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A Review on Hydropower Hybridization for Frequency Containment, Objectives and Dimensions of Auxiliary Energy Storage

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ABSTRACT

Increased penetration of the combined operation of hydraulic power plants with electrical energy storage systems has pushed the state of the art of hybrid operation of hydropower. As the body of work is growing this review article aims to provide a thematic review on the objectives of hybrid operation of hydropower and the control strategies and dimensioning methodologies of auxiliary energy storage systems to achieve these objectives. The works reviewed are categorized thematically according to whether the contribution is a commercial objective or rather contributing to increased security of supply. Increased revenue from being able to qualify for ancillary services such as frequency regulation and reduced operational costs through reducing wear are the primary commercial objectives. Improved black-start capability, stability regions and island operation are objectives relating to security of supply. State-of-the-art methodologies on control and dimensioning of hybrid systems for the proposed objectives are presented. A quantitative survey of commercial hybridization projects focusing on the Nordic countries has been performed, highlighting regional disparities in technology adoption. The review highlights gaps in the literature concerning the translation of wear reduction metrics into operational cost savings.

1 | Introduction

The term hybrid power-plant, or hybridized power-plant has become descriptive of a power-plant combined with an auxiliary energy storage system (ESS) [1–4]. The combination of fast and responsive ESS with slower but dispatchable hydraulic power plants (HPP) present an opportunity for leveraging resources and create benefits for grid operators and asset owners. An effect of the continuously increasing penetration of intermittent power generation [5] is a partial deterioration of grid frequency and an increase in the time spent outside the frequency bandwidth classified as the normal operating band [6–8]. Increasing grid fluctuations lead to increased wear and tear of hydropower turbines contributing with primary frequency response (PFR) [9]. A study on how decreasing grid fluctuations through implementation of synthetic inertia in the Nordic system decrease the wear on hydropower units providing PFR is presented in [10]. While synthetic inertia is not yet implemented as a procurable asset by transmission system operators (TSOs) in the Nordics, the volume of PFR procured is increasing [11] and new faster frequency regulatory services (FFR) have been implemented [12, 13]. Existing PFR services are revised with stricter requirements to avoid ultra low frequency oscillations (ULFO) in the grid frequency [14–16]. These changes affect supply and demand on market based

Abbreviations: ESS, energy storage system; GFL, grid following; GFM, grid forming; HPP, hydro power plant; MPC, model predictive control; PFR, primary frequency response; SOC, state of charge; SOH, state of health; TSO, transmission systems operator.

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PFR products and impose commercial motivation to revise and enhance hydropower assets that either do not meet the requirements for delivery of PFR products or by decreasing operational costs through reducing wear. Decreasing costs for lithium-ion batteries [17] has led to increased competition on PFR markets. Standalone ESS are providing an increased share of PFR in the Nordics [11] and becoming an important force for ensuring grid frequency stability and inertial response in global markets [18]. Utility scale battery-ESS (BESS) have no issues meeting the newly imposed requirements on performance and stability for PFR contribution, and can be considered ideal PFR providing assets [19] if disregarding their exhaustible energy content. The opportunity studied in this work is how ESS may effectively be combined with existing hydropower units to decrease the energy content needed for the ESS, capital investment and material footprint [1, 20].

1.1 | Scope and Aim of the Review

The focus of this review is on hybrid operation of ESS and HPP units on timescales relating to PFR contribution, that is seconds to tens of minutes. PFR provision vary regionally, automatic generation control (AGC) or frequency containment reserve (FCR) [21] are other terms used to describe similar services of regulating active power output according to the global network frequency. Names and criteria for these resources differ depending on grid states or available system inertia. This review does not detail the different PFR market services nor their prices, PFR is treated as an umbrella term denoting frequency regulation with response times from within a second to 10–15 s and a duration of up to an hour. While details in the criteria for delivery are relevant in many aspects of the hybridization process, methods investigating the integration of HPP with ESS to deliver PFR are comparable without regarding exact specifications. PFR products are usually procured as market based resources [22, 23], which is why the contribution to PFR is classified as a commercial objective in the review. Works describing decreasing operational costs from reducing wear and tear are also classified as commercial objectives. Turbine specific wear is differentiated in the review and control strategies for wear mitigation of Kaplan and Francis turbines through hybridization are presented.

In a rapidly changing geopolitical landscape, issues regarding security of supply and grid resilience are becoming increasingly important. HPPs are a valuable resource to grid operators when operating grids in challenging conditions such as islanding situations [24], system-splits and black-start operation [25, 26]. Stability issues and a larger flexibility for load control in these critical situations may effectively be improved through the introduction of ESS co-located or coordinated with HPP units [27–29]. The review includes studies considering stability analysis and load ramping capabilities for hybrid hydropower projects relevant for increased grid resilience [28, 30, 31]. Delivering services such as black-start or islanding capabilities are regulated through grid codes [32, 33], procured through bilateral agreements or market based procurement strategies [34, 35]. These services are however not as consistently market based or associated with increased revenue, thus classified as objectives relating to improving security of supply in this review.

Applications that focus on shifting larger quantities of energy, such as mitigating hydropeaking to improve aquatic ecology [36–38] and improving the possibilities for energy arbitrage by hydropower units is not the primary scope of this study. Some datapoints on the dimensions for ESS with the primary application of mitigating hydropeaking is however included in the quantitative comparison as a reference to the reader.

Other reviews relating to the subject, such as [39] by Durvasulu et al., highlight the rationale for investing in the hybridization of hydropower, including revenue streams, increased functionality, and comparisons to the hybridization of other renewable energy sources. The World Bank Group published a report on facilitating the energy transition with hybrid hydropower solutions [40]. The report takes a broader perspective on co-location or coordination with variable renewable resources and is specifically directed towards policymakers, regulators, and investors. This review focuses on the technical solutions of hybridization from a HPP perspective, particularly developments in the area of combined asset control. The primary contribution of this work is a structural comparison of control algorithms, discussing proposed solutions based on their objectives and technical implementations. The work includes a comprehensive overview of control schemes and quantitative comparisons of strategies employed to minimize wear and tear while improving the stability regions of the regulating entity using an efficiently dimensioned ESS. A meta-analysis on ESS dimensions suggested by the literature and industry lead to a discussion on the power and energy content of the proposed ESS, as well as suitable ESS technologies depending on the application and available technology.

The aim of this study is to provide a thematic analysis of works contributing to these topics, highlight best practices, and present the state of the art. The primary result of the review is a summary and critical analysis of key works, accompanied by a meta-analysis of comparable metrics from the reviewed literature. The data points from these works are compared to investments made by industry. A discussion on suitable ESS technologies and the differences between industry and academia follows. Future directions, research gaps, conclusions, and main takeaways conclude the review. The primary contributions of this work can be summarized as:

- A comprehensive compilation of control methodologies proposed for hybridization projects
- A comparison of reduced movements from the proposed methods with this objective, including ESS dimensions
- Research gaps in techno-economic optimization problems
- Quantitative comparison of industry trends for commercial hybrid projects
- Insight on improving stability regions for HPP units through hybridization
- Overview of benefits for security of supply, islanding and black start through hybridization.

1.2 | Commercial and Technical Objectives

Three turbine types; Kaplan (horizontal and vertical), Francis and Pelton are primarily used in conventional hydropower operations

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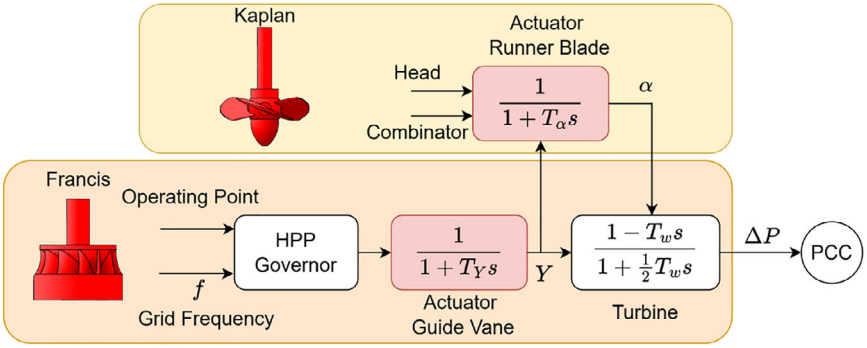

FIGURE 1 | Schematic illustrating a linear model of a doubly regulated Kaplan Turbine, controlling runner blades and guide vanes through actuating servo motors, and how the regulation differ from a Francis turbine. The unit is connected to the grid through the point of common coupling (PCC).

[41]. Pelton turbines are suitable for high head operation, Francis turbines for medium head operation and Kaplan turbines for low head operation. Different conditions for the plants foster their individual strengths, while they are susceptible to varying drivers of wear.

PFR contributions from hydropower units potentially offer increased revenue [42] but have been identified as a driver for additional wear on the HPP turbines [43]. Some distinctions should be made regarding the drivers for wear in Kaplan and Francis turbines, which are the types primarily studied in the literature reviewed and thus the main focus of this work.

The research regarding additional wear from abrasion for Kaplan turbines has been summarized by some sources as increased wear due to number of movements and the distance moved in the servos of runner blades and guide vanes [9, 10, 43]. These servo engines, or actuators, are illustrated by their associated transfer functions, highlighted in red in Figure 1. The parts most susceptible to tear has been suggested to be the runner blade bearings and link pins [44] or the cranks connected directly to the runner blades [45]. The increased cycle-stress from PFR contribution, as compared to water flow regulation, has been quantified to be 20 times greater by Benda and Wurm [46]. Efficiency loss due to non-optimal operating points is relevant for Kaplan turbines [43].

For Francis turbines, wear accumulation due to regulation cycles in the guide-vane servo engines is relevant, as shown in Figure 1. Transient operation accelerates runner blade wear and tear due to cavitation, vortex breakdown and high pressure pulsations on runner blades caused by turbines operating at non-optimal points [47]. Load rejection in fast transients, penstock fatigue and guide vane load cycles are also brought up in the literature as processes for wear relevant for medium to high head HPP units [48]. Start and stops, speed-no-load, and low load operation have been identified as significant drivers of relative damage in Francis turbines [49]. Thus, regulation mileage also leads to abrasive wear in Francis turbines. However, operating at lower discharge levels to achieve a larger span for regulation (providing a greater PFR capacity to the market) causes different wear mechanisms and affects fatigue life consumption [50, 51]. Turbine design choices can be made to alleviate these effects [52], but trade-offs exist in terms of investment costs and efficiency. Decreased efficiency due to non-optimal operating points is more pronounced for Francis turbines than for Kaplan turbines [51].

