Rating-Constrained Super-Rated Capture in Hydrostatic Wind Turbines with Integrated Mechanical Storage

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Abstract: Hydrostatic wind-turbine drives with mechanical storage can decouple rotor power extraction from generator power transmission, providing a chance to reclaim power that otherwise gets rejected during above-rated operation. In particular, the issue investigated herein concerns what extent of super-rating of the hydrostatic turbine is appropriate relative to increasing hydraulic rating and blade loads before the latter effects outweigh the annual power benefit in delivered electricity. As a specific example, the 5 MW NREL Class I reference turbine model will be considered in four modes of operation – geared conversion, hydrostatic conversion without super-rating, fully super-rated hydrostatic storage, and hydrostatic storage super-rated under a certain cap – using stated generator, gearbox, hydraulic, and mechanical efficiencies; a Class I Rayleigh distribution of wind speeds with a mean wind speed of 10 m/s; and outputting average delivered power, capacity factor, maximum rotor power, maximum hydraulic pump rating, and maximum blade bending moment. A capture-return efficiency ratio is defined to relate the average power increase due to super-rating to additional hydraulic rating, subject to the requirement that the blade bending remains unchanged – thus ensuring that energetic and mechanical effects cannot be considered independently. The non-super-rated configuration involving hydraulic drive decreases average power from 2.67 MW to 2.34 MW due to uncompensated transmission losses. Fully super-rating the turbine produces an average power of 3.28 MW and a capacity factor of 66% while needing 15.7 MW of pump rating and increasing maximum blade bending from 10.52 MN-m to 10.58 MN-m. Capping the super-rating at a pump rating of 10.3 MW reduces maximum blade bending to 10.52 MN-m and yields an average power of 3.13 MW, a yearly power output of 27.42 GWh and a capacity factor of 63%. Results reveal that capped super-rating produces an 84.0% recovery in the super-rating power gain, yet uses just 48.1% of the additional pump power needed by super-rating.

Keywords: wind energy; hydrostatic drivetrain; mechanical storage; super-rated operation; hydraulic pump sizing; NREL 5 MW turbine; capacity factor; blade bending moment

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1. Introduction

The design of modern wind turbines is strongly influenced by the disparity between the rated capacity of the turbine and its effective power output per year. The rated capacity is still a prominent feature, but its true value from an engineering standpoint lies in the ability to extract useful energy from a probabilistic wind resource subject to constraints associated with mechanics, drivetrain limitations, service demands of the grid, and manufacture. Variable-speed, pitch-regulated turbines provide an efficient solution to this challenge using a known separation of operating regimes, in which below-rated wind speeds are governed by torque-based control for effective aerodynamic extraction, while rated and above-rated wind speeds are controlled via pitch to limit both power generation and structure stress. However, it is important to recognize that under such an approach, a substantial portion of the kinetic energy during high wind speeds is deliberately wasted [1–4].

Above-rated operations have thus become the focus of design research once again. Contemporary wind farms must be able to generate power, offer ramp mitigation, provide reserves, and produce grid-friendly power profiles, and not just generate unpredictable amounts of power. The placement and type of storage are relevant in achieving these goals, where electrical storage placed downstream smooths grid output after energy is generated by the generator, while drive train-based storage could affect the operation point at the level of aerodynamics and mechanics. The latter is relevant since above-rated operations are controlled at the level of the turbine generator and prior to grid output. Storage in the drivetrain has the ability to alter the relationship between rotor capturing, generator size, and mechanical dynamics [5–7].

Hydrostatic and hydraulic drivetrains for wind turbines are particularly pertinent to the topic since the kinetic energy of a turbine is first converted to pressurized hydraulic energy before being transformed into electrical energy. Using a hydraulic system allows for moving the generator's weight, changing the torque transmission, implementing variable displacement, and including any storage devices between the rotor shaft and the electric generator. For these reasons, there have been studies conducted about reducing tower weight, annual energy production, buffer effect with an accumulator, digital hydrostatic transmission, and output smoothing using multiple accumulators [9–14]. The same literature indicates that a hydrostatic drivetrain cannot be rationalized simply based on architectural considerations. Inefficiencies, such as hydraulic losses, pump efficiency, pressure, leakage, heat effects, and control difficulties, might undermine the advantages of the idea unless the system generates enough extra power or value from grid services.

Super-rated operation presents another potential approach to recovering this compensation. Rather than constraining the rotor to operate at the generator rating regardless of whether the wind speed is above the rated value, a hydrostatic storage turbine can permit the rotor side path to accommodate an excess mechanical power value compared to the generator rating. This additional mechanical power may then be stored and discharged during another time, effectively resulting in a greater annual output despite not requiring a generator of the same capacity. Simpson and Loth suggested this super-rated operation strategy for use in Region 3 and showed that storage integration allows capturing more energy without enlarging the turbine and generator [15]. This method has great appeal due to its effectiveness at solving the fundamental problem with standard Region 3 operation – a portion of the most powerful wind events go to waste because of the generator rating limit.

The problem lies in the fact that the most aggressive super-rated envelope does not necessarily represent an optimal engineering solution. The top tail of the wind energy distribution has high instantaneous wind energy but low probability of occurring on an annual basis, whereas the hardware capable of absorbing such high energies needs to be designed for the highest load. An increase in size of the pump and hydraulic circuit to accommodate the highest energy winds will result in higher costs per kilowatt installed more quickly than increasing the average power output. The design question then becomes not one of whether super-rating can improve annual energy production, but how to limit the super-rated envelope so that it provides roughly the same energy production on an annual basis without being excessively oversized, all while maintaining the highest level of blade deflection possible from the conventional design in the NREL 5 MW hydrostatic-storage scenario.

The control-and-sizing calculations translate the 5 MW operational data into the mechanical data required for hydraulic components selection. Absolute energy gain is decoupled from relative capture return rating-wise, rating is identified next to probability-based average power, and maximum blade deflection considered as an obligatory admissibility constraint, not an annotation. Such structuring is helpful for early design because it highlights the threshold where further increase in pump capacity leads to annually decreasing gains.

