STRATEGIC ROLE OF ENERGY STORAGE IN ELECTRICITY MARKETS

ROLUL STRATEGIC AL STOCĂRII ENERGIEI ÎN PIEȚELE DE ENERGIE ELECTRICĂ

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Abstract: *The paper presents an original technical-economic approach for assessing the strategic role of battery energy storage in electricity markets, based on the author's dissertation research on a 142.6 MW wind power plant. The personal contribution consists in developing a comparative scenario-based methodology that allocates a 71.3 MWh Li-ion battery between the Day-Ahead Market and ancillary services, while also considering the initial state of charge, charging/discharging efficiency, market prices and annual economic benefit. Unlike a purely technical sizing study, the proposed approach links storage operation directly with market participation and revenue streams. Three allocation strategies are analysed: 25% ancillary services / 75% Day-Ahead Market, 75% ancillary services / 25% Day-Ahead Market, and 50% / 50%. The results indicate that the most advantageous strategy is the second one, generating an annual benefit of 16.55 million RON. Therefore, energy storage is highlighted as a strategic asset for flexibility, profitability, renewable energy integration and more efficient participation in modern electricity markets.*

Keywords: energy storage; battery storage system; electricity markets; wind power plant; ancillary services; flexibility; renewable energy integration.

Rezumat: *Lucrarea prezintă o abordare tehnico-economică originală pentru evaluarea rolului strategic al sistemelor de stocare a energiei în baterii pe piețele de energie electrică, având la bază cercetările realizate de autor în cadrul lucrării de disertație, asupra unei centrale electrice eoliene cu o putere instalată de 142,6 MW. Contribuția personală constă în dezvoltarea unei metodologii comparative bazate pe scenarii, prin care capacitatea unui sistem de stocare cu baterii Li-ion de 71,3 MWh este alocată între Piața pentru Ziua*

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Următoare și Serviciile Tehnologice de Sistem, luând în considerare, totodată, starea inițială de încărcare, randamentele de încărcare și descărcare, prețurile de piață și beneficiul economic anual. Spre deosebire de o analiză exclusiv tehnică de dimensionare, abordarea propusă corelează în mod direct exploatarea sistemului de stocare cu participarea pe piețele de energie și cu fluxurile de venituri generate. Sunt analizate trei strategii de alocare: 25% pentru serviciile tehnologice de sistem / 75% pentru Piața pentru Ziua Următoare, 75% pentru serviciile tehnologice de sistem / 25% pentru Piața pentru Ziua Următoare și, respectiv, 50% / 50%. Rezultatele indică faptul că cea de-a doua strategie este cea mai avantajoasă, generând un beneficiu anual de 16,55 milioane lei. Prin urmare, sistemele de stocare a energiei sunt evidențiate ca active strategice pentru creșterea flexibilității și profitabilității, facilitarea integrării energiei din surse regenerabile și participarea mai eficientă pe piețele moderne de energie electrică.

Cuvinte cheie: stocarea energiei; sistem de stocare cu baterii; piețe de energie electrică; centrală electrică eoliană; servicii tehnologice de sistem; flexibilitate; integrarea energiei din surse regenerabile.

1. Introduction

The accelerated transformation of European power systems has changed the economic and operational role of flexibility. The expansion of variable renewable energy sources, together with stronger market coupling and shorter trading intervals, increases the value of resources that can respond rapidly to deviations between forecast production, scheduled delivery and real-time system conditions. European market design explicitly promotes flexible generation, demand response and energy storage, while the electricity-balancing framework defines common principles for reserve procurement and activation [3] [4] [5]. In parallel, the European Green Deal and REPowerEU have reinforced the policy objective of integrating larger volumes of renewable electricity without compromising security of supply [1] [2].

Battery energy storage systems (BESS) are particularly relevant in this context because they combine energy-shifting capability with fast controllable power. Recent international assessments describe batteries as a key enabling technology for secure energy transitions and note that utility-scale battery deployment has expanded rapidly as wind and solar penetration has increased [6]. Technical literature also emphasizes that the value of Li-ion storage depends not only on cell chemistry and installed capacity, but on system design, operating strategy and the service for which the asset is dispatched [7] [8] [9]. Consequently, the same battery can produce materially different economic outcomes depending on whether its capacity is used predominantly for energy shifting, reserve provision, balancing activation or a combination of these functions.

For wind generation, this operational dimension is especially important. Wind output is weather-dependent and therefore cannot be scheduled with perfect accuracy. Deviations between the notified position and actual production must be corrected close to delivery or settled through balancing mechanisms. In a market environment characterized by volatile spot prices and high balancing prices during stressed system conditions, a battery can create value by moving energy across time, maintaining reserve headroom and responding to activation signals. This makes storage a market-coupling instrument between the physical variability of renewable generation and the commercial obligations of the market participant.

The present paper develops a scenario-based techno-economic assessment of this role using a 142.6 MW wind power plant and a 71.3 MWh Li-ion BESS as a reference case. The analysis is based on the author's dissertation research and on historical Romanian market data covering 2024 to March 2026, compiled from the Day-Ahead Market operator and the transmission system operator [10] [11]. The central research question is not whether a battery can technically support a wind plant, but how its available capacity should be allocated between the Day-Ahead Market (DAM) and ancillary services in order to maximize the annual economic benefit.

