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

ETIMA 2025

THIRD INTERNATIONAL CONFERENCE

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FACULTY OF ELECTRICAL ENGINEERING

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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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LONG-TERM POWER PURCHASE AGREEMENT FOR PHOTOVOLTAIC ENERGY AS A SOLUTION FOR ENHANCING THE PROFITABILITY OF THE TASHMARUNISHTA PUMPED-STORAGE HYDRO POWER PLANT

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Abstract

*This paper analyzes the potential of a long-term Power Purchase Agreement (PPA) as a mechanism to enhance the profitability of the Tashmarunishta pumped-storage hydro power plant (PSHPP). The study focuses on a 20-year agreement for the procurement of electricity from a 300 MW photovoltaic (PV) power plant, with purchase price of 32 €/MWh. The electricity generation of the PV power plant is modeled and simulated in PV*SOL premium on an hourly basis. Furthermore, based on data from the pre-investment study for PSHPP Tashmarunishta, the required electricity for water pumping and the expected electricity production from the PSHPP are analyzed. The proposed operational regime includes ten hours of water pumping during PV electricity production for six consecutive weeks, followed by one week with nine hours of pumping and seven hours of electricity generation from the PSHPP in the evening, when market prices are at their peak. The hourly-level analysis enables an assessment of the technical and economic benefits of this mechanism, examining the potential improvement in the economic sustainability of the Tashmarunishta PSHPP through the optimal utilization of renewable energy sources.*

Key words

Power Purchase Agreement, pumped-storage hydro power plant, photovoltaic power plant, operational regime, economic sustainability.

Introduction

The growing share of variable renewable energy sources in modern power systems is reshaping the operational and economic landscape of conventional generation and storage facilities. In this evolving environment, pumped-storage hydropower plants (PSHPPs) play a crucial role in ensuring system stability, balancing supply and demand, and supporting the integration of intermittent renewable generation. For North Macedonia, the planned Tashmarunishta PSHPP is of strategic importance for national grid stability and energy security. However, the economic viability of such large-scale projects remains a key challenge, especially in competitive electricity markets.

This research investigates the potential of a long-term Power Purchase Agreement (PPA) with a photovoltaic (PV) power plant as a mechanism to enhance the profitability of the Tashmarunishta PSHPP. The approach combines technical modeling of PV generation with economic evaluation over a 20-year horizon, aiming to determine whether stable and predictable

revenues can transform the project into an attractive investment opportunity. The first-year operational assessment is based on hourly electricity prices from the HUPX market for 2024, providing a realistic market reference for evaluating both pumping and generation activities.
The study utilizes PV*SOL premium for hourly PV generation modeling and incorporates operational parameters and investment costs from the Tashmarunishta pre-investment study (Čakar Partners, 2010), which were updated to present-day values by applying an annual inflation rate of 5%, a figure derived from the long-term average inflation statistics over the past 30 years. Price projections are based on hourly HUPX data for 2024, from which average annual prices were determined for the pumping and generation periods. These values are further adjusted downward by 2% per year, reflecting the National Bank of North Macedonia's forecast of an annual 2% inflation decrease up to 2027. By combining technical, market, and financial analyses, the research seeks to determine whether coupling PSHPP operation with PV energy under a long-term PPA can ensure financial profitability while strengthening the national power system's flexibility.

1. Literature review

In recent years, leading research has underscored the value of integrating photovoltaic (PV) energy with pumped-storage hydropower plants (PSHPP), especially in terms of economic performance and operational flexibility under market-based frameworks.

In [6] is presented a detailed performance assessment of hybrid systems combining photovoltaics, wind turbines, and PSHPP. The findings in [6] highlight that including realistic parameters such as head loss and evaporation rates improves prediction accuracy by roughly 8–9%, reinforcing the importance of technical precision in hybrid system design.

The authors in [3] developed a comprehensive multi-objective optimization model for off-grid hybrid systems—combining PV, diesel generators, and pumped hydro storage. The study demonstrates how optimizing PV sizing, pump/turbine power, and hydraulic design influences both the total net present cost and system reliability, underscoring the complex yet quantifiable trade-offs in hybrid system planning.

