GOCE DELCEV UNIVERSITY, STIP, NORTH MACEDONIA
FACULTY OF ELECTRICAL ENGINEERING

ETIMA 2025

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FACULTY OF ELECTRICAL ENGINEERING

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THIRD INTERNATIONAL CONFERENCE

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PREFACE

The Third International Conference “Electrical Engineering, Technology, Informatics, Mechanical Engineering and Automation – Technical Sciences in the Service of the Economy, Education and Industry” (ETIMA’25), organized by the Faculty of Electrical Engineering at the “Goce Delchev” University – Shtip, represents a significant scientific event that enables interdisciplinary exchange of knowledge and experience among researchers, professors, and experts in the field of technical sciences. The conference was held in an online format and brought together 78 authors from five different countries.

The ETIMA conference aims to establish a forum for scientific communication, encouraging multidisciplinary collaboration and promoting technological innovations with direct impact on modern life. Through the presentation of scientific papers, participants shared the results of their research and development activities, contributing to the advancement of knowledge and practice in relevant fields.
The first ETIMA conference was organized four years ago, featuring 40 scientific papers. The second conference took place in 2023 and included over 30 papers. ETIMA’25 continued this scientific tradition, presenting more than 40 papers that reflect the latest achievements in electrical engineering, technology, informatics, mechanical engineering, and automation.

At ETIMA’25, papers were presented that addressed current topics in technical sciences, with particular emphasis on their application in industry, education, and the economy. The conference facilitated fruitful discussions among participants, encouraging new ideas and initiatives for future research and projects.

ETIMA’25 reaffirmed its role as an important platform for scientific exchange and international cooperation. The organizing committee extends sincere gratitude to all participants for their contribution to the successful realization of the conference and its scientific value.

We extend our sincerest gratitude to all colleagues who, through the presentation of their papers, ideas, and active engagement in discussions, contributed to the success and scientific significance of ETIMA’25.

The Organizing Committee of the Conference

ПРЕДГОВОР

Третата меѓународна конференција „Електротехника, Технологија, Информатика, Машинство и Автоматика – технички науки во служба на економијата, образованието и индустријата“ (ЕТИМА’25), организирана од Електротехничкиот факултет при Универзитетот „Гоце Делчев“ – Штип, претставува значаен научен настан кој овозможува интердисциплинарна размена на знаења и искуства меѓу истражувачи, професори и експерти од техничките науки. Конференцијата се одржа во онлајн формат и обедини 78 автори од пет различни земји.

Конференцијата ЕТИМА има за цел да создаде форум за научна комуникација, поттикнувајќи мултидисциплинарна соработка и промовирајќи технолошки иновации со директно влијание врз современото живеење. Преку презентација на научни трудови, учесниците ги споделуваат резултатите од своите истражувања и развојни активности, придонесувајќи кон унапредување на знаењето и практиката во релевантните области.

Првата конференција ЕТИМА беше организирана пред четири години, при што беа презентирани 40 научни трудови. Втората конференција се одржа во 2023 година и вклучи над 30 трудови. ЕТИМА’25 продолжи со истата научна традиција, презентирајќи повеќе од 40 трудови кои ги отсликуваат најновите достигнувања во областа на електротехниката, технологијата, информатиката, машинството и автоматиката.

На ЕТИМА’25 беа презентирани трудови кои обработуваат актуелни теми од техничките науки, со посебен акцент на нивната примена во индустријата, образованието и економијата. Конференцијата овозможи плодна дискусија меѓу учесниците, поттикнувајќи нови идеи и иницијативи за идни истражувања и проекти.

ЕТИМА’25 ја потврди својата улога како значајна платформа за научна размена и интернационална соработка. Организациониот одбор упатува искрена благодарност до сите учесници за нивниот придонес кон успешната реализација на конференцијата и нејзината научна вредност. Конференцијата се одржа онлајн и обедини седумдесет и осум автори од пет различни земји.

Изразуваме голема благодарност до сите колеги кои со презентирање на своите трудови, идеи и активна вклученост во дискусиите придонесоа за успехот на ЕТИМА’25 и нејзината научна вредност.