Three allocation strategies are compared: 25% ancillary services / 75% DAM, 75% ancillary services / 25% DAM and 50% / 50%. Each strategy is evaluated for three initial states of charge (SoC): 95%, 50% and 10%. The model includes charging and discharging efficiency, state-of-charge operating limits, reserve prices, balancing activation prices, an activation coefficient and representative DAM price windows. The contribution therefore lies in linking a previously selected storage size to a structured market-participation problem, rather than treating the storage decision as a purely technical sizing exercise.

The paper is organized as follows. Section 2 explains why storage has strategic value in electricity markets and positions the proposed approach relative to the flexibility literature. Section 3 summarizes the reference wind plant and selected BESS without reproducing equipment-level installation descriptions. Section 4 presents the scenario-based methodology and the economic model. Section 5 compares the results and identifies the best performing tested scenario. Sections 6 and 7 evaluate the economic and environmental implications and Section 8 summarizes the original results, limitations and possible applications.

2. Strategic value of energy storage in electricity markets

2.1. Flexibility requirement created by variable renewable generation

The physical balance between generation and consumption must be maintained continuously, while commercial schedules are established before real-time operation. Variable renewable generation introduces uncertainty into this process because the final output depends on meteorological conditions that evolve after the day-ahead gate closure. Forecast quality can be improved, but the residual error cannot be eliminated. For a market participant, the consequence is an exposure to deviations: an over-forecast position may require energy purchases or downward correction, while an under-forecast position may create an opportunity cost or imbalancing exposure. For the system operator, the same uncertainty translates into a greater requirement for balancing reserves and fast activation capability.

Energy storage changes the character of this uncertainty because it adds a controllable resource between the renewable generator and the market. Instead of being forced to deliver all available wind energy at the moment of generation, the hybrid participant can temporarily charge the battery, later discharge it or keep a portion of its power available as reserve. This controllability is the source of the battery's strategic value. In the short term, it supports schedule management and real-time balancing. Over a longer horizon, it can reduce curtailment exposure, improve utilization of renewable production and provide an additional revenue stream independent of the instantaneous wind output.

The international literature identifies several categories of storage value: energy shifting, frequency regulation and reserve, congestion relief, capacity adequacy and integration of variable renewables [6] [7] [8]. The relative attractiveness of these applications depends on market design and price signals. Energy shifting is driven by the spread between low-price charging intervals and high-price discharging intervals. Reserve provision is driven by the remuneration for maintaining available power, while balancing activation adds a second component that depends on the probability and price of actual activation. A battery that can access multiple products therefore has a portfolio of possible revenue streams rather than a single use case.

Figure 1 summarizes the logic used in this paper. Variable wind output creates forecast deviations, the power system requires balancing and reserves, storage provides controllable charging, discharging and reserve headroom and the market participant can translate this controllability into improved schedule management and ancillary service participation. The battery is therefore not evaluated merely as additional installed capacity, but as an operating resource whose value depends on alignment with system needs.

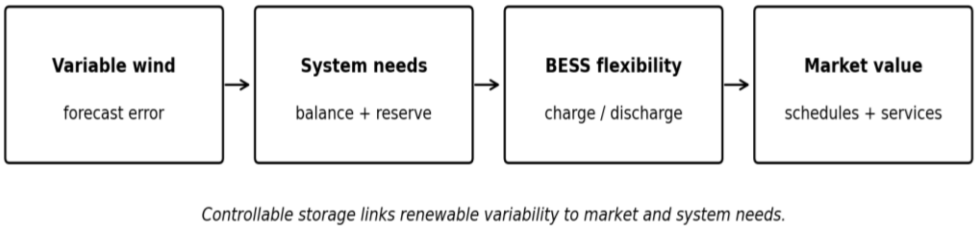

Fig. 1. Strategic value chain from variable renewable generation to market participation

2.2. Market pathways considered in the analysis

The Romanian wholesale electricity market is integrated into the European market architecture and includes day-ahead, intraday and balancing mechanisms. The DAM establishes the main short-term commercial position for the next delivery day and provides a transparent reference price. The intraday market allows positions to be adjusted closer to delivery, while the balancing market is used by the transmission system operator to restore system balance in real time. Historical results and reports published by OPCOM and Transelectrica illustrate the significant variation in short-term and balancing prices over 2024–2026 [10] [11].

The scenario model developed here focuses on two complementary uses of the BESS. The first is DAM delivery management, in which energy is charged during representative lower-price intervals and discharged during representative higher-price intervals. The second is ancillary service participation, represented by aFRR reserve availability and the associated balancing activation. The model therefore captures both the value of energy shifting and the value of fast flexibility.

This distinction is important because the DAM and ancillary services compete for the same physical flexibility. Capacity committed to reserve cannot simultaneously be assumed fully available for day-ahead energy shifting and excessive discharge for energy-market purposes can reduce the upward reserve capability of the battery. Conversely, a very high SoC can restrict downward flexibility because insufficient charging headroom remains. The allocation problem is therefore a joint energy and reserve decision and the initial SoC affects the amount of headroom available in both directions.