A broader review published in *Energies* synthesizes global lessons on PSHPP, emphasizing its dominant role among large-scale storage options, and illuminating how O&M cost efficiencies improve with scale and technology maturity—a critical consideration for long-term financial modeling [8].

Advancing PV technology choice, the analysis in [7] revealed that bifacial PV modules can increase annual water pumping capacity by ~10% compared to monofacial modules, while lowering the levelized cost of energy, indicating that PV technology selection has a strategic bearing on storage system economics.

New experimental analysis from the Institute for Energy Technology demonstrated that embedding battery storage into floating PV–hydropower hybrids can enhance annual business margins by up to 2%, factoring in ancillary services and capacity market revenues, though they note that PV-PPA schemes remain economically robust without batteries [4].

Critically, the project-specific case study in [2] focuses on the Tashmarunishta PSHPP under a PV PPA model. Through hourly PV generation modeling and financial projections, it is show that without PV, the PSHPP would yield financial losses, whereas coupling with PV under a contractual PPA transforms the operation into a profitable enterprise.

Finally, integration challenges are discussed in a study applying a techno-economic dispatch model developed by researchers at the University of Zaragoza, which allows optimal scheduling of PV, wind, and PSHPP to maximize market profits. This supports the strategic approach of aligning harvesting of PV energy with pump operation under market price profiles [9].

2. Technical analysis of PSHPP Tashmarunishta

With an installed capacity of 3 x 75 MW, the Tashmarunishta Pumped Storage Hydro Power Plant (PSHPP) is designed to provide critical reserves for tertiary regulation, playing a key role in maintaining power system stability [2]. The annual electricity consumption required for water pumping was calculated based on a schedule of ten hours of daily pumping during six consecutive weeks, followed by nine hours of pumping in the seventh week, resulting in an estimated 788,850.00 MWh per year [1].

The annual electricity production of the PSHPP was calculated to be approximately 574,875.00 MWh [1]. These figures formed the basis for an economic feasibility analysis under specific market conditions. It was assumed that the electricity needed for pumping would be purchased on the free market at prices 10% higher than the reference prices on the HUPX electricity exchange (HUPX + 10%) during the pumping period, which spans from 07:00h to 16:00h for 10 hour pumping and from 07:00h to 15:00h for 7 hour pumping. Conversely, the electricity generated by the PSHPP would be sold during high-demand hours, from 18:00 to 24:00, at a price of HUPX + 10%.

These operational parameters were analyzed to evaluate the plant's economic viability under varying conditions. The results highlight the importance of aligning operational strategies with market dynamics to maximize the financial sustainability of the PSHPP.

3. Electricity production from a photovoltaic power plant with capacity of 300MW

The designed photovoltaic (PV) power plant has a total installed capacity of 300 MW and is projected to operate under a hybrid sales model. A long-term Power Purchase Agreement (PPA) will secure the sale of electricity generated between 07:00h and 16:00h, providing price stability and predictable revenue for the investor. Outside this contracted time window, the investor of the PVPP can sell the remaining electricity production on the free market at prevailing spot prices, allowing the project to benefit from potential price peaks.

The electricity production estimates are based on design and simulation of the PV power plant in the licensed software PV*SOL premium, taking into account local solar irradiation profiles, panel characteristics, system losses, and performance degradation. The simulation results provide a precise hourly, monthly and annual generation data, which reflects seasonal variations in solar energy availability.

During the summer months, higher irradiation and longer daylight hours lead to increased production, while in winter, output decreases accordingly. The plant’s generation pattern matches well with the PPA delivery period, ensuring optimal utilization of the most valuable daylight hours.

A graphical representation of the monthly production profile is presented below, clearly illustrating the seasonal variation. Detailed numerical results are included in the Techno-Economic Analysis section for further evaluation.