Distance moved by runner blades and guide vanes, directional changes and number of movements are recurring key performance indicators (KPI) used to quantify wear. M_Y & N_Y are used hereafter to denote the distance moved and number of movements by the guide vanes, relevant for all HPP units to regulate the inflow of water to the turbines. M_α and N_α denote the distance moved and the number of movements by the runner blades, which is relevant for the doubly regulated Kaplan turbines. The units of the mentioned metrics in this review are [pu] or [%], used to quantify a change compared to a benchmark operation. Figure 1 presents a linear model of a Francis and Kaplan turbine, where the Kaplan turbine is illustrated with an additional servo-motor for the regulation of the runner blade. The runner blade combinator mechanism utilizes a lookup table that adjusts the runner blade angle to the optimal operating point (cam-curve) based on the head and guide vane opening. Themes reviewed and discussed in this review are clustered according to mileage related wear (more relevant to Kaplan) and wear avoided due to non-optimal operating points (more relevant to Francis and Pelton) to critically compare the findings from the reviewed works.

1.3 | Regional Developments and Industry Trends in the Nordics

The dispatch of utility scale ESS in the Nordics has been driven largely by revenue gains from PFR regulation markets and has experienced significant growth between 2020-2025 [53]. Industrial investments in hydropower hybridization in the Nordics have correlated with these increased revenues and capital cost reductions for utility scale BESS [54]. The results of a survey of public investment decisions on utility scale ESS systems co-located with HPP units in the Nordics is accounted for in the meta-analysis section of the results.

2 | Results

The results are clustered into thematic subsections, first outlining the control strategies employed for wear mitigation through

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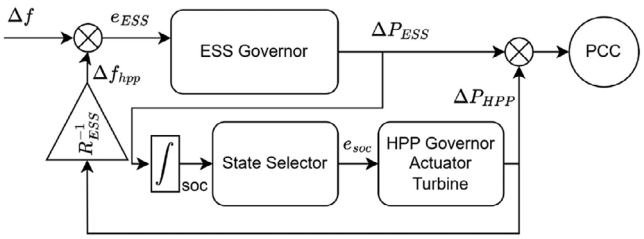

FIGURE 2 | Higher order control schematic of the hydro-recharge control algorithm.

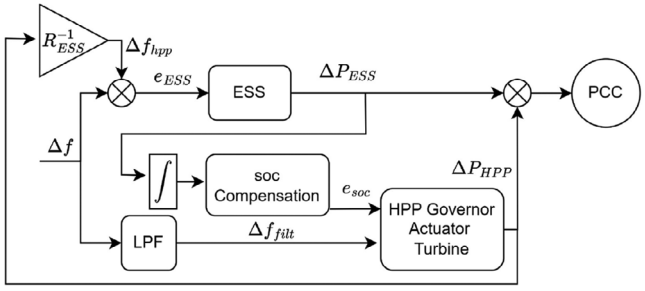

FIGURE 3 | Frequency splitting of the error signal between the ESS and HPP unit, in this case illustrated by a low-pass filter.

mileage related wear and subsequently discussing non-mileage-related wear. Then, follow a section on ESS dimensioning methodologies, which concludes the first thematic subsection. Works and insights that focus on enhancing grid resilience, security of supply, and stability analyses of the hybrid operation of hydropower follow. The results conclude with a meta-analysis of comparable findings regarding ESS dimensioning and the data points from the industrial survey.

2.1 | Control Strategies and Wear Mitigation

2.1.1 | Mileage-Related Wear

This section will focus on how wear is decreased through reducing the mileage and number of movements by the servo motors, highlighted in red in Figure 1. This goal is achieved in the hybridization process through relaxing the requirements placed on the HPP unit by modifying the error signal. The error signal is a function of the frequency deviation and droop. The droop is a scaling factor determining the magnitude of the regulation compared to the nominal power of the HPP, defined as

$$R_{\mathrm{h}} = \frac{1}{ep} = \frac{P_{\mathrm{nom}}\Delta P}{f_{\mathrm{nom}}\Delta f} \tag{1}$$

Where P_{nom} [MW] is the nominal power of the HPP, f_{nom} [Hz] is the nominal frequency of the grid, Δf the frequency deviation, usually bounded depending on which PFR resource is provided, and ΔP the change in active power output. ep is a unitless gain usually varying between 2%–10% where a lower droop implies a larger regulating strength and vice versa. Regulating strength of the ESS denoted R_{ESS} is expressed as $\Delta P_{\mathrm{ESS}}/\Delta f$ [MW/Hz].

2.1.1.1 | Hydro Recharge. A straightforward approach to mitigating the wear from the HPP unit is to forward the error signal directly to the ESS, effectively mitigating all additional movements to the servo systems arising from PFR. This approach was described by Jin et al. in [3] and [55], where the dispatchable HPP unit is employed to govern the state of charge (SOC) of the ESS. The approach is labelled hydro-recharge in [1]. A higher order control scheme of the strategy is presented in Figure 2. The frequency deviation is passed directly to the ESS, ensuring the PFR provision. The power delivered by the ESS is integrated to monitor the SOC of the ESS, when the SOC pass a defined upper or lower limit, a predefined state is selected for the HPP. The state selector defines a new operating point to the HPP governor to effectively decrease or increase the SOC of the ESS to a desired operating region. The power deviation from the HPP unit is used as feedback, with appropriate scaling according to R_{ESS} to modify the error signal input to the ESS. Thus ensuring that PFR provision is continued, with an added offset corresponding to the modified HPP active power delivery. An illustration of active power output from the implementation of the control strategy is illustrated in Figure 8.

2.1.1.2 | Frequency Splitting. The Hydro-Recharge control strategy face some limitations as the power output of the ESS is dimensioned for the full PFR capacity, driving capital cost of the ESS. To further benefit of the co-location of the ESS with a HPP unit, a control strategy where a combination of the ESS and HPP units deliver the PFR resource is proposed. The strategy is labelled Frequency Split in [1], employed in [56] for an ESS consisting of both BESS and flywheels (FESS). The strategy is also employed in [57–59], and versions of frequency splitting is common in many of the sources reviewed. This strategy effectively splits the frequency signal into a low frequency and a high frequency component treated respectively as error signals by the HPP and ESS, in the case of [56], cut-off frequencies are adjusted for the BESS and HPP, allowing the FESS to take the high frequency components, Battery mid-range frequencies and HPP take low frequencies as well as ensuring SOC of all ESS. The benchmark approach for frequency split can be considered a linear filter applied on the frequency deviation to create the error signal for the HPP unit. An additional control parameter is included to adjust the gains from the HPP unit if the SOC of the ESS deviates from within desired operating region. This is done by creating an artificial frequency deviation when the ESS drifts outside the SOC band, adjusting HPP power output. A higher order control scheme of the Frequency Split is presented in Figure 3. The active power output of the HPP unit is used as feedback to continuously modify the error setpoint of the ESS. Modifying the error signal originating from the frequency deviation to reduce the number of movements by the HPP and ensure the continued delivery of the required PFR power from the ESS may be implemented through a number of methods. Figure 4 presents different methods used in the reviewed works. Figure 4a use linear filters to reduce the high frequency components of the error signal forwarded to the HPP, employed in [1, 56]. Figure 4b describes a frequency dead-band, is used as a benchmark to compare a model predictive control based approach in [60], proposed in [58]. Figure 4c use variational mode decomposition as proposed by [61], building on a study employing empirical mode decomposition for hybridized units [62] to divide the frequency deviation error signal into components or modes containing higher respectively lower frequencies while ensuring the energy neutrality of the faster components passed on to the

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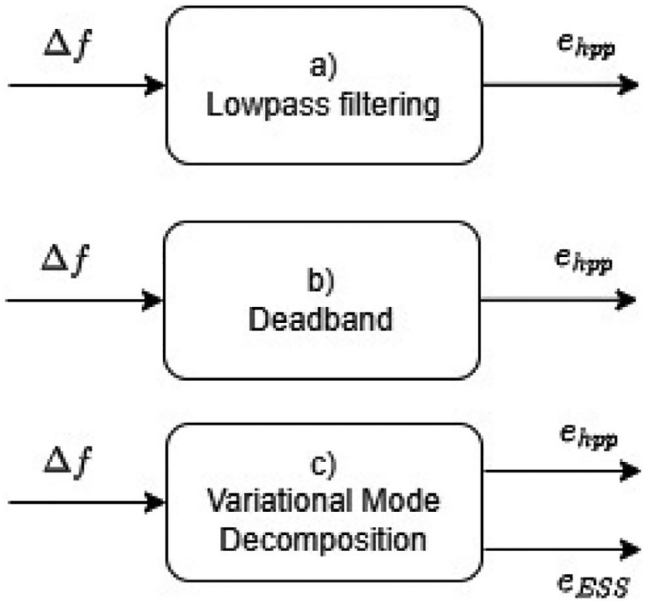

FIGURE 4 | Three methods for decreasing the number of movements performed by the HPP by modifying the error signal input to the HPP governor.

ESS. Critique has been expressed on the use of linear filters as they does not significantly reduce the number of guide vane movements [57].

2.1.1.3 | Model Predictive Control. Recent works propose using model predictive control (MPC) to actively mitigate mileage and the number of movements by the servo-systems, while ensuring SOC-control. Gerini et al. propose a double layer MPC method (DLMPC) for reducing mileage in Kaplan turbines [60]. The two layers consist of an upper layer with the objective of dispatch planning of the HPP unit, considering the SOC of the ESS and a forecast of the regulating energy. The lower layer MPC solves an optimization problem every second, where the frequency, forecasted frequency, HPP active power feedback, dispatch plan of the HPP and SOC of the ESS are considered as inputs. The optimization problem is solved to produce an active power setpoint for the ESS and HPP. The objectives for the lower layer MPC algorithm consider optimal tracking of the PFR provision while minimizing the number of movements and total mileage of hydropower servos, all while maintaining the physical constraints of the ESS. A control scheme for the method is presented in Figure 5.

