Journal of Power Technologies 104 (4) (2024) 251 -- 259

Analysis of the cooperation of electricity storage with renewable energy sources

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Abstract

In connection with the dynamic development of distributed renewable energy sources, the problem of cannibalization arises. The production of individual renewable energy sources (RES) units is highly correlated within a given technology. The low marginal costs of RES production drive down the wholesale prices during periods of high insulation and windspeed - profits of the producers decrease. Conversely, prices increase significantly during periods of low-RES production - particularly windless, cold evenings. The answer to this issue is hybrid installations with energy storage systems (ESS). By using ESS, it is possible to control the energy produced by such a system appropriately, shifting production from low- to high-price hours (price arbitrage). This increases the profits coming from selling electricity in the day-to-day market. In this publication, seven scenarios will be analyzed to determine the potential profits for energy storage systems operating alone, with a wind farm, a photovoltaic farm, and both installations. In addition, analysis will be carried out on generation units without storage. This analysis will confirm which system is optimal from the point of view of maximizing the generated profit for the plant operator, which also translates into stabilizing the operation of the electricity grid.

Keywords: energy storage, optimization, renewable energy, virtual power plant, hybrid installations

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Introduction

Amid concerns about climate change and the need to reduce carbon emissions, renewable energy has become a vital component of the global energy strategy. Over the past decade, renewable energy growth has consistently exceeded expectations. By 2026, it is estimated that global renewable energy capacity will increase by more than 80% compared to 2020 levels (to more than 5022 GW), with two-thirds of this growth coming from wind and solar power, an increase of 150% (3404 GW) [1], [2]. Parallel to global trends, the Polish renewable energy sector is also developing. According to data as of the end of June 2023, the installed capacity of RES in Poland was an impressive 25 GW, noticeably increasing by 5.1 GW compared to June 2022 [3]. Despite this significant progress, RES units are still influenced by weather conditions and time of day, which affects their efficiency. Operating these plants independently in the energy market can limit their efficiency and generate additional costs due to generation instability. In response to these challenges, hybrid installations that integrate different energy sources, such as photovoltaic (PV) panels, wind turbines (WO), and energy storage have emerged. Such solutions make it possible to smooth out fluctuations in electricity production and increase supply reliability [4]-[6].

In Poland, they were introduced with amendments to the RES Act and the Energy Law by introducing provisions for cable pooling, i.e., linking at least two RES installations to one connection or creating a definition of a hybrid installation [7], [8].

Energy storage also provides a backstop to the transmission grid by allowing surplus energy produced during lower demand, such as midday, to be stored and used during the evening peak. Such hybrid systems allow flexible adaptation to external conditions and offer operational advantages for both the grid operator and the plant owner.

In this article, we analyze seven scenarios, considering a variety of system configurations, including hybrids. Our research focuses on the revenue generated by each installation, with optimized operation of the energy storage used. The results shed light on the economic potential of these solutions and contribute to the discussion on the future of sustainable energy development and further progress of the energy transition. This analysis is carried out based on actual data and experience from projects implemented by Transition Technologies Systems.

Materials and methods

Scenarios

The analysis was carried out for seven scenarios. Scenarios 1, 2, 4, and 5 assume installed capacity of 11 MW of a single RES resource. Scenarios 3 and 6, on the other hand, consider a combination of two types of RES technologies, where 5.5 MW is attributed to wind turbines and 5.5 MW to photovoltaic installations. In scenarios 1-6, charging the energy storage is done solely by RES resources while discharging is done in series, total output capacity is 11 MW. This approach is designed to consider the limitations of the energy available from RES at any given time.

Scenario 7 involves charging energy storage directly from the grid, while eliminating constraints related to connection capacity. The only constraint in this case remains the storage capacity. A summary of the various elements of each scenario is included in Table 1.

Table 1: List of scenarios
Where: WO - wind turbines, PV - photovoltaic installation, ESS - electricity storage system

Scenario	Name	WO	PV	ESS
1	WO	+		
2	PV		+	
3	PV+WO	+	+	
4	PV+ESS	+		+
5	WO+ESS		+	+
6	PV+WO+ESS	+	+	+
7	ESS			+

Optimization problem

The goal of the optimization is to maximize the objective function, which we define as the revenue from the sale of electricity (the sum of the product of the price and the volume of energy sold). Sales are made in the day-ahead market, so the optimization is performed for a full day at a time.

The optimized variable is the storage operation profile, i.e., the planned energy flow from/to storage.

$$C = \sum_{h=1}^{n=24} p_h \cdot g_h$$

$$g = g_{RES} + g_{ESS}$$

Where:

C – revenue [PLN]

p – price of electricity [PLN/MWh]

g_{RES} – RES generation [MWh]

g_{ESS} – energy flow from/to storage [MWh].

