilization rate is the ratio of pumped hydro consumption to the final consumption of the entire system. The rate is very volatile, ranging from 0.09 percent to 5.50 percent, with an average of 1.72 percent. The linear trend displayed in the figure shows a small, sustained increase, as noted by Kougias [17].

3 Future Investments

Although pumped hydro storage originated more than a century ago, its large scale expansion occurred between 1960-1990 as a complement to investments in large-scale nuclear and coal-fired power stations [7, 15]. Most of Spain's pure pumped hydro storage units were installed in the 1980s at the same time as Spain's remaining seven nuclear reactors. The recent expansion of renewable generation in Spain, as elsewhere, presents a new role for pumped hydro storage. Accordingly, in 2015, Spain inaugurated its newest and largest pure pumped hydro station, La Muela.

In the public discussion surrounding renewable generation and the need for storage, the focus has largely been on the development of new battery technologies. Opportunities to expand pumped hydro storage are often overlooked. It was, and still is, a common misconception that suitable locations to construct new pumped hydro facilities were limited as few assessments of pumped hydro potential were conducted [6, 3, 14, 19, 24, 1]. For example the most comprehensive assessment of pumped hydro conducted in the United States was by the Army Corps of Engineers in 1982 and "no comprehensive assessment of [pumped hydro storage] potential has been conducted in the United States since" [22, 23]. Moreover, environmental impacts have historically been a justified concern. Conventional pumped hydro construction would sometimes require damming a river to create a reservoir. This in turn disrupts the natural aquatic ecosystem, can trap and kill fish, and destroy the terrestrial habitat and landscape of the area now flooded. Extensive lobbying from environmental groups caused many pumped hydro projects to be cancelled [24, 23]. However, alternatives can be explored which avoid these problems. Adaptation of existing infrastructure can expand capacity without introducing new environmental problems. Two of the investments analyzed with our modeling include retrofitting existing hydropower plants with pumping mechanisms (i.e. pump-back storage) and upgrading older pure pumped hydro systems to have higher efficiency turbines (older generations have around 70 percent, newer ones up to 85 percent) [17, 1, 7]. Another alternative is optimizing non-traditional locations, such as off-stream systems which would not require damming a river and thus pose fewer problems for aquatic ecosystems [24]. Pumped hydro can use already made reservoirs, such as underground reservoirs, groundwater systems and abandoned quarries and mines which would avoid impacts to existing water bodies and ecosystems [24].

As exemplified in Spain's construction of La Muela, the increasing need for storage is spurring a fresh look at pumped hydro as an option. Recent studies have shown that pumped hydro site potential locations are much more common than originally thought [24, 6, 5]. In 2009 global capacity was around 130 GW [24]. This has increased by over 40 percent in the last decade [8].

In this section, we turn our attention to the value of pumped hydro storage to the Spanish grid as it evolves toward deeper decarbonization. We analyze how the availability of pumped hydro capacity alters the dispatch of various other technologies and lowers total GHG emissions. To do this, we employ a dispatch optimization model. The inputs to the model are (i) the portfolio of capacities of different technologies, together with their operating constraints such as start-up times, minimum operating levels, maximum ramp rates, minimum downtimes, minimum river flows, reservoir capacities, and such (ii) fuel and other variable operating costs, (iii) the profile of renewable resource factors through the 8,760 hours of the representative year, including the wind, solar and hydro resources, and (iv) the load through the 8,760 hours of the representative year. The model calculates the minimum cost dispatch to serve load. To implement this dispatch modeling, we utilize the GenX unit commitment and dispatch model developed by Jenkins and Sepulveda [16]. Our implementation for this paper ignores transmission constraints. We use the model exclusively to serve hourly load, without provision for operating reserves or other ancillary services. More detail on the implementation is in Chapter 7 of [18].

We perform two experiments with the model. First, we analyze how the existing pumped hydro capacity affects the dispatch of low-carbon generation and other generation. Second, we analyze the impact of incremental investments in pumped hydro on GHG emissions, and we translate this into a marginal cost of abatement. We compare the marginal abatement cost for incremental investment in pumped hydro against the marginal abatement cost of incremental investments in wind and solar PV capacity.