2.1.1.4 | Experimental References. Some experimental references treat implementations of ESS in hydropower operations. The European project XFLEX Hydro has investigated the wear and tear of hydropower contributing to PFR in a grid with a larger penetration of renewables. Valentín et al. investigated a battery co-located with a Kaplan turbine HPP unit in [44]. The study addresses a battery installation in parallel with a Kaplan unit at the Vogelgrun power plant. The battery size represents 16.25% of the maximum balancing power (PFR capacity) provided of the hydro unit. The BESS consists of 650 kW with 300 kWh energy storage. The study compares the power plant operation in standalone and hybrid modes to estimate the difference in turbine wear and tear between the two modes. The mileage of the servomotors of the guide vanes M_Y and runner blades M_α are calculated. The authors quantify the wear and tear by determining the forces in the servomotors and translating the force to averaged torque in every guide vane, as well as force exerted on the runner blade.

$$W = KPM \tag{2}$$

The wear W being estimated in μm through the bearing contact pressure P, a friction coefficient K and the mileage of the servomotors M_Y & M_α. The study also conducts a tear assessment and a fatigue lifetime determination for different components of the regulation system. Numerical simulations and a finite element method (FEM) analysis of the runner blade regulating system identified the link pin connecting the blade lever and the blade link as the most critical component. Link pins were also determined as the critical point of failure for the guide vane regulating system. Using the forces obtained from the servomotor pressure analysis, the stress in the link pins are calculated. A rainflow counting algorithm is used to obtain the number of cycles and associated stresses for estimating the remaining lifetime of the component. The study serves as an experimental reference for tear mitigation in a Kaplan unit; however, it is not explicitly stated which control methodology is applied for the parallelized ESS. Another result of the study was an increase in PFR available to the market through hybridization, corresponding to a power increase of 16.25%. Insights from Vogelgrun have served as the foundation for a series of studies [58, 63]

A BESS of 5 MW, 6.2 MWh was installed in parallel with the Kaplan unit Forshuvud in Sweden in 2019 [64]. Laban et al. have used the plant to compare linear HPP and ESS models against field data from the operation to verify the applicability of the selected models in studying the hybrid operation of HPP [65]. The control of the hybrid plant utilizes the frequency split algorithm with an added filter time constant to slow down the HPP units response. A comparison of the stand-alone operation of the HPP unit, the HPP model, and the hybridized model is conducted. The conclusions of the study highlight that linear models are applicable for dimensioning design and power system studies; however, non-linearities are not accurately captured by these models. The study highlights a non-linear phenomenon labelled stick-slip, in which low amplitude regulation signals sent to the guide vane cause the hydraulic valve to operate in a step-size fashion due to static friction. As pressure builds, the friction is overcome, and the HPP regulates a step. This nonlinear effect is not captured in the model, under which conditions the model overestimates the number of movements performed by the HPP unit between 87%–118%. When the phenomenon is active, the model also underestimates the cycling of the ESS which continuously tracks the frequency signal as the HPP output is static due to stick-slip. The stick-slip phenomenon may be compared to a mechanical deadband or backlash.

2.1.1.5 | Comparative Remarks. In many of the works reviewed, an indication on the efficiency of the hybridization and its control has been described through a reduction in mileage and number of movements by the guide vanes (and runner blades where applicable). The comparison is made through simulations or data collection over a period of time, with the impact on servo motor movements quantified and compared to a benchmark,

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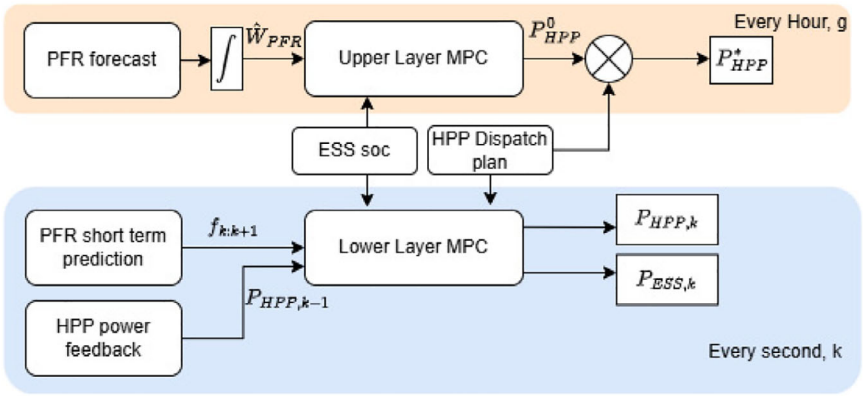

FIGURE 5 | Two-layer MPC algorithm as proposed by Gerini et al. in [60], the upper layer MPC modifies the dispatch plan of the HPP and the lower layer MPC ensures continuous PFR provision, optimizing to reduce wear and maintaining ESS SOC.

TABLE 1 | Reduction in mileage and number of movements from sources with compiled information on the KPIs. Control scheme indicate which type of control is used to separate the frequency error between ESS and HPP unit. PFR gain indicates the regulation strength, P_{ESS} the available ESS capacity and ESS/PFR is the ratio between supplied PFR and ESS capacity. *Experimental comparisons.

Control scheme	M_Y [%]	N_Y [%]	M_α [%]	N_α [%]	P_{ESS} [MW]	PFR gain [MW/Hz]	$P_{\text{ESS}}/P_{\text{PFR}}$ [%]	Author	Turbine
Dead Band	−91.5	−92.9	−90.7	−91.6	5×10^{-3}	125×10^{-3}	20	Gerini et al. [60]	Kaplan
Dead Band	−98	−98.6	−97.9	−98.6	9×10^{-3}	125×10^{-3}	36	Gerini et al. [60]	Kaplan
DLMPC	−93.2	−96.8	−94	−97.1	5×10^{-3}	125×10^{-3}	20	Gerini et al. [60]	Kaplan
DLMPC	−98	−99.3	−98.2	−99.4	9×10^{-3}	125×10^{-3}	36	Gerini et al. [60]	Kaplan
LPF	−38.9	−65.1	−23.6	−61.8	179×10^{-3}	30	5.96	Narkhede [59]	Kaplan
LPF+DB	−43	−67	−40.8	−50.7	650×10^{-3}	20	16.25	Kadam et al. [58]	Kaplan
Unspecified*	−28	NA	−25	NA	650×10^{-3}	20	16.25	Valentín et al. [44]	Kaplan
Hydro recharge	−73.6	−97.8	NA	NA	5	50	100	Laban [1]	Kaplan
LPF	−78.4	−91.4	NA	NA	5	50	100	Laban [1]	Kaplan

usually the stand-alone operation of the HPP unit when delivering PFR. Information on the reduction of movements depending on the applied control strategy is summarized in Table 1. The reduction of movements in % is presented for different control schemes together with the regulation strength and ESS capacity. The available ESS capacity is compared with the PFR capacity, which varies for different PFR products described in the reviewed works. For example, the regulation strength investigated in the Vogelgrun power plant is 20 MW/Hz, but the PFR product to be delivered has a bandwith of 0.2 Hz the total regulation capacity P_{PFR} for the unit being 4MW. This can be compared with the FCR-N product in the Nordic system, which has a bandwidth of 0.1 Hz and a regulating strength of 50 MW/Hz, translating to $P_{\text{PFR}} = 5$ MW as studied in [1]. Another factor to be considered when comparing the reduction in mileage is that the time series for the studies vary in length and frequency quality, which affects the mileage and number of movements. Direct comparisons between studies should thus be made with caution. A sensitivity analysis performed in [1] concludes that estimations of HPP wear are sensitive to the frequency data used. Another point on the wear comparison is addressed in [44], stressing the importance of selecting an appropriate sampling rate to avoid measurement noise that could overestimate mileage when gathering this information experimentally. And as pointed out in [65], non-linearities present in HPP units are not captured in the models, which may lead to an underestimation of the reduction of movements in model studies compared to experimental studies, especially in the field. With the above caveats, the information in Table 1 is still interesting for comparison, and some conclusions may be drawn.

- Advanced control methods such as MPC reduce movements with smaller relative ESS dimensions compared to linear filters such as LPF,
- The stochastic nature of grid frequency calls for a modified dispatching of the hybridized unit to avoid over-dimensioning the energy content of the ESS.
- It is possible to reduce the number of movements by a factor 10^2 if allowing an ESS dimensioned to 36% of the PFR capacity to perform part of the regulation

Formulating accurate and relevant limitations for wear is critical for deriving an objective-based dimensioning criteria for hybridized ESS with the purpose of limiting mechanical degradation. There is a discrepancy between the utilization of parameters

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quantifying wear and the actual effects of the movements quantified. Wear on bearings is normally evaluated through the use of M_Y & M_α the connection of wear with the actual sliding distance of bearings [66] and the nominal load of the sliding material [67] is relevant for evaluating the physical wear. The difference in applied load has an exponential effect on wear over the number of load cycles. If this factor is not included in the wear estimate, it may induce a significant estimation error. Some of the sources reviewed has used Rainflow counting algorithms to estimate the movements contribution to the fatigue life consumption of the unit [44] [68], a necessity for a reasonable quantification of which movements are contributing to significant damage of the unit. High cycle fatigue will determine the lifetime of HPP components, which is primarily influenced by mean stress, stress amplitude and material properties [69]. Appropriate assumptions on these parameters yield an improved estimation of the wear mitigated when hybridizing the unit.

More advanced control methods such as the MPC method used by Gerini et al. [60] may be tuned to avoid movements that lead to actual physical wear as proposed to mitigate penstock fatigue by Cassan and Sossan [48].

2.1.2 | Non-Mileage Related Wear

This subsection treats non-mileage related wear and fatigue life consumption mitigated through hybridization, as mentioned in the introduction, this is more relevant for medium to high head turbines such as Francis or Pelton.

2.1.2.1 | Avoiding Harmful Operating Points. Liao et al. presents a control strategy for a hybridized hydropower-battery system with the goal to avoid vibration zones (VZs) [70]. A description of the zones and their avoiding in regular dispatch planning has been described in [71, 72]. The vibration zones described in the paper are occurring at high head situations and non-optimal operating points. VZs are classified according to severity as general vibration zones and forbidden zones. The forbidden zones can be compared to speed-no-load or partial load conditions as described by [49] for Francis turbines. The VZs are non-linear and site specific, but are simplified as rectangular operating areas in the article. The authors develop a control algorithm to avoid the VZ operating regions while also reducing distance and number of movements by the guide vanes while keeping the SOC of the ESS within desired limits.

The general principles that guide the control are specified as:

1. Operating point of HPP should neither stay in the VZ nor traverse them frequently.
2. The battery should avoid being overly charged or discharged.
3. Frequent movements and wide-range regulation of the HPP should be prevented.
4. Minimize the error between PFR control signal and hybridized unit.

The principle of the control is similar to what has previously been discussed, passing high frequency components to the ESS and a filtered error setpoint to the HPP. An additional control objective is included, defining operating points where the HPP shall not enter regardless of the PFR signal setpoint. When the PFR signal enters the VZs, all regulation is executed by the ESS. An illustration of the forbidden and VZs as illustrated in the work is presented in Figure 6 Simulations are performed to verify the hybridized operation using an auxiliary ESS of 20MW/5MWh. The study compares a base case of stand-alone operation with the hybridized operation of the proposed controller. KPIs compared are control accuracy, time operating in forbidden zone (T_{fbd}), time operating in general vibration zone (T_{vbr}) and a unit specifying regulation mileage implying wear on the unit (M_r). It is assumed this parameter corresponds to M_Y. Key results from the comparison are presented in Table 2, where the reduction of M_Y is compared to a HPP unit operating independently. Four scenarios reflecting different operating conditions are investigated.

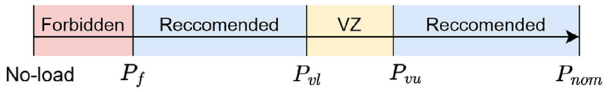

FIGURE 6 | Forbidden zones, recommended zones and vibration zones as illustrated by Liao et al. in [70].

