II SAVJETOVANJE O
ELEKTRODISTRIBUTIVNIM MREŽAMA CRNE GORE

15-18. jun 2026, Bečići, Crna Gora

Broj rada: R4-05

TEHNO-EKONOMSKA PROCENA KO-LOCIRANOG PV–VETAR–BESS SISTEMA U USLOVIMA VELEPRODAJNIH TRŽIŠNIH CENA UZ OPTIMIZACIJU EMS-A ZASNOVANU NA LINEARNOM PROGRAMIRANJU

TECHNO-ECONOMIC ASSESSMENT OF A CO-LOCATED PV–WIND–BESS SYSTEM UNDER WHOLESALE MARKET PRICES WITH LINEAR PROGRAMMING-BASED EMS OPTIMIZATION

Dragan MINOVSKI, Faculty of Electrical Engineering, Goce Delcev University Stip, Severna Makedonija*
Sara ANEVA, Faculty of Electrical Engineering and Information Technologies, University Ss. Cyril and Methodius in Skopje, Severna Makedonija
Vasilija SARAC, Faculty of Electrical Engineering, Goce Delcev University in Stip, Severna Makedonija

KRATAK SADRŽAJ

Ovaj rad analizira tehno-ekonomske performanse kolocirane fotonaponske elektrane i vetroelektrane, pri čemu svaka elektrana ima instalisanu snagu od 36.8 MW, u uslovima veleprodajnog tržišta električne energije u Severnoj Makedoniji. Razmatrana su tri scenarija rada: referentni slučaj bez baterijskog skladištenja energije, slučaj sa baterijskim sistemom i upravljanjem zasnovanim na pravilima implementiranim u Excel-u, i slučaj sa baterijskim sistemom i optimizovanim sistemom upravljanja energijom razvijenim u MATLAB-u. U skladišnim konfiguracijama, svaka elektrana je povezana sa zasebnim baterijskim sistemom dimenzionisanim na 20% instalisane snage, sa trajanjem pražnjenja od dva sata. Analiza je sprovedena u dve faze. Najpre je izvršena operativna i prihodovna analiza za baznu 2025. godinu, na časovnom nivou, korišćenjem časovnih cena električne energije sa makedonskog tržišta električne energije (MEMO). Časovna proizvodnja fotonaponske elektrane dobijena je projektovanjem i simulacijom u softveru PV*SOL premium, dok je časovna proizvodnja vetroelektrane zasnovana na merenim podacima proizvodnje vetroparka Bogdanci. Zatim je sprovedena finansijska analiza za period od 25 godina, koja obuhvata godišnje prihode, operativne troškove, otplatu kredita, amortizaciju, neto novčani tok i neto sadašnju vrednost (NPV). Rezultati pokazuju da integracija baterijskog sistema povećava tržišne prihode u odnosu na slučaj bez skladištenja, dok optimizovani EMS dodatno poboljšava ekonomske performanse u poređenju sa upravljanjem zasnovanim na pravilima. Od tri osnovna scenarija, slučaj sa optimizovanim EMS-om ostvaruje najveći godišnji prihod, najveću neto sadašnju vrednost i najkraći period povrata investicije. Dodatno je sprovedena analiza osetljivosti za optimizovani EMS scenario promenom snage i energetskog kapaciteta baterijskog sistema. Rezultati ukazuju da se profitabilnost projekta može dodatno unaprediti odgovarajućim dimenzionisanjem BESS-a, pri čemu je najveća NPV ostvarena za ukupnu projektnu konfiguraciju od 29.44 MW / 88.32 MWh. Rad potvrđuje da ekonomska vrednost baterijskog skladištenja u kolociranim PV-vetar sistemima u velikoj meri zavisi i od strategije upravljanja i od izabrane veličine baterijskog sistema.

Ključne reči: Fotonaponska elektrana, Vetroelektrana, Baterijski sistem za skladištenje energije, strategijaupravljanja isporukom, dimenzionisanje baterijskog sistema

ABSTRACT

This paper evaluates the techno-economic performance of a co-located photovoltaic power plant and wind power plant, each with an installed capacity of 36.8 MW, under wholesale market conditions in North Macedonia. Three operating scenarios are considered: a reference case without battery energy storage, a storage case with rule-based dispatch implemented in Excel, and a storage case with an optimized energy management system developed in MATLAB. In the storage configurations, each plant is coupled with a dedicated battery energy storage system sized at 20% of the installed power, with a discharge duration of two hours. The analysis is conducted in two stages. First, an hourly operational and revenue assessment is performed for the base year 2025 using hourly electricity prices from the Macedonian Electricity Market Operator (MEMO). Hourly photovoltaic

