The importance of hydropower flexibility in integrating renewable energy

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Abstract
Hydropower, the greatest form of renewable energy now in use, is essential for integrating and balancing variable renewable energy sources(VRE), combined with pumped hydro storage. Although hydropower is a mature technology, many older systems need to be modernized, renovated, and given new operating protocols. Various hydropower capacities become important to aid in the integration of variable renewable energy sources(VRE) at varying system shares. Hydropower, unlike many alternatives, offers a distinctive array of potential flexibility capabilities that must be thoroughly studied as the world's energy systems change and ongoing reforms take into consideration competing approaches, markets, and technology. Hydropower must compete with a variety of alternative technologies, such as batteries, other dispatchable generation technologies, demand-response, smarter networks, etc., to supply these system services. This review paper's objective is to provide a high-level summary of the main issues in order to draw attention to the ones that need more in-depth evaluations and analyses. It talks about the necessity of flexibility in the future electrical grid and the function of hydropower.

Key words; Hydropower, variable renewable energy sources (VRE), flexibility, pumped hydropower

1. Introduction

Instead of only supplying big volumes of energy, which is increasingly given by variable renewable energy sources (VRE), As VRE integration increases, it is more important than ever to offer the right capacity at the right times. As the demand for flexible and balancing capacity grows, there are fewer or no competitors to hydropower that can offer emission-free solutions, especially over extended periods. The value of flexibility to the power system and electricity customers is difficult to calculate because it is impossible to envisage modern life without a stable energy supply [1]. The value that flexibility-related products add to the electricity grid should, in theory, be reflected in their market value. Nevertheless, these services are now neither completely acknowledged nor fairly compensated in any marketplace. In order to provide all the services required to ensure a secure, dependable, and affordable supply of energy in order to achieve an efficient system over the long term, authorities should create markets that offer business opportunities that encourage investments in the demand side of the energy system or in generation and system infrastructure [2]. Owners of both new and existing hydropower plants should evaluate their assets' current and potential future capabilities before choosing the type(s) of flexibility that will work best for them.
It is a global challenge to develop reliable, affordable, and environmentally responsible electrical systems. Policy makers, regulators, and industry are paying close attention to the rapidly changing costs of energy technologies, the aging of existing facilities, and the rapidly changing mix of power generation. Decarbonizing the energy industry is another important mitigation strategy to combat climate change and stop the alarming rate of global warming. Despite the fact that many nations and regions have chosen various strategies for decarbonizing their power supply, increasing the share of renewable electricity production is practically universal and continues to be a major priority in many countries. The ability of the system operator to maintain an equilibrium between supply and demand for electricity is necessary for a dependable energy system [3].Therefore, it is crucial for the power system to have flexible resources to ensure that users can get electricity when they need it.
In order to increase energy access and enable electrification based on clean energy, or, more simply put, to change the structure and operation of the power system, variable renewable energy (VRE) sources like wind and solar photovoltaic (PV) energy are becoming increasingly important energy

sources. Favorable policy conditions, commercial prospects, and major cost reductions are what are driving this progress. This has effects on the system's specific resources, as well as the system as a whole, such as power plants, grids, demand, and storage [3].

2. Research Method

This piece of writing is a review. Periodicals, books, and past project works that were relevant to the topic at hand were carefully reviewed and carefully sampled. Several works were reviewed and summarised in order to compile the information needed to create the paper. This investigation was carried out using a meta-analysis.

3. Status of hydropower

Hydropower is a form of sustainable energy source that produces electricity by through the convertion of the potential energy stored in the water to kinetic energy when it descends from a high elevation. A well-developed and common technology is hydropower. There were 1292 GW of installed hydropower capacity worldwide in 2018, and it generated 4200 TWh of electricity across 159 nations. Pumped storage now has 160 GW of installed capacity worldwide. With "water-to-wire," an efficiency of 90% or above is normal. Hydropower ranks among the most effective technologies for producing sustainable electrical energy [4].Where natural resources are abundant, the cost of electricity from hydropower is competitive with or less expensive than that from thermal energy sources like coal, oil, or gas, often in the range of 2 to 5 US cents per kilowatt hour. In many nations, wind and solar PV energy are currently being used without the need for subsidies or additional costs, and they are increasingly competitive with thermal generation. With a share of 62% of all renewable electricity output, hydropower is the most significant form of renewable energy globally. The technical capacity to generate more hydropower is sufficient to support significant further deployment both in the medium (2030) and long periods (2050). By 2050, it is reasonable to expect yearly generation to have doubled from its 2016 level of 4102 TWh to over 8000 TWh. However, it is anticipated that the roughly 160 GW of installed pumped storage hydroelectric capacity currently in place will more than double by 2050, rising to between 412 and 700 GW [5]. Three categories of hydropower exist: pumped storage, run-of-the-river, and reservoir storage. The link between the reservoir's storage volume, inflow, and water residence times is commonly described by these categories. Actually, there is a range of reservoirs. It is also possible to use natural lakes as a form of reservoirs, frequently by blocking or damming themin order to increase the lakes volume as well as surface area. The most versatile types of renewable energy are biofuels and hydropower with reservoirs. Plant operational flexibility is based on the interactions between inflow into the reservoir, the reservoir storage, and the power plant installed power capacity. Further more, a variety of regulatory and technical characteristics are crucial in determining how flexible a hydroelectric facility is [6]. These are:

• The dimensions, functionality, and layout of thestructure members that are used to feed water to the turbines and drain it(tunnels, gates, conduits and pipelines).
• Start and stop periods, turbine ramping rates;
• Number of turbines as well as generators;
• Mode of operation during part-load;
• availability and reliability of the grid connection
• Time, volume, and inflow variability, along with the reservoir or intake's storage capacity and accessibility.
• Laws and regulations, such as environmental restrictions and mandates to provide energy as well as additional services like navigating and maintaining water supplies during droughts, etc.

Similar technological and legal considerations are crucial for pumped hydro storage. Several hydroelectric stations with pumped storage receive little to no intake. In these situations, flexibility is determined by the size of the reservoirs upstream together with downstream, the machinery type, the units quantity, and the capacity of installed pump and turbine. The majority of currently operational pumped storage hydropower plants were built primarily to provide ancillary services like grid restoration, islanding operation, black start capabilityand network frequency as well as voltage magnitude stabilization in addition to enabling effective generation of base load by covering periods of peak demand and consuming energy when there is little demand. When more VRE is implemented, these system services become more vital [7].

Reversible pump turbines or separate turbines and pumps are both used in pumped storage systems. Compared to traditional hydropower plants, pumped storage hydropower plants are designed with more stops and starts, including change in direction of energy as well as alternate electricity power generation. Establishing the system's safe dynamic behavior is essential and should take into account the waterways, turbine, pump, and generator. On the one hand, the dynamic behavior is tied to the conduit system design and the plant's performance characteristics. On the other hand, there is a need for an effective machine that can operate steadily under both heavy and light loads that ishigh and lowflow or high and low production. In order to prevent failure in operation, fatigue breakdown, or other occurrences, vibrations, noise, and pulses in pressure can also be managed on a very highdynamic operation status [7].

The same difficulties face reservoir hydropower as they do standard hydropower, which will be frequently employed for generation of a flexible power. Increased repair and more continuous monitoring,surveillance and inspection of the condition of the plant's elements are necessary for more flexible hydropower operation. The management of these difficulties is being aided by contemporary technology, digitization, enhanced maintenance techniques, and advances in the technical elements and system design. Moreover, hydropower plants from run off river with little storing space can be frequently operated or modified in order to perform even more adaptably [8]. Hydropower offers services including water supply, irrigation, flood control, drought mitigation, support for navigation, tourism, and recreation in spite ofenergy storage and renewable energy. If hydropower is not created and operated in accordance with contemporary sustainability practices, it may potentially have significant detrimental effects on the aquatic ecology and societal issues.

4. What types of flexibility are required?

Flexibility of the power system, as a whole, is the capacity to efficiently handle changes in the electricitysupply-demand. To keep the entire load and generation in a stable balance, in other words. System flexibility is becoming increasingly important to preserving the system's balance in systems with significant percentages of wind and solar energy due to the fluctuation and unpredictability of these resources. Nonetheless, different power systems in various regions of the world will be able to meet the increased flexibility requirements based on a combination of their technological and institutional structure. The immanent flexibility of a power system is supported by a variety of elements, includingGeographical spread of various generation sources in addition to VRE; Availability to demand-side flexibility and storage;The size of the electricity system as a whole; flexibility of power plants;Internal restrictions and regional connectivity;VRE production and demand are correlated, as is a regional connection of VRE production[9].

The institutional variables that control the operation of the system's assets and the types of assets that are created include market design, technological standards, and system operation protocols. The International Energy Agency's suggested steps for VRE integration can give a first-rate insight of the types of flexibility the power system needs. The prerequisites for the types of flexibility that hydropower (and conventional energy) may cost-effectively help to are set by creating a standard structure for the necessary flexibility[10]. The stages structure is established by the typical progression of difficulties faced by system operators when more and more VRE sources are connected to the grid, as opposed to focusing on specific shares of VRE deployment [9]. Short descriptions of each phase of VRE integration are provided in Table 1.