TABLE 2 | Operating scenario, and reduced mileage M_Y compared to standalone operation [70].

Scenario	M_Y [%]
Operation in recommended zone [%]	63
Operation in forbidden zone [%]	99.6
Operation in general vibration zone [%]	99.8
Operation traversing the general vibration zone [%]	38

The HPP effectively avoid entering or frequently traversing VZs. The HPP flexibility is enhanced and the hybridized unit has a considerable decrease in regulation movements. The significant reduction of regulation mileage in the scenarios when operating in the forbidden and general vibration zone is due to the HPP unit not entering the vibration zone, and the ESS performing all of the regulation. The control strategy change from what can be classified as a frequency split, to fixing HPP output when the regulation signal enters the vibration or forbidden zone where the ESS perform all regulation. The effect of this is evident from the reduction of mileage in Table 2, and illustrated in Figure 8 with the description "operating point aversion". The authors suggests a discussion on the capacity of the battery as future work [70]. The limited ESS capacity studied can only narrow the vibration zones, not eliminate them. The authors suggest a techno-economic evaluation of an ESS with larger capacity.

2.1.2.2 | Mitigating Penstock Fatigue. Cassano & Sossan investigate the mitigation of penstock fatigue arising in medium head turbines in [48]. Penstock fatigue is relevant for medium- to high head hydraulic power plants and is caused by water hammers resulting from rapid variations in the power setpoint, operating conditions which may be induced by PFR provision. The study presents a model predictive control (MPC) strategy for the HPP unit, adjusting the setpoint of the HPP to limit

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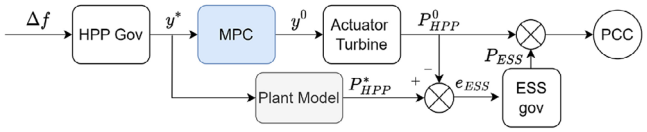

FIGURE 7 | Illustration of real-time MPC model developed by Cassano & Sossan in [48] to mitigate penstock fatigue in medium-high head turbines. MPC higlighted in blue.

mechanical stress. The MPC algorithm modifies the output of the HPP by minimizing a cost function formulated to avoid physical wear, and reiterates the BESS power setpoint to compensate for the adjusted power from the turbine. See Figure 7 for a higher level schematic of the control. The limitations on penstock stress serve as the basis for formulating the cost function under the assumption provided by Wohler's curve for ferrous materials, according to which cycles below a certain fatigue limit ($\overline{\Delta\sigma}$) do not accumulate fatigue. The water head H induce force and thus stress on the penstock. Departing from characteristic curves for the turbine, derived from experimental results, non-linear models for water head H_t and torque of the turbine T_t, dependent on rotational flow of water Q, rotational speed ω and guide vane opening y are derived. The models are linearized by considering the penstock's resistance as a constant value, and the turbines head H_t and torque T_t as a first order Taylor approximation. The linear model is expressed as a discrete time state-space model and can be used in the MPC control. Limitations for guide vane operation are presented considering ($\overline{\Delta\sigma}$), and the MPC selects a new guide vane set point while minimizing the squared deviation between the new and original set points. The contribution of the ESS is calculated as the difference between the original and the selected set points. The authors present the capacity needed from the ESS to mitigate penstock fatigue but do not specify the ESS's energy content. The proposed MPC is compared to a traditional LPF with a cut-off frequency of 1.46 Hz, which has a regulation power comparable to that of the MPC. A comparison of a relative damage index across the penstock shows that the damage index of the proposed MPC outperformed the LPF solution (and utilized the BESS to a larger degree).

2.1.2.3 | Comparative Remarks. Ensuring operation at nominal operating points is important for minimizing the premature ageing of Francis runners [73] [49], a concern that Liao et al. addressed in [70]. Avoiding an operating point places greater demands on the energy content of the auxiliary ESS, as noted by the authors. The control strategy to fully avoid an operating point is relevant to include in a fundamental framework for mitigating wear and tear on HPP units, presented alongside hydro recharge and frequency split in Figure 8.

Cassano and Sossan discuss a different driver for mechanical failure in their study [48]. In which the ESS facilitates the avoidance of certain transient movements that lead to water hammers and penstock fatigue, preventing transients results in power intensive rather than energy intensive dimensioning requirements for the ESS [74]. The authors also include a non-linear filter in [74], which reduces the fatigue life consumption of the penstock compared to the linear LP-filter used as the benchmark in [48]. This reinforces the assumption that linear filters are not optimal for reducing wear in HPP turbines. The approach taken in the study by Cassano and Sossan, which identifies the movements contributing to actual fatigue life consumption, could be applicable to derive a more stringent reduction for wear related to mileage and movement.

Figure 8 presents how the active power is shared between the HPP unit and the auxiliary ESS using the three control strategies: hydro recharge, frequency split and operating point aversion.

2.1.3 | Optimization of Energy Storage System Dimensions

Many studies mentioned to this point select the dimension of ESS somewhat arbitrarily or heuristically. This section highlights methodologies for selecting dimensions of the auxiliary ESS in hybrid hydropower units.

2.1.3.1 | Techno-Economic Considerations. Quantifying operational costs and lifetime estimations of the ESS through appropriate degradation [75], wear and operational costs of HPP, and the capital cost of the auxiliary ESS presents a techno-economic optimization problem.

Casarín et al. present a solution for reducing wear and tear in a pumped-storage hydro power plant (PSHP) using flywheels and batteries [56, 76]. The solution consists of a power dense energy storage system in the form of a flywheel energy storage system (FESS) combined with a BESS. The inclusion of FESS is proposed to improve the lifespan of the BESS. An estimate of BESS degradation regarding cycling is included using the mean SOC value, the number of charge/discharge cycles, and their depth. The distance moved by the guide vanes M_Y is used as a wear estimator, together with an index that includes the shaft torque and its fluctuations, to keep track of movements contributing to wear on the variable-speed pump (Mei Wang Fluctuation Index [77]). The techno-economic optimization analysis includes capital costs and wear indicators M_Y, N_Y, as well as the Mei Wang fluctuation index. The authors are transparent about the limitations of these estimations regarding the extent to which they contribute to the wear of the plant and suggest that they should be used to gain qualitative insight into the reduction of wear. A power ramp proposed by [78] is used to establish the cost of regulation movements as a fixed expense per regulation divided by the time taken to perform it. the faster the change in output power, the higher the cost.

One hundred combinations of BESS and FESS were analysed, ranging from 0.5 to 5 MW, while evaluating the criteria for wear. The study does not consider varying the energy content of the BESS and FESS in the optimization but fixes the energy content to 1 MWh per MW of power. Similarly, the FESS model had a fixed speed range of 6000 to 9000 rpm. The hybridization of BESS and FESS indicates that wear induced by BESS cycling was reduced by at least 45%. The study concludes that there is no optimal solution to reduce wear of BESS and PSHP while optimizing capital costs, as there are tradeoffs between the objectives. A configuration of 2 MW/2 MWh BESS and 1.5 MW FESS capacity is suggested as a suitable tradeoff to reduce capital investment while still achieving increased commercial revenue and reduced operational costs. In contrast, while the configuration that minimizes PSHP wear is 5

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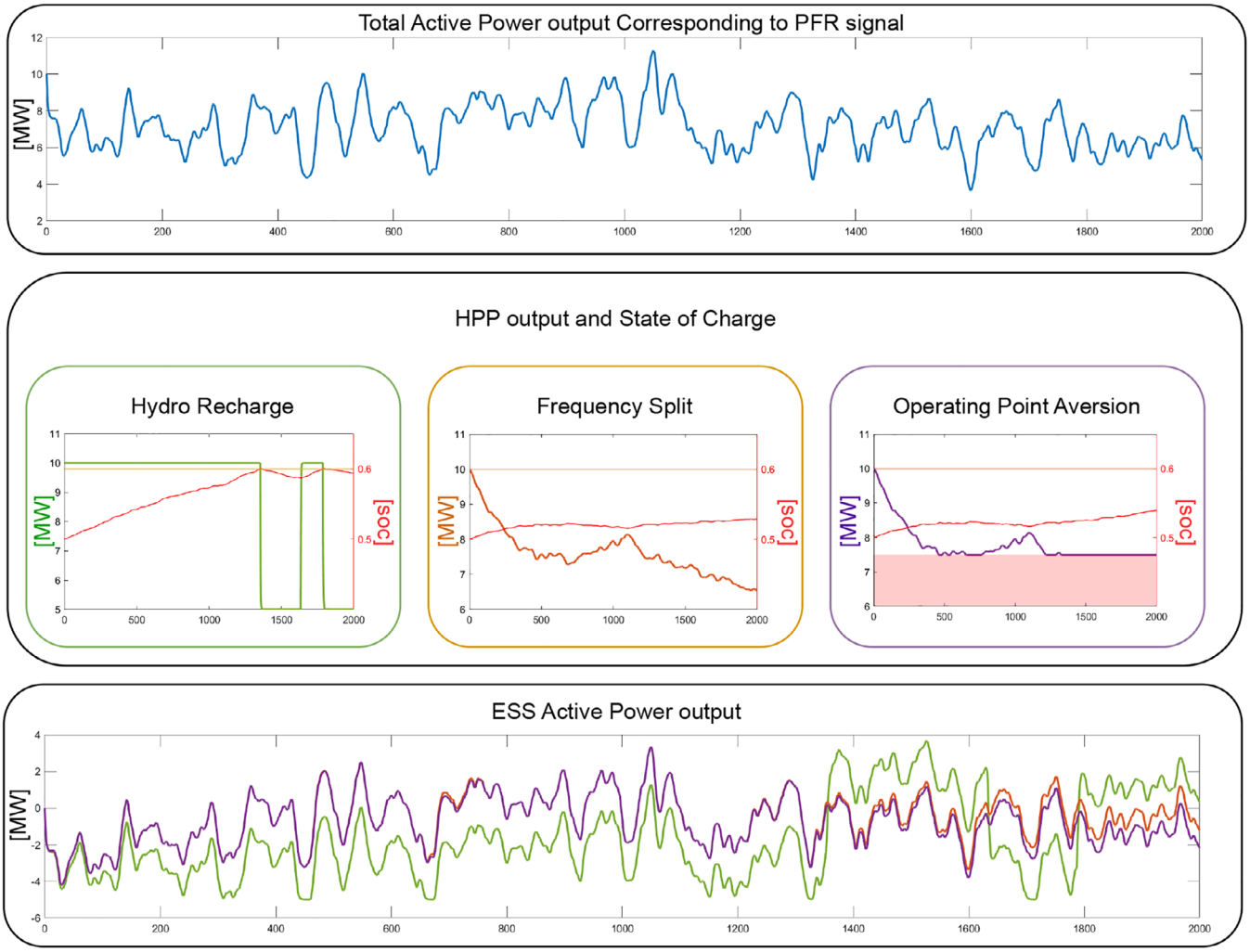

FIGURE 8 | A graphical representation of the primary control strategies suggested in the manuscripts reviewed regarding decreased wear on HPP. hydro-recharge, frequency splitting and avoided operation condition is illustrated, the three control strategies placing individual requirements on the HPP and ESS subsystems.