* Dragan Minovski dragan.minovski@ugd.edu.mk; Sara Aneva anevasara@yahoo.com; Vasilija Sarac vasilija.sarac@ugd.edu.mk

generation is obtained through plant design and simulation in PV*SOL premium, while hourly wind generation is based on measured production data from the Bogdanci wind farm. Second, a 25-year financial assessment is carried out, including annual revenues, operating costs, loan servicing, depreciation, and net cash flow, net present value (NPV). The results show that battery integration increases market revenues relative to the case without storage, while the optimized EMS provides further improvement compared with the rule-based dispatch strategy. Among the three main scenarios, the optimized EMS case achieves the highest annual revenue, the highest NPV, and the shortest payback period. In addition, a sensitivity analysis is performed for the optimized EMS case by varying battery power and energy capacity. The results indicate that project profitability can be further improved through appropriate BESS sizing, with the highest NPV obtained for a total project BESS configuration of 29.44 MW / 88.32 MWh. The study confirms that the economic value of battery storage in co-located PV-wind systems depends strongly on both the dispatch strategy and the selected battery size.

Keywords: PV power plant, Wind power plant, Battery Energy Storage System, dispatch strategy, storage sizing

1 INTRODUCTION

The rapid integration of variable renewable energy sources increases the need for flexible management of electricity production and delivery. In such conditions, battery energy storage systems can increase the market value of renewable generation by shifting energy from lower-price hours to higher-price hours. However, the economic effect of BESS depends not only on the presence of storage, but also on the applied dispatch strategy and the selected storage size [1], [2], [8], [11], [12]. This paper examines the techno-economic performance of a co-located system composed of a photovoltaic power plant and a wind power plant, each rated at 36.8 MW, with electricity sold on the wholesale market in North Macedonia. The analysis is based on hourly generation profiles and hourly market prices for 2025, and compares operation without storage, with BESS and heuristic EMS dispatch implemented in Excel, and with BESS and an optimized EMS developed in MATLAB. In the regional context, recent studies have addressed municipal renewable energy management, techno-economic PV deployment in North Macedonia, and surplus-management strategies that compare storage-based and alternative flexibility concepts [5]-[7]. The objective is to quantify the effect of BESS integration and dispatch strategy on market revenues, and net present value, and to show through a sensitivity analysis how battery power and energy capacity influence the whole project economic value and profitability.

2 METHODOLOGY

Hourly photovoltaic generation was obtained through PV power plant design and simulation in PV*SOL premium [3], while hourly wind generation was based on measured production data from the Bogdanci wind farm. Market valuation of the generated electricity was performed using hourly prices from the Macedonian Electricity Market Operator (MEMO) for the base year 2025 [4]. In the reference BESS configuration, each plant is coupled with a dedicated battery system rated at 7.36 MW, corresponding to 20% of the plant capacity, with a discharge duration of two hours and an energy capacity of 14.72 MWh per battery. Technical battery constraints include charging and discharging power limits, state-of-charge limits, and charging and discharging efficiencies. The financial model is based on a 25-year project horizon, with a 2% annual decline in market prices, PV generation degradation of 0.4% per year, and wind generation degradation of 0.17% per year [13]. The assumed 2% annual decline in market prices was derived from the authors' analysis of historical HUPX day-ahead market prices, where an average decreasing trend of approximately 2% per year was observed over the analyzed historical period. Therefore, this price trend was used as a long-term projection assumption for the financial model. The wind generation degradation rate of 0.17% per year was adopted as a conservative assumption, representing a possible worst-case performance decline based on the findings reported by Hamilton et al. [13]. Project financing is represented by 30% equity and 70% debt, with a 3% interest rate and a 10-year repayment period. Three scenarios are evaluated. Scenario A is the reference case without battery storage, in which all generated electricity is injected into the grid at the time of production. Scenario B represents the same BESS configuration operated with a rule-based EMS implemented in Excel. In this case, the battery is charged during the eight lowest-price hours of each day, subject to available generation, and discharged during the two highest-price hours. Scenario C uses the same BESS configuration but replaces the rule-based dispatch with an optimized EMS developed in MATLAB. Annual revenues are projected from the achieved or optimized 2025 revenues using the assumed market price trend and generation degradation factors. For BESS, fixed annual O&M costs are assumed at 2.5% of CAPEX, consistent with NREL cost assumptions for utility-scale battery systems, where fixed O&M includes augmentation-related expenses [1], [2]. The financial model includes O&M, loan servicing, depreciation, tax, and net cash flow, while project performance is evaluated through NPV and payback period. The NPV calculation was performed using a discount rate of 4%. The 4% discount rate was used as an adopted financial modelling assumption for discounting annual net cash flows; a project-specific