From a regulatory perspective, this multi-service logic is consistent with the broader European objective of non-discriminatory market access for storage and market-based remuneration of flexibility [3] [4]. From an investment perspective, it is also consistent with the finding in the storage literature that economic performance depends on application specific operation and revenue stacking [8] [9]. The present study applies these principles to a Romanian wind plus storage case and quantifies how three fixed capacity allocation strategies perform under the same technical and market assumptions.

2.3. Portfolio and virtual-power-plant perspective

The strategic value of storage becomes even more evident when the battery is considered as part of a portfolio rather than as an isolated device. A virtual power plant (VPP) or aggregation platform can coordinate renewable generators, storage units and flexible consumption through a common forecasting and optimization layer. In such a structure, the physical assets remain geographically distributed, but their commercial positions and controllable flexibility can be managed jointly. The European market framework increasingly supports aggregation and participation of distributed flexibility, creating a natural institutional context for this type of operation [3] [4].

For a wind plus storage portfolio, aggregation provides two complementary effects. First, forecast errors from different assets may partially offset each other, reducing the net imbalance of the portfolio. Second, a centrally managed BESS can be dispatched against the residual portfolio position rather than against a single generator. This increases the economic value of each MWh of storage because the battery responds to the net requirement of the portfolio. The same principle can be extended to a mixed portfolio containing wind, photovoltaic generation, controllable thermal production and flexible demand.

From a market perspective, the VPP layer can coordinate day-ahead nominations, intraday corrections and reserve commitments while respecting the physical limits of each asset. The battery then acts as the fastest controllable resource in the portfolio. It can absorb excess renewable production, compensate shortfalls, preserve upward or downward reserve headroom and respond to activation signals. The value created is therefore not limited to a single buy-low/sell-high cycle, it includes the reduction of portfolio imbalance risk and the ability to offer standardized flexibility products to the system operator.

This portfolio interpretation is consistent with the case study methodology even though the calculations in this paper remain focused on one wind plant and one BESS. The fixed allocation coefficients used in the three scenarios can be viewed as high-level portfolio policies: one policy prioritizes energy-market management, one prioritizes ancillary services and one diversifies evenly. In a real VPP, these coefficients would be updated dynamically based on forecasts, current SoC, market liquidity, reserve obligations and expected activation. The scenario results therefore provide a transparent benchmark against which a more advanced optimizer could later be tested.

A practical implication is that storage economics should be evaluated together with the commercial organization that controls the asset. The same battery can have different value for a standalone generator, a balance responsible party, an aggregator or a multi-asset trader because the opportunities to net deviations and stack revenues are different. The present paper focuses on the asset level market allocation, but the results support a broader strategic conclusion: storage is most valuable when its controllability is embedded in an integrated decision process that combines forecasting, portfolio management and market execution.

3. Case study: reference wind plant and selected BESS

The reference project is an onshore wind power plant with 142.6 MW installed capacity, consisting of 23 wind turbines rated at 6.2 MW each. The annual energy production used in the underlying project study is 495.4 GWh. The present paper does not reproduce detailed descriptions of turbines, transformers, substation equipment or grid connection installations. Only the system-level parameters required for the market analysis are retained.

The storage solution was selected in the preceding technical-economic project assessment and was carried forward into this paper as the reference BESS. Four storage capacities were originally compared: 28.52 MWh, 35.65 MWh, 71.3 MWh and 427.8 MWh. The 71.3 MWh option produced the most favorable balance between flexibility and investment cost among the relevant alternatives. It corresponds to 35.65 MW of battery power and a two-hour discharge duration, equivalent to a nominal C-rate of approximately 0.5. The selected technology is Li-ion, with a reference durability of up to 15,000 charge-discharge cycles in the underlying project assumptions.

Table 1 contains the system level parameters used in the subsequent calculations. The BESS is large enough to provide a meaningful fraction of the wind plant's controllable power without approaching the scale of the entire generating facility. This is relevant for the strategic framing of the study: the battery is not intended to replace the variability of the wind plant completely, but to provide a controllable flexibility layer that can be allocated to the most valuable market products.

Table 1. **System-level parameters of the reference case**

Parameter	Value	Unit
Installed wind capacity	142.6	MW
Number of wind turbines	23	-
Nominal turbine rating	6.2	MW
Annual wind production	495.4	GWh/year
Selected BESS energy capacity	71.3	MWh
Selected BESS power	35.65	MW
Nominal discharge duration	2	h
Nominal C-rate	0.5	h^{-1}
Reference operating cycles	2	cycles/day
Charge efficiency	95	%
Discharge efficiency	95	%

The analysis uses three representative initial SoC levels: 95%, 50% and 10%. These states deliberately span the upper, central and lower parts of the operating range. A 50% initial SoC provides symmetric headroom for charging and discharging and is therefore expected to offer the best bidirectional flexibility, while the 95% and 10% states test whether the strategy remains economically robust when one direction of operation is constrained.

4. Scenario-based methodology

4.1. Scenario definition and market inputs

The methodology allocates the available BESS capacity between ancillary services (AS) and the DAM. The allocation coefficient is fixed within each scenario and is applied to the power available after accounting for the initial SoC and the charging/discharging constraints. Three principal scenarios are considered. Scenario 1 is DAM oriented, Scenario 2 is ancillary services oriented and Scenario 3 is balanced. Each is evaluated at 95%, 50% and 10% initial SoC, producing nine subscenarios in total.