MW/5 MWh BESS and 4.5 MW FESS. The analysis considered potential revenue from PFR markets and secondary regulation markets (FRR).

An attempt is made to estimate the cost savings from reducing the number of movements in [59], where the frequency split control algorithm is investigated using a techno-economic study. Comparing M_Y, N_Y, M_α, N_α from simulations of an HPP unit and auxiliary ESS with varying sizes and capital expenditures (CAPEX). The study suggests an ESS with dimensions that qualify for TSO requirements if these have not already been met. The added benefit of increased revenue motivates the CAPEX in ESS and shows a reduction in HPP wear, especially during high frequency fluctuations. The work identifies increased reduction in wear parameters with increasing ESS power. The work highlights that wear can be estimated using the movements of Y and α, but the actual cost of wear is difficult to determine. Results for the reduction in performance, according to 1 h of frequency test data, are presented in Table 1. The ESS power rating of the proposed system is 179 kW, with 134 kWh of energy storage to support a turbine delivering 3 MW of PFR.

2.1.3.2 | Optimizing Against Requirements. The case proposed by Narkhede [59] of dimensioning ESS to meet TSO requirements is further explored by Laban and Lundin, who motivate their study of selecting an optimal storage system design for improved primary frequency response from hydropower units [79]. The study utilizes the revised PFR criteria in the Nordic synchronous area, specifically the stability and performance criteria in the frequency domain. Their study focuses on dimensioning an ESS to augment the performance of HPP in order to meet the upcoming Nordic FCR criteria. Evaluating the frequencies at which the units do not meet either of the criteria, a bandpass filter is designed to control the ESS, with a gain normalized to the PFR capacity of the plant.

$$F_{bp}(s) = \frac{K_{bp} w_l s}{s^2 + (w_h + w_l)s + w_h w_l} \tag{3}$$

The filter gain (K_{bp}), cut-in (w_h) and cut-off (w_l) frequencies ensure that the ESS provides the minimum gain and phase shift required to meet the criteria in the frequency domain. Time variant simulations of the ESS contribution during the qualification tests are used to estimate the energy content needed from the ESS.

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TABLE 3 | Optimization results from [80] three hydropower units are considered and three energy storage technologies with associated costs of power, energy and degradation effects. The cut-in and cut-off frequencies are omitted from the original table.

Technology	Z^{opt}	P_{ESS}^{opt} [kw/MW]	W_{ESS}^{opt} [kWh/MW]	L^{opt} [years]	C_{min} [EUR/MW-year]
Unit 2					
BESS	99.9	102.9	26.4	4.2	9677
FESS	10.4	102.9	2.8	9.2	12,919
SCESS	1.6	103.4	0.4	6.9	8335
Unit 3					
BESS	15.0	27.7	18.7	5.2	3135
FESS	1.0	27.6	1.12	8.1	4217
SCESS	1.0	28.3	1.0	12.4	5793
Unit 6					
BESS	14.5	142.3	166.2	5.3	20,661
FESS	1.0	142.3	11.5	8.9	26,606
SCESS	1.0	179.6	4.6	10.4	29,696

8 units were evaluated, and the ratios of P_{ESS}/P_{PFR} varied between 3.6% and 24.4%, with energy ratings corresponding to 13 to 157 s of nominal power discharge of the ESS. The method is generalizable and applicable to units with appropriate test data.

2.1.3.3 | Technology Selection and C-Rates. The method developed in [79] is further explored in a techno-economic optimization regarding which ESS technologies is most suitable to supply the designed power and energy requirement of the bandpass filter [80]. The study utilizes results from the optimal ESS capacity and energy for three units described in [79]. Information on the capital cost, maintenance cost, round-trip efficiency, and cycling life (based on depth of discharge and number of cycles) of batteries, flywheels, and supercapacitors is included to estimate the life cycle cost of the systems. An over-dimensioning parameter Z allowing for the adjustment of energy-content W_{ESS} is included in the optimization, as the depth of discharge affects the lifetime of the possible systems. To obtain representative cycling of the ESS, the operation is simulated using grid frequency data from four full weeks: the first week of March, July, October, and December 2022. The weeks are chosen to represent the seasonal variations in frequency while retaining the yearly average quality. The equivalent full cycle approach is used to determine the ESS degradation and lifetime in years L. The capital and operational costs are normalized according to the PFR capacity supplied and the estimated system lifetime. The optimization results regarding capacity, energy, and cost for the units described in the study are presented in Table 3, where the power and energy are normalized according to the PFR supplied from the plant. The optimization procedure does not account for HPP wear or potential revenue, as this is not the aim of the study.The benefits of evaluating the performance of the HPP against requirements in the frequency plane, as described in [79], include the granularity of the derived results. A unit that has issues meeting the stability requirements for higher frequency oscillations requires more power and has lower energy needs than a unit that fails to meet performance requirements at mid-range or lower frequencies. For a description of the PFR-requirements in the Nordics, see [15].

2.1.3.4 | Comparative Remarks. An introductory remark to conclude this section concerns the volatility of price and revenue estimates. The prices of BESS have fallen [17], and revenue from PFR in the Nordics has experienced dramatic shifts due to changes in supply and demand as well as wholesale electricity prices over the period 2019-2024 [23]. Deriving techno-economically optimal solutions is not an easy task, considering the moving targets. For the reader to use studies on the subject, the choices made regarding assumed costs and revenues must be transparent, and conclusions on technology selection may change depending on developments in CAPEX for different technologies.

The approach taken in [56] is a rigorous techno-economic optimization that includes CAPEX, OPEX (of ESS and HPP), and potential revenue. Due to the knowledge gap relating to the operational cost of the HPP unit, the source utilizes a cost index based on somewhat arbitrarily chosen ramp-costs [78]; however, the authors are transparent about the selection and the uncertainties. Some key parameters are locked in the study, such as the choice of FESS and BESS, along with their dimensioned energy in relation to the power.

Narkhede et al. perform a techno-economic evaluation in [59]; however, the determination of costs incurred from additional movements due to PFR regulation makes it difficult to estimate the gains for the HPP units.

The optimization algorithm proposed in [79] is not a techno-economic optimization but proposes a generalizable method to dimension and control an ESS for a specific purpose: the qualification for PFR markets for HPP units that do not meet the requirements for stand-alone operation. The study, however, does not include SOC management, which may require adjustments to the suggested energy content. Another optimization process is suggested in [80] to evaluate which ESS technology is optimal for reproducing the power and energy content proposed in [79]. The results from the study are somewhat counter-intuitive, as a BESS with a large over-dimensioning factor arrives at the most cost effective solution for two out of the three units investigated,

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while supercapacitors are the most cost efficient when the energy need from the ESS is very low (see Table 3).

Some reflections can be made from these studies. The first point is that site specific optimizations are needed, as HPP performance varies; the ratings of ESS correspondingly influence the optimal selection of technology. Secondly, the approach is sensitive to the capital cost of the ESS; depending on how the costs for the ESS develop, the results from using the method will differ. From the perspective of HPP operators, a larger energy capacity may be desirable, as the ESS could be used for services beyond PFR, thus mitigating the risk of exposure to a single market. Expanding the use-case would, however, also alter the cycling of the ESS, inviting a reiteration of the optimization procedure including multiple objectives in the analysis.

2.1.3.5 | Reflections on Wear-Cost Modeling. A concluding remark on the section highlighting the commercial objectives for the hybrid operation of hydropower summarizes the authors reflection on the parameters affecting wear and fatigue life damage. Wear and fatigue due to regulation load cycles are summarized and distinguished below:

- Wear is a function of contact pressure, accumulated distance travelled, and the wear coefficient. Thus, the wear of servos in Kaplan and Francis units is proportional to the accumulated distance travelled [43], but a function of contact pressure due to regulatory forces should be included to avoid under- or overestimating wear.
- Fatigue life consumption due to load cycling is estimated through stress-cycle diagrams, where primarily the higher amplitudes will impact fatigue life, while low stress amplitudes will not have any effect [44, 48]. To assess fatigue life consumption, knowledge of the forces involved is necessary, and the number of movements is suggested not to be an adequate index for estimating fatigue life. A closer dialogue between turbine manufacturers and scholars aiming to mitigate fatigue damage through hybrid operation may help bridge this research gap.

Fatigue of Francis runners due to off-design operation is a different phenomenon, and the desire to deliver PFR induces operation at non-optimal operating points, subjecting the turbine to a higher degree of relative damage due to vibration and cavitation [49].

It is outside the scope of this review to weigh the drivers and costs of wear and tear, but the authors want to highlight that 1. drivers for wear and fatigue must be separated, and 2. indicators of wear must correlate to physical damage and lifetime [43, 81]. If this gap is bridged, stringent design requirements for hybrid systems to mitigate operational costs may be formulated.

2.2 | Enhancing Grid Resilience and Security of Supply

Up to this point, participation in PFR markets and reduced operational costs have been the focus. The works reviewed in the upcoming section focus more on perspectives not directly related to commercial markets. The section begins by reviewing works that focus on describing the stability regions of HPP in detail and later follows studies investigating grid resilience through improved island operation, isochronous control and black start capability with the addition of auxiliary ESS coordinated with HPP units.

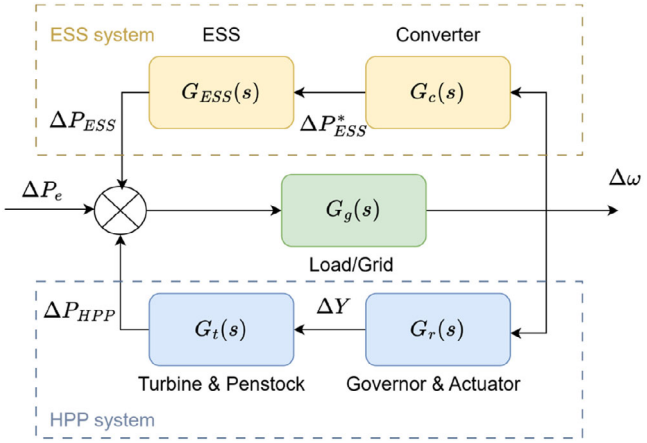

FIGURE 9 | Figure used to describe the integrated system model of ESS, HPP and grid/load used to derive the open loop transfer function by Liao et al. [31].

