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Alternative Uses of Hydroelectric Power Plants in a Decarbonized Energy Scenario

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Abstract. Drastic reduction of greenhouse gases emissions depends, among other factors, on a quick and efficient integration of renewable sources in the energy generation pool. In this context, hydropower nowadays represents the biggest share of the world renewable energy generation. However, in the case of European Union, many hydropower plants are about to reach their end-of-life stage and environmental regulations on the recovery of natural water flows require these plants to be dismantled. In the controversial scenario where the need to recover natural waterflows and the loss of a key source of green energy clash with each other, the objective of this work is to provide an exhaustive review of the different auxiliary services that hydropower plants can provide in the current and especially future decarbonized electricity paradigm. To this end, services such as participation in secondary and tertiary regulation markets, power purchase agreements, local energy communities, reduction of curtailments, renewable energy storage or contribution to physical inertia to the grid are analyzed and final conclusions are drawn.

Key words. Hydroelectric power plants, hydropower, ancillary services, flexibility, local energy communities, inertia

1. Introduction

Reduction of greenhouse gases emissions to substitute fossil fuels and polluting sources demands enormous efforts in the integration of renewable energy sources, which, in turn, must be accompanied by the installation of energy storage systems, [1], [2]. Besides, preservation of well-established renewable sources, such as hydropower plants, also plays a crucial role.

Integration of renewable energy sources is one of the keys to reduce greenhouse gases emissions to substitute fossil fuels and polluting sources. In this context, hydropower plants are a crucial actor. In 2021, hydropower generated more than half the world renewable generation, 7.9 TWh approximately. Their importance was even greater before solar and wind growth: more than 97 % of renewable energy was generated in hydropower plants in 1980 [3].

However, this energy paradigm shift leads to some issues. Firstly, some renewable sources, like solar or wind, are stational and their power production depend on the time of day, the time of year and weather conditions, among other factors. Thus, their energy production cannot be scheduled, and they are less manageable than conventional sources like gas or coal, which are fully controllable. Secondly, electrical systems have been traditionally formed by synchronous generators rotating at grid frequency and hence providing the so-called physical inertia, i.e., the capacity of the system to recover from power imbalances. On the other hand, excluding hydropower plants and some other renewable sources such as geothermal or biomass, distributed and extensive synchronous generation is currently possible mostly with gas-fired or coal-fired CO_2 producing plants, while photovoltaic or wind power plants are inherently unable to provide physical inertia. Hence, the progressive decarbonization of the grid is also making it more unstable and weaker to power imbalances, so that other countermeasures have to be implemented to compensate for the elimination of syncronous generators.

Hydropower plants have the characteristics to overcome and reduce some of these problems. For example, their storage capacity (if available) can serve to store renewable energy and their generators can provide physical inertia to the grid. Hence, this type of power generation plants are a valuable energy resource since they provide solutions to some of the problems generated by the integration of renewable generation into electric systems.

Hydropower plants do not have only valuable characteristics in a decarbonized energy scenario, they are also frequently located in rural environments, which makes them an important resource in regions with risk of depopulation. In fact, some people, especially in rural environments, are organising to recover and use already built hydropower plants, to increase energy independence and reduce energy poverty in their regions [4].

However, hydropower plants, facilities who “reigned” renewable generation in the last century, are on withdrawal, as their share in the renewable pool is progressively being overcome by new renewable sources (solar and wind), and several hydropower facilities are reaching their end-of-life stage. Moreover, both construction of new hydropower facilities and the possibility to refurbish and extend the life of already exisiting ones conflicts with compelling environmental constraints. In particular, the conservation and restoration of rivers health is a central part of the fight against the increasing loss of biodiversity because the greatest concentration of biodiversity is indeed found in river ecosystems and wetlands. In the European Union, there is a target of restoring 25 000 km of river to its natural flow as part of the 2030 Biodiversity Strategy and the Nature Restoration Law [5].

Society is inmersed in huge transformations involving almost every aspect of our lives, from what we eat and how we move to the way energy is produced. For the future decarbonized electrical systems, there is a clash of interests between storage, flexibility and inertia requirements and opportunities for rural regions on one hand against biodiversity recovery in natural flows on the other hand. This topic may sometimes result controversial, generating tensions, and decisions made today will shape the future. It is therefore time to decide if hydropower plants are part of the future or if their time has already passed.