WACC and cost of equity were not separately estimated in this study. IRR was not included as a separate indicator, since the financial assessment was focused on NPV and payback period within the available scope of the paper. The optimized EMS is formulated as a linear programming problem over the full-year horizon. For each battery, the hourly charging power, discharging power, and state-of-charge are determined so as to maximize electricity market revenues, while respecting battery power limits, energy capacity limits, charging and discharging efficiencies, and state-of-charge constraints. In each hour *t*, the energy delivered to the grid is expressed as:

$$E_{grid,t} = E_{gen,t} - E_{ch,t} + E_{dis,t}$$

where $E_{gen,t}$ is the generated electricity, $E_{ch,t}$ is the energy charged into the battery, and $E_{dis,t}$ is the energy discharged from the battery to the grid. The objective is to maximize the total annual market revenue:

$$max \sum_{t=1}^{8760} \lambda_t \left(E_{gen,t} - E_{ch,t} + E_{dis,t}\right)$$

where λ_t denotes the hourly market price. The battery state-of-charge is updated according to:

$$SOC_t = SOC_{t-1} + \eta_{ch} E_{ch,t} - \frac{E_{dis,t}}{\eta_{dis}}$$

subject to:

$$0 \leq E_{ch,t} \leq \min\,(E_{gen,t}, P_{BESS})$$

$$0 \leq E_{dis,t} \leq P_{BESS}$$

$$SOC_{min} \leq SOC_t \leq SOC_{max}$$

The battery energy storage system is allowed to charge only from the co-located renewable generation unit, i.e. from the PV power plant or the wind power plant, and not from the electricity grid. Therefore, the analyzed BESS operation represents renewable energy shifting rather than independent grid arbitrage. This assumption was adopted in order to evaluate the added value of storage when directly coupled with the renewable generation assets and under the considered grid-connection and market participation framework. It should not be interpreted as a general regulatory limitation, but as a modelling assumption applied in this paper. Thus, the optimized EMS allocates part of the generated electricity to direct grid injection and part to storage, while determining the economically most favorable charging and discharging schedule over the analyzed year. Similar optimization-based scheduling approaches are widely used in recent BESS literature [9], [12].

3 BESS SIZING AND CONSTRAINTS

The battery energy storage systems (BESS) considered in this study are sized as 20% of the installed capacity of each generation unit. Since both the photovoltaic power plant and the wind power plant have an installed capacity of 36.8 MW, a dedicated battery system is assigned to each plant with a rated power of:

$$P_{BESS} = 0.2 \cdot P_{plant} = 0.2 \cdot 36.8 = 7.36 MW$$

A discharge duration of 2 hours is assumed, resulting in a nominal energy capacity of:

$$E_{nom} = P_{BESS} \cdot t = 7.36 \cdot 2 = 14.72 MWh$$

Thus, each generation unit is coupled with a 7.36 MW / 14.72 MWh battery system, while the total project configuration corresponds to two identical battery systems. The battery operation is subject to state-of-charge (SOC) constraints in order to ensure technically feasible charging and discharging. In the analysis, the minimum and maximum SOC limits are set to $SOC_{min} = 0.1$, $SOC_{max} = 0.9$, while the initial state-of-charge is assumed as $SOC_0 = 0.5$. Accordingly, the usable battery energy capacity is determined as:

$$E_{usable} = E_{nom} \cdot (SOC_{max} - SOC_{min})$$

This means that the technically usable storage range of each battery is 11.776 MWh. The charging and discharging efficiencies are both assumed to be 0.96, and the battery charging and discharging power are limited by the rated battery power.

4 TECHNICAL PERFORMANCE

The technical performance analysis was carried out for the three considered scenarios in order to assess how the integration of battery storage and the applied dispatch strategy affect the energy flows of the co-located PV and wind system. For the reference scenario, the monthly and annual electricity production of the photovoltaic power plant and the wind power plant are presented. For the storage-based scenarios, the analysis is extended to include the energy directly delivered to the grid, the energy stored in the battery system, the energy delivered from the battery to the grid, and the total energy injected into the grid. In this way, the operational effect of BESS integration and EMS strategy can be evaluated before the corresponding revenue and economic indicators are discussed.