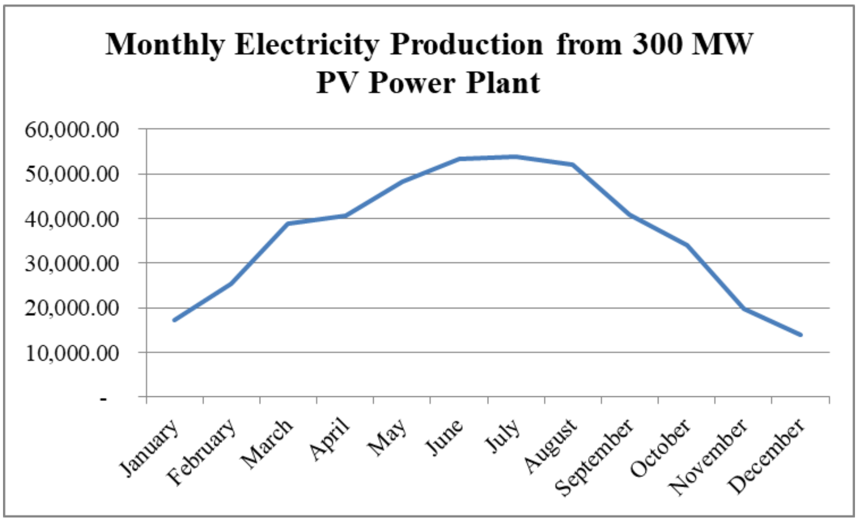

Fig. 2 Expected monthly electricity production from 300MW photovoltaic power plant

4. Techno-economic analysis for the first year of operation

The technical analysis is based on hourly simulation results, aggregated into monthly values (Table 1). For each month, the following parameters are presented:

- Electricity production from the PV plant (MWh) – total gross PV output;
- Required electricity for pumping (MWh) – the energy needed to pump water for subsequent generation cycles;
- Used PV electricity for pumping (MWh) – share of PV output directly used for pumping operations;
- Electricity production from the PSHPP (MWh) – electricity generation from released water;
- Additional required electricity for pumping (MWh) – electricity purchased from the market when PV production is insufficient.

Table 1 Results from the technical analysis for PSHPP using PV electricity

Month	Electricity Production from 300 MW PV Power Plant	Required Electricity for pumping operations	Used PV Electricity for Pumping	Electricity Production from the PSHPP	Additional Required Electricity for pumping
January	17,155.02	68,850.00	17,154.75	48,825.00	51,695.25
February	25,266.04	62,100.00	25,249.57	44,100.00	36,850.43
March	38,829.40	68,850.00	38,335.37	48,825.00	30,514.63
April	40,703.20	66,375.00	39,117.48	47,250.00	27,257.52
May	48,316.52	68,850.00	45,267.75	48,825.00	23,582.25
June	53,425.52	66,600.00	49,360.23	47,250.00	17,239.77
July	53,910.51	68,625.00	50,313.20	48,825.00	18,311.80
August	51,946.09	68,850.00	49,436.02	48,825.00	19,413.98
September	40,973.66	66,375.00	39,759.75	47,250.00	26,615.25
October	34,116.66	61,875.00	33,502.43	48,825.00	28,372.57
November	19,731.24	59,850.00	19,663.40	47,250.00	40,186.60
December	13,928.40	61,650.00	13,891.53	48,825.00	47,758.47
Total (MWh)	438,302.26	788,850.00	421,051.49	574,875.00	367,798.51

Figure 2 shows the electricity produced by the PV power plant that can be used for pumping operations in the PSHPP, as well as the surplus electricity that is not consumed for pumping. The surplus electricity can either be sold on the free market by the PV power plant operator or stored in a battery system for later use.