Table 1. international energy agency phase classification of VRE integration

Source International Energy Agency (2017)

Phases	Descriptions	Example
1	VRE adoptionduring early stagewithout significant influence on system performance	Still many countries
2	Little changes to current operations can be made to better accommodate additional flexibility needs.	Brazil, China, India, Sweden, Texas
3	VRE generation controls system activities In order to	Italy, Germany, Portugal,

	keep the system stable	Spain, UK, California
4	To balance the system, additional investments in flexibility resources are required.	Ireland, Denmark, South Australia
5	VRE generation structural surpluses from weeks to months may result in a reduction.	
6	The necessity for sector coupling is supported by structural supply that is overor under spanning from seasons up to years.	

5. How can hydropower help to offer flexibility?

Hydropower from reservoirs and pumped storage is already widely used in many nations to provide flexibility, energy storage, and auxiliary services for the electrical grid. However, in lots of nations and locations with abundant hydropower resources, such as Norway, Venezuela, British Columbia, Quebec, Tajikistan, Tasmania and Costa Rica, hydropower additionally is extensively used in generating base load electricity. In these nations and areas, hydropower supplies practically all of the system's electricity. Hydropower also supplies base load generation in nations including Sweden, Austria, Switzerland, Russia, China, India, the United States, and Brazil, despite the fact that it makes up a smaller portion of their energy mix. It is vital that hydropower also delivers base load electricity and flexibility in the future to support the transition to renewable energy sources [11].

Also, several nations and areas have supply security thanks to reservoir hydro. In most places, seasonal and inter-annual changes in precipitation and inflow are characteristic, and hydroelectric reservoirs have been used as buffers to guarantee a consistent supply of energy throughout the year. With a long-term cycle for filling and emptying, this seasonal use of reservoirs enables considerably more widespread use in the intervals between times of minimum and maximum levels of reservoir. And This requires that the rapid and gradual draining and refilling over the course of minutes, hours, or days have no impact on the long-term seasonal cycle [12].

Without adding new dams or enlarging existing ones, there are two ways to renovate existing reservoir hydro to assist in enhancing flexibility at various duration span, enable increased VRE involvement in the power system, and avert the reduction of other renewable energy sources: the first is that a reservoir hydroelectric plant can be redesigned to comprise a pumped storage facility if it discharges to another reservoir or a lake by installing pumps or reversible pump turbines. The second option is to increase the capacity of currently operating power plants in the absence of an exploitable lower reservoir (by rising the capacity of the turbine). Both solutions will call for additional equipment, civil engineering projects, and occasionally even strengthened grid connections. Yet, as no more reservoirs or dams will be required for such a purpose, the environmental impact will either be negligible or non-existent. Installing pumps will allow reservoir hydropower to engage in short - term and medium-term flexibility considerably more frequently than when merely raising the capacity since the plant may be used as a battery and water can be "re-used" several times [11]. These choices, however, are site-specific and rely on the size and design of the plant, the amount of active reservoir storage, and any applicable licenses.

Hydropower can increase flexibility throughout all phases, taking into consideration the phases of VRE integration in the system as indicated in section 4. However, the most effective importance of hydropower can change depending on the requirements in various phases as well as the characteristics of the hydropowerplants.

Hydropower is not needed to add any more flexibility in Phase 1. More short-term flexibility is required in Phase 2 to accommodate small-scale fast variations in power generation. Although there are a number of rival technologies including flywheels, batteries and different types of demand-supply side flexibility that potentially can take part in this stage, Such types of services and transient variations in the power system can benefit from the increased flexibility that hydropower can providePhase 3 may favor hydropower over traditional thermal resources due to its capacity to launch and ramp quickly any moment, includes alternating between energy production and consumption, given There are no limitations on transmission or water management [12]. This is because of technical, financial, and greenhouse gas emissions factors. Hydropower may similarly have limitations and inefficiency under partial loads, but thermal facilities frequently have higher costs and operate less efficiently.

Phase 4's increased reliance on weather variability places a high priority on long-term flexibility in contrast to hyper, short, and moderate flexibility. There are fewer rivals that offer medium- and long-term flexibility than pumped hydro and hydropower with storage. Phase 4 can identify greater system value by supplying the appropriate capacity at the appropriate times as opposed to supplying volume of energy, which VRE suppliers are providing more of. Any type of technology used to firm up will only be profitable If it is successful in capturing what is known as the energy option value. VRE production Hydropower can provide significant short-term capacity-driven flexibility in phases 5 and 6, as well as medium- and long-term capacity plus energy-driven flexibility (power and energy) [12].