4.1 Scenario A – PV + Wind

Table 1 presents the monthly and annual electricity production of the wind power plant and the photovoltaic power plant for the reference case without battery storage. The results show that the wind power plant provides the dominant share of annual energy production, with a total of 107,577.60 MWh, while the photovoltaic power plant contributes 52,782.72 MWh. The monthly profiles confirm the expected seasonal behavior of the two technologies. The photovoltaic generation reaches its highest values during the late spring and summer months, with the maximum monthly production recorded in June and July, while the lowest production occurs during the winter period. In contrast, the wind power plant exhibits a more distributed annual profile, with relatively high generation during winter and early spring months. This complementarity between PV and wind production is beneficial for the overall hybrid system, as it reduces seasonal variability and provides a broader generation profile over the year.

Table 1 – Electricity production from the power plants

Month	WPP Production (MWh)	PVPP Production (MWh)
January	16,459.34	1,981.96
February	9,828.74	2,549.02
March	9,844.48	4,123.62
April	7,712.78	5,379.63
May	5,364.26	6,733.00
June	7,943.40	7,188.29
July	10,488.69	7,103.92
August	9,476.52	6,263.33
September	7,793.02	4,671.57
October	8,597.39	3,240.28
November	7,723.71	1,925.11
December	6,345.27	1,622.99
Total (MWh)	107,577.60	52,782.72

4.2 Scenario B – PV+Wind+BESS

Table 2 presents the total monthly technical results for the storage-based scenario with the rule-based EMS implemented in Excel for the PV power pland and the wind power plant together. For the photovoltaic plant, part of the generated energy is delivered directly to the grid, while another part is stored in the battery and later discharged to the grid during higher-price periods. On an annual level, 48,719.34 MWh of PV energy is delivered directly to the grid, 4,063.37 MWh is charged into the battery, and 3,750.46 MWh is later discharged from the battery to the grid. As expected, the discharged energy is lower than the charged energy due to battery efficiency losses. The total PV energy delivered to the grid in this scenario amounts to 52,469.80 MWh. A similar pattern is observed for the wind power plant. Out of the total annual wind production, 103,743.87 MWh is delivered directly to the grid, 3,833.73 MWh is charged into the battery, and 3,538.82 MWh is returned from the battery to the grid. The total annual wind energy delivered to the grid is 107,282.68 MWh. These results indicate that the battery system allows part of the generated energy to be shifted in time, but under the applied heuristic EMS the battery operation remains constrained by the predefined charging and discharging logic.

Table 2 – Energy balance of Scenario B

Month	PV+Wind energy directly in grid	PV+Wind Energy in BESS	PV+Wind Energy in the grid from BESS	Total Energy in the grid
January	17,838.74	602.56	566.63	18,405.37
February	11,744.40	633.36	583.70	12,328.10
March	13,298.33	669.77	617.26	13,915.59
April	12,402.69	689.72	635.65	13,038.34
May	11,389.81	707.46	651.99	12,041.80
June	14,450.78	680.91	627.53	15,078.30
July	16,898.88	693.73	639.34	17,538.22
August	15,012.29	727.56	670.52	15,682.81
September	11,803.57	661.02	609.19	12,412.77
October	11,141.76	695.91	641.35	11,783.11
November	9,105.50	543.32	500.72	9,606.22
December	7,376.47	591.78	545.39	7,921.86
Total (MWh)	152,463.21	7,897.10	7,289.27	159,752.48

4.3 Scenario C – PV+Wind+Optimized BESS

Table 3 presents the monthly technical results for the optimized EMS scenario for the both power plants together. In comparison with the heuristic Excel-based strategy, the optimized EMS results in a larger amount of energy being charged into the battery and subsequently discharged to the grid for both generating units. For the photovoltaic plant, the annual direct delivery to the grid decreases to 46,749.09 MWh, while the annual charged energy increases to 6,033.62 MWh and the discharged energy to 5,566.24 MWh. Consequently, the total PV energy delivered to the grid reaches 52,315.33 MWh. For the wind power plant, the same trend is observed. The annual direct wind energy delivered to the grid is 100,381.94 MWh, while 7,195.66 MWh is charged into the battery and 6,637.17 MWh is discharged from the battery to the grid. The total annual wind energy delivered to the grid amounts to 107,019.11 MWh. These results show that the optimized EMS makes more intensive use of the battery systems and allocates a larger share of the generated energy to storage in order to exploit price differences more effectively. Therefore, although the direct grid injection from the generating units is reduced, the battery-supported energy delivery increases, which provides the technical basis for the higher revenues and improved economic performance obtained in the optimized scenario.