The impact of pumped hydro on dispatch and the impact of incremental investments in capacity depends upon the portfolio in which it operates. Therefore, we begin by describing our set of four benchmark portfolios.

3.1 Benchmark Portfolios

The top half of Table 3 shows the four different benchmark portfolios of generation capacity around which we will construct our analysis of the value of pumped hydro storage.

The bottom half shows the four resulting minimum cost dispatch portfolios calculated to meet the 2030 hourly load profile for the Distributed Generation (DG) scenario in the Ten-Year Network Development Plans 2018 [21]. The last line shows the resulting GHG emissions.

The Base Case portfolio, shown in column [A], is based on the 2030 Distributed Generation (DG) scenario [21]. Compared to Spain's current portfolio of generation capacity, the Base Case includes a dramatic increase of 42 GW solar PV capacity, 8 GW of wind capacity, 2.7 GW of hydro capacity, and 2.4 GW of battery capacity. It also includes an almost complete shutdown of Spain's coal plants, a small decrease in natural gas CCGT plants, and a small increase in cogeneration capacity. Notably, the Base Case assumes all of Spain's nuclear plants are shutdown. This Base Case portfolio yields GHG emissions of 29.948 million tons CO_{2e}.

The next three portfolios assume additional low-carbon generating capacity, whether nuclear, as in the first alternative portfolio, wind, as in the second, or solar PV, as in the third. As a result, they each have less markedly lower emissions than the Base Case portfolio, and so we call them the deep decarbonization portfolios. We construct them so that this lower emissions level is the same across the three portfolios, 11.533 million tons or less than 40% of the Base Case emissions. The nuclear portfolio in column [B] assumes Spain extends

Table 3: Four Portfolios of Capacities and the Resulting Minimum Cost Dispatch to Meet 2030 Load

		Base Case [A]	Deep Decarbonization Portfolios: Expanded Nuclear [B]	Expanded Wind [C]	Expanded Solar PV [D]
	Capacity (MW)				
[1]	Nuclear	0	7,117	0	0
[2]	Wind	31,000	31,000	63,696	31,000
[3]	Solar PV	47,157	47,157	47,157	882,900
[4]	Combined cycle	24,560	24,560	24,560	24,560
[5]	Hydro (excl-PHS)	18,059	18,059	18,059	18,059
[6]	Solar thermal	2,419	2,419	2,419	2,419
[7]	Other renewables	2,550	2,550	2,550	2,550
[8]	Coal	847	847	847	847
[9]	Cogeneration and other	8,500	8,500	8,500	8,500
[10]	PHS	6,491	6,491	6,491	6,491
[11]	Batteries	2,358	2,358	2,358	2,358
[12]	Total	143,940	151,058	176,636	979,683
	Generation, annual (GWh)				
[13]	Nuclear	0	56,271	0	0
[14]	Wind	63,462	61,363	122,906	35,082
[15]	Solar PV	88,122	86,558	80,961	173,610
[16]	Combined cycle	81,540	31,459	31,412	31,348
[17]	Coal	0	0	0	13
[18]	Hydro (excl-PHS)	39,190	39,190	39,190	39,190
[19]	Solar thermal	4,022	4,022	4,022	4,022
[20]	Other renewables	11,871	11,871	11,871	11,871
[21]	Cogeneration and other	38,901	38,901	38,901	38,901
[22]	PHS	5,132	10,540	9,843	20,463
[23]	Batteries	2,944	3,833	3,521	4,475
[24]	Total generation	335,184	344,009	342,627	358,975
[25]	Storage consumption	-10,965	-19,790	-18,408	-34,756
[26]	Non-served energy	0	0	0	0
[27]	Demand	324,219	324,219	324,219	324,219
[28]	GHG ($MtCO_{2e}$)	29.948	11.537	11.537	11.537

the life of its 7 nuclear plants which total 7,117 MW of capacity.[5] This assumption is what sets the emissions level. We then choose the added wind capacity for the portfolio in column [C] so that the portfolio results in the same emissions level. This requires a more than doubling of total wind capacity over the Base Case, or 63,696 MW. Similarly, we choose the added solar PV capacity for the portfolio in column [D] to achieve the same emissions level, which requires total solar PV capacity to be dramatically increased to 882,110 MW. Each of these three portfolios keeps constant the other elements of the Base Case portfolio.