Организационен одбор на конференцијата

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OPTIMIZATION OF SURPLUS ELECTRICITY MANAGEMENT FROM MUNICIPAL PHOTOVOLTAIC SYSTEMS: VIRTUAL STORAGE VS BATTERY SYSTEMS

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Abstract

*This study presents a comparative analysis of two models for managing surplus electricity generated by photovoltaic (PV) systems installed on eight municipal buildings in a Macedonian municipality. The first model is based on distributing the surplus electricity among 20 municipal buildings, utilizing them as a virtual storage to maximize local consumption of the generated electricity. The second model involves storing the surplus electricity in battery systems at each PV-equipped building and using the stored electricity the following day within the same building, while any surplus is sold on the market. For the purpose of the analysis, electricity consumption of the 28 municipal buildings and electricity production from the PV systems data were obtained from a municipal representative and allocated on an hourly basis using the standard load curve from EVN Macedonia and simulations performed with the licensed PV*SOL premium software. Financial analyses were conducted based on electricity prices from the HUPX electricity exchange for the year 2024. This study provides an assessment of the economic and technical advantages and drawbacks of both approaches, evaluating their impact on municipal energy independence, financial feasibility, and the optimization of renewable energy management.*

Key words

Photovoltaic systems, virtual storage, battery storage, financial analyses, municipal energy independence.

Introduction

The increasing penetration of renewable energy sources, particularly photovoltaic (PV) systems, has raised important questions about their integration, efficiency, and economic viability in public infrastructure. Municipal buildings, which often represent a significant portion of local electricity demand, are increasingly targeted for renewable energy deployment due to their potential to lower operational costs, reduce carbon emissions, and promote sustainability. However, the variable and intermittent nature of solar energy creates challenges in aligning production with consumption.

This paper investigates the electricity consumption and production of 28 municipal buildings, of which eight are equipped with PV systems. In the initial analysis, surplus electricity produced by PV systems is consumed first by the building in which it is generated, and any surplus is redistributed among other municipal buildings without PV installations. In the second case, a new scenario is developed in which each of the eight PV-equipped buildings is integrated with a 10 kWh battery energy storage system (BESS). This allows surplus electricity to be stored at

the production cost and used during the following day, thereby altering both the cost structure and the potential for economic savings.
The scope of this research is to compare the economic performance and energy efficiency of the two scenarios: direct consumption with redistribution versus storage with next-day utilization. The main objective of the study is to determine which solution provides greater long-term benefits for the municipality, both in terms of cost savings and energy self-sufficiency.

1. Literature review

Recent research underscores the challenge of deriving cost-effective value from battery energy storage system (BESS) installations in public and residential buildings. In [4] is investigated shared BESS in apartment complexes and conclude that financial benefits depend heavily on load profiles and tariff structures; often, battery systems remain underutilized due to limited arbitrage opportunities.

Similarly, the study in [2] focuses on municipal buildings and shows that lower institutional electricity tariffs, coupled with modest PV-to-load matching, severely limit the economic viability of BESS investments. These finding highlights that surplus-sharing strategies may offer a more advantageous return.

Exploring the communal dimension, in [5] is employed a scenario-based optimization framework to compare community electricity storage versus individual household storage. They demonstrate that shared systems can offer 9% lower investment cost per household and better utilization, especially when combined with demand-side flexibility.

Further emphasizing the practical implications, [3] evaluate PV-battery systems in public buildings across Cyprus, Greece, and Italy, incorporating advanced battery degradation models and load shifting. The findings are that load flexibility significantly enhances economic viability; however, even when technically feasible, strict self-sufficiency targets often remain economically unattractive without subsidies.

Finally, [1] presents that municipal-level decision-making benefit greatly from localized PV simulation and cost dynamics. The work supports the argument that virtual storage or surplus-sharing may be more economically viable than standalone battery systems in municipal contexts.