Since it can store primary energy (GWh) with incredibly low waste as the potential energy of water and offer power capacities (GW) with a high degree of foreseeable dependability, hydropower occupies a unique position from the perspective of a flexibility supplier. When decentralized alternatives are intended to give (short-term) flexibility but in a less predictable way as flexible thermal units are phased out (batteries, e-mobility, demand-side management, etc.), this becomes even more crucial.

6. What are the benefits of flexibility?

It is challenging to put a monetary value on flexibility for the power system and the electricity customer. Flexibility was included into non-market systems and the value was factored into the consumer's energy cost. With the implementation of market systems, this altered. Flexible units' production schedules are modified in market based and non-market-based systems with the goal of maintaining continuous supply and demand balance at the most affordable price. The value of offering these solutions, however, varies depending on the region as well asthe systemstate, and the main difficulty is to guarantee that products and services are properly compensated in order to provide long-term investment incentives[14].

When the power system is run at its extremes, that is, during times when there is a shortage or surplus of power and/or energy, flexibility services have the highest value. Flexible units are valuable during times when there is a scarcity of power and/or energy because they increase production or decrease demand, which restores quality of the power (frequency and voltage), prevents or limits shedding loads and, worst cases, prevents blackouts. This prevents the electricity users and system operators from incurring excessive costs. Flexible units add value during times of excess power and/or energy by reducing production or raising demand, which restores quality of the power (frequency and voltage) and limits the reduction of VRE. Flexible units contribute to higher VRE installed capacity value and system costs lower than if significant available energy amounts had to be decreased by limiting the amount of surplus energy that is curtailed[13].

On top of units that are flexible and merely consume or produce energy, pumped hydro storageadds some value to the system during the periods of deficit and surplus. A hydro-reservoirdoes not use electricity, however, it may delay output for both periods (short-term and long-term), by shifting production to the times whenit is most needed. These flexibility services required, as stated in earlier sections, should be defined by the necessary capabilities and components, like the power capacity, the ramp rate, energy and duration. There will be a variety of technology options available to distribute the good (the supply) [15]. As a result, the price of offering the necessary services can differ greatly between markets and goods. The necessity for these flexibility services also will vary depending on the period of time, the products, and the power systems. Although there may be a big need for short-term flexibility, there may also be more than enough supply of technology that can meet those needs [16]. However, prices may vary widely, and in these types of systems that are market-based, the price of the most expensive technology needed to keep the balance will determine the worth of offering such services.

The times when power and energy are needed for extended periods of time can be riskier because there are so few current and possible new technologies that can provide these services. This is especially true when taking into account scenarios or systems where the majority of the thermal units have been retired. Batteries, pumped hydro, and other storage devices may not have enough time to recharge if brief periods of low production from solar and wind energy approach one after the otherwhile there is high demand[16]. Such circumstances can be difficult for the power system, so it's crucial that these services are properly taken into account when the system is being planned long-term. It quickly becomes expensive to build a variable renewable power generating and transmission capacity that can handle the "worst and highest-conceivable cases." So, even though they are rarely employed, alternative long-term flexibility options could lower the overall cost of investment of switching to a lowcarbon-consuming system.

7. Market based systems benefits from flexibility

In competitive power markets, the power price is determined by the marginal or minimum cost of the final demand or supply resources that are required to maintain the merit order(supply-demand equilibrium).This gives assurance that the balance is maintained for the marginal or the smallest possible price. Currently, the energy sale, in which the energy product item sold is per unit of energy irrespective of the quality of the product item, is the main source of income for producers of power in restructured power systems. When output is adapted to high price times, the value of storage and flexible power generation is primarily exploited, resulting in a higher actual power price than non-flexible technologies. [17].In order to ensure that there is enough capacity to balance variations in demand and supply, the majority of nations also establish separate markets for balancing and related services. Some nations additionally have markets that have separate capacities to guarantee investments that have enough capacity to satisfy long-term and high-peak demands [17].

The value that flexibility-related products add to the electricity grid should, in theory, be reflected in their market value. This, however, assumes that the market mechanisms and goods are enough for the power producers to realize the true value of the entire spectrum of system services [18]. The revenues generated by various technologies competing in the energy market may not accurately reflect the total cost of an effective, secure, and reliable power system if they are not compensated appropriately. Long-term, this may result in less-than-ideal investments, which, in turn, may create additional difficulties for the reliable and secure operation of the system as well as increased system expenses. Depending on the state of the electricity system, providing flexibility to the grid has a different value.