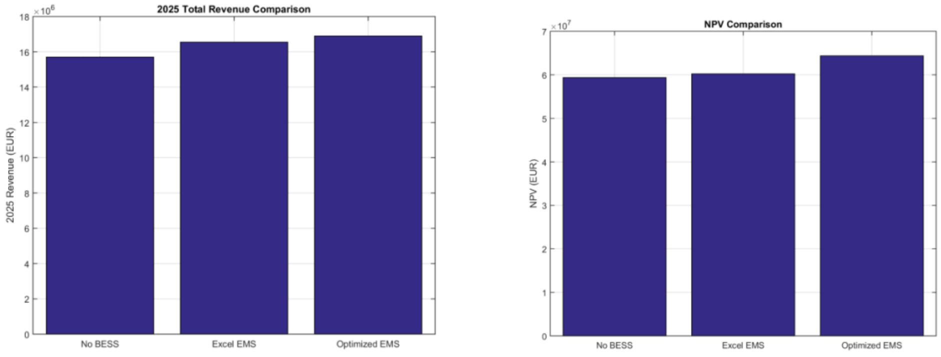
Table 3 - Energy balance of Scenario C

Month	PV+Wind energy directly in grid	PV+Wind Energy in BESS	PV+Wind Energy in the grid from BESS	Total Energy in the grid
January	17,359.96	1,081.34	1,007.87	18,367.83
February	11,375.03	1,002.73	924.11	12,299.14
March	12,884.04	1,084.06	995.12	13,879.16
April	11,931.31	1,161.10	1,074.01	13,005.33
May	10,941.36	1,155.91	1,065.28	12,006.64
June	14,073.82	1,057.86	974.93	15,048.75
July	16,431.62	1,161.00	1,069.97	17,501.59
August	14,539.06	1,200.78	1,106.64	15,645.71
September	11,295.28	1,169.31	1,077.63	12,372.92
October	10,640.78	1,196.89	1,103.05	11,743.83
November	8,656.49	992.33	903.22	9,559.71
December	7,002.28	965.98	901.55	7,903.83
Total (MWh)	147,131.03	13,229.28	12,203.41	159,334.44

5 RESULTS AND DISCUSSION

5.1 Comparison of the main scenarios

The comparison of the three main scenarios confirms that the integration of battery storage increases the market value of generation, while the optimized EMS provides the best overall performance. Scenario A, representing the reference case without storage, achieves a 2025 revenue of EUR 15.70 million and an NPV of EUR 59.36 million. When battery storage is introduced and operated according to the rule-based Excel dispatch strategy (Scenario B), the 2025 revenue increases to EUR 16.55 million and the NPV rises to EUR 60.21 million. The optimized MATLAB-based EMS (Scenario C) further improves the technical and economic performance, yielding the highest 2025 revenue of EUR 16.90 million and the highest NPV of EUR 64.37 million.



(a) (b)

Figure 1 - Comparison of total revenues in 2025 (a), and comparison of NPV for the three main scenarios.

These results show that the positive effect of BESS does not depend only on the presence of storage, but also on the applied dispatch strategy. Under the same battery configuration, the optimized EMS creates higher value than the heuristic EMS because it allocates charging and discharging more effectively over the annual horizon. Since Scenarios A and B were validated to reproduce the Excel results exactly, the comparison with Scenario C is methodologically consistent. Figure 1 illustrates the increase in annual market revenue and NPV across the three scenarios. The revenue comparison confirms that both storage-based scenarios outperform the reference case, while the NPV comparison shows that the optimized EMS provides the largest long-term economic benefit. Figure 2 shows the annual net cash flow profiles for the analyzed period. All scenarios exhibit a declining trend in the first ten years due to declining market prices, generation degradation and credit annuity, while the increase after 2034 corresponds to the end of loan repayment. Throughout the analyzed period, Scenario C retains the most favorable net cash flow profile, which explains its higher NPV. In addition to NPV, the payback period was also used as an investment-recovery indicator. The reference case without BESS has a payback period of 11.954 years, while the rule-based Excel EMS case has a longer payback period of 12.496 years. This shows that, although BESS integration increases annual revenues and NPV, the additional investment cost can extend the recovery period if the storage system is operated according to a simple rule-based strategy. The optimized EMS scenario achieves the shortest payback period of 11.905 years, together with the highest 2025 revenue and the highest NPV. Therefore, the results confirm that the economic benefit of BESS depends not only on the installed storage capacity, but also on the applied dispatch strategy.