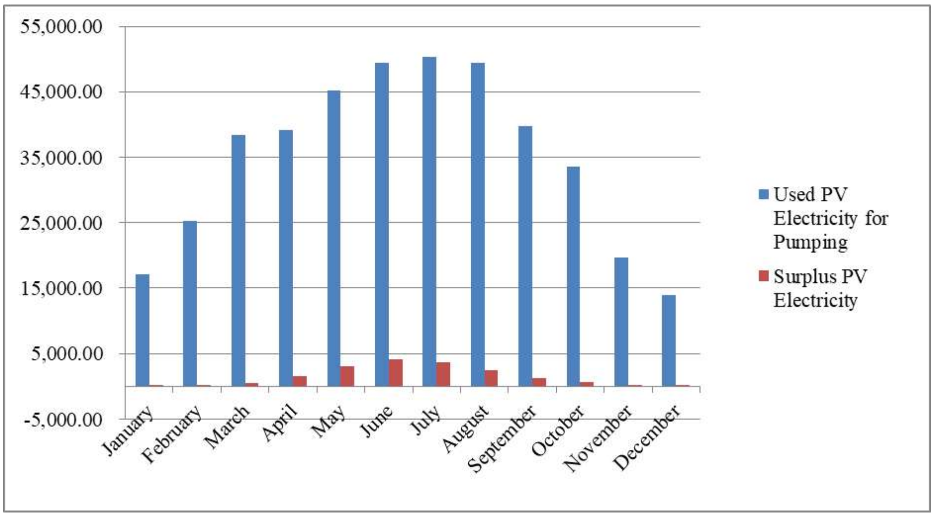

Fig. 2 PV power plant generation for PSHPP and surplus electricity

In the financial analysis, transmission and system operation costs were considered. These include:

- **MEPSO Transmission costs**: €4.5/MWh of transmitted energy;
- **Market Operator (MEMO) costs**: €0.2734/MWh;
- **Active power capacity charges**: €237.72/MW of contracted maximum capacity.

The financial evaluation was carried out under two scenarios:

1. **Case 1 – Free market**: All electricity purchases for pumping are from the market at the prevailing wholesale price (HUPX +10%), and PSHPP output is sold entirely on the market (HUPX +10%).
2. **Case 2 – PV electricity PPA + free market**: Part of the pumping electricity demand is met via a Power Purchase Agreement (PPA) at €32/MWh from 300 MW PV power plant, with the remainder purchased on the free market at HUPX +10% prices.

Table 2 presents the monthly results from the financial analysis. Two cost scenarios for the same amount of electricity required for pumping are compared: purchasing electricity from the PV power plant at a fixed price of 32 €/MWh, and purchasing the same amount of electricity from the grid at HUPX day-ahead market price + 10%.
The results clearly show that sourcing electricity from the PV power plant significantly reduces pumping costs compared to grid purchases. This cost difference directly increases the net savings, as indicated in the last column of the table.

Table 2 Results from the financial analysis for PSHPP using PV electricity

Month	Total Expenses for Pumping Operations (HUPX+10%)	PV Electricity Expenses (32eur/MWh)	PV Electricity Expenses (HUPX+10%)	Additional Electricity Expenses	Revenues from Generated Electricity from PSHPP
January	12,956,125.59	931,087.69	3,582,326.56	9,755,934.62	8,292,789.45
February	10,475,177.27	1,157,901.53	4,285,578.18	6,539,514.22	7,583,466.83
March	8,807,785.52	1,608,867.34	4,886,830.01	4,303,091.10	6,656,834.25
April	7,240,598.33	1,622,080.77	4,365,288.34	3,245,631.41	6,494,499.00
May	5,583,385.22	1,830,703.53	3,686,570.71	2,278,950.09	6,019,848.45
June	6,060,271.37	1,950,922.75	4,402,006.44	2,029,660.36	6,270,823.35
July	6,160,596.30	1,991,084.11	4,660,081.20	1,881,576.67	6,863,563.58
August	6,467,423.04	1,964,088.18	4,441,558.92	2,407,999.71	7,060,469.63
September	6,633,353.93	1,642,633.29	3,837,577.44	3,166,097.91	6,543,187.20
October	6,864,926.63	1,420,918.89	3,774,476.60	3,439,291.15	6,211,787.18
November	7,307,653.82	968,403.87	2,419,663.00	5,227,165.81	5,429,773.80
December	6,534,979.79	792,296.17	1,859,338.93	5,023,407.97	4,331,417.63
Total (€)	91,092,276.77	17,880,988.13	46,201,296.33	49,298,321.02	77,758,460.33

Annual results (Table 3) show that Case 1 yields a negative gross margin of –€13.33 million, primarily due to high pumping electricity costs. In contrast, Case 2 results in a positive gross margin of €14.98 million, confirming the significant economic benefit of securing low-cost PV electricity under a PPA.