In addition, the literature background indicates a need for differentiation between energy capture and designed capacity. Modern wind turbines development relies on larger rotor diameter, lower specific power and better turbine controls for increasing yearly energy production without corresponding rated generator power growth. On the other hand, studies related to grid and energy storage technologies indicate that an energy unit is not always equally valuable in terms of time and location of generation [16]. Thus, hydrostatic super-rating concept is the crossing point for three research fields – aerodynamic control, fluid mechanics, and system planning. It is an aerodynamic control technique as it affects above-rated rotor operation, a fluid mechanic technique due to dependence on pump and accumulator sizes, and finally, a system planning technique in the sense that it is aimed to convert spillage into generated electricity. Hence, a proper early stage analysis cannot ignore any of them. For this reason, the current paper specifically does not provide a one-dimensional rating-oriented analysis but checks if the pump capacity is effectively used year-round.

The justification for performing such an analysis is also bolstered by the interrelationship between hydrostatic elements and the operation of turbines. Efficiency of pumps and motors is dependent on displacement, pressure, speed of rotation, leakage, and thermal conditions. Storage of energy via accumulators and storage tanks has benefits but also comes with limitations related to pressure and state-of-charge that determine how much time rotor power will be stored. Over-speed wind management will require consideration of aerodynamic torque, blade pitch angle, displacement in the hydrostatic system, charging of storage, and power delivery from the generator. An approach based on limiting the power to a known upper value allows coordinating all these parameters because the most infrequent occurrences during wind operation would not dictate the size of the system. In hydraulic wind turbines research to date, focus was placed on smoothing the energy output, reducing tower mass, maximizing energy capture per year, and improving drive-train reliability [10–14]; the calculations below apply to the case of selecting a limit based on such parameters.

2. System Case and Operating Evidence

The technical case features the NREL 5 MW reference turbine, a three-blade upwind design featuring variable speed with pitch-to-feather control, designed for use in offshore wind technology assessments [17]. With the specified turbine's aerodynamics, structural design, and control capabilities, it makes an appropriate baseline for comparing proposed drivetrain and control strategies on the same turbine scale. In such a comparison, the utility of the 5 MW turbine model lies in not just its capacity rating, but its specific structural and control limitations. The substitution of a super-rated drivetrain that increases average power without consideration for the traditional load limits results in the replacement of one limitation for another.

Operating conditions for the system consist of four different states. Conventional is used as a baseline with a geared turbine and generator. Hydro static is based on replacing the geared drivetrain with a hydrostatic transmission without employing super-rated energy capture. Fully super-rated hydrostatic storage is based on allowing for much larger amounts of above-rater rotor power and the use of storage to decouple the processes of energy capture and delivery. Capped super-rated hydrostatic storage is similar to the fully super-rated except a power cap is imposed before reaching the fully super-raters peak rotor power [15].

It is essential to have an understanding of how the turbine configuration illustrated in Figure 1 integrates the power-conversion system. Torque is extracted using the hydraulic turbine located in the nacelle. From there, it is conducted via pressurized lines into a storage component, as well as into a hydraulic motor connected to the generator. Such presentation is critical since the storage component is not positioned downstream of the electrical conversion stage. Instead, the storage mechanism operates along with other mechanical components that process power coming from the rotor. Due to such configuration, it is possible to accept more power than needed until reaching the limitation on the generator side. Hence, the stated ratings of 5.3 MW, 10.3 MW, and 15.7 MW should be interpreted as hydraulic capacity differences.

Figure 1. Hydrostatic capture layout.

Efficiency assumptions are given in Table 1. These assumptions are critical because they allow super-rated storage to be distinguished from lossless energy recovery. The conventional drivetrain has generator efficiency of 97.2% and gearbox efficiency of 97.2%. In both hydraulic cases, the generator efficiency remains the same while an additional hydraulic efficiency of 85% is added. Finally, the efficiencies in storage cases are similar to those in the hydraulic case, however, a new parameter called storage efficiency of 80% is added [15]. Therefore, to outperform the conventional drivetrain, the hydrostatic approach has to compensate not only for its inefficiency but for additional losses due to the presence of conversion devices as well. It is this aspect of the hydrostatic path that makes it crucial to study the non-super-rated storage case first.

Table 1. Efficiency assumptions.

Component efficiency	Conventional	Hydraulic	Hydraulic with storage	Super-rated with storage
Generator efficiency	97.2%	97.2%	97.2%	97.2%
Gearbox efficiency	97.2%	N/A	N/A	N/A
Hydraulic efficiency	N/A	85%	85%	85%
Storage efficiency	N/A	N/A	80%	80%

The wind speed distribution is assumed to follow Class I Rayleigh distribution with a mean wind speed of 10 m/s. The reason for the necessity of this assumption is clear: contrary to the intuitive notion of average power, the value used here is not simply the arithmetic average but rather it is the expected value, weighted by the operating frequency at every point on the power curve. As the higher wind speeds tend to provide higher power density despite having a relatively low frequency, the approach that maximizes the power at high wind speeds looks very attractive until frequency is taken into account.

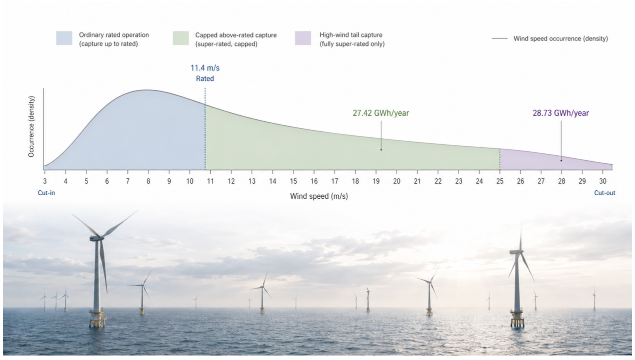


Figure 2. Wind-weighted capture zone.

The wind-weighted capture zone of Figure 2 indicates the rated transition point at 11.4 m/s and differentiates between the normal rated range, the capped above-rated range, and the high wind tail accessed exclusively through full super-rating. The capped above-rated range includes the part of the above-rated range that is still common enough to affect annual output significantly, resulting in 27.42 GWh/year. Full super-rating involves accessing the tail, increasing annual output to 28.73 GWh/year; however, the extra 1.31 GWh/year produced in this process results from access to a range that has a very heavy hydraulic rating requirement.