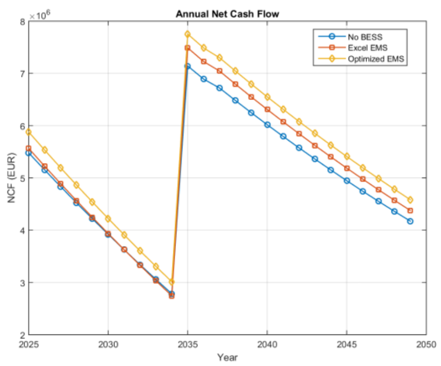
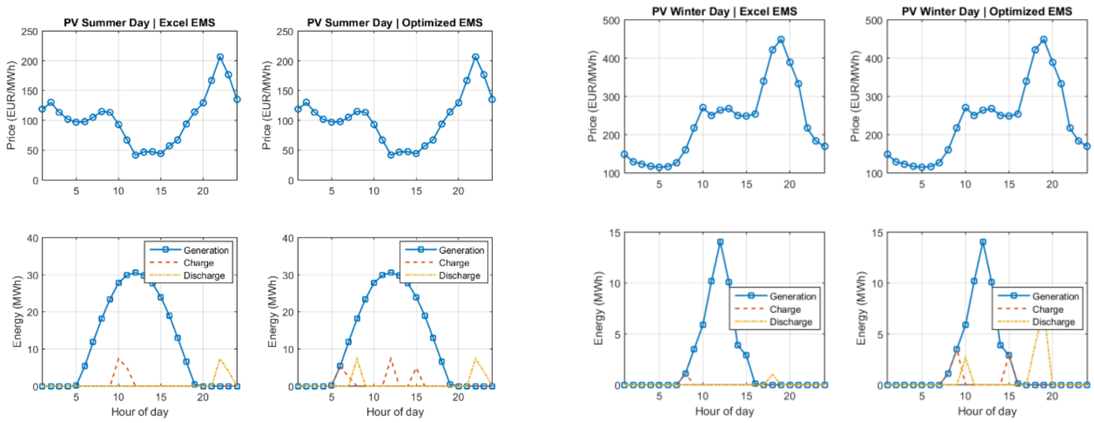


Figure 2 - Annual net cash flow for all three scenarios in the period 2025-2049

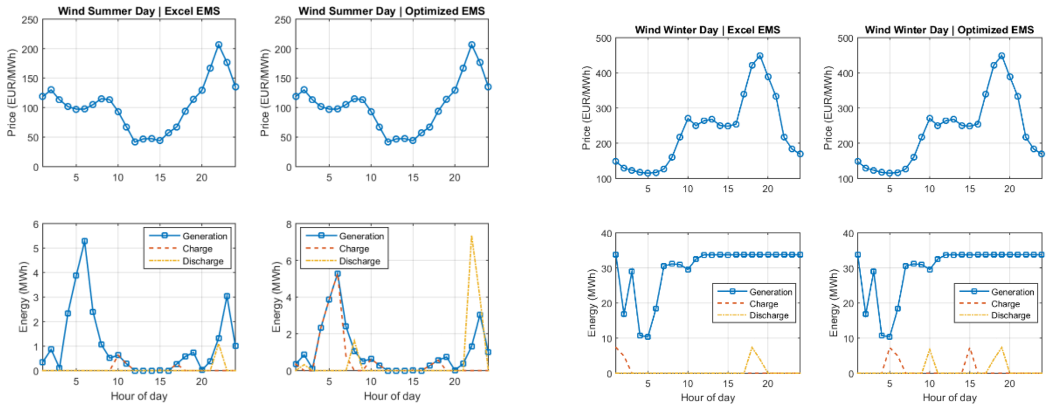
5.2 Representative daily BESS operating profiles

The representative daily operating profiles provide a clearer insight into the difference between the rule-based and optimized EMS strategies. In the PV case, the summer profile is characterized by pronounced midday generation, which allows substantial battery charging during hours of high solar output. Under the optimized EMS, charging and discharging are distributed more flexibly than in the Excel-based heuristic strategy, which enables more effective shifting of energy toward higher-price periods. In the winter PV profile, when available generation is lower and concentrated in fewer hours, the optimized EMS uses the available storage capacity more selectively, which is particularly important under limited PV production. For the wind power plant, the daily profiles are more dispersed, since wind generation is not concentrated around midday. This makes the role of optimization even more important. In both the summer and winter wind profiles, the optimized EMS responds more flexibly to hourly price signals and available generation, resulting in a different distribution of charging and discharging events compared with the rule-based dispatch. Overall, the daily profiles confirm that the optimized EMS uses the battery systems more actively and more adaptively than the heuristic strategy, which provides the operational basis for the higher revenues and NPV obtained in Scenario C.