Comparing the generation dispatch across the four portfolios brings out a key feature which is important to appreciating the subsequent modeling results. Lines [13]-[15] show the dispatch of nuclear, wind, and solar PV, and these are the three low-carbon generation technologies which show variation in annual generation across the four portfolios. Line [16] shows the dispatch of combine cycle natural gas-fired generation, which is the fossil fuel technology that shows significant variation across the four portfolios. Line [17] shows the dispatch of coal-fired generation. Total coal-fired capacity is very small in the first place, and given the marginal cost, the dispatch is generally zero, except in a few cases when it is very small. One of these cases appears in column [D]. While our modeling keeps track of coal dispatch, its contribution to our results is negligible if anything. Line [18] shows the hydro generation, excluding pumped hydro, which is constant across the four portfolios. While the hourly profile of hydro generation may vary across the scenarios, the aggregate through the year is constant across the scenarios by construction. We have assumed a given annual inflow of hydro resources, and the model utilizes this inflow, assuring that the final reservoir level matches the initial reservoir level. While the model may move the hydro generation across hours to improve dispatch, it will always be optimal to fully utilize the available hydro. Lines [18]-[21] show the dispatch of solar thermal, other renewables (primarily biofuel), and cogeneration. We fix the dispatch of these units and do not allow it to vary across any of our cases. Lines [22] and [23] show generation from batteries and pumped hydro storage, and line [25] shows the total consumption by these two sources of storage. Changes in generation from batteries and pumped-hydro only impact emissions indirectly through changes to other generation, in particular, from the combined cycle natural gas-fired units. Line [26] shows non-served energy, which will generally be zero and always very small. To summarize, almost all of the annual variation in generation across scenarios and modeling cases is attributable either to three low-carbon generation technologies–nuclear, wind, and solar PV–or to one fossil fuel generation technology–combined cycle natural gas-fired units. Therefore, in our presentation of modeling results we focus on these. We also report the storage generation and consumption because this is indirectly driving some of the variation in aggregate generation by the low-carbon generators and by the combined cycle units.

We turn now to evaluating how pumped hydro storage impacts dispatch.

[5] All seven of Spain's plants reach the end of their original 40-year design life before 2030, and decisions must be made before then whether to make the investments needed to extend the life of each plant. At the beginning of 2019, the Spanish government in coordination with the executives of the three companies that operate nuclear facilities in Spain (Iberdrola, Endesa, and EDP) agreed the plants would close as early as 2025 but no later than 2035 [2]. However, that decision could be reviewed.

Table 4: The Impact of Pumped Hydro Storage on Dispatch

	Base Case [A]	Deep Decarbonization Portfolios: Expanded Nuclear [B]	Expanded Wind [C]	Expanded Solar PV [D]
Change in Generation, annual (GWh)				
[1] Nuclear	0	2,354	0	0
[2] Wind	4,136	6,681	9,200	437
[3] Solar PV	3,204	6,151	4,901	30,428
[4] Combined cycle	-5,164	-10,678	-9,884	-21,998
[5] Coal	0	0	0	-71
[6] PHS	5,132	10,540	9,843	20,463
[7] Batteries	-98	-39	-4	108
[8] Storage consumption	-7,209	-15,009	-14,056	-29,366
[9] Non-served energy	0	0	0	0
[10] Demand	0	0	0	0
[11] Change in GHG ($MtCO_{2e}$)	-1.902	-3.944	-3.635	-8.162

3.2 The Impact of Pumped Hydro on Dispatch

One way to assess the impact of pumped hydro storage on dispatch is to contrast the dispatch with pumped hydro storage against the dispatch that would obtain if there were no pumped hydro. Table 4 shows the result of this experiment.