Table 3 Comparison of the two analyzed scenarios

Month	**Case 1 - free market**	**Case 2 - PV electricity PPA + free market**
January	-4,663,336.14	-2,012,097.27
February	-2,891,710.44	235,966.21
March	-2,150,951.27	1,127,011.41
April	-746,099.32	1,997,108.24
May	436,463.24	2,292,330.41
June	210,551.98	2,661,635.68
July	702,967.28	3,371,964.37
August	593,046.59	3,070,517.32
September	-90,166.72	2,104,777.42
October	-653,139.45	1,700,418.26
November	-1,877,880.02	-426,620.89
December	-2,203,562.16	-1,136,519.40
Total (€)	-13,333,816.44	14,986,491.77

5. Long-Term Analysis of PSHPP Operation with PV Electricity Supply

A detailed 20-year financial analysis was conducted to evaluate the operation of the Pumped Storage Hydropower Plant (PSHPP) using electricity supplied from a photovoltaic (PV) power plant instead of sourcing it from the electricity market.

The analysis assumes:

- Base PV electricity price: 32 €/MWh.
- Market electricity prices are derived from hourly HUPX data for 2024, from which average annual prices were determined separately for the pumping and generation periods. These values are adjusted downward by 2% per year in line with the National Bank of North Macedonia's forecast of annual inflation decrease until 2027. Transmission tariffs, market operator fees, and other regulated costs are also included, with an assumed 2% annual increase to account for rising system service costs and the growing share of renewable energy in the grid.
- PSHPP operating profile: Annual required electricity for pumping operations remains constant at 788,850 MWh.
- PV generation profile: Gradual annual reduction in available PV electricity for pumping due to performance degradation, resulting in an increased need for additional grid electricity over time.

The following section presents the results from the long-term technical and financial analysis of PSHPP operation with PV electricity supply under the proposed PPA framework. Technical results (Table 4) include annual electricity for pumping, PV electricity production, PSHPP electricity production, and the remaining electricity needed from the grid. Financial results (Table 5) summarize additional electricity expenses, total annual expenses, savings, and revenues over a 20-year operational horizon.

Table 4 Results from the long-term technical analysis of PSHPP Operation with PV Electricity Supply

Year	Required Electricity for pumping operations (MWh)	Electricity production from the PVPP (MWh)	Electricity Production from the PSHPP (MWh)	Additional Required Electricity for pumping (MWh)
1	788,850.00	438,302.26	574,875.00	367,798.51
2	788,850.00	433,919.24	574,875.00	371,476.50
3	788,850.00	429,580.04	574,875.00	375,191.26
4	788,850.00	425,284.24	574,875.00	378,943.18
5	788,850.00	421,031.40	574,875.00	382,732.61
6	788,850.00	416,821.09	574,875.00	386,559.94
7	788,850.00	412,652.88	574,875.00	390,425.53
8	788,850.00	408,526.35	574,875.00	394,329.79
9	788,850.00	404,441.08	574,875.00	398,273.09
10	788,850.00	400,396.67	574,875.00	402,255.82
11	788,850.00	396,392.71	574,875.00	406,278.38
12	788,850.00	392,428.78	574,875.00	410,341.16
13	788,850.00	388,504.49	574,875.00	414,444.57
14	788,850.00	384,619.45	574,875.00	418,589.02

15	788,850.00	380,773.25	574,875.00	422,774.91
16	788,850.00	376,965.52	574,875.00	427,002.66
17	788,850.00	373,195.86	574,875.00	431,272.68
18	788,850.00	369,463.91	574,875.00	435,585.41
19	788,850.00	365,769.27	574,875.00	439,941.26
20	788,850.00	362,111.57	574,875.00	444,340.68

Table 5 Results from the long-term financial analysis of PSHPP Operation with PV Electricity Supply