Table 2. **Capacity-allocation strategies**

Scenario	Ancillary services	Day-Ahead Market	Operational profile
S1	25%	75%	DAM oriented
S2	75%	25%	Ancillary services oriented
S3	50%	50%	Balanced

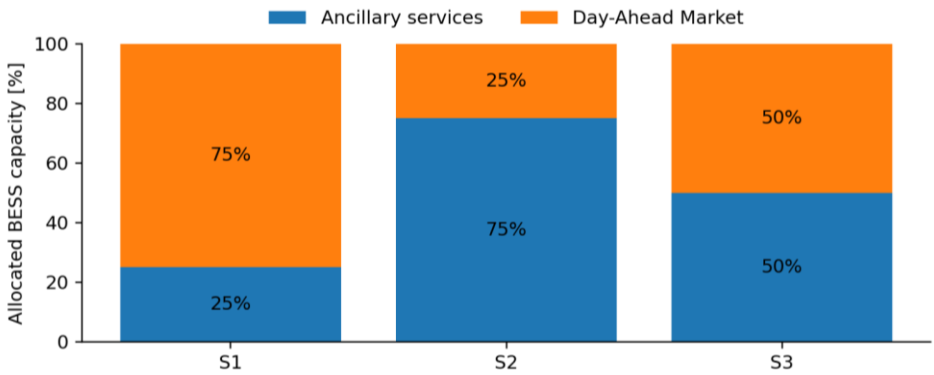

Fig. 2. BESS capacity allocation in the three analysed strategies

The market inputs are historical averages used in the dissertation model. Day-ahead prices were derived from representative high-price and low-price windows, while reserve and activation prices were derived from Romanian ancillary service and balancing data. The economic analysis presented used historical market data from 2024 to March 2026. The values should therefore be interpreted as a calibrated historical scenario rather than a forecast of future prices.

Table 3 shows the market and operating values that drive the annual benefit calculation. The large difference between the upward balancing activation price and the downward activation price is particularly important. Under these assumptions, preserving upward flexibility has a high marginal value, which creates an economic rationale for allocating a substantial share of the BESS to system services. The DAM price spread remains positive and economically relevant, but it competes with reserve/activation value for the same battery capacity.

Table 3. **Principal market and operating inputs used in the annualized model**

Input	Value	Unit / interpretation
aFRR Up reserve price	33.15	RON/MWh
aFRR Down reserve price	5.30	RON/MWh
aFRR Up activation price	1,637	RON/MWh
aFRR Down activation price	74.56	RON/MWh
Reserve activation coefficient	20	%
DAM representative discharging price	755	RON/MWh
DAM representative charging price	444	RON/MWh
Operating days	365	days/year
Reference cycles	2	cycles/day

4.2. Energy availability and state of charge treatment

The initial energy stored in the battery is obtained from the selected initial SoC. Equation (1) defines the starting energy as a fraction of the nominal BESS capacity. The model then determines the feasible charging and discharging quantities while respecting the lower and upper state of charge limits embedded in the dissertation methodology. Charging and discharging efficiencies are both taken as 95%.

$$W_0 = \alpha_{SoC} \times W_{BESS} \quad (1)$$

Where W_0 is the initial energy stored in the battery, α_{SoC} is the initial state of charge coefficient and W_{BESS} is the nominal battery energy capacity. For the 71.3 MWh BESS, the three initial states correspond to approximately 67.74 MWh, 35.65 MWh and 7.13 MWh respectively. At a high initial SoC, downward flexibility is restricted because little charging headroom remains and at a low initial SoC, upward flexibility is restricted because little stored energy is immediately available.

The selected 0.5 C operating rate and two-hour duration constrain the energy that can be transferred within a representative cycle. In the annualized model, the available cycle energy is split according to the scenario shares. The same physical BESS is therefore evaluated under different commercial commitments without changing the installed storage size. This separation between technical sizing and operational allocation is a central feature of the approach.

4.3. Annual benefit model

The annual benefit is decomposed into three components: (i) remuneration for reserving BESS capability for ancillary services, (ii) benefit associated with balancing activation and (iii) benefit from DAM energy shifting. This decomposition makes it possible to identify which market service is responsible for the superior performance of a given scenario.

For ancillary services, the reserved upward and downward capacities are calculated from the corresponding scenario allocation. The annual reserve component is represented in simplified form by Equation (2), where the reserved power in each direction is multiplied by the respective mean reserve price and annualized by the assumed operating frequency.

$$B_{AS} = (P_{up} \times \rho_{up,res} + P_{down} \times \rho_{down,res}) \times N_c \times 365 \quad (2)$$

The activation component is calculated separately because only a fraction of the reserved capacity is assumed to be activated. Equation (3) applies the activation coefficient k_{act} to the difference between upward activation value and the negative contribution of downward activation under the model assumptions.

$$B_{BM} = (P_{up} \times \rho_{up,act} - P_{down} \times \rho_{down,act}) \times k_{act} \times N_c \times 365 \quad (3)$$

For the DAM component, the model assumes that the allocated BESS energy is charged in representative lower-price windows and discharged in representative higher-price windows. The resulting annual benefit is given by Equation (4). Charging and discharging losses are already reflected in the energy quantities derived from the cycle model.

$$B_{DAM} = E_{sell} \times \pi_{high} - E_{buy} \times \pi_{low} \quad (4)$$

The total annual benefit generated by the BESS strategy is the sum of the three components, as shown in Equation (5). This value is a gross operational benefit before the annual BESS operating and maintenance cost is deducted in the investment analysis.

$$B_{total} = B_{AS} + B_{BM} + B_{DAM} \quad (5)$$

The model is intentionally scenario based and annualized. It is not a chronological optimal dispatch simulation and does not reproduce every 15-minute market interval. Its purpose is to compare strategic capacity allocation under a consistent set of technical and price assumptions. This design allows the effect of market orientation and initial SoC to be isolated clearly, while retaining enough technical detail to account for efficiency and headroom constraints.