Constraints

The constraints of the optimization process are due to the physical and operational conditions of the system.

$$P \in, \langle -P_{max}; -P_{min} \rangle \cup \{0\} \cup \langle P_{min}; P_{max} \rangle$$

Where:

P – energy storage power

P_{min} – minimum storage capacity

P_{max} – maximum storage capacity

The setting power of the storage must not exceed its nominal power, and low power operation is not allowed ($P_{min} = 0.15MW$, $P_{max} = 1.5MW$). Idling is allowed.

$$E_{min} < E < E_{max}$$

Where:

E – state of charge

E_{min} – minimum state of charge

E_{max} – maximum state of charge

The state of charge must fall between a fixed minimum and maximum ($E_{min} = 20\%$, $E_{min} = 100\%$). Operation at state of charge below 20% shortens the lifespan of the battery [9].

$$\max(E) = E_{max}$$

The storage unit's highest capacity must reach the maximum charge level at least once daily. This means that the storage will perform at least one complete cycle.

$$0 < c < c\_max$$

$$c = \frac{\sum_i^n abs(P_i)}{2 \cdot E_0}$$

Where:

c – equivalent number of cycles

c_{max} – maximum permissible number of cycles

E_0 – nominal storage capacity

A maximum of one charge/discharge cycle is allowed. Compared to multiple cycles, this extends battery life and increases the average profit per unit of energy generated. The storage facility will operate during periods of lowest and highest prices.

$$0 < F < F_{max}$$

$$F = P_{RES} + P$$

Where:

F – total energy flow through the main supply point

P_{RES} – RES generation power

According to the configuration of the equipment, it is not allowed to charge the storage from the grid (except for scenario No. 7), and the power output from the system must not exceed the connection capacity ($F_{max} = 11MW$).

In addition, there is a constraint on the monotonicity of charging/discharging: the charging process must be completed before the discharge stage. Another constraint is continuity: charging/discharging can only occur continuously - idling between stages is not allowed. The reason for these restrictions is to take care of the balance of cells in the battery energy storage system. With frequent changes in the direction of energy flow or intermittent charging/discharging process, individual cells begin to differ in their charge level, adversely affecting their service life.

Input data

In order to carry out the optimization for the next day (d+1), data acquired on the current day (d) on forecast generation and forecast prices in the day-head market (DAM) are needed. The resolution of the data is hourly, as there are instruments on the DAM for a minimum of 1 hour [10].

The time range of the analysis conducted in this article is 15.04.2023 to 30.09.2023.

Generation forecast

The generation forecast is updated every 4 hours, and the horizon is from the nearest whole hour to the end of the day (d+3). The source of the forecast is a vendor specializing in renewable forecasting, and a summary of forecasts, measurements, and their evaluation are summarized in Table 2.

Table 2: Summary of forecast data, measurements and quality assessment of RES generation forecasts
Where: CF - Capacity Factor, ME - Mean Error, MPE – Mean Percentage Error, MAE - Mean Absolute Error, WMAPE - Weighted Mean Absolute Percentage Error

Measure	WO		PV		PV+WO	
	Forecast	Measurement	Forecast	Measurement	Forecast	Measurement
MIN	0	0	0	0	0.002	0
AVG	1.016	1.230	2.509	2.571	1.762	1.900
MAX	9.597	9.934	11.194	11.484	7.601	8.986
CF	9.2%	11.2%	22.8%	23.4%	16.0%	17.3%
ME	-0.21		-0.062		-0.138	
MPE	-17.4%		-2.4%		-7.3%	
MAE	0.764		0.484		0.521	
WMAPE	62.1%		18.8%		27.4%	

The time range of the analysis (summer season) results in a low-capacity factor for WO (about 11%) and a high-capacity factor for PV (about 23%). The WO forecast is biased (APE about 17%), and its precision is low (WMAPE about 62%). The PV forecast is unbiased (APE about 2%), and its precision is much higher (WMAPE about 19%) [11]. The forecasts used in the analysis are of low quality compared to the industry benchmark.

Based on our operational experience, relying only on the generation forecast "directly" often leads to incomplete plan execution. In practice, generation forecasts, while low but not reaching zero, are sometimes overestimated so that full storage recharge does not occur. Conversely, forecasts with a high value but not over installed capacity are sometimes underestimated so much that full discharge does not occur. In response to these challenges, we have developed an adjustment function (Figure 1) to minimize the risk of incomplete charging or discharging of storage. This function considers the nuances of forecasting, adjusting the forecasts to reflect actual generation capabilities better.