Year	Additional Electricity Expenses (€)	Total Expenses (€)	Total Expenses without PV Electricity (€)	Revenues from the produced Electricity from the PSHPP (€)	Case 2 - PV electricity PPA + free market (€)
1	44,890,980.43	50,507,021.57	74,383,279.77	91,068,711.35	40,561,689.78
2	32,952,293.78	50,144,687.32	73,071,907.80	89,247,337.13	39,102,649.81
3	32,616,180.38	49,786,333.46	71,790,289.14	87,462,390.39	37,676,056.93
4	32,283,495.34	49,431,948.85	70,537,899.24	85,713,142.58	36,281,193.72
5	31,954,203.69	49,081,523.32	69,314,225.46	83,998,879.73	34,917,356.41
6	31,628,270.81	48,735,047.61	68,118,766.84	82,318,902.13	33,583,854.52
7	31,305,662.45	48,392,513.44	66,951,033.91	80,672,524.09	32,280,010.65
8	30,986,344.69	48,053,913.49	65,810,548.48	79,059,073.61	31,005,160.12
9	30,670,283.98	47,719,241.44	64,696,843.47	77,477,892.13	29,758,650.70
10	30,357,447.08	47,388,491.93	63,609,462.68	75,928,334.29	28,539,842.36
11	30,047,801.12	47,061,660.63	62,547,960.63	74,409,767.61	27,348,106.98
12	29,741,313.55	46,738,744.20	61,511,902.36	72,921,572.25	26,182,828.06
13	29,437,952.15	46,419,740.34	60,500,863.27	71,463,140.81	25,043,400.47
14	29,137,685.04	46,104,647.77	59,514,428.95	70,033,877.99	23,929,230.22
15	28,840,480.65	45,793,466.29	58,552,194.97	68,633,200.43	22,839,734.14
16	28,546,307.75	45,486,196.72	57,613,766.76	67,260,536.42	21,774,339.70
17	28,255,135.41	45,182,840.98	56,698,759.44	65,915,325.70	20,732,484.72
18	27,966,933.03	44,883,402.07	55,806,797.61	64,597,019.18	19,713,617.11
19	27,681,670.31	44,587,884.09	54,937,515.29	63,305,078.80	18,717,194.70
20	27,399,317.27	44,296,292.27	54,090,555.69	62,038,977.22	17,742,684.96

The technical analysis shows a gradual decline in annual PV generation over the project lifetime due to performance degradation, resulting in a progressive increase in grid-purchased electricity for pumping. Despite this trend, the PV–PSHPP configuration consistently reduces the need for high-priced grid electricity, particularly during peak pumping hours. The financial analysis confirms that the hybrid operation yields substantial annual savings compared to sourcing all pumping electricity from the market at HUPX+10% prices, with the benefits remaining significant throughout the 20-year period, even as PV output declines.

4.1. Investment and Financing Structure

The total investment cost for the PSHPP Tashmarunishta was derived from the pre-investment feasibility study conducted in 2010. To reflect present-day values, the original cost was adjusted using an annual inflation rate of 5% over the period 2010–2025, resulting in a total updated investment value of €166,517,937.34.

In line with current financing practices for renewable energy projects in North Macedonia, the investment is planned to be covered through a combination of own capital and long-term debt financing. The financing model assumes 30% own capital and 70% loan financing, corresponding to €49,955,381.20 and €116,562,556.14 respectively.

Own capital contributions are distributed across the five-year construction period as follows: 15% in the first year, 20% in the second year, 30% in the third year, 20% in the fourth year, and the remaining 15% in the fifth year.

The loan parameters are based on common market conditions for renewable energy infrastructure projects in the country. The applied interest rate is 3%, with a 10-year repayment period and a 5-year grace period corresponding to the plant's construction phase. Loan servicing begins in the sixth year, which coincides with the start of commercial operation. Depreciation is calculated over a 20-year period, which corresponds to the assumed technical and economic lifetime of the asset.

Annual operation and maintenance (O&M) expenses are estimated at 5% of the total investment cost**.** This value is based on the latest IRENA (International Renewable Energy Agency) report [5].

The results presented in Table 6 reflect the projected long-term financial performance of the PSHPP Tashmarunishta under the assumed technical, operational, and market conditions. The pre-operational years (Years –4 to 0) show negative cash flows corresponding to the phased equity contributions during the five-year construction period, in line with the defined investment structure. Commercial operation begins in Year 1, when revenues from electricity sales and capacity provision are realized.