In summary, the literature consistently indicates that while PV and BESS integration offers technical potential, the economic case is often weak, especially for public buildings with modest load profiles and narrow tariff spreads. In contrast, shared or virtual storage architectures provide stronger ROI and higher asset utilization, aligning with the findings of the current research in North Macedonia.

2. Municipality analysis

In order to assess the potential benefits of photovoltaic (PV) systems and storage integration in the public sector, an analysis was carried out for a municipality located in North Macedonia. For confidentiality reasons, the names of the individual public buildings where PV systems have been installed will not be disclosed. Instead, they will be denoted as Public Building (PB) 1, PB2, … PB8 throughout the text. This approach ensures a consistent representation of the buildings while protecting sensitive institutional data.
The data used in this analysis are real operational records of both electricity consumption and PV electricity production. These data were officially provided by the municipal representative

responsible for energy management, which ensures the reliability of the assessment. The analysis covers both the buildings with installed PV systems and those without, with the objective of quantifying the contribution of PV generation to the overall electricity demand of public institutions in the municipality.

2.1. General information

The municipality under study has administrative authority over a total of 28 public institutions. Among them, eight public buildings are equipped with PV systems, while the remaining twenty buildings currently rely entirely on electricity purchased from the national grid.
The PV-equipped buildings have a combined installed capacity of 187.53 kWp, which corresponds to an expected annual production of 281,774.31 kWh. On the demand side, the total annual electricity consumption of these eight buildings, without accounting for self-consumption of PV electricity, is 2,517,420.85 kWh. This means that the share of PV-generated electricity compared to their annual consumption is relatively small, covering only about 11% of the demand of these eight institutions.
In other words, although PV systems are already in place, their impact at the municipal level is modest. Nonetheless, the availability of actual production and consumption data enables a detailed evaluation of the potential role of both battery storage and virtual storage approaches. The results for the remaining twenty buildings will further strengthen the basis for evaluating municipality-wide strategies in the following sections of the paper.

2.2. Technical analysis

The total annual electricity consumption of the remaining twenty buildings without PV systems amounts to 594,343.12 kWh. When this is added to the consumption of the eight PV-equipped buildings, the overall electricity demand of all 28 public institutions in the municipality reaches 3,111.76 MWh per year (excluding PV-generated electricity).
The installed PV capacity for each of the eight public buildings is as follows:

- PB1 – 28.05 kWp;
- PB2 – 39.6 kWp;
- PB3 – 15.12 kWp;
- PB4 – 15.12 kWp;
- PB5 – 15.12 kWp;
- PB6 – 15.12 kWp;
- PB7 – 19.8 kWp;
- PB8 – 39.6 kWp.

Together, these installations add up to 187.53 kWp, generating 281,774.31 kWh annually. The expected hourly, monthly, and yearly production of each PV system was obtained through PV*SOL premium simulations, which consider local meteorological conditions and system configuration.
To quantify the electricity balance, the hourly demand of each building was compared with its PV production. The required additional electricity was calculated as the deficit between consumption and production, whereas the surplus electricity represents the fraction of PV generation that exceeds demand at any given hour. These calculations were performed using Microsoft Excel, based on real consumption data and simulated PV production profiles.

Table 1 summarizes the aggregated results for the eight PV-equipped buildings. It shows the total monthly consumption, PV production, additional electricity required from the grid, and the surplus electricity that could not be utilized on-site.
Although the annual PV production represents about 11% of the total electricity demand of all public buildings in the municipality, the analysis highlights that there are significant periods during the year with electricity surpluses. These surpluses are particularly pronounced in the summer months, when PV generation is highest and building consumption is relatively lower. Since these surpluses cannot be used directly by the buildings at the time of generation, they open the possibility for exploring two alternative scenarios, which will be analyzed in Sections 3 and 4 of this paper: the use of a virtual storage concept (energy transfer between buildings), and the installation of battery storage system.