With the idea of bringing more light upon this controversy, this paper provides a review of the different auxiliary services that hydropower plants can provide in the current and especially future decarbonized electricity paradigm, with the aim of showing alternatives to demolition and options for uses beyond simple energy generation. Spanish case is analyzed with special attention, as it is an example scenario of the effects that a great integration of renewables will have in other electric systems.

In this paper hydropower plants are meant to include storage facilities (water is accumulated by dams and generation is controllable if reserves are sufficient), run-of-river facilities (water is not accumulated and generation cannot be totally controlled when flowing water is not available) and pumped storage facilities (water is stored and they work as a giant and controllable battery) [6]. A special focus on mini-hydro power plants is also presented, aiming to give more precise information about one of the family of hydropower plants more present in rural environments and likely to be affected by environmental regulation and decommissioning.

In the first section, participation in balancing mechanisms is analyzed for Spanish case, with special focus on energy prices and micro-hydro presence in these markets. In the second section, opportunities related with hydropower plants, micro-hydro facilities, local energy consumption and Power Purchase Agreements are commented. In the third section, an analysis of hydropower supporting electric system and ensuring its quality and robustness by providing physical inertia and avoiding curtailment is presented.

2. Participation in secondary and tertiary regulation markets (Spanish case)

In the daily energy market, managers of generation plants offer their energy production and both electricity price and which generator plants are producing in each time slot the next day are fixed. Besides this market, every electric system operator needs to adjust generation units to balance generation and demand at every moment. Methods could differ between countries or systems, but a way to modify generation plants energy inputs and outputs is unavoidable. Without this measures and prevision, unexpected incidents, failures and frequency variation could lead to a lower grid quality or even blackouts [7]. The main balancing mechanisms are called primary, secondary, and tertiary regulation, and this section aims to provide an overview of secondary and tertiary regulation in the Spanish electrical system. This analysis provides special attention to data available related to mini-hydro (<10 MW) power facilities.

In Table I, three key characteristics of regulation types in Spanish electric system are shown. Primary regulation is a non-remunerated compulsory service that all generation plants have to offer while producing power into the grid. This regulation is activated automatically and aims to recover grid frequency from disturbances and generation-demand imbalances, following system operator orders.

Table I. Characteristics of regulation types (Spanish electric system).

Regulation type	Remuneration	Maximum activation time	Minimum performance time
Primary	None	15 s (<100 mHz)* or 30 s (<200 mHz)*	None
Secondary	Market mechanisms, both by energy reserved and used	30 s	15 minutes
Tertiary	Market mechanisms	15 minutes	30 minutes

** Primary regulation maximum activation time depends on the value of the frequency deviation*

The secondary regulation, according to the guide published by Red Eléctrica de España (Spanish System Operator) to be a provider of balancing services [8], aims to maintain the generation-demand balance, automatically correcting deviations from the planned exchange program and deviations from the frequency of the system. Its time horizon of action reaches from 20 seconds to 15 minutes. Its activation is also automatic and only plants wishing to participate have to offer it. Both primary and secondary regulation are the first “barrier” when dealing with frequency events.

Tertiary regulation is, again according to this guide [8] an active power reserve activation balancing service that aims to maintain the frequency and generation-demand balance of the system. This service, of manual activation in a time equal to or less than 15 minutes, is managed by the system operator through market mechanisms and allows the restitution of the use of automatic reserve of secondary regulation. It is only activated if secondary regulation reserve reaches a critical threshold. In the case of Spain, there is a minimum power that all facilities participating in this balance services should offer of 1 MW.

The yearly averaged remuneration price of secondary and tertiary regulations are shown in Fig. 1 and Fig. 2. In the last two years there has been a change in trend, increasing their prices yearly despite not substantially increasing the energy used in these services. This change in trend coincides with moments of high instability of energy prices and economic situation, making difficult make long-term estimations. It is important to consider (both in the case of secondary and tertiary) the correlation with the price of energy in the daily market.