As shown in Figure 3, the conventionally operated machine operates at an average power of 2.67 MW with a capacity factor of 53% and a maximum blade bending moment of 10.52 MN-m. The hydrostatic non-super rated machine produces the same maximum blade-bending moment, but the power is reduced to 2.34 MW with a 47% capacity factor due to increased hydraulic losses. Full super-rating increases both average power and capacity factor to 3.28 MW and 66% but requires 15.7 MW pump capacity and has the only bending moment value higher than the conventional reference point. Capping keeps the maximum blade-bending moment at 10.52 MN-m and generates 3.13 MW of power with a 63% capacity factor at 10.3 MW pump rating.

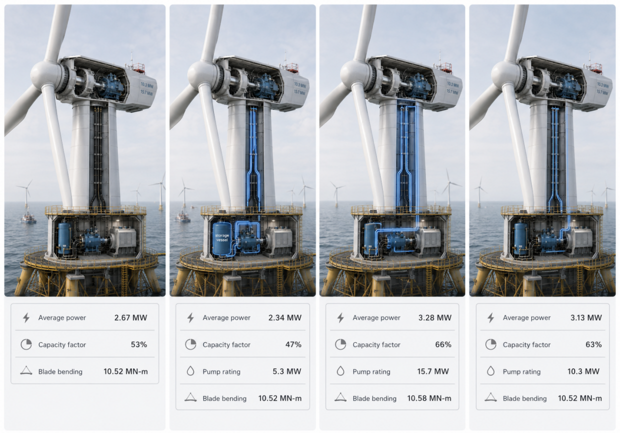


Figure 3. Operating-state evidence.

The quantitative evidence presented in Table 2 consists of the data that was used to analyze the results in the manuscript. The maximum blade-bending moment and maximum rotor power for the hydrostatic non-super-rated state are the same as those of the conventional case; however, the average power is decreased from 2.67 MW to 2.34 MW, and the capacity factor is reduced to 47%. Thus, we can conclude that using solely a hydrostatic drivetrain provides no energy efficiency gains in comparison to the conventional case based on the specified efficiency factors. In contrast, the fully super-rated machine achieves the highest average power (3.28 MW) and capacity factor (66%) with the maximum blade-bending moment equal to 10.58 MN-m. At the same time, both rotor and pump power have reached 15.7 MW. The intermediate mechanical solution of capping brings the blade-bending moment to 10.52 MN-m, average power of 3.13 MW, and a 63% capacity factor, while keeping the pump power to 10.3 MW.

Table 2. Four-state numerical evidence.

Quantity	Conventional	Hydraulic	Super-rated	Capped super-rated
Maximum blade bending moment (MN-m)	10.52	10.52	10.58	10.52
Maximum rotor power (MW)	5.3	5.3	15.7	10.3
Maximum hydraulic pump power (MW)	N/A	5.3	15.7	10.3
Average delivered power (MW)	2.67	2.34	3.28	3.13
Average-power change	0%	-13%	23%	17%
Capacity factor	53%	47%	66%	63%

They also explain why the formulation of the problem of optimal turbine state is important. Considering just average delivered power, the fully super-rated state wins. Blade-bending equivalence leaves all conventional, hydraulic, and capped states satisfied in terms of a maximum value of the parameter. Hydraulic rating only leaves the non-super-rated hydraulic configuration with the lowest hydraulic rating among all hydraulic states. Thus, none of the aforementioned single-parameter interpretations can determine the winner. To make an informed choice, one needs to consider delivered energy, additional pump power, and maximal blade-bending value collectively.

It can be seen that the numerical data provided above sheds light on the reason why it is reasonable to compare the conventional and capped super-rated configurations rather than peak rotor power directly. Adding the capped super-rated state to the conventional turbine brings about an increase of average delivered power by 0.46 MW, which amounts to 4.03 GWh/year, while keeping the maximal blade-bending value constant (10.52 MN-m). As for the fully super-rated configuration, it brings another increase in average delivered power by 0.15 MW; however, it implies that the power pumped through the path should be increased from 10.3 MW to 15.7 MW, bringing the bending parameter up to 10.58 MN-m. Engineering interpretation in this case comes down to the magnitude of the increments: most of the annual energy gain takes place at below the fully super-rated hydraulic rating. The results are consistent with the literature in the domain of control problems [18].

3. Formulation for Rating-Constrained Screening

The screening formulation utilizes the four states and turns the problem of decision-making into an assessment of two competing states among the super-rated designs. The hydraulic non-super-rated state will serve as the baseline for additional hydraulic rating since it has the hydraulic pump transmission in place but does not enjoy any benefits from super-rating due to the absence of above-rated capture. The turbine design is chosen as the reference configuration in terms of structural performance, providing an upper limit on blade bending for a new design.

Let $\bar{P}_s$ represent the expected delivered power of a candidate state s and $P_{p,s}^{\max}$ represent its maximum hydraulic pump power. The hydraulic non-super-rated state is referred to by H. The capture return of a super-rated candidate per unit of additional rating is defined by

$$\mathcal{R}_s = \frac{\bar{P}_s - \bar{P}_H}{P_{p,s}^{\max} - P_{p,H}^{\max}}. \tag{1}$$

This measure has the units MW/MW and quantifies the amount of the probability-weighted average delivered power received per extra megawatt of pump rating over and above the hydraulic non-super rated state. This measure is not a thermodynamic efficiency. It is rather a density-of-design index that relates the annual energy payoff to the hydraulic pathway size that must be built.

The criterion for admissible structure is written in terms of the maximum blade-bending moment. Denote by $M_s^{\max}$ the maximum blade bending moment at state s and denote by $M_C^{\max}$ the conventional value. A candidate will be admissible if and only if

$$M_s^{\max} \leq M_C^{\max}. \tag{2}$$

This criterion is very straightforward. It cannot substitute fatigue design, turbulent load-cases modeling, or even the certification studies performed based on IEC design load-cases [19,20]. However, this is a criterion for screening out an above rated capture configuration that achieves an increase in the average delivered power but raises the maximum blade-bending moment.