2.2.1 | Stability Improvement Through Hybridization

Due to their dispatchability and response time, Hydropower units have been used for primary frequency regulation (PFR) or load regulation since their inception. The issue of defining the operating conditions and governor parameters under which the system is stable has been treated in the last 70 years [82]. Many references describe in detail the stable regions of the hydropower unit, using the Routh Hurwitz criterion [83] and eigenvalue analysis on state-space representations of the system studied [84]. Frequency stability is intrinsically related to the system in which the PFR providing entity is situated [85]. The stability of the system in which the HPP unit regulates frequency is dependent on parameters affecting the speed, linearity and accuracy of the HPP unit, such as water start time, mechanical start time of the generating unit and the electrical and mechanical damping present in both the unit and the governed system. Stability criteria must be reiterated depending on the system to be controlled, as reflected in the revised PFR criteria in the Nordics [21]. Island operation and operation in an isolated grid or during system splits are examples of challenging operating conditions for the governing unit, investigated in the stability studies highlighted below.

Liao et al. present a stability analysis in [31]. The scope of the paper is to investigate the mechanisms of battery hybridized hydropower plants, the characteristics of battery control strategies, and the regulatory performance of these systems. The study investigates how ultra low frequency oscillations (ULFO) may be mitigated, and how a single HPP unit is operating under varying loads in an isolated grid. The integrated system is presented in Figure 9, where transfer functions of ESS, HPP and the grid represent the three systems. The study includes a stability

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analysis using root locus and participation factor methods for three different battery control strategies, quantifying the effects on the stability of the hybridized unit compared to a stand-alone HPP, using the Hurwitz stability criterion. The study contributes insights into the increased stability regions of the hybridized power plants and presents a framework for understanding the interplay of the state variables identified in the state space model of the integrated hybridized system. The battery control strategies investigate three main cases:

- Droop control gain $P_{\text{BESS}} \propto f$
- Synthetic inertia $P_{\text{BESS}} \propto df/dt$
- Synthetic control $P_{\text{BESS}} \propto f \;\&\; df/dt$

including a proportional gain K_e and a derivative gain M_e for the ESS. The outer loop controller equation of the ESS incorporating the proportional and derivative gain is:

$$\Delta P_{\text{bset}} = -M_e \frac{d\Delta f}{dt} - K_e \Delta f \tag{4}$$

where f is the system frequency, P_{bset} is the active power command output for the battery. The open loop transfer function of the system is modified according to the control strategy of the ESS. A discussion on battery capacity contribution to stability is conducted, departing from a suitable selection of control parameters K_e determining the damping effect and M_e the inertial effect. A simulation of the hybridized system perturbed by a 10% load, presents a plane of the ESS capacity as a function of K_e & M_e, increasing ESS capacity with increasing proportional and derivative gain factors. Imposing an assumption of a battery limitation of 5% of the HPP unit, the plane of K_e & M_e parameters is constrained to ensure that the battery operation does not exceed its rated value while still contributing to a stable primary frequency response performance. A sensitivity analysis on ESS capacity is conducted, indicating that the stability regions can be expanded by increasing the ESS capacity. The study presents a structured framework on how the mechanisms of PFR for a hybrid HPP unit are modified by the inclusion of additional hardware (ESS), and the control strategy of the ESS. Results from the study suggests that a larger K_e alleviates the ULFO effects, while increasing M_e moves the system deeper into the ULFO-area in the root locus analysis.

2.2.2 | Control Strategies for Black Start and Islanded Operation

Ojo et al. present a control methodology for the improved frequency response of small hydropower units in [30]. The primary objective of the study is to evaluate the improved frequency response for disturbed operational states, such as island or microgrid operation. The control method includes a frequency controller that produces the active power references based on the frequency derivative and proportional control. A voltage and current control loop for a DC–DC inverter used to integrate the ESS is described and presented. The feedback loops include a bounded integral control strategy that guarantees closed-loop stability independent of the plant. The control includes SOC-management of the ESS. The ESS utilizes the fact that it is co-located with the HPP unit and employs a grid-following control strategy. The proposed controller is investigated from several perspectives. A stability analysis of the plant, including ESS, is conducted using the root-locus method to evaluate stability regions for the proportional and integral gains of the HPP. Transient simulations of load steps are investigated to determine the bounding frequency for large transients. A case investigating extended loading conditions is also presented, increasing the load in the system and evaluating at what loading the system frequency collapses. The resource is a detailed description of the implementation of a stringent and stable frequency controller to support the HPP unit. It includes a current and voltage control scheme that incorporates the frequency controller on the DC–DC converter interface of the ESS and the inverter interface to the PCC.

Shafiul Alam et al. present a hardware in the loop Hydropower and supercapacitor test-bed in [28] with the stated objective of studying the black start capability of a run-of-river (RoR) hydropower plant (HPP) system combined with an energy storage system (ESS) consisting of supercapacitors. The study provides a detailed description of the technical implementation of the system, demonstrating that an efficiently scaled energy system can enhance the capability of HPP units to provide black start and island operation. The control of the SC ESS is droop based, and the authors investigate different droop settings and frequency deviations when applying a load in an islanded system, observing that the frequency nadir improves with the integration of the SC ESS. The study suggests that hybridizing an HPP with an ESS, delivering fast frequency reserve, enhances the capability for black start and controlled operation in island conditions.

2.2.3 | Inverter Control Modes (GFL vs. GFM)

Yan et al. have conducted a study on regional power system black starts with a run-of-river hydropower (RoR HPP) unit and BESS in [27]. The study investigates reconstructing a regional power system using a hydropower generator and BESS. The study investigates the BESS used to damp frequency oscillations in grid forming (GFL) and grid-following (GFM) control modes. The work contributes to understanding how BESS may be used in combination with HPP for increased resilience in black start situations. The study investigates different placements of the BESS in the regional power system and evaluates GFM and GFL control methodologies. The BESS operating in GFM provides the best damping when placed closer to the critical load in the system, where it may energize a portion of the critical load and decrease the load step needed on the hydropower generator, which faces limitations in its response to load changes in islanded grids, as described in [30] and [28]. A BESS operating in GFL supports the system best when placed close to the voltage and frequency regulating entity in the power system, that is the HPP unit. When the GFL ESS is placed adjacent to the synchronous generator, it may provide stability enhancement functions during the early stage of the system restoration process. An illustration of the ESS co-located with the HPP unit operating in GFL is presented in Figure 10a. Figure 10b illustrates when the ESS is located near the critical load and must operate in GFM while contributing to black-start capability.

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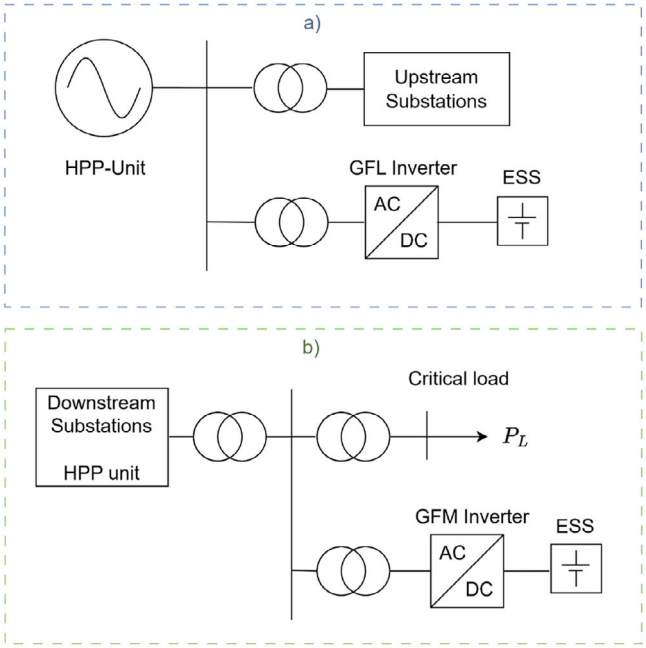

FIGURE 10 | Simplified illustration of ESS connection from [27]. The ESS is co-located with HPP unit in (a) and located in close proximity to the critical load in (b).

2.2.4 | Dimensioning ESS for Islanding Transition

A study by Sunjaq et al. [29] investigates the smooth transition to islanded operation for a microgrid that includes a hydropower plant and a pulp and paper factory. The ESS is integrated using the GFM control strategy, and the paper outlines a comprehensive method for designing and tuning a frequency controller to ensure that the transient frequency deviation $\Delta f^{\max}$ and steady state frequency deviation $\Delta f_{ss}^{\max}$ are maintained within desired limits. The work utilize the limitations in steady state gain and ramp rate of the HPP unit to design appropriate transient and steady state gains for the frequency controller of the ESS. The study evaluates the controller in simulation and laboratory tests and concludes that the ESS energy capacity is largely dependent on the steady-state droop and transient response of HPP unit, while the power capacity is related to the dimensioning disturbance of the microgrid.

Kim et al. present a coordinated frequency controller (CFC) dispatching power commands to a SCESS and HPP (variable speed pumped storage hydropower) to enhance short-term frequency stability [86]. The power setpoint control of the PSHP and SC-ESS uses variable weights, wherein the contribution from the SCESS is scaled according to its operating voltage to avoid tripping, including a SOC parameter in the control algorithm. The result is a dynamic droop gain that increases when the SOC of the SC is within stated limits and decreases when the SC voltage exceeds those limits. Time domain simulations are presented in a test system consisting of a 20-MW SC-ESS, a 50 MW PSHP, a variable load, and a synchronous generator to represent the remainder of the power system. The source presents relevant conclusions for commercial aspects, as the proposed controller increases the available PFR capacity while efficiently reducing the nadir of the frequency deviation following a large disturbance. It utilizes the SCESS to arrest frequency deviation while respecting the energy constraints of the supercapacitors, allowing the HPP to restore the SOC. The work continues the development of a dynamic SCESS model in [87].

2.2.5 | Comparative Remarks

The improved stability and damping from including an auxiliary ESS have been investigated by several studies mentioned above. The scope has narrowed during the last few years from broader proof-of-concept studies [87, 88] to experimentally driven and developing HIL platforms [28], and to the application of these tools for complex control design [30] and regional power system analysis [27].

Liao et al. investigate the stability mechanics of the hydropower unit governor settings and how these are affected by the inclusion of the ESS and its control [31]. Ojo et al. describe a similar frequency controller, contributing both synthetic inertia and proportional control, while including operational constraints on the ESS. The contribution of Ojo et al. also extends to proposing current and voltage control schemes that incorporate a frequency control policy, guaranteeing stability in the feedback loop [30]. The level of detail in the sources complements each other.

Several studies investigating the grid resilience aspects of the combination of ESS and HPP include the perspectives of GFL [30, 89] and GFM [27, 29] inverter control, leading to interesting discussions regarding the placement of the ESS and its contribution of value depending on placement and control strategies. These results may contribute to further discussions on the optimal placement, dimensions, and control of the ESS resources, as partly discussed in the comparison of co-optimization and virtually connected power plants in [39]. The dimensioning factor for the ESS in [27–29] is the critical load or disturbance that the islanded system or microgrid must withstand, or that the black-start system must energize [26]. Further development of a method to dimension ESS capacity according to a disturbance is an increasing path for future work.