Table 1 Results of technical analysis for buildings with PV systems

Month	Electricity Consumption	Electricity Production	Required Additional Electricity	Surplus Electricity
January	257,355.75	12,200.95	246,807.65	1,652.86
February	241,813.90	16,520.16	228,320.57	3,026.84
March	205,803.80	23,368.16	191,358.78	8,923.14
April	206,432.52	26,853.96	191,129.51	11,550.95
May	190,650.90	33,059.00	173,846.72	16,254.82
June	176,924.89	34,572.67	165,317.16	22,964.93
July	185,329.42	34,540.06	175,099.89	24,310.53
August	188,862.28	32,093.13	178,823.48	22,054.34
September	184,341.12	25,457.23	172,242.47	13,358.58
October	205,190.69	19,842.08	192,997.19	7,648.58
November	213,255.09	12,467.25	202,337.08	1,549.24
December	261,460.50	10,799.65	251,903.00	1,242.15
Total (kWh)	2,517,420.85	281,774.31	2,370,183.50	134,536.96

3. Virtual storage

The second scenario examines the concept of virtual storage as a collective energy management model for the municipal buildings. Under this approach, each of the buildings equipped with PV systems primarily uses the electricity generated for its own consumption. During hours when surplus electricity is available, the generated surplus is virtually transferred to the remaining 20 public buildings in the municipality. The surplus is allocated at prices equivalent to those on the HUPX market, enabling the buildings without PV systems to benefit from lower electricity costs compared to procuring the same amount directly from the free market.
Any electricity produced by the PV systems that is not consumed by the 28 municipal buildings is assumed to be sold on the free market at HUPX–10% prices. Since the total electricity produced by the PV systems is not sufficient to meet the demand of all municipal buildings, additional procurement is required. For this purpose, the municipal energy enterprise purchases the remaining electricity needed at HUPX+20% and sells it to all public buildings at the same price.
Table 2 presents the monthly distribution of electricity consumption for the 20 municipal buildings after utilizing the virtual storage mechanism, the total surplus electricity, and the additional electricity procurement required for all 28 buildings. The results indicate that

transferring surplus electricity reduces the electricity consumption of non-PV buildings by approximately 20%, while 16.9 MWh of surplus electricity remains available for market sale.
Table 3 summarizes the financial outcomes, including the savings achieved by the municipal buildings, the revenues from surplus electricity sold on the market, and the additional revenues obtained from transferring surplus PV electricity to non-PV buildings. The results highlight that the total savings for all municipal buildings amount to approximately €38,900 annually, while revenues from surplus electricity sales reach €10,870.

Table 2 Results of technical analysis when using virtual storage for the transfer of surplus electricity

Month	Electricity Consumption for the 20 Buildings when using the surpluses from the PV Systems	Total Surpluses from the PV Systems	Total Electricity Procurement for all the Buildings in the Municipality
January	59,360.54	67.25	306,168.20
February	54,887.24	309.85	283,207.81
March	41,142.46	1,317.69	232,501.23
April	38,640.36	1,650.18	229,769.88
May	31,329.32	2,261.34	205,176.04
June	21,952.56	3,793.01	187,269.72
July	21,310.66	2,725.15	196,410.55
August	23,834.95	2,084.60	202,658.43
September	31,317.77	1,413.74	203,560.24
October	41,945.28	1,191.21	234,942.48
November	49,234.10	34.22	251,571.18
December	61,747.52	48.35	313,650.52
Total (kWh)	476,702.76	16,896.60	2,846,886.26

Table 3 Results of analysis of savings, revenues and costs when implementing a virtual storage

Month	Savings	Revenues from Surplus Electricity sale	Revenues from Surplus Electricity sale to the 20 Buildings	New Electricity Expenses	Expenses without PV Electricity
January	2,853.57	12.61	263.28	58,457.28	61,093.39
February	3,330.75	38.89	367.68	50,760.76	53,815.34
March	3,643.78	129.51	763.20	32,415.02	35,919.88
April	3,908.07	115.41	941.60	29,320.50	33,132.12
May	3,665.46	146.03	905.30	20,771.06	24,097.90
June	4,092.45	195.91	1,508.26	20,965.94	25,263.11
July	4,099.03	187.04	1,622.27	21,739.34	26,106.94
August	3,920.87	113.53	1,514.13	23,815.77	27,975.52
September	3,291.48	99.84	965.41	24,624.65	27,884.57
October	2,747.11	116.26	561.07	29,443.00	31,996.59
November	1,943.52	2.50	144.09	32,011.65	33,619.23
December	1,491.39	4.83	96.71	32,723.67	33,899.45
Total (€)	38,987.47	1,162.38	9,653.00	377,048.65	414,804.04

Overall, the virtual storage model reduces the total electricity expenses of the 28 municipal buildings from €414,800 to €377,050, representing a 30% cost reduction.