Annual equivalent energy is determined as follows,

$$E_s = 8760\,\bar{P}_s. \tag{3}$$

Since $\bar{P}_s$ already carries the weight of wind speeds via probability weighting, E_s can be regarded as annual equivalent energy output and not as extrapolated rated output capacity. The difference matters for super-rated wind turbines. It is possible to have a peak power capacity significantly higher than the turbine rating during certain periods within a year only.

For the two super-rated states, Eq. (1) gives

$$\mathcal{R}_{\mathrm{SR}} = \frac{3.28 - 2.34}{15.7 - 5.3} = 0.090\ \mathrm{MW/MW}, \tag{4}$$

and

$$\mathcal{R}_{\mathrm{CSR}} = \frac{3.13 - 2.34}{10.3 - 5.3} = 0.158\ \mathrm{MW/MW}. \tag{5}$$

These two values represent the core sizing dilemma. The completely super-rated configuration has higher absolute average power but offers lower probability-adjusted gains for each additional MW of pump capacity. The limited super-rated approach provides a higher relative return since it harnesses the better part of the above rated configuration and avoids the less common and more rating intensive part of the completely super-rated configuration.

The following is one way to look at it based on the comparison between the capped addition and the full super-rating. It takes 5.4 MW more of pump rating from the capped addition to get to the fully super-rated, increasing from 10.3 MW to 15.7 MW, but gives you an average increase of 0.15 MW in power delivery, increasing from 3.13 MW to 3.28 MW. In other words, the marginal increase in efficiency from this last addition is 0.028 MW/MW, a figure much lower than the marginal increase in efficiency of 0.158 MW/MW for the capped addition compared to the hydraulically non-super rated system.

4. Results and Discussion

The drivetrain replacement without super-rating is not enough. The hydraulic case reduces the power output by 0.33 MW compared to the conventional turbine. Using the relation (3), we can express the yearly equivalent of conventional power output of 2.67 MW as 23.39 GWh/y and that of hydraulic power output of 2.34 MW as 20.50 GWh/y. Thus, a loss of 2.89 GWh/y becomes the cost of the hydraulic conversion process assuming that any super-ratings cannot be accounted for. This result is in agreement with previous works on hydrostatic wind turbines that focused on both the advantage of power transfer flexibility and the inefficiency due to pumps and hydraulic motor losses [9,11–13].

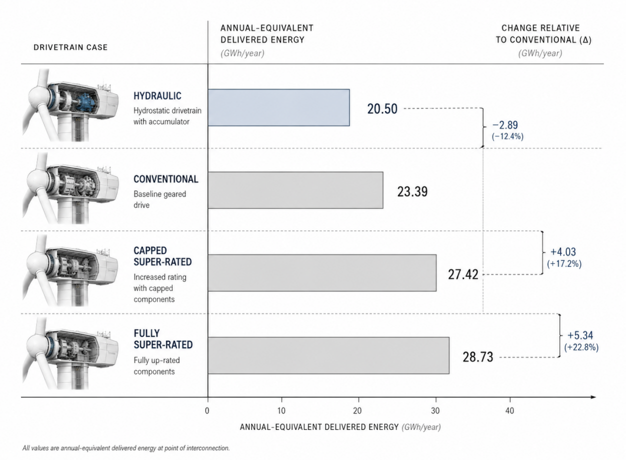
The numbers in Table 3 indicate that the hydrostatic drive becomes a good choice only when above-rated storage is possible. Super-rated operation provides 28.73 GWh/year of electricity output, exceeding the numbers from conventional case by 5.34 GWh/year and those from hydraulic non-super-rated case by 8.23 GWh/year. Capped super-rated state results in 27.42 GWh/year, or gains 4.03 GWh/year relative to conventional turbine case and 6.92 GWh/year compared to hydraulic non-super-rated case. The difference between fully super-rated and capped cases is thus 1.31 GWh/year. While it may look small, it should be considered against additional 5.4 MW pump rating and absence of bending symmetry in the fully super-rated envelope.

Table 3. Annual-equivalent energy.

Configuration	Average power (MW)	Annual-equivalent energy (GWh/year)	Change vs. conventional (GWh/year)
Conventional	2.67	23.39	0.00
Hydraulic	2.34	20.50	-2.89
Super-rated	3.28	28.73	5.34
Capped super-rated	3.13	27.42	4.03

The annual-equivalent values put things into perspective regarding the storage capacity claim made earlier. A 4.03 GWh/year increment over the conventional turbine production is significant enough to warrant careful attention for annual performance, yet no upgrade of the generator ratings to anything larger than 5 MW class has been suggested here. Full super-rated state would produce 1.31 GWh/year extra relative to the capped super-rated turbine; however, this increment comes at the cost of operating the drivetrain in its rarest and hardest-to-maintain region. In terms of design of a generator-turbine set or entire wind farm, this means that decision making goes beyond just determining what energy levels can be reached and moves into consideration of the amount of hydraulic equipment one needs to add to the drivetrain to reach these levels on yearly basis. The advantages of hydraulic transmission include the ability to shift and store energy; however, they rely on the frequency of the energy being returned within their operational zones for the system to be valuable enough based on its rated power output [9,10,13].

The annual energy calculation of Figure 4 results in the same outcome as the delivered-energy balance. The hydraulic drivetrain comes lower than the conventional drivetrain since the additional hydraulic conversion loss cannot be offset by generation above rated power. With capped super-rating, the annual-equivalent energy output rises from 23.39 GWh/year to 27.42 GWh/year, an increase of 4.03 GWh/year compared to the conventional design. Full super-rating yields 28.73 GWh/year, although the further increase of 1.31 GWh/year over the capped design must be evaluated with consideration of the increased pump capacity and load on the blades. The figure thus demonstrates the energetic insight of the paper: even with capped super-rating, most annual benefits have been captured before entering the low-yield region at high wind speeds.



All values are annual-equivalent delivered energy at point of interconnection.

Figure 4. Annual energy accounting.