The table illustrates how revenues remain consistently above total annual operating expenditures, including the cost of electricity for pumping, loan annuity and interest payments, O&M expenses, depreciation, and income tax. The initial ten years of operation include loan servicing, after which the annuity and interest cost components drop to zero, resulting in a marked increase in net cash flow from Year 11 onwards.

Table 6 Long-term financial performance of PSHPP with PV electricity supply

Year	Annual Revenues	Electricity Expenses	Annuity	Interest Rate	O&M Costs	Depreciati on 2%	Income tax 10%	Net Cash Flow
	[€]							
-4	/	/	/	/	/	/	/	-7,493,307
-3	/	/	/	/	/	/	/	-9,991,076
-2	/	/	/	/	/	/	/	-14,986,614
-1	/	/	/	/	/	/	/	-9,991,076
0	/	/	/	/	/	/	/	-7,493,307
1	91,068,711	50,507,022	13,664,688	3,496,877	8,325,897	3,330,359	2,540,856	12,699,891
2	89,247,337	50,144,687	13,664,688	3,191,842	8,325,897	3,330,359	2,425,455	11,356,252
3	87,462,390	49,786,333	13,664,688	2,877,657	8,325,897	3,330,359	2,314,214	10,040,899
4	85,713,143	49,431,949	13,664,688	2,554,046	8,325,897	3,330,359	2,207,089	8,753,161
5	83,998,880	49,081,523	13,664,688	2,220,727	8,325,897	3,330,359	2,104,037	7,492,376
6	82,318,902	48,735,048	13,664,688	1,877,408	8,325,897	3,330,359	2,005,019	6,257,892
7	80,672,524	48,392,513	13,664,688	1,523,790	8,325,897	3,330,359	1,909,997	5,049,071
8	79,059,074	48,053,913	13,664,688	1,159,563	8,325,897	3,330,359	1,818,934	3,865,283
9	77,477,892	47,719,241	13,664,688	784,409	8,325,897	3,330,359	1,731,799	2,705,909

10	75,928,334	47,388,492	13,664,688	398,001	8,325,897	3,330,359	1,648,559	1,570,341
11	74,409,768	47,061,661	/	/	8,325,897	3,330,359	1,569,185	14,122,666
12	72,921,572	46,738,744	/	/	8,325,897	3,330,359	1,452,657	13,073,915
13	71,463,141	46,419,740	/	/	8,325,897	3,330,359	1,338,714	12,048,430
14	70,033,878	46,104,648	/	/	8,325,897	3,330,359	1,227,297	11,045,677
15	68,633,200	45,793,466	/	/	8,325,897	3,330,359	1,118,348	10,065,131
16	67,260,536	45,486,197	/	/	8,325,897	3,330,359	1,011,808	9,106,276
17	65,915,326	45,182,841	/	/	8,325,897	3,330,359	907,623	8,168,606
18	64,597,019	44,883,402	/	/	8,325,897	3,330,359	805,736	7,251,625
19	63,305,079	44,587,884	/	/	8,325,897	3,330,359	706,094	6,354,845
20	62,038,977	44,296,292	/	/	8,325,897	3,330,359	608,643	5,477,786
NPV								49,679,567
IRR								12%

The positive net cash flows in all operational years, together with the net present value (NPV) of €49.7 million and an internal rate of return (IRR) of 12%, confirm the project's economic feasibility. The difference between the short-term gross profit of €14 million and the long-term projection of €40 million arises from the use of hourly market prices and current tariffs in the first case, versus averaged HUPX prices with annual escalations of 2% for both electricity costs and regulated system charges in the long-term analysis.

Importantly, the cost of electricity for pumping is substantially reduced due to the contractual supply from the PV power plant under the PPA, compared to the alternative of purchasing electricity from the market. This arrangement provides a structural hedge against electricity price volatility, thereby improving financial resilience and long-term profitability.

The financial assessment demonstrates that the PSHPP Tashmarunishta is economically feasible under the assumed market and financing conditions. The combination of long-term debt with a grace period and competitive interest rates results in a stable cash flow profile and a positive NPV. The significant cost advantage of sourcing pumping electricity from PV production instead of grid purchases further improves project viability, ensuring resilience against market price volatility.