4. Battery Energy Storage

To complement the photovoltaic (PV) systems installed on the selected municipal buildings, battery energy storage systems (BESS) were introduced in the analysis. Each building with PV was equipped with a 10 kWh battery storage system of the type Huawei LUNA2000, with the exception of the fifth building, which shows no surplus electricity due to extremely high electricity demand. This specific building is also responsible for about 70% of the total electricity consumption of all 28 municipal facilities, thus representing the main driver of overall energy demand in the municipality.

The analysis assumes that part of the surplus electricity generated by each of the seven PV-equipped buildings is stored in the battery system and later utilized on the following day in the same building. Surplus electricity exceeding the storage capacity, as well as unused stored energy, is considered exported to the electricity market.

The financial analysis is conducted according to the contracts currently applied by the municipal facilities, based on the following assumptions:

- Sale of surplus electricity: average monthly HUPX prices reduced by 10%;
- Purchase of additional electricity: average monthly HUPX prices increased by 20%.

4.1. Technical Specifications of the battery energy storage system

The specifications of the battery system used in this study are presented in Table 4. Since Huawei does not officially provide the round-trip efficiency coefficient, a value of 0.9215 was adopted based on practical references for battery systems with similar characteristics. This coefficient was applied in the calculations of stored and discharged energy.

Table 4 Technical specifications (Huawei LUNA2000-5/10/15-S0)

Parameter	Value
Usable Energy (per module)	5 kWh
Max. Usable Capacity	15 kWh (3 modules)
Depth of Discharge (DoD)	100%
Operating Voltage Range (single-phase system)	350–560 V
Operating Voltage Range (three-phase system)	600–980 V
Operating Temperature	-20°C to +55°C
Cell technology	Lithium-iron phosphate (LiFePO4)

The usable energy of the battery is derived as:

$$E_{usable} = E_{nominal} \cdot \eta_{rt} \qquad (1)$$

Where:

$E_{nominal}$ Is the nominal capacity of the battery;
η_{rt} Is the round-trip efficiency coefficient.
The monthly balance of electricity flows with integrated battery storage is presented in Table 5. The table provides the distribution of electricity consumption after PV usage, surplus generation, storage, discharge, new surpluses, and final consumption.

Table 5 Monthly electricity balance with battery energy storage integration

Month	Electricity Consumption after PV electricity	Surplus Electricity	Stored Electricity in BESS	Used Electricity from BESS	New Surplus Electricity	New Electricity Consumption	Unused Stored Electricity in BESS
January	20,704.2	1,652.9	800.6	737.8	852.2	19,984.0	1,274.2
February	19,858.1	3,026.8	945.9	871.6	2,081.0	18,995.2	1,063.4
March	10,300.2	8,923.1	1,734.5	1,598.4	7,188.6	8,816.9	482.8
April	9,185.7	11,551.0	1,906.2	1,756.6	9,644.7	7,581.2	672.8
May	8,387.1	16,254.8	1,994.2	1,837.7	14,260.6	6,921.8	685.0
June	3,712.4	22,964.9	2,164.9	1,995.0	20,800.0	2,217.2	710.5
July	3,336.6	24,310.5	2,237.1	2,061.5	22,073.4	1,819.8	748.3
August	3,402.2	22,054.3	2,237.1	2,061.5	19,817.2	1,715.0	575.6
September	6,421.4	13,358.6	2,012.1	1,854.2	11,346.5	4,949.0	700.0
October	11,285.3	7,648.6	1,687.1	1,554.7	5,961.4	9,934.4	723.4
November	21,034.6	1,549.2	812.5	748.7	736.8	20,321.3	1,009.0
December	32,259.2	1,242.1	549.7	506.6	692.4	31,731.0	906.4
Total (kWh)	149,887.1	134,537.0	19,082.1	17,584.2	115,454.8	134,986.8	8,277.3