Capacity factor, on the other hand, plays a crucial role in renewable-energy generation planning. For the conventional turbine design, the capacity factor is 53%, while it drops to 47% in the hydraulic non-super-rated state. A capacity factor of 66% is reached in full super-rated mode, while in the case of capped super-rating, a capacity factor of 63% is achieved. The additional ten percentage points in the capacity factor in comparison to the conventional turbine and an additional sixteen percentage points compared to the hydraulic non-super-rated turbine thus indicate that capacity factor is affected by the integration of storage. This means that integration does not only affect drivetrain losses, but alters the usable part of the wind regime. As such, improved delivered-energy fraction allows for better use of generator and electrical system components in grid integration [6–8].

The capacity-factor comparison further emphasizes the fact that the hydraulic energy storage idea is not really an uprating of the turbine-generator. An uprating process involves a larger electrical conversion path and changes in the balance-of-plant facilities. With the capped energy storage solution, increased energy generation is achieved through making the path at the rotor side capable of capturing excess mechanical power while delivery from the generator side continues to be limited. The difference between capture and delivery is what makes the benefit of hydraulic energy storage within the drivetrain. It enables the turbine to utilize wind exceeding its rated speed in a manner that not all captured power is necessarily transmitted electrically. The penalty of using the hydraulic method is evident in the 47% capacity factor of the hydraulic non-super-rated system. Thus, the energy storage branch is not just a supplement but an important operational component in improving the energy yield of the system with a lower conversion efficiency.

It should be noted that the hydraulic rating increases faster than the annual energy benefit for the super-rated range. In fact, the hydraulic fully super-rated state requires a pump path of 15.7 MW rating, or thrice the 5.3 MW pump path of the hydraulic non-super-rated system. On average, it delivers 0.94 MW of extra electricity compared with the hydraulic non-super-rated state. For the capped state, the required pump path is 10.3 MW, or 5.0 MW more than the hydraulic non-super-rated system. However, it is able to deliver an additional power of 0.79 MW on average. Thus, it gains 84.0% of the extra delivered power of the fully super-rated state with a mere 48.1% increase in pump rating. This disproportionate preservation of energy benefit is the principal reason the capped design is favored.

In that sense, the return comparison shown in Table 4 and Figure 5 clarifies the sizing argument. The rated-capped state achieves a normalized pump rating return of 0.158 MW/MW, versus the 0.090 MW/MW return associated with the fully super-rated state. As a proportionate improvement, the return of the capped state is about 74.8% better. This does not imply that the capped state will yield more energy than the fully super-rated state; it implies merely that the capped state utilizes its hydraulic capacity more effectively. In the context of early mechanical design, this consideration will be absolutely critical because it determines cost, weight, volume, high pressure line routing, cooling requirements, controllability, and service exposure.

Table 4. Rating-normalized capture return.

Configuration	Average-power gain vs. hydraulic (MW)	Added pump rating (MW)	Return (MW/MW)
Super-rated	0.94	10.4	0.090
Capped super-rated	0.79	5.0	0.158
Capped share of super-rated value	84.0%	48.1%	174.8%

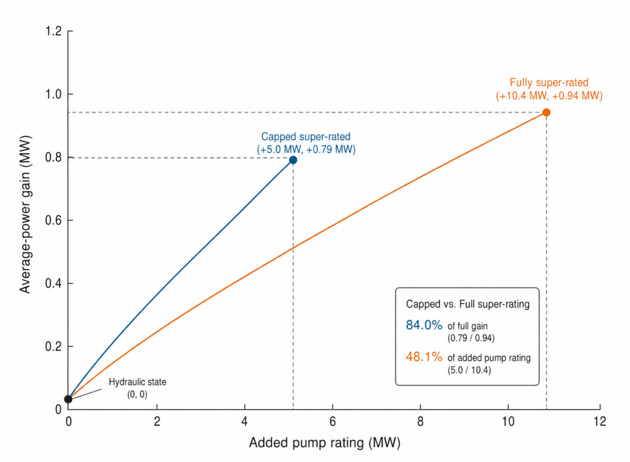


Figure 5. Pump-rating leverage.

The implication is even more damaging when one realizes that the fully super-rated pump of 15.7 MW is no mere modest oversizing of a 5 MW turbine. Rather, it represents an actual hydraulic pathway about three times the typical turbine rating and around 52% larger than the capped state of 10.3 MW. All of the effects that come from pump size will thus be amplified by this factor in addition to whatever improvements accrue due to rating normalization. Rating normalization serves precisely to recast the additional annual energy production in terms of the metric under which hydraulic equipment is purchased and serviced. The capped state is not selected due to reduced power capture; it is chosen as the alternative to an expensive peak interval whose annual energy is small compared to its component-rating demands [11,12,14].

This marginal segmentation demonstrates that the cap is more than simply a degraded version of the fully super-rated system (Table 5). The transition from hydraulic non-super-rating to hydraulic capped super-rating involves an addition of 5.0 MW of pump rating and an average delivered power increase of 0.79 MW or 6.92 GWh/year. On the other hand, the transition from hydraulic capped super-rating to fully super-rating yields an even higher addition of pump rating (5.4 MW), but at the expense of producing only 0.15 MW of average delivered power or 1.31 GWh/year. In other words, the recovery on the upper tail following the cap point is only 17.6% of the gains realized before the cap. This dramatic difference serves as further evidence of the high hardware cost that the upper tail imposes relative to its annual gains.

Table 5. Incremental super-rating segments.

Design segment	Pump increment (MW)	Average-power increment (MW)	Energy increment (GWh/year)	Return (MW/MW)
Hydraulic to capped super-rated	5.0	0.79	6.92	0.158
Capped to fully super-rated	5.4	0.15	1.31	0.028

The comparison of segments provides an explanation of the relationship between pump rating and wind probability. For instance, the capped operating region incorporates above-rated winds that occur with sufficient frequency to affect annual delivered power. The remaining fully super-rated region extends farther along the high-wind tail, which offers a possibility of higher power but low probability events. Because peak hydraulic power is required regardless of the annual probability weight of any event, it is an expensive option. In contrast, the capped system accepts those portions of the tail that are highly annual-valuable, while discarding those regions that are highly annual-costly. This is why the capped configuration can remain close to the fully super-rated configuration in annual energy even though its peak hydraulic power is much lower.