The results clearly show that pumped hydro storage facilitates the dispatch of more low-carbon generation and reduces the dispatch of combined cycle natural gas-fired generation. Column [A] shows the result for the Base Case. Generation of both wind and solar are significantly increased because of the availability of the pumped hydro storage. In contrast, generation from combined cycle plants is significantly reduced. Consequently, GHG emissions are significantly reduced. Columns [B]-[D] show the results for the three deep decarbonization portfolios. Column [B] demonstrates that pumped hydro storage increases nuclear dispatch along with increasing the dispatch of wind and solar PV. Pumped hydro storage reduces combined cycle generation even more in the three deep decarbonization portfolios as compared to the Base Case portfolio. Therefore, it decreases emissions even more in the three deep decarbonization portfolios. The impact is especially large in the solar PV portfolio in column [D].

Looking across the 4 portfolios, it is clear that pumped hydro is least vital for the Base Case, which has the lowest total capacity of low-carbon technologies. Without pumped hydro, the redispatch only modestly increases curtailments and carbon emissions. For all of the alternative portfolios with expanded low-carbon generation, the loss of pumped hydro increases curtailments and GHG emissions substantially more than for the Base Case. The impact is outsized for the portfolio of expanded solar PV where the increase in GHG emissions is even greater still.

3.3 Value of Incremental Investment in PHS Capacity

An alternative way to appreciate the role of pumped hydro is to evaluate the impact on GHG emissions of an incremental investment in pumped hydro relative to the impact of an incremental investment in low-carbon generation such as wind and solar PV capacity. Several different types of investments in pumped hydro could be made. The European Commission's Joint Research Centre's Report *Assessment of the European potential for pumped hydropower energy storage* presents three distinct options classified based on the interaction of the investment with other, pre-existing assets: (i) investments in pumping capacity which connects two existing reservoirs, (ii) investments in one new reservoir and pumping capacity to connect with one existing reservoir, and, (iii) investments to repower existing pumped hydro storage capacity to improve the efficiency from 70 percent to 85 percent [13]. The Report identifies significant opportunities in Spain for each of these types of investments, even accounting for environmental, transport, and infrastructure constraints

We evaluate these incremental investments first for the Base Case portfolio and then for each of the three deep decarbonization portfolios. In order to make the calculations comparable, for each portfolio and for each type of incremental investment, we find the quantity of capacity required to achieve a 0.1 megaton incremental reduction in emissions. We then incorporate the unit cost of each type of capacity in order to calculate a marginal gross abatement cost per ton CO_{2e}. The abatement cost calculation is gross of the fuel and other variable operating and maintenance cost savings from running the combined cycle gas-fired generation less. Since we are concerned with choices across investments in low-carbon technologies, we only need to compare the gross figures. One could make an assumption about natural gas fuel costs and other operating and maintenance costs to derive a net cost, but this is not relevant to our analysis.

Table 5 shows the calculations for the Base Case portfolio.

The first three columns show the impact of incremental investments in pumped hydro capacity–column [A] is for the investment in new capacity created by connecting two existing reservoirs, column [B] is for investment in new capacity created by connecting one existing reservoir with one new one, while column [C] is for investment in repowering existing pumped hydro facilities The last two columns show the impact of incremental investments in wind and solar PV capacity. Row [1] states the fact that we are examining investments sized to reduce emissions by 0.1 megaton of GHGs. Row [2] shows the incremental capacity required. For both types of new pumped hydro storage capacity, 440 MW of capacity will produce a 0.1 megaton reduction in GHGs, whereas a repowering of existing capacity for improved efficiency will have to be implemented for 1,281 MW of capacity. For wind capacity, an additional 148 MW will produce a 0.1 megaton reduction in GHG emissions, whereas for solar PV an additional 209 MW is required. Rows [3]-[11] show how this incremental capacity changes the dispatch of different technologies. The incremental pumped hydro storage capacity in column [A], yields an increase of wind generation of 183 GWh and an increase in solar PV generation of 38 GWh, for a total increase in low-carbon generation of 221 GWh.[6] In contrast, the dispatch of combined cycle plants is reduced by 270 GWh.