The results indicate that from the 134,536.96 kWh of annual surplus electricity, only 19,082.13 kWh was stored, with 17,584.18 kWh effectively discharged and used. This corresponds to a storage utilization efficiency of approximately 92.1%, confirming the consistency of the adopted round-trip coefficient.
Graphical representation of these flows is shown in Figure 1.

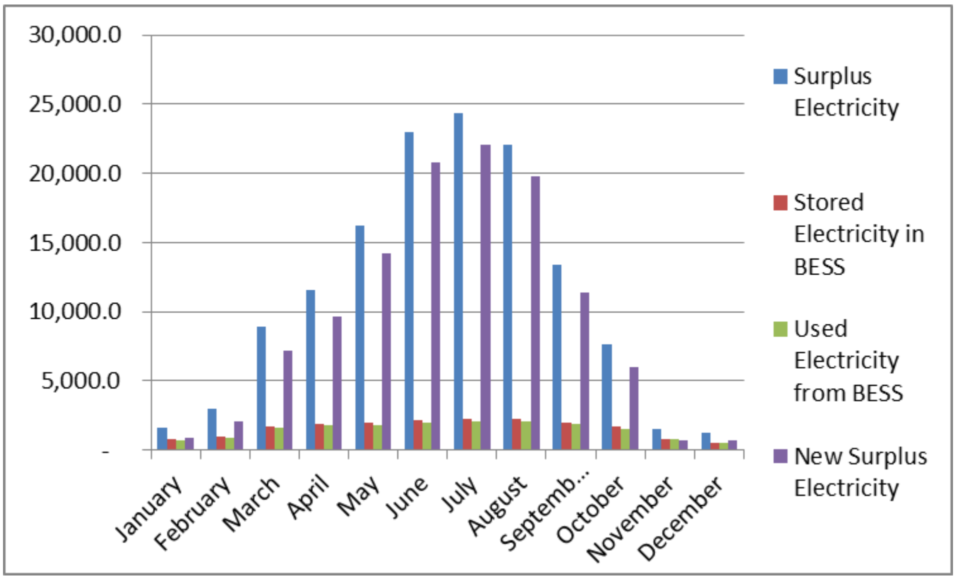

Fig. 1 Graphical representation of the energy balance of the system

4.3. Financial Performance with BESS

The financial impact of battery storage is presented in **Table 6**, showing the monthly electricity expenses, revenues from surplus electricity, new consumption costs, and revenues from new surpluses.

Table 6 Monthly financial performances with BESS integration

Month	Electricity Consumption Expenses after using PV Electricity	Revenues from surplus electricity	Electricity Expenses for the new consumption	Revenues from the new surplus electricity
January	€2,506.78	€1,372.01	€2,385.54	€79.87
February	€2,574.58	€1,255.96	€2,433.07	€173.78
March	€1,433.15	€801.25	€1,245.46	€391.77
April	€1,035.28	€1,189.63	€841.30	€599.26
May	€1,052.18	€1,062.83	€908.59	€702.73
June	€945.95	€1,416.84	€784.79	€1,137.79
July	€914.89	€1,473.36	€754.70	€1,200.36
August	€935.59	€1,397.79	€745.40	€1,123.10
September	€933.43	€1,045.44	€762.89	€664.87
October	€1,145.74	€942.11	€985.83	€361.58
November	€1,565.25	€1,064.52	€1,483.60	€51.93
December	€2,285.67	€950.26	€2,237.28	€28.38
Total (€)	€17,328.50	€13,972.02	€15,568.47	€6,515.41

The financial balance demonstrates that battery storage allows a partial shift of electricity expenses into revenues, although the majority of financial benefit still depends on the magnitude of surplus generation and the ability of the building to use the stored electricity.
Table 7 summarizes the monthly cash flows under the PV + BESS operational scheme on municipality level.