The upper segment reading avoids an inaccurate interpretation of the difference of 1.31 GWh/year between the capped state and the fully super-rated state. While the difference looks promising on its own, the actual difference of 0.028 MW/MW is not when it is scaled by the extra 5.4 MW of pumping power path, compared to the productive capped increment of 0.158 MW/MW. Thus, while the upper segment increment is of comparable absolute magnitude to that of the productive capped increment, the ratio of average power generated to the incremental rated pumping power is significantly smaller than the latter by nearly a factor of five. It is at this point that super-rating ceases to be a beneficial process of energy storage utilization for peak tailing.

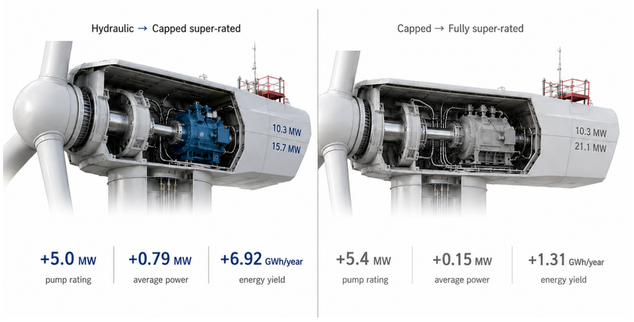


Figure 6. Marginal super-rating value.

The marginal illustration in Figure 6 reveals the diminishing returns of the upper portion of the super rating. The first increment between hydraulic pumping and capped operation increases the rating by 5.0 MW with an average power improvement of 0.79 MW which translates into an improvement of 6.92 GWh per year. In contrast, the second increment between the capped point and the super rating adds a higher capacity of 5.4 MW to the pump rating but only manages a smaller average power increase of 0.15 MW, which is equal to 1.31 GWh per year. This contrast shows that the upper interval is not simply more of the same operating benefit; it is a mechanically expensive tail with weak annual return.

The load check in this case takes the form of the maximum blade bending, depicted in Figure 7. The traditional, hydraulic, and capped states of super-rating all have maximum blade-bending moment equal to 10.52 MN-m. However, the fully super-rated state has a maximum value equal to 10.58 MN-m. Thus, there is an absolute difference of 0.06 MN-m, which translates to about 0.57%. While the increase appears rather negligible, it is essential to bear in mind that above-rated operations are typically evaluated based on their ability to generate increased energy without imposing additional load constraints. The impact of such a minor exceedance might be more significant when turbulence, gustiness, misaligned yaw angle, shear effects, start-stop events, and actuator dynamics are taken into account. Thus, the superiority of the capped state is evident since its load metric does not exceed the corresponding conventional one despite higher rating.

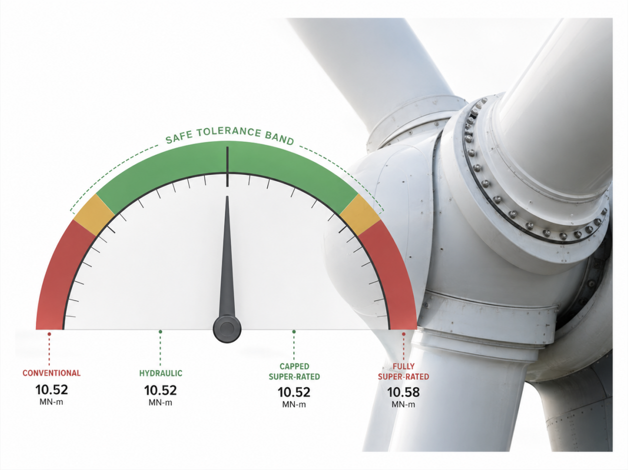


Figure 7. Blade-load admissibility.

One has to bear in mind that the above results should not be viewed as a complete certification claim for the proposed turbine modification. Loads on wind turbines involve numerous scenarios of operation. Maximum steady blade-bending moment is just one of several parameters that have to be addressed during the design procedure. Other critical loads include turbulence-related fatigue, coherent gust effects, loss-of-grid transient effects, pitch-actuator performance restrictions, tower loads, drivetrain torque, and hydraulic system pressure dynamics [19,20]. Therefore, the present analysis has its limited scope of application, but it is still valuable. It allows us to conclude that the numerical analysis supports the preference for the 5 MW capped super-rated turbine operation based on its load properties.

This is relevant to the question of implementation in controls as well, since the bending-cap comparison concerns the same range of wind speed in which pitch control typically provides blade protection from excessive load. Without coordination between pitch and torque responses in addition to the command signal to absorb more power, the use of a hydraulic path that commands further power absorption would be expected to cause higher flapwise loads, actuator actuations, or even stronger transients associated with entry and exit from Region 3+. In fact, the capped approach is mechanically desirable in that it ensures that the hydraulic path will only have to handle a smaller maximum power than if super-rating were the only criterion applied. It does not replace the need for load-case analysis, but rather provides a more realistic starting point than a super-rated envelope already exceeding the conventional bending value in the steady comparison.

Storage needs to be viewed as a component in the active controller as opposed to simply a storage device. Hydrostatic storage can play a role in wind energy integration in large part due to its impact on the rotor operating envelope. For the capped case, in particular, hydrostatic storage is beneficial in allowing rotor power to reach beyond rated power while the generator power limit remains the limiting factor, which avoids the problem of designing the hydraulic path to meet the most challenging high-wind scenario. This is in accordance with general discussions about the value of integrating wind and storage [21,22], where timing, grid power demand, and functionality are important. The separate design of the storage capacity, power rating, and turbine control will ignore the coupling effect that leads to the capped-state advantage.

The practical implications of the cap are best illustrated by examining the marginal region between the cap and full super-rating. This region represents the difference between the cap and super-rating. Although the region adds another 5.4 MW of pump rating, it only adds an additional 0.15 MW in average delivered power. On an equivalent annual basis, this 0.15 MW adds 1.31 GWh/year. If this additional capacity were economical or worthwhile would depend on a range of factors such as components costs, electrical worth of the extra output, maintenance, and physical location. But mechanically speaking, the marginal gain of going past the cap into full super-rating is considerably lower than the gain from shifting from hydraulic non-super rating into capped super-rating. In effect, the cap strips away from the design space a lower density section of the design space.