(a) (b)

Figure 3 - Comparative BESS operation for the PV power plant during a representative summer day (a), and representative winter day (b)



(a) (b)

Figure 4 - Comparative BESS operation for the wind power plant during a representative summer day (a), and representative winter day (b)

6 SENSITIVITY ANALYSIS

The sensitivity analysis was performed for the optimized EMS case by varying the power and energy capacity of both battery systems. Four battery power levels per unit were considered, namely 3.68 MW, 7.36 MW, 11.04 MW, and 14.72 MW, together with four discharge durations of 1 h, 2 h, 3 h, and 4 h. The results show that increasing BESS size generally leads to higher 2025 revenues and higher NPV, but the relationship is not linear. After a certain point, additional energy capacity does not provide proportional economic benefit, indicating the existence of an optimal sizing range rather than a simple “larger is always better” trend. The highest NPV is obtained for the total project BESS configuration of 29.44 MW / 88.32 MWh, with a 2025 revenue of EUR 18.77 million and an NPV of EUR 68.31 million. A very similar result is achieved for the configuration 29.44 MW / 58.88 MWh, which reaches an NPV of EUR 68.01 million with a lower total energy capacity. This indicates that the latter configuration may be considered a rational compromise between investment size and achieved economic value. By contrast, the largest investigated energy capacity, 29.44 MW / 117.76 MWh, does not yield the highest NPV, confirming that oversizing the battery can reduce the economic efficiency of the project. Overall, the sensitivity analysis confirms that proper battery sizing is a key factor for profitability improvement. The optimized EMS already improves the performance of the base BESS case, while additional gains can be achieved if the battery power and energy capacity are selected within the most favorable sizing range. The payback period results from the sensitivity analysis further support this conclusion. Although larger BESS configurations generally increase annual revenues, they do not always shorten the investment recovery period. The shortest payback period among the analyzed sensitivity cases is obtained for the 29.44 MW / 29.44 MWh total project BESS configuration, with a payback period of 11.777 years, while the largest investigated configuration of 29.44 MW / 117.76 MWh results in a longer payback period of 13.365 years. This confirms that BESS oversizing may increase revenues but can reduce the overall investment recovery efficiency due to higher investment and operating costs.

Table 4 - BESS configurations from the sensitivity analysis for the optimized EMS

Total project BESS (MW / MWh)	Revenue 2025 (EUR)	NPV (EUR)	Payback (years)
7.36 / 7.36	16,043,085.06	61,105,525.40	11.87
7.36 / 14.72	16,319,512.24	62,103,739.83	11.89
7.36 / 22.08	16,546,255.60	62,513,394.70	12.00
7.36 / 29.44	16,730,719.53	62,428,035.17	12.17
14.72 / 14.72	16,364,536.93	62,636,468.62	11.82
14.72 / 29.44	16,895,340.95	64,368,570.95	11.90
14.72 / 44.16	17,326,913.11	64,926,350.76	12.14
14.72 / 58.88	17,674,226.66	64,499,424.37	12.51
22.08 / 22.08	16,674,336.74	64,027,964.65	11.79
22.08 / 44.16	17,444,926.25	66,316,409.61	11.96
22.08 / 66.24	18,065,383.01	66,834,891.81	12.34
22.08 / 88.32	18,559,458.56	65,876,811.85	12.91
29.44 / 29.44	16,976,005.34	65,320,660.29	11.78
29.44 / 58.88	17,973,360.93	68,008,861.25	12.04
29.44 / 88.32	18,767,215.56	68,305,466.73	12.58
29.44 / 117.76	19,392,755.28	66,625,290.74	13.36

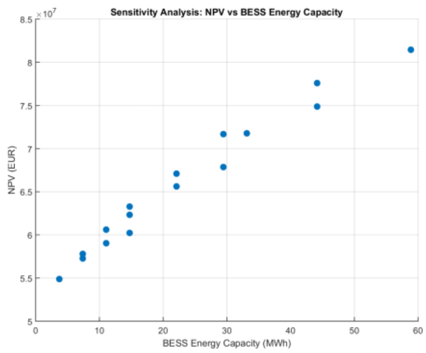


Figure 5 - Sensitivity analysis results for the optimized EMS as a function of total project BESS energy capacity: NPV