2.3 | Meta-Analysis of Literature and Industry

This section is dedicated to quantifying the contributions from the aforementioned literature, and commercial hybridized HPP in the Nordics is included in the analysis.

2.3.1 | Normalized ESS Capacity Across Use Cases

Figure 11 presents the dimensions of the auxiliary ESS in relation to turbine capacity. This is the most basic index relevant for comparing a large share of the works studied.

The comparison in Figure 11 is available as a reference for the reader. The works investigating "PFR qualification" span between 0.5%–1.2% "improved PFR capability" and "reduced wear" span between 1.5%–18%. When the objective is on shifting larger power and energy content as in Chalishazar et al. [36], the ESS storage system is dimensioned above 60% of the HPP.

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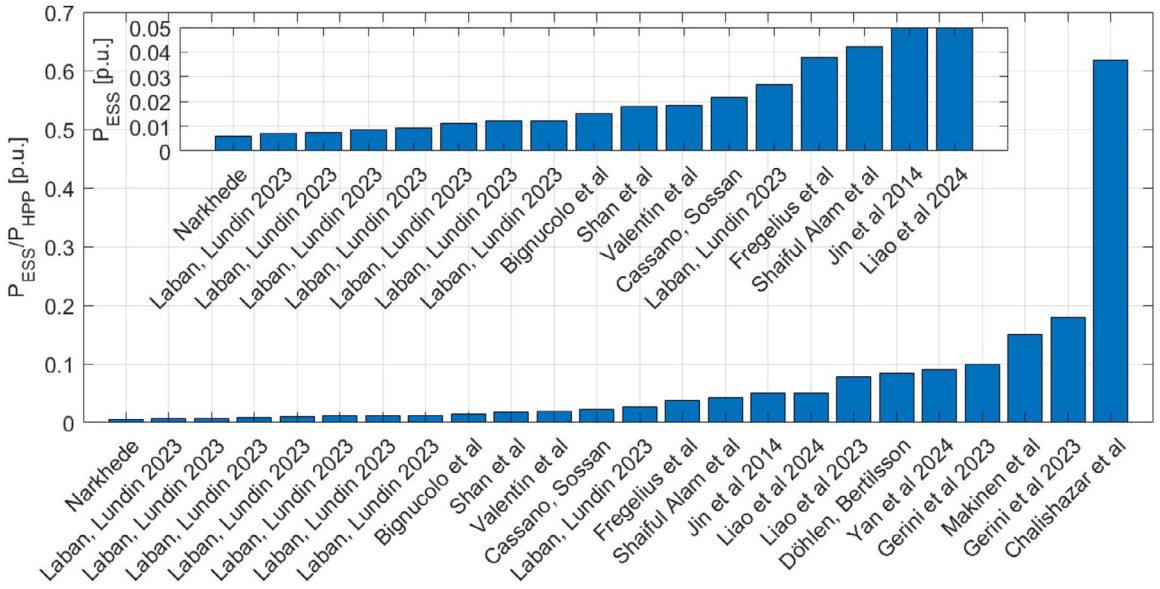

FIGURE 11 | Quantitative comparison of references specifying capacity of ESS and capacity of turbine to be hybridized.

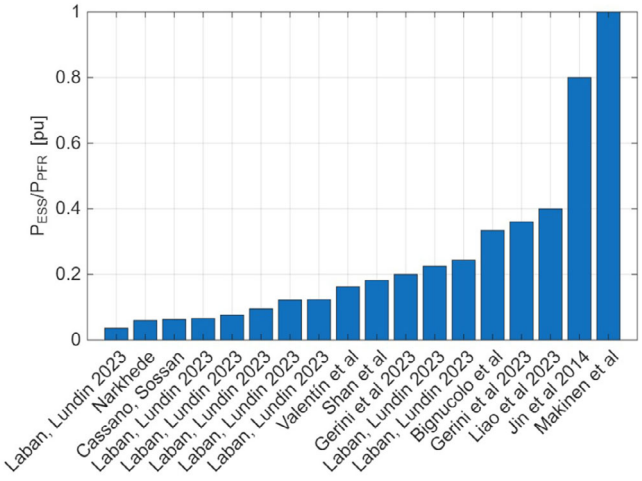

FIGURE 12 | Compilation of data from sources specifying ratio of auxiliary ESS and pre-qualified PFR capacity.

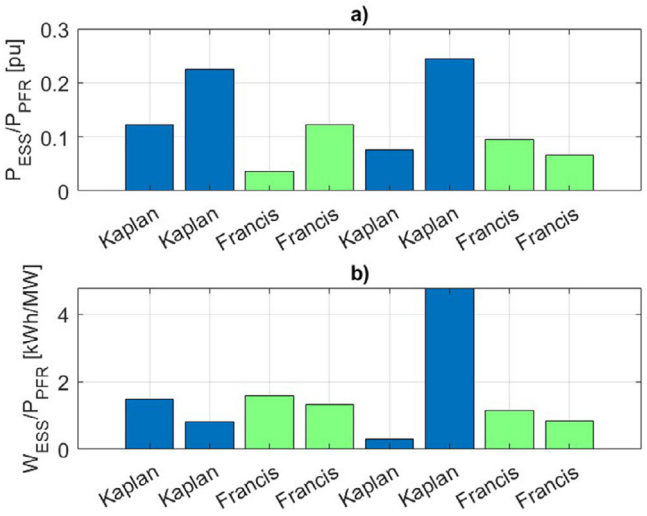

FIGURE 13 | Results from Laban et al. [79] on ESS capacity needed to pre-qualify units for PFR delivery in the Nordics presented in (a). Energy content needed to pass the pre-qualification tests presented in (b).

2.3.2 | Pre-Qualification for PFR: Literature Versus Practice

A more relevant comparative index when investigating the contribution of PFR is the ratio of auxiliary ESS to the qualified capacity of PFR. A compilation of the referenced works with available information on these parameters is presented in Figure 12. A point made earlier that should be reiterated when analysing Figure 12 is that several sources suggest that ESS dimensions are either arbitrarily chosen or defined through comparisons with others. Also, objectives differ between reducing wear and qualifying for PFR services. The only source analysed in this work which conducts an optimization on ESS dimensions not dependent on potential revenue is performed in [79] and presented in Figure 13. Figure 13a presents capacity from ESS to qualify for PFR delivery and Figure 13b presents energy content needed. The figure is included to illustrate the individual dynamics and differences between HPP units and how this reflects on ESS dimensions for power and energy to meet stringent criteria.

2.3.3 | Technology Trends

Figure 14 presents an index relevant to technology selection, defined as the ratio of power capacity to energy content for the proposed ESS. The figure has been derived from sources that specify the energy content of the ESS. The *y*-axis denotes the C-rate of the systems, an index derived from comparing the nominal output power of the ESS with its energy content. The C-rate is commonly referred to as the charging and discharging ratios of energy storages compared to their rated capacity. In the works reviewed, when the power capability and the energy content of an energy storage system are given, the C-rate is used as a metric

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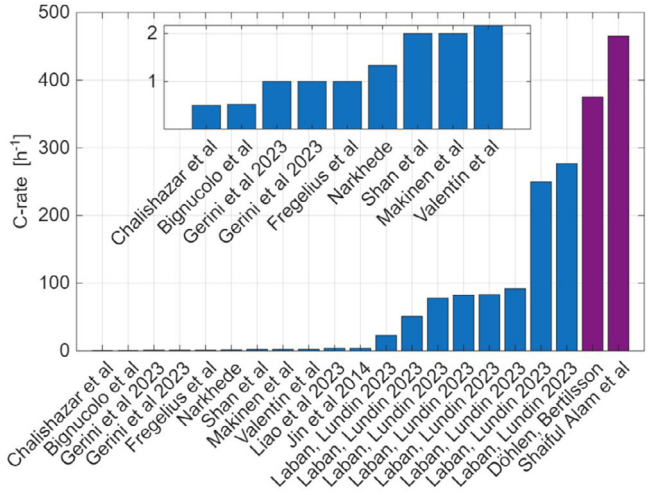

FIGURE 14 | Ratio of energy and rated power, or C-rate of reviewed systems from literature. Purple bars denote systems explicitly consisting of supercapacitors.

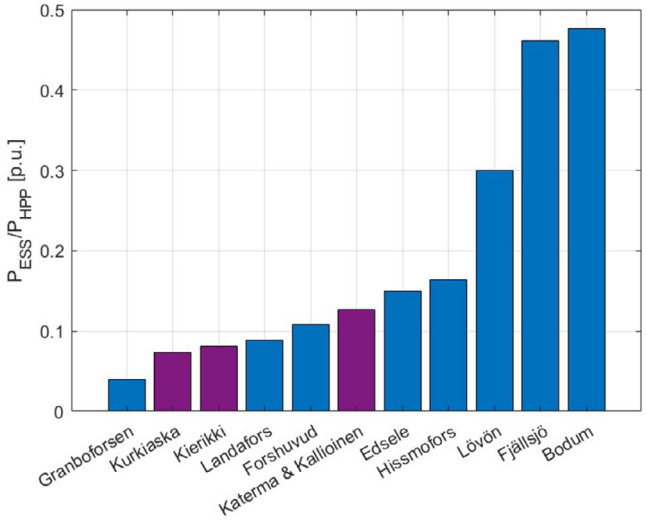

FIGURE 15 | Barplot of P_{ESS} normalized to HPP unit, data retrieved from public information on industry investments. Purple bars are supercapacitor-based systems.

to describe the ratio between the installed power in kW and the installed energy in kWh. The C-rate in Figure 14 assumes that the energy storage system can charge and discharge at the power defined in the references.

Although there is much research interest in increasing charging times for Lithium ion batteries, values above 6C cause rapid deterioration of negative electrodes [90], indicating that batteries are not suitable ESS technology for ESS configurations with high C-rates if the ESS is charged and discharged symmetrically (discharge rates for Lithium based batteries are often higher than their charging rates). The systems presented in the inset have C-rates between 0.5 and 4 C, which is a suitable range for lithium ion batteries. For the systems with the highest C-rates in the figure, supercapacitors are explicitly mentioned as the proposed ESS technology, denoted in purple [91] & [28]. Some studies propose flywheels [56] or leave the proposed ESS technology unspecified.

Chalishazar et al. [36] is a study investigating the objective of reducing hydropeaking. This datapoint is an outlier compared to the other objectives for hybridization in terms of the relationship between dimensions of the ESS compared to the HPP unit. A large energy content is needed to mitigate peak power production in the HPP unit [36], placing the study in the lowest end of the C-rate spectrum presented in Figure 14 and the far right in Figure 11.