Table 7 Electricity Expenses & Revenues

Month	New Electricity Expenses for all 28 PB	Total Revenues (PV+BESS)
January	€53,641.12	€1,451.88
February	€49,134.16	€1,429.74
March	€32,470.64	€1,193.02
April	€30,380.25	€1,788.89
May	€23,197.57	€1,765.56
June	€24,304.63	€2,554.63
July	€25,189.80	€2,673.72
August	€27,176.17	€2,520.90
September	€26,811.36	€1,710.31
October	€29,944.37	€1,303.69
November	€29,171.07	€1,116.45
December	€29,910.13	€978.63
Total (€)	€381,331.27	€20,487.43

The first column aggregates the new electricity costs of the seven PV-equipped buildings that deploy 10 kWh batteries, and the electricity costs of the remaining 21 public buildings without PV or BESS. The second column consolidates all income earned by the municipality from market transactions of PV-generated surplus and any unutilized battery energy sold to the market according to the pricing rules adopted in the analysis (i.e., monthly average HUPX benchmarks with the specified discounts/premiums). Hence, the table provides a month-by-month net view of what the municipality still pays for electricity across the entire portfolio after PV self-consumption and BESS operations, and what the municipality earns from selling surplus PV/BESS energy.

From a portfolio perspective, the PV + BESS case yields annual electricity expenses of €381,331.27 and total annual revenues of €20,487.43. Importantly, these costs already include the updated consumption of the seven PV-BESS buildings plus the electricity costs of the other 21 public buildings. Revenues represent the municipality-wide income generated by selling PV/BESS surplus according to the stated market rules.

To implement the BESS case, seven Huawei LUNA 10 kWh systems are required (one per PV site except PB5, which shows no meaningful surplus). With an indicative unit price of ~€5,000 per battery (based on typical offers from EU retailers), the initial investment is ~€35,000 for hardware alone. In addition, operational costs must be budgeted, further increasing lifetime expenditure. At the single-building level, annual savings are modest (on the order of €25–€65 per building) rendering the investment not cost-effective under current price assumptions and load/surplus patterns.

By contrast, the virtual-storage strategy avoids BESS capital outlay, yet still unlocks material portfolio-level savings and revenues by reallocating surplus PV across buildings. In our results, the virtual-storage option delivers significantly higher net monetary benefit at the municipal level with no upfront equipment cost, making it the more economical approach at present. This conclusion holds especially because the PV fleet's aggregate surplus windows are intermittent and relatively small compared with the portfolio's demand, limiting the monetizable arbitrage of small batteries while the sharing model captures value without new capex.

Conclusion

The study compared two models of integrating photovoltaic systems within a municipal energy framework: (a) battery energy storage systems (BESS) using 10 kWh Huawei LUNA2000 units at PV-equipped buildings, and (b) a virtual storage strategy that redistributes PV surplus among municipal buildings without additional hardware investments.

Our findings reveal that current PV generation in the analyzed municipality addresses only a modest fraction of municipal electricity demand, both overall and at individual buildings, underscoring the need for coordinated strategies to maximize utilization. The BESS scenario offered technical flexibility but the annual financial gains were minimal, only €25–65 per building that fall vastly short of making a €5,000 battery investment viable, resulting in payback periods exceeding several decades when including operating costs.

By comparison, the virtual storage model demonstrated considerably stronger financial outcomes at zero capital cost. The municipality benefits from surplus PV redeployment that yields substantial reductions in electricity spend and meaningful revenues, without incurring equipment expenses.

This supports the growing consensus that coordinated, multi-building energy management can outperform distributed battery deployments, especially where tariff spreads are narrow and PV surpluses are small, intermittent, and seasonally mismatched to demand. It also aligns with theories of scaling asset efficiency: sharing resources across a cluster improves utilization and cost-effectiveness. Therefore, at present, the optimal strategy for municipalities with low PV production is to pursue virtual storage and surplus sharing across institutions.

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