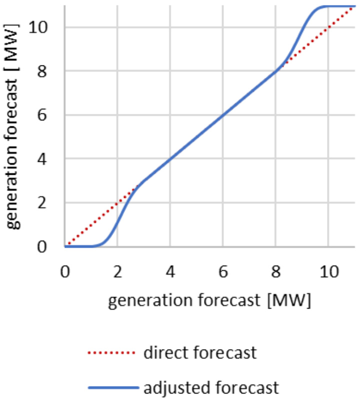

Figure 1: Pruning function of RES generation

Price forecast

The source of the forecast is an ensemble model of multiple commercial suppliers. Ensemble models are popular because of their high precision and robustness to the complexity of factors affecting energy markets [12]. These models offer more reliable results, crucial for risk management and decision-making.

The price forecast is updated once a day and covers the period from the first hour of day d+1 to the end of day d+1. This data is summarized in Table 3.

Table 3 - Summary of forecast data, measurements and quality assessment of price forecasts

Table 3: Summary of forecast data, measurements and quality assessment of price forecasts

Measure	Forecast	Measurement
MIN	-10.00	20.00
AVG	533.19	514.51
MAX	1 010.47	963.58
ME	18.68	
APE	3.6%	
MAE	64.45	
MAPE	12.5%	

The price forecast has a low bias (APE of about 3.6%), and the mean absolute percentage error is 12.5%. The hours with the lowest/highest prices are the most important for optimization. Considering this criterion, the forecast correctly indicates the most expensive/cheapest hours in 77 days out of 100.

Results

Optimization is carried out for a given day. A storage operation plan is prepared based on the generation and price forecasts. If the resulting work plan does not meet the constraints, the plan is reset to zero, i.e., the storage is not charged/discharged. If the resulting average unit profit per 1 MWh of energy discharged from storage is lower than the threshold, the work plan is reset to zero. The threshold has been set based on the operational experience of traders and analysts and is 170 PLN/MWh.

Finally, the actual operation of the storage is simulated - if there is not enough power to charge, the storage is not fully charged, and the discharge stage is also not carried out fully. The mechanisms described create three series of storage operations - the initial plan, work plan, and execution shown in Figure 2 and Figure 3.

By analogy with the initial plan, work plan, and execution, the number of equivalent work cycles of the storage can be determined. The number of days analyzed is 149 - taking this into account, the storage utilization rate can be determined. A system consisting only of storage will be optimized daily. However, the restriction on unit profit reduces the rate from 100% to 64%. The data shows that the theoretical supply of energy storage in the summer with a photovoltaic installation does not limit the storage operation. There is enough power to charge the storage. The wind farm, on the other hand, cannot charge the storage efficiently. The hybrid installation achieves the best results - the planned number of cycles is higher than for the photovoltaic or wind farm alone. This indicates that a complete hybrid installation (PV+WO+ESS) can effectively benefit from price arbitrage. A summary of the results is shown in Table 4.

The objection function can be understood as projected revenue. At the time of optimization, we do not have access to actual DAM prices or measured generation. Revenue traded is the result of concluded transactions resulting from the generation forecast and storage operation but considering actual DAM prices. Revenue is the actual generation/energy flow of the installation, considering actual DAM prices.

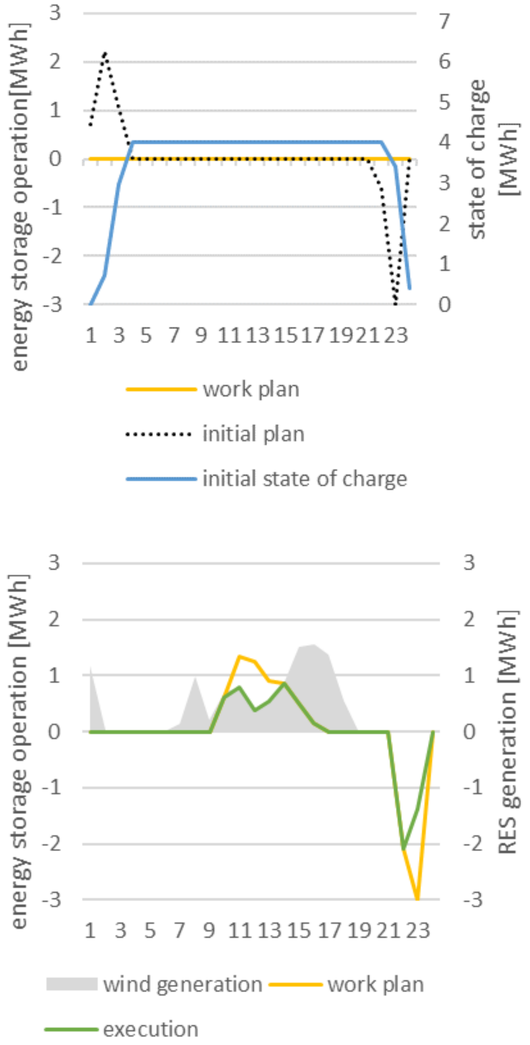

Figure 2: Illustration of incomplete storage charging cycle and missing RES generation