Finally, the example provides more context on what the hydraulic non-super rating means to our understanding of the problem. The hydraulic non-super rated design is not one of failure; rather, it serves as a baseline against which the costs of the hydrostatic design can be measured before allowing for super-rating. In the absence of the non-super rating comparison, the improvements gained by super-rating may be mistakenly attributed to the drivetrain. As it turns out, the hydrostatic transmission causes mechanical losses as defined by the assumed constraints; yet, the extra energy only becomes visible when the control law permits additional above-rated aerodynamic power capture.

There are several implications of the outcome for hydraulic components. An extremely high flow path size of 15.7 MW is very challenging to size for a 5 MW turbine. Such a large pump displacement, maximum flow path pressure, heat dissipation, hydraulic fluid quality, pipeline sizing, valves, mounting structure, and failure modes become critical considerations. Decreasing the peak pump to 10.3 MW will still not simplify such a design; however, it greatly decreases the gap between the conventional scale and the super-rated hydraulic scale. Considering that hydraulic systems also require efficient operation at different speeds and pressures, avoiding overrated peak size might help to maintain efficiency in common scenarios [23].

From another perspective, the proposed cap can be seen in the context of the emerging field of constrained wind turbine control. Constrained power-reference-based control strategies have been researched recently and proved effective in improving energy extraction by modifying set-points within given load and speed limitations [18]. Therefore, it is safe to consider that the mechanical case discussed in the current paper is an equivalent of that approach but applied to mechanical power reference control. In other words, the concept behind both approaches is very similar: any additional energy extracted is beneficial as long as the constraints hold true.

The admissible corridor shown in Figure 8 shows what makes the capped super-rated design option the best one to use for an early-stage design. The conventional generator uses the 10.52 MN-m load reference of the turbine blades but cannot take advantage of any energy that spills beyond rated speed. The hydraulically-operated non-super-rated design allows for drivetrain adaptability but will result in lower power generation due to the efficiencies mentioned before. The fully super-rated design results in the highest power generation of 28.73 GWh/year but will also end up in the region where the maximum pump ratings and blade bending occur. The capped super-rated design option ends up within the allowable corridor because it has 27.42 GWh/year, 10.3 MW pump ratings, a 63% capacity factor, and 10.52 MN-m bending compatibility. The visual conclusion matches the quantitative return calculation: the cap is the point at which energy recovery, pump sizing, and load preservation are most coherently aligned.

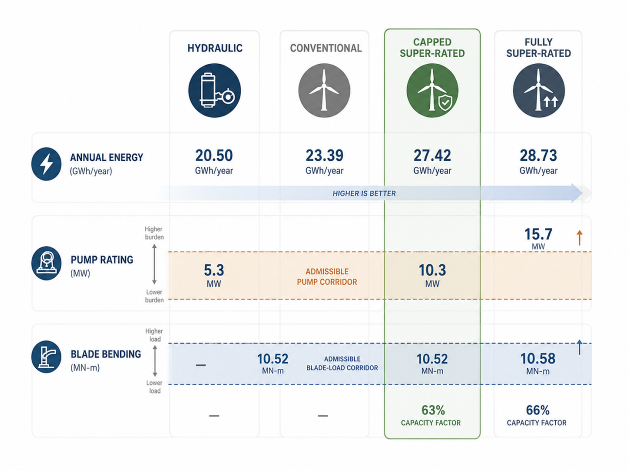


Figure 8. Capped capture corridor.

This analysis also offers an effective means for comparing the hydrostatic super-rating strategy against normal storage placement. When storage is placed downstream of the generator alone, it will allow for time shifting but not the creation of new rotor capacity beyond what can be accommodated within the limited generator operating envelope. On the other hand, the hydrostatic storage approach involves changing the upstream mechanical boundary such that additional rotor power is able to be tapped prior to the conversion into electricity. As such, the effectiveness of the approach will rely upon its proportional sizing to the fraction of the wind regime that stands to gain from it. The capped state performs well because it uses storage to reshape the above-rated operating boundary without treating every possible high-wind event as a design target.

Moreover, these results indicate that capacity factor must be considered carefully. Capacity factor should be as high as possible, however, its increase cannot be an absolute criterion for judging a design since the fully super-rated case demonstrates the maximum capacity factor equal to 66%, while its pump rating is the highest, and maximum bending exceeds the conventional reference level. The capped version of the mechanical design demonstrates the lowest capacity factor equal to 63%, although the difference from the previous case is only three percentage points but saves 5.4 MW of pumping capacity and returns the value of maximum bending to the conventional level. In terms of a mechanical system, such trade-off is extremely beneficial.

5. Implications for Component-Sizing

First, the primary design implication that can be drawn is that hydrostatic turbines must never be selected according to their maximum rotor power output capacity. While the peak values help determine the limitations of particular components, they are not measures of the annual usability of the equipment in question. Hydrostatic turbines with the highest possible above-ratings could thus demand the sizing of their hydraulic path according to infrequent events. However, if the contribution of these events to the annual delivered power is minimal, then the rated power of the design will bear a substantial burden for the sake of its modest benefits. In other words, the probabilistic cap shifts the emphasis from maximum power capture to the most efficient one, with efficiency being defined as the yearly benefit derived per added hydraulic capacity unit.

Thus, in terms of the example discussed above, while a super-rated hydrostatic turbine with a capacity of 10.3 MW is far from maximizing average power, it yields higher gains in terms of its yearly power generation and maintains the conventional peak of blade bending. As a result, a key message for engineers is not to use lower ratings. Instead, they should increase the rated power of the pump to the moment when it yields dense enough returns on yearly basis. Once the design enters a region where several extra megawatts of pump capacity yield only a small average-power increase, the cap becomes an active design feature rather than a conservative restriction.