The required level of power system flexibility should be broken down into many categorizations and related goods, with each product's value depending on its specifics. Operation and Power system planning, in both market and nonmarketbased systems, aims to provide affordable and dependable supply of power in short- and long-term through appropriate power system operation as well as investments. Long-term system efficiency requires the markets to offer economic possibilities that spur investments in the generation, system infrastructure, and demandensuring all the necessary services are provided while taking into account the changing mix of resource [18].

As a result, mechanisms of new market may be necessary to guarantee that various scales are sufficiently flexible. This includes having the ability to deal with sporadic occurrences like prolonged periods of weather-related VRE under- or overproduction. It is particularly difficult to achieve a cost-effective and dependable supply of power during transitional periods when the energy system is undergoing significant changes. Even with dropping average energy costs, modifying production to high price timesand the value of delivering energy is anticipated to be crucial and provide long-term revenue source for producers of flexible power[18]. It is consequently anticipated that day-ahead trading and trading in intraday markets would continue to serve as a main income sourcefor many years. The price fluctuation/variation is predicted to rise, though, and energy's value will depend more on when it is provided than it does now given the increased fluctuation and uncertainty in profiles of generation. As a result, the importance of being able to change demand or output in response to the pricingis predicted to rise, and the realized price of power differences between various technologies is also predicted to widen. This indicates that the value of flexibility increases Despite an average decrease in price per delivered unit of energy.The size and frequency of the extreme low and high prices will determine the differences among technologies in actual power prices.

When evaluating the flexible operation value, it's vital to consider the frequency and size of the extremes, or the minimum and maximum prices of power. In recent years, European nations (such as

Germany) have experienced longer stretches of cheap electricity prices, including times when thereare no pricing at all. This can be seen in relation to the quickly rising VRE generation, but is also affected by changes in CO2 and fuel pricing, energy policies and costs of technology. The price of electricity will be determined by VRE from low to zero minimal costs during many hours per year and for extended time periods in energy systems that are decarbonized have attained an integration of VREphase 3 or above [2].

The demand-supply(merit-order impact) tends to lower the average electricity wholesale price as VRE shares rise. Negative prices frequently come from long-term power purchase agreements or feed-in tariffs, which allow VRE resources to generate power at a profit even when there are negative power prices. Nevertheless, the costs for a start-up, bottleneck transmissions, and many other inflexibilities in the power system can also be the cause of negative power pricing. Also, when flexible thermal generation units are decommissioned, there might be more or less frequent times when there is a lack of available generation. The minimumpossible costs of flexible generation or storages that are demand-response alternatives, will determine the price of electricity during these times. A price cap is frequently used in markets to prevent sharp price increases.

The solution to this conundrum is to make the appropriate investments in flexible storage goods and services. However, if price spikes occur more frequently, this will help to raise average power prices, possibly countering the downward pressure on prices from increasing VRE adoption from the merit order. Similar patterns have been seen in several regions of the United States, but the decline in natural gas costs over the past few years has been the primary factor in decreasing electricity market pricing. The system's remaining controllable resources take on greater significance as energy prices become more volatile and generation profiles grow more unknown. As a result, it is anticipated that the service value offered by generators of flexible electricity will rise. Given that just a few technologies are capable of offering this kind of flexibility in an effective manner, the supply of seasonal and/or long-termstorage is probably more beneficial. Related goods are anticipated to appreciate in value and play a bigger role in hydropower producers' and other flexible resource providers' income as demand for flexibility rises.

Conclusion

Resources with flexibility are essential for a reliable and secure power system. Due to the dependence of the majority of the modernized society on technology and electricity, the system will always be expected to be flexible enough to offer inexpensive, secure, safe, and clean energy at all times. The most effective way to guarantee a dependable and affordable power supply quickly and a sustainable, effective, and dependable power system in the long run, however, is still a challenging problem. Increased VRE sharesmake the power supply more unpredictable and variable, which makes the system more flexible. When fossil-based power production is decommissioned, which is limiting the system's flexibility, it aggravates the reliability issue. Future system flexibility demands at various time scales will most likely result in a rise in the value of flexibility services provided by hydropower. Therefore, it can provide a wide range of flexibility services, ranging from short-term frequency and inertia response to long-term storage which is seasonal, hydro power is exceptional. As a result, hydropower can adjust to the demands of various systems. The power system's flexibility should ideally be provided by the least expensive technology. In a future low-carbon power system, hydropower can be crucial as a source of flexible, clean energy. To assure investments that are suitable, and to enable the smooth transition of energy generating systems, further evaluations and assessments of technological, commercial, policy, and regulatory requirements are necessary.

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