4.4. Methodological scope and modelling assumptions

Several assumptions are deliberately held constant so that the comparison isolates the effect of capacity allocation. The BESS size, nominal power, efficiencies, number of cycles and historical market price inputs are identical in all nine subscenarios. The activation coefficient is also fixed at 20%. Consequently, any difference between S1, S2 and S3 is generated by the share of battery capability committed to each market function and by the initial energy available in the storage system.

The model uses representative annual prices rather than a chronological price series. This has two advantages for a strategic comparison: the calculation is transparent and the source of the value difference can be traced directly to the allocation decision. It also has clear limitations. Extreme prices, negative price intervals, sequences of consecutive activations, reserve non-delivery penalties and intraday opportunities are not represented explicitly. Similarly, the wind production profile enters the study through the selected project and storage sizing assumptions rather than through a full hourly or quarter-hourly dispatch trace.

Battery degradation is not monetized in the operational benefit calculation. The reference cycle life provides a technical plausibility check, but the model does not assign a marginal degradation cost to each discharge. In practice, such a cost can materially change the ranking of high cycling energy shifting strategies relative to reserve strategies that may preserve energy throughput while monetizing power availability. Including state of health, depth of discharge dependent degradation and augmentation requirements would therefore strengthen a future operational version of the model.

The analysis is also price taking: it assumes that the studied battery does not influence the market price. This is reasonable for a single 35.65 MW BESS in a large market comparison, but the assumption may become less accurate as storage penetration increases. Large fleets of batteries can compress intraday and day-ahead spreads and increase competition for reserve products. For this reason, the numerical results should be interpreted as a historical case study and the scenario framework as the transferable contribution.

5. Results and discussion

5.1. Comparison of the three strategies

All nine subscenarios produce positive annual benefits. However, the level of benefit changes systematically with the share of BESS capacity allocated to ancillary services. Table 4 summarizes the complete set of results. The DAM oriented strategy, S1, produces average annual benefit of 14.894 million RON, the balanced strategy, S3, produces 15.665 million RON and the ancillary services oriented strategy, S2, produces 16.437 million RON.

Table 4. **Annual total benefit generated by the BESS under each strategy**

Initial SoC	S1: 25% AS / 75% DAM	S2: 75% AS / 25% DAM	S3: 50% AS / 50% DAM
95%	14,962,073	16,512,552	15,737,313
50%	14,999,572	16,553,937	15,776,755
10%	14,719,317	16,244,640	15,481,978
Average	14,893,654	16,437,043	15,665,349

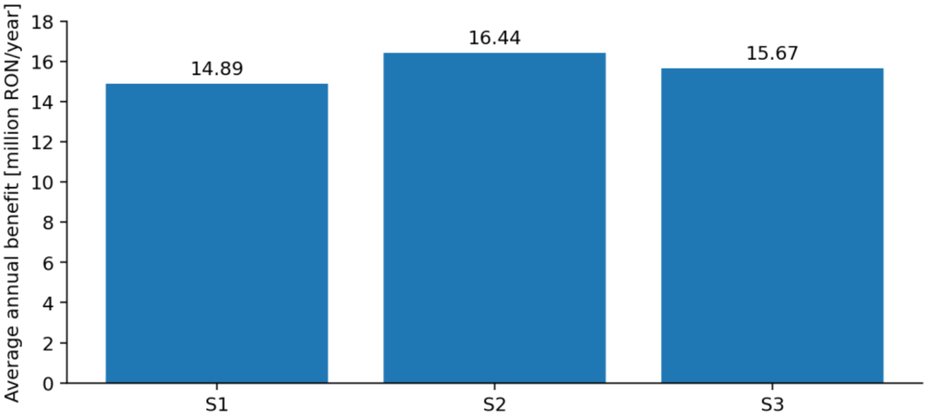

Fig. 3. Average annual benefit for the three BESS allocation strategies

Figure 3 highlights the ranking of the strategies. Relative to S1, the average benefit of S2 is approximately 10.36% higher. Relative to the balanced S3 strategy, S2 is approximately 4.93% higher. These differences are material because the storage capacity is identical in all cases, only the operating allocation changes. The result directly supports the paper's main proposition that operation strategy is as important as storage sizing.

The DAM oriented case remains economically attractive because the assumed price spread between charging and discharging windows is positive. Nevertheless, allocating 75% of the battery to DAM limits the capacity that can earn reserve and balancing activation revenues. In contrast, S2 captures a larger share of the high value flexibility products while retaining 25% of BESS capacity for day-ahead delivery management. The balanced S3 case diversifies revenues more evenly but does not maximize either component.