[6]The allocation of dispatch between wind and solar PV is relatively arbitrary because many hours with

Table 5: The Value of an Incremental Investment in Pumped Hydro Storage Capacity Versus Investment in Other Low-Carbon Technologies for the Base Case Portfolio

			PHS capacity				
			Connect 2 Reservoirs [A]	Add 1 Reservoir [B]	PHS repower [C]	Wind [D]	Solar PV [E]
[1]	Incremental GHG	($MtCO_{2e}$)	-0.1	-0.1	-0.1	-0.1	-0.1
[2]	Incremental Capacity	(MW)	440	440	1,281	148	209
	Incremental Generation	(GWh)					
[3]	Nuclear		0	0	0	0	0
[4]	Wind		183	183	32	296	-45
[5]	Solar		38	38	-102	-11	366
[6]	Subtotal Low-C		221	221	-70	285	322
[7]	Combined cycle		-270	-270	-269	-272	-273
[8]	Storage Gen		269	269	276	33	124
[9]	Total		221	221	-63	46	173
[10]	Storage Cons		-221	-221	63	-46	-173
[11]	Net		0	0	0	0	0
	Costs						
[12]	Capex, unit cost	(€/kW)	650	1,500	275	867	640
[13]	Annuity factor		0.0666	0.0666	0.0666	0.0802	0.0802
[14]	Capex, annual unit cost	(€/kW/y)	43.27	99.85	18.307	69.504	51.326
[15]	Fixed O&M, annual unit cost	(€/kW/y)	9.75	22.50	4.125	19.067	10.880
[16]	Total annual unit cost	(€/kW/y)	53.02	122.35	22.432	88.571	62.206
[17]	Total annual cost, gross	(million €/y)	23.329	53.836	28.735	13.109	13,001
[18]	GHG Abatment, gross	(€/tCO_{2e})	233	538	287	131	130

Notes:

[1] Target, by assumption.
[2] Model calculation to achieve target.
[3]-[11] Model calculation assuming [2].
[12] By assumption from DG scenario, Ten-Year Network Development Plan 2018.
[13] Assumes 7% discount rate, 60-year life for PHS investments, 25-year life for wind and solar PV investments.
[14] =[12]*[14].
[15] By assumption from DG scenario, Ten-Year Network Development Plan 2018.
[16] =[14]+[15].
[17] =[2]*[16]/1,000.
[18] =[17]/[1].

This is what produces the reduction in GHGs. Note that the reduction in combined cycle generation is approximately the same across the columns, which is necessary if the reduction in GHGs is approximately the same across the columns.

Column [C] shows that 440 MW of new pumped hydro capacity would be required to achieve the same reduction in GHGs. The extra storage enables an increase in both wind and solar PV generation and therefore a reduction in combined cycle generation.

Rows [12]-[16] show how we translate these incremental capacities into incremental costs. Row [12] is our assumed capital cost for each type of capacity which is taken from the European Commission's Joint Research Centre's report on Energy Technology Reference Indicator projections for 2010-2050" [13]. In order to translate this capital cost into an annual charge, row [13] shows the annuity factor based on the life of the capital–60 years for pumped hydro storage and 25 years for wind and solar PV investments. The discount rate used in calculating the annuity factor is 7 percent. Row [14] is the resulting annual capital charge per unit of capacity. Row [15] is the assumed fixed operating and maintenance charge per unit of capacity, which is also taken from [13], and row [16] is the resulting total annual cost per unit. Row [17] uses the incremental capacity required to yield an annual cost. Row [18] translates this to a marginal cost of abatement per unit of GHG emission avoided.[7]

According to the values in row [18], starting from the Base Case portfolio, a marginal investment in pumped hydro is a more costly tool for abatement than a marginal investment in either wind or solar PV capacity. Therefore, if the Base Case portfolio is a good benchmark for where Spain anticipates being in 2030, these results argue against additional pumped hydro investments, if the purpose is to serve a balancing function. Additional investment could be warranted for other services from pumped hydro, although this is outside of our analysis.