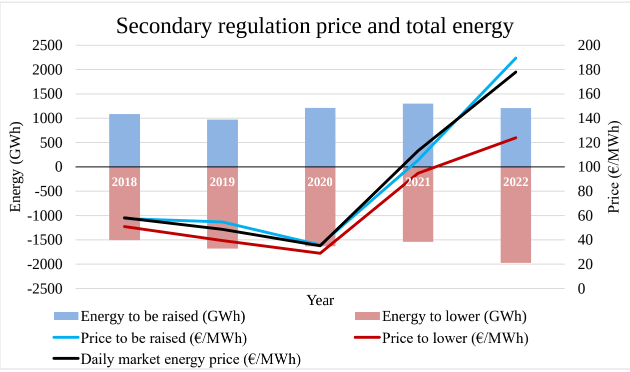

Fig. 1. Secondary regulation energy and price. Own elaboration based on data from [9]

The secondary regulation had an average remuneration in 2021 of 105.43 €/MWh to be raised and 94.78 €/MWh to lower. On the other hand, tertiary regulation was remunerated at 126.34 €/MWh on energy to be raised and 54.29 €/MWh on energy to be lower on average. These figures are compared in both cases in the average price of the energy price in the daily electricity market, which stood at 113.30 €/MWh in 2021, for example. These prices show that a smart management of plants able to participate in secondary and tertiary regulation markets could increase their revenue, since energy to be raised price is higher than daily market energy price.

Hydropower facilities able to store water and energy and pump from a lower to a higher reservoir have great flexibility capacity and are perfect candidates to participate in these balancing mechanisms, since they can both lower energy production and raise energy consumption if needed (starting to pump water, for example). Thanks to control techniques, even mini-hydro power plants, that cannot provide physical inertia the way that big synchronous generators do, can play a role in restoring frequency values after load disturbances when combining flow regulation and dump load control [10].

In 2020, mini-hydroelectric power plants (<10 MW) accounted for 226.3 MW of the power enabled for secondary regulation (10 % of the total power in secondary) and 255 MW of the power enabled in tertiary and deviation management (12 % of the total power in tertiary and deviations), as can be seen in Table II.

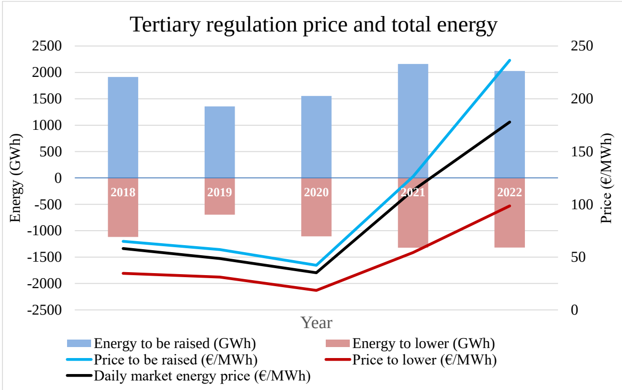

Fig. 2. Tertiary regulation energy and price. Own elaboration based on data from [9]

Mini-hydro had a total cumulative installed capacity in Spain of 1 953 MW [11] at the end of 2015. In total, the installed capacity linked to hydroelectric generation amounted to 20 353 MW [12], so it is estimated that around 9.6 % of all this type of generation came from mini-hydro plants.

Table II. – Mini-hydro (<10 MW) power in system adjustment services as of December 2020 in Spain [13].

Installed power (MW)	Power enabled in secondary regulation (MW)	Power enabled in tertiary regulation (MW)
2 180.6 (9.6 %)	226.3 (10 %)	255 (12 %)

On the other hand, in 2020 mini-hydro plants represented 10 % and 12 % of the power enabled in secondary and tertiary regulation balancing services, as shown in Table II. It can be concluded that the hydroelectric plants considered to belong to the category of mini-hydro have great facility to enter the markets of secondary and tertiary regulation, since their participation in these markets is greater than in the total installed power.

It is important to notice that the biggest cost of a hydroelectric power plant is the initial investment to build it. Once built and commissioned, operation and maintenance (O&M) costs are very low compared with initial investment because continuous water is a cheap source of energy. Also, an efficient and intelligent management of hydropower resources in regulation markets could generate bigger economic returns than daily energy market. Furthermore, data available shows that mini-hydro is easily included in regulation mechanisms, so hydropower plants are a good way to provide balancing mechanisms and adjustment services to the grid, and this service should be considered as an ancillary service that hydropower plants can offer.