Table 7 presents the corresponding financial results for the case without using PV electricity, where pumping electricity is sourced exclusively from the market, leading to persistently negative cash flows and an overall net present value (NPV) of –€122.98 million.

Table 7 Long-term financial performance of PSHPP without PV electricity supply

Year	Annual Revenues	Electricity Expenses	Annuity	Interest Rate	O&M Costs	Depreciation 2%	Income tax 10%	Net Cash Flow
	[€]							
-4	/	/	/	/	/	/	/	-7,493,307
-3	/	/	/	/	/	/	/	-9,991,076
-2	/	/	/	/	/	/	/	-14,986,614
-1	/	/	/	/	/	/	/	-9,991,076
0	/	/	/	/	/	/	/	-7,493,307
1	91,068,71	74,383,28	13,664,688	3,496,877	8,325,897	3,330,359	153,230	-8,788,741
2	89,247,33	73,071,90	13,664,688	3,191,842	8,325,897	3,330,359	132,733	-9,278,247
3	87,462,39	71,790,28	13,664,688	2,877,657	8,325,897	3,330,359	113,819	-9,762,661
4	85,713,14	70,537,89	13,664,688	2,554,046	8,325,897	3,330,359	96,494	-10,242,194
5	83,998,88	69,314,22	13,664,688	2,220,727	8,325,897	3,330,359	80,767	-10,717,056

6	82,318,90	68,118,76	13,664,688	1,877,408	8,325,897	3,330,359	66,647	-11,187,455
7	80,672,52	66,951,03	13,664,688	1,523,790	8,325,897	3,330,359	54,144	-11,653,597
8	79,059,07	65,810,54	13,664,688	1,159,563	8,325,897	3,330,359	43,271	-12,115,689
9	77,477,89	64,696,84	13,664,688	784,409	8,325,897	3,330,359	34,038	-12,573,933
10	75,928,33	63,609,46	13,664,688	398,001	8,325,897	3,330,359	26,462	-13,028,533
11	74,409,76	62,547,96	/	/	8,325,897	3,330,359	20,555	184,996
12	72,921,57	61,511,90	/	/	8,325,897	3,330,359	-24,659	-221,927
13	71,463,14	60,500,86	/	/	8,325,897	3,330,359	-69,398	-624,580
14	70,033,87	59,514,42	/	/	8,325,897	3,330,359	-113,681	-1,023,126
15	68,633,20	58,552,19	/	/	8,325,897	3,330,359	-157,525	-1,417,725
16	67,260,53	57,613,76	/	/	8,325,897	3,330,359	-200,949	-1,808,537
17	65,915,32	56,698,75	/	/	8,325,897	3,330,359	-243,969	-2,195,720
18	64,597,01	55,806,79	/	/	8,325,897	3,330,359	-286,603	-2,579,431
19	63,305,07	54,937,51	/	/	8,325,897	3,330,359	-328,869	-2,959,823
20	62,038,97	54,090,55	/	/	8,325,897	3,330,359	-370,783	-3,337,051
NPV								-122,977,996

Conclusions

This study has examined the combined technical and economic implications of coupling a 300 MW photovoltaic (PV) power plant with the Tashmarunishta pumped storage hydropower plant (PSHPP) under a power purchase agreement (PPA) framework. The proposed operational model allocates PV-generated electricity primarily to meet pumping demands between 07:00h and 16:00h. Hourly PV generation simulations, combined with market-based economic modeling, reveal that PSHPPs relying solely on grid-purchased electricity for pumping operations are prone to annual financial losses. In contrast, the hybrid PV–PSHPP configuration significantly improves gross annual profit by reducing exposure to high market prices during peak pumping periods.

The technical analysis confirms that the PV capacity has been optimally sized to align with the PSHPP's pumping profile, maximizing self-consumption and minimizing curtailment. The results further indicate that the integration supports grid stability by shifting renewable production to high-demand periods via storage operations. Beyond the financial gains, the hybrid system contributes to increasing the share of renewable energy in the electricity mix, improving system flexibility, and advancing national decarbonization objectives. These findings reinforce the role of PV–PSHPP hybridization as a strategic pathway for enhancing both economic resilience and renewable energy integration in the regional power sector.

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