2.3.4 | Insights From Industry

From the survey of investments made by industry into hybridization projects the following investments were identified. In Sweden, Uniper [92], Fortum [64, 93], and Jåmtkraft [94] have invested in 55 MW of BESS co-located with HPPs since 2019. An interesting contrast to the expansion of HPP with BESS in Sweden is a wave of investments in supercapacitor based systems in Finland, mentioned in [53]. Kemijoki Oy invested in a 2 MW supercapacitor based system (SCESS) with the goal of providing Fast Frequency Reserve, co-located with the Kuriaska power plant in 2023 [95]. PVO Vesivoima made an investment decision to invest in a 3 MW SCESS co-located with the Kierikki power plant in 2023 [96], and UPM Energy invested in a 3 MW supercapacitor plant to support the two HPP units, Katerma and Kallioinen, with an established grid connection in 2022 [97]. An additional installation is scheduled to be installed at the Kuusankoski site in the summer of 2025; however, dimensioning data is not available [98]. Hybridization projects in Norway are not as common, however an investment decision was made in 2024 to hybridize Mørre HPP, a 14 MW Francis turbine with a 2.5 MVA BESS system [99] [100].

Figure 15 presents industrial investments, the ESS capacity is normalized with the turbine capacity. Supercapacitor based ESS projects are highlighted in purple. A summary of industrial investments is presented in Table 4.

3 | Discussion

A quantitative comparison of ESS system dimensions for hybrid HPP operation has been presented. Differences in methodology and assumptions are important aspects to consider when analysing the results of the meta-analysis.

As discussed in Section 1.2, wear in hydraulic turbines varies depending on the turbine and operating conditions. A hybridized unit designed to avoid certain operating points will differ from a design aimed at minimizing the movements of guide vanes and runner blades. The reduction of the distance moved by the servo-motors is a performance indicator often referenced in the literature. Recent work suggests that the use of nonlinear filters is more efficient than traditional low-pass filters in reducing mileage related wear on the HPP [68] [60]. An in depth comparison of wear mitigation using a greater variety of filters or control algorithms has not been conducted. None of the studies quantify how reduced wear indicators affect the lifetime or operational costs of HPP, as previously mentioned. The authors would like

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TABLE 4 | Results from publicly available information on hybrid HPP units in the Nordics. Vogelgrun powerplant in France is included as comparison as it has been referenced in the previous sections.

Power plant	Turbine rating [MW]	ESS capacity [MW]	ESS energy [kWh]	Technology	Operator	Commissioned
Forshuvud	46	5	6200	BESS	Fortum	2019
Landafors	11.2	1	250	BESS	Fortum	2021
Granboforsen	25	1	1100	BESS	Jåmtkraft	2021
Edsele	60	9	9000	BESS	Uniper	2021
Lövön	40	12	12,000	BESS	Uniper	2021
Bodum	12,6	6	6000	BESS	Uniper	2022
Fjållsjö	13	6	6000	BESS	Uniper	2022
Katerma & Kallioinen	10 + 13.5	3	NA	SC	UPM Energy	2022
Kurkiaska	27	2	NA	SC	Kemijoki Oy	2023
Kierikki	37.5	3	NA	SC	PVO-Vesivoima	2024
Kuusankoski	37	NA	NA	SC	UPM energy	2025
Vogelgrun	39	0.65	300	BESS	EDF	2021

to emphasize this research gap and a structured analysis of wear reduction from the primary drivers identified in this work:

1. Distance moved.
2. Contribution to fatigue end of life from regulation cycles.
3. Avoiding harmful operating points.

A consistent framework for estimating costs related to wear would enable stringent techno-economic optimizations of ESS dimensions for reduced operational costs.

A system designed for efficient wear mitigation [60] will increase the stability limits [31] of the hybridized HPP, possibly qualify for stricter requirements on PFR provision [79] and improve black start capability in a regional system [27]. However, research on systems providing a broad spectrum of services is limited. No studies investigated in this review have evaluated a combination of commercial activity, supply security and system design for a wider range of services. Determining which objectives are dimensioning for power and energy content would be valuable contributions to the research community. From the meta-analysis it is difficult to draw any clear conclusions on what objective is dimensioning as ESS dimensions have been selected somewhat arbitrarily in many cases. However, from Figure 14 and [79] it is clear that the energy needed for PFR qualification is low compared to all studies highlighting reduced wear, that is Gerini et al. [60] Liao et al. [70]. As Liao et al. discuss in their work on vibration zones [70], it is also clear that to completely avoid these zones, the energy content of the ESS system must be increased compared to what was previously studied. Here, it becomes obvious that to decrease wear on the HPP, the dynamic performance of the HPP is reduced, and the power and energy content of the ESS must increase to ensure continued delivery of PFR. This tradeoff is investigated by Casarin et al. in [56], but for this techno-economic optimization to be concluded, the operational cost of wear is crucial.

Design choices on inverter control strategies, GFM/GFL and placement of ESS as discussed by Yan et al. in [27] adds a very interesting new dimension to the optimization of power and energy content of the ESS. Considerations on how assets that are not physically co-located, but contribute to effective PFR provision and greater grid-resilience through their coordinated control with HPP units open new possibilities. Both using already existing ESS infrastructure, or utilizing strategic grid placements for placing ESS with the objective of hybrid operation of hydropower. TSOs requirements and how coordinated assets are treated by TSOs have not been part of this review, but it is an interesting aspect to highlight in future studies related to hybrid assets not physically co-located. How these assets are treated will be crucial for their commercial and strategic viability.

Regarding technology trends, Figure 14 shows that several suggested energy storage systems (ESS) have a high C-rate, indicating a higher power requirement and a lower energy requirement for many applications (except for hydropeaking [36]). This is reflected in the literature, where several resources investigate flywheels and supercapacitors as possible ESS technologies for this application. This is further evidenced by industrial actors co-locating SCESS based energy systems with HPP units; see Figure 15. Dispatch planning of HPP units, as proposed by [60], is crucial for the continued delivery of PFR from efficiently sized ESS. Reducing energy content and focusing on optimal solutions has partly been the rationale for hybridization projects [55, 79, 101]. However, the results from [80] regarding how an overdimensioned BESS achieves the most cost effective solution for two of the three systems studied raise new questions about optimizing ESS technology according to the power and energy needs of the system. This highlights the need to be pragmatic when investigating which type of ESS technology is most appropriate, as the cost per kW, kWh and system costs are affected by rapid development and global supply chains. Swedish industry representatives were consulted regarding the fact that industry projects are based exclusively on BESS, compared to the neighbouring country Finland, which has very similar requirements

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for PFR, but where SCESS is the technology of choice. Swedish actors suggest that the costs of SCESS have been higher compared to those of BESS projects. The authors attribute the disparity to the influence of national proof-of-concept projects.

In Figure 11 it is clear that hydropeaking [36] is an outlier compared to the other academic works reviewed, partly because it is included in the quantitative analysis. However, some of the investments in hybrid projects by industrial actors, as presented in Figure 15, are similar P_{ESS} [p.u.] to those suggested by Chalishazar et al. These systems are also suitable for operating in the energy wholesale markets and can maintain energy dispatchability if environmental restrictions on flows are imposed. This merging of time scales, which considers primary frequency regulation as well as shifting into hourly dispatch, creates a new set of possibilities and presents an interesting path for future work.

4 | Future Work

This review presents results and summaries of studies that provide valuable information on how the hybridization of HPP units affects commercial objectives by enhancing the capability to deliver PFR, mitigate wear from various phenomena, and contribute to supply security. The merger of perspectives for commercial applications and those focused on resilience is highlighted as a relevant direction for future work.

- Combine perspectives on reducing operational costs, increasing revenues, and enhancing regional resilience.

The knowledge of how the reduced wear indices relate to operational cost has gaps in the reviewed works. Attempts to merge the body of work on HPP wear and tear with estimates of reduced operational costs and incorporate these parameters into the techno-economic optimization of hybrid HPP systems represent a valuable path for future research.

- Improve cost estimates for wear reduction and design object-oriented hybrid systems to mitigate these costs.

A limitation of many reviewed sources is the narrow time span of considering PFR. Some works include an aspect of hourly dispatch [60], but the focus is generally exclusively on shorter timescales. Combining considerations for flow limitations imposed by environmental regulations or water scarcity [36, 38], improved energy arbitrage [102] and PFR has not been comprehensively compiled. The merging of gains on short and longer timescales through the hybridization of hydropower is therefore suggested as a path for future work.

- Hybridization methodologies considering multiple objectives on short and long time-scales.

As many of the suggested ESS are high power systems, a discussion on which converter topologies are suitable for this integration is an interesting field for future work The cost of the converter increases as it is sized according to the power capacity

- Optimal system integration for high power ESS considering converter topologies.

The study by Yan et al. [27] investigates how and at which locations in the grid GFL and GFM controlled ESS contribute with most value in a black-start operation. This comparison should be extended to include commercial and policy aspects to investigate how these systems increasing grid resilience may be commercially viable, and whether any legislation or policy facilitates or hinders this coordination.

- Comparative study of coordinated control of grid forming ESS and HPP units with co-located grid following ESS and HPP including commercial objectives.

5 | Conclusions

All hybrid systems reviewed, which aimed to reduce guide vane movement and cycle counts achieved these goals, as presented in Table 1.

- Movements and mileage of servo motors in Kaplan turbines can be reduced by over 90% with an ancillary ESS corresponding to 20% of the PFR capacity using state-of-the-art mitigation techniques [60]

The review has highlighted that how the reduction translates into an increased lifespan of HPP units is less certain, and there is a research gap on how to strengthen the correlation between wear indices and operational cost. Efficiently dimensioned storage systems can be designed to ensure that the HPP unit meets the PFR requirements.

- Auxiliary ESS designed with 4%–25% of the desired PFR capacity can ensure that the plant meets the new, stricter PFR requirements implemented in the Nordic synchronous area [79].

The dimensioning of both power and energy is greatly dependent on the plant's dynamics.

The body of work on how ESS and HPP units can contribute valuable services to enhance grid resilience is reviewed.

- The hybrid operation of energy storage systems (ESS) and hydropower improves the black-start capability of run-of-river (RoR) hydropower units [27, 28].
- Hybridization improves frequency containment in islanding operation and enhances stability regions in challenging operating conditions [29, 30, 89]

The quantitative summary of the reviewed work suggests that normalized dimensions of ESS capacity designed primarily for commercial purposes can contribute to increased grid resilience. Continued studies on grid forming versus grid following inverters and their impact on the location and coordination of ESS and hydropower are suggested. The investments in BESS made by industry are large enough in many cases to contribute to all or most of the services highlighted in the academic works reviewed according to the quantitative analysis, including energy intensive objectives.

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Author Contributions

Viktor Nils Johan Döhlen: conceptualization, data curation, formal analysis, methodology, writing – original draft. **Henrik Lindsjo:** methodology, supervision, writing – review and editing. **Kent Bertilsson:** conceptualization, supervision, writing – review and editing.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Data supporting the findings of this study are available from the corresponding author on a reasonable request.

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