3. Local Energy (Self-) Consumption

Distributed generation is a decentralized electricity production mechanism characterized by the proximity between generation equipment and final consumers. This idea of power generation contrasts the traditional and stablished idea of a high-power, centralized generation that generates all the required electricity demand, to be transported by high-tension lines to reach distribution grids and consumers.

1. Local Energy Communities

Decentralizing energy generation and avoiding energy transport is one of the pillars of the future electric scenario. One of the most direct manners to achieve this goal is by Local Energy Communities (LECs).

LECs are composed of several users who make their energy resources available to the members of the community so that through an agreed distribution all users benefit from all available resources in the area.

Energy communities have many advantages compared to the individual performance of users [14]. On the one hand, in terms of environmental advantages and benefits, energy communities encourage investment, integration and implementation of renewable energies. This bet reduces the use of fossil energies, as well as the dependence on external energies. All this implies a reduction of the carbon footprint and an increase of consumer's energy efficiency. On the other hand, socio-economic benefits are a consequence of the self-management of energy by users. This implies greater collaboration and involvement of users, creating a fair and balanced distribution of resources, reducing energy poverty and creating local investment that encourages the creation of employment and the development of the local economy.

Hydropower facilities are, in most cases, already built infrastructure, which reduces initial investment costs of new local energy communities. Furthermore, their flexible characteristics as a manageable resource are an advantage to be part of energy communities. Related with rural environments, rural inhabitants can take advantage of the location and availability of hydropower facilities when stablishing local energy communities, as it has been shown in some studies [15]-[17]. This is the reason hydro-power plants show some characteristics, especially mini-hydro, [18] that gives them the potential to be part of a manifold of distributed energy resources in energy communities, augmenting its number and importance [19]. To sum up, cheaper energy than daily market can be acquired for energy community members, helping local industries and members to save resources, increase their competitiveness and, consequently, reduce depopulation if located in rural areas.

2. Power Purchase Agreement

A physical bilateral contract is a direct electricity purchase agreement between a producer and a consumer. This contract establishes the purchase price of a certain amount of electricity for a period of time agreed between both parties.

The committed energy does not enter the daily market. The price set is independent of the price set by the electricity market, reducing its volatility. The exchange of energy takes place and can last for hours, days or years. In addition, the volume of energy transmitted and a minimum guaranteed power is established.

Table III. Energy average price and energy negotiated by PPAs in Spain [20]

Year	Average price (€/MWh)	Bilateral average price (€/MWh)	Bilateral energy (GWh)
2018	57.29	--	65 668
2019	47.68	--	69 021
2020	33.96	35.63	66 374
2021	111.93	40.50	70 072

Bilateral exchange contracts include long-term renewable bilateral contracts named Power Purchase Agreements (PPAs). The energy established through these contracts always comes from renewable energy sources. In addition, unlike bilateral contracts that can be made in the short term, PPAs are contracts with a duration of several years. There are two types: physical (those with a physical and direct connection between generation and consumption) and virtual or financial (price contracts dependent on daily energy price between generators and consumers connected to the grid). In Table III, energy average price and total energy negotiated by PPAs in the last years are shown for Spanish case.

Hydro-power plants are manageable, and they can provide cheap energy to industries nearby, making them an attractive energy provider to form PPAs with local industries. In a context of popularization of distributed generation, they can play a role in rural environments, providing cheap energy and making use of already built plants to generate energy in a different market. This can help to reduce depopulation and provide cheap energy to industries nearby, helping them to be more competitive.

4. Electric system support

In this section a review of the importance of hydropower plants for grid support (curtailment reduction and physical inertia) is presented.

1. Curtailment reduction

Energy curtailments are power cuts to the grid made by renewable energy generation plants following System Operator orders. They occur at times of high electricity generation, when production is greater than demand or an important part of production occurs at the same point saturating the network. In these cases, it is necessary to restrict or reduce the energy generated and therefore the contribution of energy to the grid of some generation centers is reduced.

With the introduction of renewable energies curtailments tend to occur more frequently. This is the case of solar energy, for example, whose highest production happens during the central hours of the day and can be greater than the demand, or congestions might occur if storage or energy exportation is not available in the congested grid zones. To tackle these problems, energy storage or demand response programs, that reschedule the energy consumption of some manageable loads can offer technically simple and affordable solutions.