5.2. Influence of the initial state of charge

The initial SoC affects the result less strongly than the market allocation decision. In all three scenarios, the 50% initial SoC gives the highest benefit, while the 10% initial SoC gives the lowest. For S2, the difference between the best and worst subscenario is 309,297 RON/year, or less than 2% of the scenario's average benefit. The corresponding ranges in S1 and S3 are similarly moderate. This indicates that the scenario ranking is robust across the three representative starting states.

The 50% SoC result is consistent with the physical requirement for bidirectional flexibility. A battery starting near the middle of its operating range can absorb energy if the system is long or if wind output exceeds the planned position, while also retaining sufficient stored energy for upward activation or high price discharge. At 95% SoC, charging headroom is limited and at 10% SoC, immediate discharge capability is reduced. The central SoC therefore provides the most balanced initial flexibility for a strategy that combines upward and downward services.

It is important, however, not to interpret this finding as a universal optimal SoC setpoint. The analysis tests three representative starting states within an annualized model. In real operation, the optimal SoC trajectory would depend on expected wind production, reserve commitments, intraday prices, activation probability and battery degradation. A dynamic dispatch optimizer could therefore move the target SoC over time. The present result should be understood as evidence that a midrange starting SoC is advantageous under the specific scenario assumptions.

5.3. Best performing scenario and components of value

The best individual result is subscenario S2.2: 75% of BESS capacity allocated to ancillary services, 25% allocated to the DAM, and 50% initial SoC. The annual total benefit is 16,553,937 RON. The value is composed of 1,436,260 RON/year from reserve availability, 11,562,080 RON/year from balancing activation and 3,555,597 RON/year from DAM delivery management.

As shown in Figure 4, balancing activation accounts for approximately 69.8% of the total benefit, DAM management for 21.5% and reserve availability for 8.7%. The dominance of the activation component explains why the ancillary services oriented strategy outperforms the DAM oriented strategy under the historical price assumptions. The battery's fast response capability is being monetized most effectively when the market places a high value on upward balancing energy.

This result also illustrates a broader point about revenue stacking. Reserve availability alone is not the dominant source of value, rather, the combination of reserved headroom and the expected activation of that headroom drives the result. At the same time, preserving a 25% share for the

DAM avoids a fully single market strategy and allows part of the battery to continue capturing day-ahead price differences. The optimal case is therefore not a pure ancillary service solution, but a portfolio allocation in which system services receive priority.

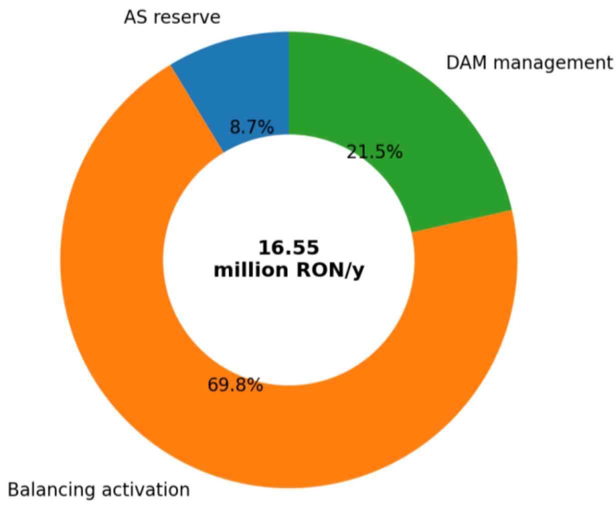

Fig. 4. Composition of annual benefit in the optimal S2.2 strategy

The result should be interpreted within the market period used for calibration. Balancing prices are volatile and can change structurally as reserve procurement, renewable penetration, cross-border integration and battery competition evolve. A strategy optimized on 2024–March 2026 historical averages may not remain optimal under a future price regime. The methodological contribution is the allocation framework itself: the same model can be recalibrated periodically with updated price distributions and activation statistics.

5.4. Cross-market trade-off at 50% initial SoC

The 50% initial SoC provides a useful basis for comparing the internal composition of the three strategies because it is the best performing starting condition in each case. Table 5 shows how the same battery benefit is redistributed as the allocation moves from DAM oriented operation to ancillary services oriented operation. The result is close to linear for the individual components because the scenario shares are fixed, but the total benefit is not neutral: the market value per unit of capacity differs substantially between the two uses.

Table 5. **Benefit components for the three strategies at 50% initial SoC**

Component	S1: 25% AS / 75% DAM	S2: 75% AS / 25% DAM	S3: 50% AS / 50% DAM
AS reserve [RON/year]	478,753	1,436,260	957,506
Balancing activation [RON/year]	3,854,027	11,562,080	7,708,054
DAM management [RON/year]	10,666,792	3,555,597	7,111,195
Total [RON/year]	14,999,572	16,553,937	15,776,755

In S1, approximately 71% of the annual value at 50% SoC comes from DAM management, whereas in S2 almost 79% comes from the combined reserve and balancing components. The balanced S3 strategy produces a correspondingly diversified structure. This comparison demonstrates that the higher value of S2 is not caused by greater energy throughput or a larger battery, it is caused by directing more of the existing flexibility toward the historically more valuable service.