The conclusion changes dramatically, however, if we look at the three deep decarbonization portfolios, as shown in Table 6.

As we move from the Base Case portfolio to the alternative portfolios, the marginal cost of abatement using each type of investment changes. The direction and magnitude of the change depends upon the technologies used in each alternative portfolio. In the case of each of the investments in pumped hydro capacity–shown in columns [A]-[C]–the marginal abatement cost is significantly lower in all of the deep decarbonization portfolios than in the Base Case portfolio. This is because, as shown in subsection 3.2 above, pumped hydro storage is complementary to each of the low-carbon generation technologies: a larger installed capacity of these technologies will benefit from more pumped hydro storage. In

both types of generation require some curtailment. Since both types of generation are zero marginal cost, the determination of which type of generator is curtailed in these hours is arbitrary from the perspective of cost minimization. Therefore, it makes more sense to look at the change in dispatch for low-carbon generation as a whole instead of focusing on the distribution across low-carbon technologies.

[7] The DG scenario in the Ten-Year Network Development Plan 2018, from which our Base Case is derived, assumes a price of natural gas of €8.8/GJ, which translates to €57.64/MWh, based on a thermal efficiency of 55% [21]. It also assumes other variable operating and maintenance costs of €8.77/MWh, for a total variable operating and maintenance cost of €66.41/MWh. Given the 270 GWh reduction in generation at combined cycle plants shown in Table 5, this yields a total offset to the gross cost of 180 €/tCO_{2e}, bringing the marginal gross abatement cost of 233 €/tCO_{2e} down to a marginal net abatement cost of 54 €/tCO_{2e}.

Table 6: The Value of an Incremental Investment in Pumped Hydro Storage Capacity Versus Investment in Other Low-Carbon Technologies Across All 4 Portfolios

	PHS capacity				
(€/tCO$_{2e}$)	Connect 2 Reservoirs [A]	Add 1 Reservoir [B]	PHS repower [C]	Wind [D]	Solar PV [E]
[1] Base Case Portfolio	233	538	287	131	130
Deep Decarbonization Portfolios					
[2] Wind	117	269	250	228	214
[3] Nuke	-87	-201	25	-27	52
[4] Solar	16	36	166	52	> 1,800

contrast, the marginal abatement cost for investments in wind or solar PV can increase over the marginal cost in the Base Case portfolio, depending upon which deep decarbonization portfolio is being considered. Column [D] shows that the marginal abatement cost for wind increases when the deep decarbonization portfolio is constructed using capacity in either wind or nuclear, but declines if it is constructed using solar PV capacity. Column [E] shows that the marginal abatement cost for solar PV increases for all of the deep decarbonization portfolios.

Although additional investment in pumped hydro capacity is not the cheapest source of incremental abatement from the Base Case portfolio, some form of incremental pumped hydro storage becomes the cheapest incremental abatement option given any of the deep decarbonization portfolios. The more expensive form of pumped hydro storage capacity becomes the cheapest abatement option depending upon the deep decarbonization portfolio, and repowering remains too expensive. Once again, these results only apply to pumped hydro being used for balancing. It may be a valuable investment for other services.

4 Conclusion

This analysis has demonstrated the contribution pumped hydro storage can play in improving the dispatch of low-carbon generating technologies, thereby contributing to the decarbonization of the electricity system. This role becomes increasingly vital as the penetration of low-carbon technologies deepens and it becomes increasingly necessary to manage the variability of the renewable resources so as to minimize curtailments in order to keep system costs as low as possible. Although the Spanish system has a relatively large installed base of pumped hydro storage, we show that further investments are warranted as investments in additional low-carbon generating capacity are made. Our focus has been on the role pumped hydro storage can play as a tool for balancing generation and load and managing the variability of renewable resources. Of course, the other roles of pumped hydro storage, in particular as a source of frequency regulation and operating reserves would reinforce this case, although this paper did not analyze these other roles.

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