Table 4: Energy storage utilization rate

Case	Initial number of cycles	Planned number of cycles	Actual number of cycles
PV+ESS	96%	54%	51%
WO+ESS	36%	16%	15%
PB+WO+ESS	95%	69%	65%
ESS	100%	64%	64%

The PV+ESS installation generates the highest revenue. This is due to the significant and predictable PV generation. To identify the best-performing installation, the unit revenue (revenue divided by the volume of energy generated) was determined. According to this measure, the WO+ESS installation is the best on the Polish DAM. This is due to the significantly modified price profile during the analysis period caused by photovoltaic generation - the wind farm generates energy during periods with a higher price on average. Despite the absence of constraints from the power supply, energy storage alone generates significantly lower revenue than renewable installations. In addition, the unit revenue at 216 PLN/MWh is more than twice as low as that of the PV farm alone. A summary of revenues is shown in Table 5.

Table 5: Projected revenue, revenue traded and revenue

Case	Projected revenue [PLN]	Revenue traded [PLN]	Revenue [PLN]	Revenue per unit [PLN/MWh]
PV	3 884 472	4 006 826	4 093 041	445
WO	1 798 778	1 771 498	2 093 769	476
PV+WO	2 841 625	2 889 162	3 093 405	455
PV+ESS	4 021 127	4 110 167	4 192 178	458
WO+ESS	1 838 641	1 803 409	2 122 379	484
PV+WO+ESS	3 018 877	3 026 594	3 225 182	479
ESS	142 659	118 285	118 285	216

Therefore, the addition of energy storage can represent a measurable improvement in the financial performance of RES installations. Analyzing the revenue deviation between the RES and RES+ESS scenarios indicate how much the installation's revenue increases when energy storage is added. It is the PV+WO installation that gains the most by cooperating with the storage, as shown in Table 6.

Table 6: Revenue growth after adding energy storage

Case	Increase
PV	2.42%
WO	1.37%
PV+WO	4.26%

The final element of the analysis is the assessment of imbalance and its cost. In this case, the imbalance is defined as the difference in generation and position on DAM [13]. The balancing cost, conversely, is the product of the imbalance and the price on the balancing market (CRO). The day-ahead forecast error for a wind farm is high, and the forecast itself is biased, so the balancing cost is high (balancing cost share 13.6%). The photovoltaic farm's imbalance and cost are low due to the low day-ahead forecast error. The storage itself has no balance cost (we assume complete control over its operation).

The addition of energy storage helps to slightly reduce imbalance and its cost, even though the optimization goal was price arbitrage, as shown in Table 7.

Conclusions

During the analysis of the proposed scenarios, important conclusions emerged. First, integrating energy storage with renewables allows for a noticeable increase in the revenue generated by such a system by as much as 4.26%. An additional benefit is the system's ability to reduce imbalance and the associated reduction in balance costs, which translates into an ultimate increase in profit.

Another vital insight concerns the role of energy storage as a critical element in maximizing profits and using storage only for arbitrage results in significantly lower revenues, mainly due to the imposition of a minimum profit criterion and restrictions on the storage operation mode. To improve the operation of such a system in the Polish reality, we suggest the participation of the storage facility in the power market or its integration into the newly created, reformed balancing market. In such a context, energy storage facilities can be crucial as scheduling units offering energy and balancing power services [14].

Table 7: Imbalance of individual systems

Case	Imbalance [MWh]	Balancing cost [PLN]	Share of costs in revenue [%]	Impact of adding storage on imbalance [%]
PV	1 730 120	39 444	1.0%	-
WO	2 730 547	284 316	13.6%	-
PV+WO	1 863 583	161 880	5.2%	-
PV+ESS	1 726 457	37 961	0.9%	-0.21%
WO+ESS	2 724 470	281 508	13.3%	-0.22%
PV+WO+ESS	1 848 288	159 513	4.9%	-0.82%
ESS	0	0	0.0%	-

To extend the life of energy storage, it is necessary to impose certain limits on the operating range and the number of charging and discharging cycles. The analysis considered these factors when defining the optimal storage operation plan to maximize arbitrage revenues.

In conclusion, the use of energy storage in hybrid systems translates into increased generated revenue, stabilization of plant operation, and reduced costs associated with the instability of renewable generation forecasts, which is a crucial step towards sustainable and efficient energy use. However, the analyzed topic can be extended to include aspects related to minimizing the imbalance volume of the system, thus reducing the potential balancing costs and lowering the final profit from the use of the installation. This issue will be the subject of further analysis aimed at presenting the optimal layout of a hybrid installation using electricity storage.

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