For an operator, this result supports a hierarchy of decisions. The first decision is technical: determine the power and energy capacity that the site can justify. The second is commercial: decide how much headroom to reserve for different products. The third is dynamic: update that allocation as prices and forecasts change. The present study addresses the second level explicitly and provides a benchmark for the third. A future optimizer should be expected to outperform all three fixed strategies by changing the allocation when the relative value of DAM spreads and system services changes over time.

The trade-off also has a risk dimension. A DAM oriented strategy relies on the persistence of a price spread between charging and discharging windows. An ancillary services oriented strategy relies more strongly on reserve procurement rules, activation frequency and balancing prices. A balanced allocation sacrifices some expected value in the historical case but reduces dependence on a single revenue source. Therefore, the strategy with the highest expected benefit is not automatically the strategy with the lowest risk. This distinction should be incorporated in investment grade optimization through scenario probabilities or risk adjusted objective functions.

6. Economic assessment of the storage investment

6.1. Incremental investment case

The operational benefit must be compared with the incremental cost of installing and operating the BESS. The economic assessment treats the wind plant as an already defined reference investment and evaluates the storage system as an incremental project. This is important because the reported internal rate of return and payback period describe the battery investment, not the entire wind power plant.

The BESS specific CAPEX used in the project is 100,000 EUR/MWh. For 71.3 MWh, the resulting initial battery investment is 7.13 million EUR. Annual BESS operating and maintenance expenditure is assumed to equal 4% of battery CAPEX, or 285,200 EUR/year. Using an exchange rate of 5.1 RON/EUR, the optimal annual gross benefit of 16.554 million RON corresponds to approximately 3.246 million EUR/year. After battery OPEX, the annual net incremental benefit is approximately 2.961 million EUR/year.

For a 25-year analysis period and a 10% discount rate, the present value of a constant annual net benefit is calculated using the annuity factor. Equation (6) expresses the net present value of the incremental BESS investment.

$$NPV = -I_{BESS} + B_{net} \times \frac{[1 - (1 + r)^{-n}]}{r} \tag{6}$$

where I_{BESS} is the initial BESS investment cost [EUR], B_{net} is the annual net incremental BESS benefit after operating and maintenance costs [EUR/year], r is the discount rate and n is the analysis period [years].

The corresponding simple payback period is obtained from Equation (7). The model assumes constant annual benefit and does not explicitly include midlife augmentation or replacement, financing structure, taxation or degradation related reduction in usable energy. These simplifications are discussed below as limitations.

$$T_{payback} = \frac{I_{BESS}}{B_{net}} \tag{7}$$

where $T_{payback}$ is the simple payback period [years].

Table 6 shows that the incremental storage investment is economically attractive under the adopted assumptions. The NPV is approximately 19.74 million EUR, the simple payback is 2.41 years and the IRR is 41.52%/year, substantially above the 10% discount rate. The benefit-cost ratio of 3.03 indicates that the present value of gross benefits is about three times the present value of the investment and operating costs included in the calculation.

The BESS increases the total project CAPEX from 185.38 million EUR for the reference wind plant to 192.51 million EUR, an increase of approximately 3.85%. The key strategic observation is therefore that a relatively limited increase in total project investment can materially change the commercial flexibility of the asset. Nevertheless, the reported return metrics should not be generalized without recalibration. Battery costs, reserve prices and activation patterns can change rapidly and real projects must include degradation, augmentation, financing and tax effects. The present values are best interpreted as a comparative economic signal demonstrating the potential of the identified operating strategy.

Table 6. **Economic indicators of the incremental BESS investment**

Indicator	Value
BESS energy capacity	71.3 MWh
Specific BESS CAPEX	100,000 EUR/MWh
Initial BESS investment	7.130 million EUR
Annual BESS OPEX	0.285 million EUR/year
Gross annual benefit	3.246 million EUR/year
Net annual benefit	2.961 million EUR/year
Analysis period	25 years
Discount rate	10%/year
Net present value	19.744 million EUR
Simple payback	2.41 years
Internal rate of return	41.52%/year
Benefit-cost ratio	3.03

6.2. Economic sensitivity and investment caveats

The strong base-case indicators are primarily driven by the difference between the incremental battery cost and the annual benefit implied by the historical market prices. This means that market price sensitivity is more important than small variations in the wind plant CAPEX, which is outside the incremental storage cash flow. If balancing activation value falls or competition compresses ancillary service margins, the payback period will lengthen even if battery CAPEX remains unchanged. Conversely, lower future battery costs would improve the investment case and could make larger storage configurations competitive.

A second sensitivity concerns usable capacity over time. The financial calculation assumes a constant annual benefit, but a Li-ion BESS gradually loses usable energy and may require augmentation to maintain contracted power and duration. A rigorous project finance model should therefore include a degradation curve, replacement or augmentation expenditure, availability assumptions and possible revenue reduction during maintenance. These effects are not included in the 19.744 million EUR NPV and should be treated as additional diligence items before applying the result to an investment decision.

A third consideration is the relationship between reserve and activation revenues. The optimal scenario receives only a modest share of its value from availability payments and a much larger share from balancing activation. This makes the result sensitive to activation frequency and price distribution. A more conservative valuation could separate contracted or capacity like revenue from activation dependent revenue and apply different confidence levels to each. Such a treatment would preserve the scenario methodology while converting the expected benefit comparison into a risk adjusted business case.