7 CONCLUSION

This study evaluated the techno-economic performance of a co-located 36.8 MW photovoltaic power plant and a 36.8 MW wind power plant under three operating scenarios: without battery storage, with rule-based battery dispatch, and with optimized EMS-based battery dispatch. The results show that the integration of BESS increases market revenues relative to the no-storage case, while the optimized EMS provides the best overall performance among the three main scenarios. In particular, the optimized EMS achieves the highest revenue in 2025 and the highest NPV, confirming that the economic value of storage depends not only on the installation of the battery system, but also on the dispatch strategy used to operate it. The optimized EMS also provides the shortest payback period among the three main scenarios, further confirming the importance of the applied dispatch strategy for investment recovery. The sensitivity analysis further shows that the profitability of the project can be improved through appropriate BESS sizing. From the NPV perspective, the best result is obtained for a total project BESS configuration of 29.44 MW / 88.32 MWh, while the 29.44 MW / 58.88 MWh configuration provides a very similar NPV with a lower energy capacity and may therefore be considered a balanced alternative. However, the payback results show that larger BESS configurations do not necessarily lead to faster investment recovery. The shortest payback period among the analyzed sensitivity cases is obtained for the 29.44 MW / 29.44 MWh configuration. Therefore, the final selection of BESS size should consider both long-term value creation, expressed through NPV, and investment recovery time, expressed through payback period. These findings indicate that both EMS quality and battery sizing are decisive factors for maximizing the economic value and improving the investment recovery profile of co-located PV-wind systems under market-based operation.

REFERENCES

[1] Cole W and Karmakar A, 2023, "Cost Projections for Utility-Scale Battery Storage: 2023 Update", National Renewable Energy Laboratory, NREL/TP-6A40-85332.

[2] National Renewable Energy Laboratory, 2024, "Utility-Scale Battery Storage", Annual Technology Baseline (ATB).

[3] Valentin Software GmbH, 2025, "PV*SOL premium - Design software for photovoltaic systems".

[4] MEMO DOOEL Skopje, 2025, "Macedonian Electricity Market Operator - hourly market data and electricity market information".

[5] Aneva S, Minovski D and Sarac V, 2025, "Energy Transition in Municipalities - A Model for Sustainable Renewable Energy Management", Journal of Energy Technology, 18(1), 5-21, doi:10.18690/jet.18.1.5-21.2025.

[6] Aneva S, Minovski D, Sarac V and Citkuseva Dimitrovska B, 2025, "Techno-Economic Analysis and Cost-Effectiveness of Photovoltaic Systems for Restaurants in Macedonia", Natural Resources and Technology, 19(1), 17-28, doi:10.46763/NRT2519117a.

[7] Aneva S, Minovski D, Sarac V, Bogatinov D and Kostevska S, 2025, "Optimization of Surplus Electricity Management from Municipal Photovoltaic Systems: Virtual Storage vs Battery Systems", ETIMA, 3(1), 43-52, doi:10.46763/ETIMA253143a.

[8] Mercier T, Olivier M and De Jaeger E, 2023, "The value of electricity storage arbitrage on day-ahead markets across Europe", Energy Economics, 123, 106721, doi:10.1016/j.eneco.2023.106721.

[9] Mumtahina U, Alahakoon S and Wolfs P, 2025, "A Day-Ahead Optimal Battery Scheduling Considering the Grid Stability of Distribution Feeders", Energies, 18(5), 1067, doi:10.3390/en18051067.

[10] Nirbheram JS, Mahesh A and Bhimaraju A, 2024, "Techno-economic optimization of standalone photovoltaic-wind turbine-battery energy storage system hybrid energy system considering the degradation of the components", Renewable Energy, 222, 119918, doi:10.1016/j.renene.2023.119918.

[11] Emrani A and Berrada A, 2024, "A comprehensive review on techno-economic assessment of hybrid energy storage systems integrated with renewable energy", Journal of Energy Storage, 84, 111010, doi:10.1016/j.est.2024.111010.

[12] Grimaldi A, Minuto FD, Perol A, Casagrande S and Lanzini A, 2025, "Techno-economic optimization of utility-scale battery storage integration with a wind farm for wholesale energy arbitrage considering wind curtailment and battery degradation", Journal of Energy Storage, 112, 115500, doi:10.1016/j.est.2025.115500.

[13] Hamilton S D, Millstein D, Bolinger M, Wiser R and Jeong S, 2020, “How Does Wind Project Performance Change with Age in the United States?”, “Joule”, 4(5), 1004–1020