Some studies remark the possibility of using pumped storage hydropower manageable capacity to provide flexibility to the grid [21]. It is possible to avoid curtailment of renewable plants by increasing energy consumption when generation is higher than demand, or by storing energy by the pumped hydro facility in congested zones. However, only those hydropower plants provided by pumping and storage capacity can offer the second option, since they can absorb peaks of renewable energy by pumping up water and use it as massive storage system.

2. Synchronous generators to provide inertia

The inertia of the electric system is provided by the mass of synchronous generation that is rotating connected to the system at any given time, such as the generators of a hydroelectric power plant (driven by water pressure) or the turbines of a coal power plant (moved by the pressure of water vapor heated through the combustion of coal). Inertia constitutes the primary regulation of the system and is directly related to the system's ability to withstand a frequency event. A system with greater inertia experiences fewer frequency variations at a slower rate due to the sudden loss of part of the generation or consumption [22]. An excessive variation in frequency can lead to the disconnection of generators and/or load and therefore aggravate the problem, even with cascading failures until a general blackout.

The shift that electric systems are experiencing worldwide from a centralized system of large synchronous generators to one with multiple unmanageable lower power units many of them electronics-based (PV and wind power). The reduction of connected synchronous generators poses several challenges for the stable and safe operation of the system.

Inertia could also be maintained by synchronous compensators. Synchronous compensators are synchronous generators, as the name suggests, connected to an electric motor. Once in operation, the generator remains spinning connected to the grid at synchronism speed (50-60 Hz). As a result, it provides inertia and short-circuit power and absorbs or provides reactive power. The only active power it consumes is the one related to mechanical losses (friction). However, as it has been shown in previous sections, hydropower facilities with storage and pumping capacity can provide more services than synchronous compensators, such as power regulation, black start recovery or energy storage.

Another way to respond to frequency deviations is through virtual inertia, which are suitable control techniques of grid-connected inverters and control of their switching pattern, so that they emulate synchronous generators behavior in response to frequency events [23]. This solution is already being implemented, e.g., in the Great Britain’s national grid, where the mandatory minimum frequency response conditions that wind plants must provide are stated in their grid code [24]. However, synchronous compensators remain the best option for enhancing frequency stability than virtual inertia in low-inertia systems, as stated in [25]. Furthermore, most energy systems worldwide are still dependent on inertia provided by synchronous generators, mainly powered by fossil fuels, and virtual inertia solution are still far from being widely implemented. In those cases, maintaining hydropower generation can play an important role in integrating more renewable sources into energy mix in the short term.

5. Conclusion

As it has been shown, hydroelectric power plants are a valuable energy resource that has numerous options for use and services to the grid.

Spain, and other countries in the European framework, are undergoing a transformation of its sources of energy. Coal plants and some hydropower facilities are being substituted by photovoltaic and wind generation. This transformation, together with its current and potential share of renewable energy generation, is turning Spain into a test scenario of the effects that a decarbonized electricity mix will have in other countries. Problems and opportunities are appearing, and hydropower can play an important role in addressing them, as it has been presented in this paper.

In the first place, being a manageable energy resource (in case of pumped-storage plants, both its consumption and its generation can be controlled; in case of being only run-of-river facilities, its generation can be controlled) can be very useful both by controlling its generation and by offering network balancing mechanisms or regulation services through secondary or tertiary regulation markets.

Secondly, the energy scenario is directed towards new forms of generation, distribution, and consumption, increasing the importance of distributed generation and local consumption. Under these conditions, mini-hydro plants can be part of the energy elements of energy communities, lowering investment costs, in addition to being able to participate in bilateral power purchase agreements.

Thirdly, the energy scenario is headed towards a greater integration of renewables, which poses numerous challenges in the safe management and stability of the electricity system. The reduction of generators suppliers of inertia can be reduced by counting on the synchronous generators of already built hydroelectric power plants.

In conclusion, hydroelectric power plants do not only serve for energy generation, but their uses and applications extend to particularly important factors in the future of the electricity system and should be considered as an important resource that should not be discarded yet. Biodiversity concerns are of extremely importance as well, so solutions that both maintain hydropower benefits and reduces its environmental impact should be developed and implemented to make the most of hydroelectric characteristics while respecting river ecosystems and biodiversity.

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