Finally, the 25-year horizon is a theoretical project-life benchmark aligned with the wind plant, not an assumption of unchanged battery operation. At 2 reference cycles per day, it implies 18,250 equivalent cycles, above the 15,000-cycle reference durability considered for the selected Li-ion BESS. A bankable model should include degradation, usable-capacity fade, availability reduction and mid-life augmentation or partial replacement. As a 12-year sensitivity with the same net benefit and 10% discount rate, NPV remains approximately 13.04 million EUR and payback remains 2.41 years. Therefore, the 25-year indicators are screening values, not guaranteed lifetime returns.

7. Environmental contribution and renewable integration

The environmental analysis evaluates the wind project on a life cycle basis and quantifies avoided emissions relative to alternative conventional generation assumptions. With annual wind production of 495.4 GWh and a reference Romanian power system conversion factor of 0.33 tCO_2/MWh, the annual avoided emissions are estimated at 163,482 tCO_2/year. These avoided emissions are attributable primarily to the renewable generation itself. The strategic contribution of the BESS is to improve the ability to integrate and use that renewable production by adding temporal flexibility and reducing mismatch between production and delivery.

The estimated life cycle emissions of the project are 63,899 tCO_2, including component manufacturing, transport, installation, operation, maintenance and decommissioning. Distributed over 25 years of production, this corresponds to a specific life cycle intensity of approximately 5.16 gCO_2/kWh. Relative to the annual avoided emission reference, the life cycle carbon burden is compensated in approximately 0.39 years, or less than five months of operation. Table 7 summarizes these indicators.

Table 7. **Selected environmental indicators of the reference wind-plus-storage project**

Indicator	Value
Annual wind production	495.4 GWh/year
Reference avoided emissions vs. SEN	163,482 tCO_2/year
Avoided emissions over 25 years	4,087,050 tCO_2
Estimated life-cycle emissions	63,899 tCO_2
Net avoided emissions over 25 years	4,023,151 tCO_2
Specific life-cycle emission intensity	5.16 gCO_2/kWh
Life-cycle carbon compensation time	0.39 years (<5 months)

The role of storage in this environmental context should be framed carefully. A BESS does not create zero carbon energy, but it consumes and later returns energy with efficiency losses and has its own embodied emissions. Its environmental value arises when flexibility allows more renewable energy to be delivered when useful, reduces curtailment or fossil balancing requirements and supports a system capable of operating with a higher share of variable renewable generation. The present study therefore treats environmental benefit as complementary evidence supporting the strategic value of the hybrid wind plus storage configuration rather than attributing the full avoided emission quantity to the battery alone.

8. Conclusions

This paper presented a scenario based techno-economic methodology for evaluating the strategic role of a Li-ion BESS in the market participation of a 142.6 MW wind power plant. The original contribution is the explicit allocation of a fixed 71.3 MWh / 35.65 MW battery between two competing value streams: Day-Ahead Market delivery management and ancillary services, while accounting for initial state of charge, charging/discharging efficiency, reserve and activation prices, DAM price spreads and annual economic benefit.

Three allocation strategies and three initial SoC levels were assessed. All nine subscenarios generated positive annual benefits, but the strategy allocating 75% of battery capacity to ancillary services and 25% to the DAM consistently produced the strongest results. The best individual configuration, with 50% initial SoC, generated 16.554 million RON/year. Its value was dominated by balancing activation (11.562 million RON/year), followed by DAM delivery management (3.556 million RON/year) and reserve availability (1.436 million RON/year). The result confirms that fast response flexibility can be more valuable than energy shifting alone when balancing prices provide strong economic signals.

The economic assessment further showed that, under the adopted historical market and cost assumptions, the 7.13 million EUR BESS investment can generate a net annual benefit of approximately 2.96 million EUR, an NPV of 19.74 million EUR, a 2.41 year simple payback, a 41.52% IRR and a benefit-cost ratio of 3.03. These values indicate high attractiveness for the incremental storage investment, but they remain scenario dependent and should not be interpreted as guaranteed future returns.

The analysis also confirms that the initial SoC affects performance less strongly than the market allocation decision. A midrange SoC provides balanced headroom for both charging and discharging, but the ranking of the three strategies remains unchanged at 95%, 50% and 10% initial SoC. This robustness supports the practical relevance of the allocation result while also highlighting the need for dynamic SoC control in real operation.

The principal limitation is the use of an annualized deterministic model based on representative prices and a fixed activation coefficient. The model does not include a chronological 15-minute dispatch, stochastic wind forecast errors, intraday re-optimization, battery degradation, replacement or endogenous price effects. Future work should therefore extend the methodology to time series co-optimization across DAM, intraday and balancing markets, include degradation cost as a function of depth of discharge and cycle count and use probabilistic price and wind forecasts. Such an extension would allow the fixed scenario approach developed here to evolve into an adaptive decision support tool for hybrid renewable portfolios.

Overall, the study demonstrates that energy storage should be evaluated as a strategic flexibility asset rather than only as additional installed capacity. For the reference case, the commercial strategy applied to the battery is as important as the technical size of the battery itself. Prioritizing ancillary services while retaining a portion of capacity for day-ahead management provides the best balance between flexibility, profitability and renewable energy integration under the historical Romanian market conditions considered.

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