The same concept also holds true for accumulator/ storage size. A storage system sized to accommodate the super-rated peak output will need to endure much larger charge flows, higher pressure fluctuations, and possibly more heat cycles, although these events may occur only intermittently within the annual wind distribution. It is possible to design the capped storage system based on a more narrow operating window of power, which should reduce requirements in pressure vessel sizing, control valve choice, cooling capacity, and battery management. For implementation, the cap would be defined by a control rule combining the aspects of rotor speed, displacement control, pitch angle operation, and storage charge limits along with generator side dispatch. This numerical comparison reveals where the cap would be most useful – for the 10.3 MW hydraulic path retaining 27.42 GWh/year and 10.52 MN-m bending value.

This concept also has implications from the production and maintenance standpoint. A hydrostatic storage turbine adds components that do not occur in a conventional geared turbine (or are different in form): pumps and motors, pressure vessels/ accumulators, valves, cooling equipment, sensors, fluid conditioning, and associated control hardware. Each new component adds its share of manufacturing cost, inspection needs, and risk. An approach where the maximum stress levels are lower, but where almost all annual power improvement is retained is more product development friendly than a pure power maximization method.

The sizing procedure is deterministic and system-wide; it does not address the turbulent aeroelastic transient histories, fatigue-equivalent loads, tower bottom moments, drivetrain torque transients, or hydraulic-pressure pulsations. The Class I Rayleigh weighting represents an obvious annualizing approach, but local wind distributions, turbulence intensities, air densities, shear, wake interactions, and energy price curves can affect optimal storage-capacity selections. If the wind site were an offshore one with a relatively high average wind speed, the upper limit might look favorable; on the contrary, in a site with relatively few above-rated periods, it would favor the lower limit choice. Hence, future studies must view this parameter as a continuum, rather than as two discrete states.

Furthermore, there is room for expanding the hydraulic circuit description. The 85% efficiency factor chosen for this pump is reasonable for the present screening purposes, but, in a complete design analysis, the hydraulic and storage efficiency maps should be known. In addition, the model should include the pressure dependencies, temperature balance, state of charge of the accumulator, and other parameters like pressure losses in valves and delays in controls. Such a description is required to ensure that the sizing done under a peak condition will provide satisfactory performance at part-load conditions. Hardware-in-loop testing or even building a scaled-down version may help determine the response of the capped path to rotor power command transients.

Another implication relates to reliability in the case of variable duty cycle. Full super-rating requires the hydraulic path to withstand a peak power of 15.7 MW, yet many hours of the year will operate below this point. Larger components might struggle with poor part-load operation, slow reaction, larger oil volume, and thermal inertia, depending on the chosen pump and motor technologies. Capped super-rating reduces the operation range, retaining almost all of the energy increase, which would make displacement control and pressure regulation easier to accomplish. This is critical since the wind turbine is an industrial machine that experiences stochastic torque loading, frequent control intervention, responses to gusts, shut-down situations, and grid commands. Thus, smaller but highly utilized hydraulic storage might be an engineer's choice as compared with the oversized hydraulic path sized for occasional peak values [13,23].

Lastly, economic feasibility represents the limiting condition as well. Since the return index $\mathcal{R}_s$ is free from speculative cost estimates, it is easy to track. The return index is not a replacement for the levelized cost of energy, cost of valued energy, or value-based economic studies. Rather, it determines at which state of operation more power is provided annually for each megawatt of pump super-rating. The return index does not consider costs of pumps, storages, operations, maintenance, electricity, etc. It can serve as the foundation for a future techno-economic analysis of component costs, availability, power value delivery, and grid services' prices [7,16,21].

In this case, the comparison is different from research efforts that view energy storage facilities in terms of separate asset components to the power plant. Storage systems based on pumped hydro storage, compressed air, or hybrid designs can aid in the integration of renewable energies on the network level; however, their parameters include the size of the reservoir, its compression pressure, the charging time, or its dispatching policies, but rarely the rotor-side capture and rating of the pumps embedded in the turbine [24,25]. Super-rating within a hydrostatic environment integrates some of the storage challenges into the transformation process. It is this aspect of the solution that gives it a unique mechanical nature: storage is valuable precisely because it modifies the admissible range of operation for the turbine, and not merely in its storage capacity.

Under the absolute criteria of average delivered power, the super-rated state dominates. With the inclusion of the pump rating and maximum bending stresses at the rotor blades, the capped state emerges as the preferred one. This is due to significant discrepancies in hydraulic ratings and slight variations in average delivered power between the two states of the super-rated turbine.

6. Conclusion

In this context, the design question was the extent to which a hydrostatic wind turbine with mechanical storage should be super-rated in terms of average delivered power, pump power, and blade-bending. In this regard, it can be stated that the capped super-rated state represents a better operational balance. Fully super-rated states generate 3.28 MW of average delivered power and 28.73 GWh/year of annual energy output and have a hydraulic pump capacity of 15.7 MW and a maximum blade-bending moment of 10.58 MN-m. Capped states generate 3.13 MW and 27.42 GWh/year of energy and achieve a capacity factor of 63%, use only 10.3 MW of the pump path and maintain the traditional limit on maximum blade-bending moment at 10.52 MN-m.

The evidence does not lie in the ranking of average power gains, however. The fully super-rated state contributes 0.94 MW of average delivered power with an extra 10.4 MW of pump capacity relative to the hydraulic non-super-rated state and yields an increase in power of 0.090 MW/MW. In the same comparison, the capped super-rated state gains 0.79 MW from adding 5.0 MW of pump power, or 0.158 MW/MW. In this way, the capped state achieves 84.0% of the fully super-rated average power gains using only 48.1% of the added pump capacity, while the return per unit additional pump capacity is about 74.8% higher in the capped state. In transitioning from the capped to fully super-rated states, it is noted that 5.4 MW more pump capacity is necessary to gain 0.15 MW of average delivered power and lose bending admissibility.

The research question is, thus, addressed through a constrained design approach. It is suggested that integrated hydrostatic storage is most useful in admitting dense probabilities in above-rated capture while excluding least efficient peak-rating tail probabilities. In the 5 MW case study, such a constraint leads to the capped super-rated operating state as the preferred solution. It is concluded that future hydrostatic wind turbine designs can incorporate the practical design principle of capturing above-rated power via annualized capture return and mechanical admissibility, not just maximum rotor power.

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