Analysis of the financial implications of solar panels and battery storage integration in the port infrastructure of Heraklion

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Abstract. The European Union (EU) aims to significantly reduce greenhouse gas (GHG) emissions by 2050, necessitating an extensive energy transition across numerous industries and economic sectors. Urban ports are a key sector affected by this transition. As ports increasingly adopt electric-powered infrastructure (such as cold ironing, reefers, stackers, and cranes), their reliance on the electrical grid grows, potentially leading to higher operational costs. This creates a challenge of achieving the required transition in a cost-effective manner. This paper addresses this issue by proposing a photovoltaic (PV) and battery installation to meet electricity demands, focusing on determining the optimal system size, cost, and expected earnings. The study utilizes electricity consumption data from the port of Heraklion for 2021 and solar data from a nearby photovoltaic park in Heraklion, Crete. The methodology's results include determining the appropriate PV capacity and battery storage, with an estimated annual profit of €165,818.44.

1 Introduction

The energy transition in the European Union (EU) impacts a wide range of industries and economic sectors, including urban port operations. Although shipping is among the least carbon-intensive methods of transporting goods, it still accounted for 2.9% of global anthropogenic CO_2 emissions in 2018. Within the EU, ships were responsible for 13.5% of all transport-related greenhouse gas (GHG) emissions that year, which is significantly less than the contributions from road transport (71%) and aviation (14.4%)[1]. According to the same source, the Commission proposed that starting in 2025, the annual average GHG intensity of energy used on board ships should decrease by 2% compared to a 2020 baseline. The requirements will become progressively stricter, aiming for a 6% improvement by 2030 and a 75% reduction by 2050. Additionally, from January 2030, freight and passenger ships docked at EU ports for more than two hours will be required to

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connect to shore-side electricity supply (also known as onshore power supply or cold ironing) and use this electricity for all energy needs while at berth, unless they utilize zero-emission technologies or are in an emergency situation.

Current electricity pricing policies and the high investment costs for cold ironing (CI) infrastructure pose financial viability challenges for CI installations. Existing literature addresses these issues, offering potential solutions to improve the financial feasibility of CI implementation ([2],[3]). Additionally, many functions within the port's infrastructure are transitioning to electric power. This includes cold ironing, which allows ships to plug into shore-side electricity while docked, thereby reducing emissions; reefers, which are refrigerated containers powered by electricity; and electric-powered stackers and cranes used for handling cargo [4]. Moreover, ports are introducing electric vehicles for transporting goods and personnel within the port area [5]. As a result of these transitions, the port's dependency on the electrical grid significantly increases. This heightened dependency underscores the need for reliable and sufficient power supply, which poses both challenges and opportunities for integrating renewable energy sources and enhancing energy efficiency within port operations.

To meet the ever-increasing electricity demands of the port, relying solely on renewable energy sources (RES) is insufficient due to variable weather conditions and the unpredictable nature of renewable energy generation. Despite this, the development of renewable energy has expanded rapidly in recent years, driven by reduced installation costs, technological advancements, and strong political support. Current political events and developments are further accelerating the growth of electricity generation from renewables, increasing the pressure to install more capacity and integrate higher rates into electricity systems. This surge in renewable energy generation places significant strain on electricity grids, which must manage the unique challenges associated with intermittent and dispersed production.

Additionally, the process of energy offsetting, where production is spread out across consumption areas, adds further stress to the grids by necessitating the management of excess production. This combination of challenges has spurred extensive research and literature on energy storage solutions, both for ship installations ([6]) and port infrastructure, to enhance the stability and reliability of electricity supply in ports [7],[8].

The objective of this paper is to tackle these problems by proposing a PV-battery installation to contribute to electricity demand and determine the proper size of the instalment, along with its cost and expected earnings. The methodology's input is the demand of the port for 2021 and the PV production. The parameters include the efficiency of the battery. On the financial aspect, the costs applied for grid consumers situated in Greece that require medium voltage (MV) have been taken into account.

2 Materials and methods

In this study, the port of Heraklion is analysed as a large consumer of medium voltage. The consumption period considered is the year 2021. The total consumption was 2376MWh with a maximum peak power of 669.55kW.

For the implementation of the methodology, the load data, PV data, a realistic billing scheme, and the battery system's technical characteristics were used to accurately simulate the operation of the reinforced energy system. Then, for the determined PV and battery capacity, the expenditure and cashflows are calculated to investigate the feasibility and profitability of the investment.

2.1 Port consumption

The analysis is based on hourly load demand data for the Port of Heraklion in the year 2021 (Figure 1). The peak value occurred in the morning hour on 30/10/2021, while the average demand value is 271.58kW.

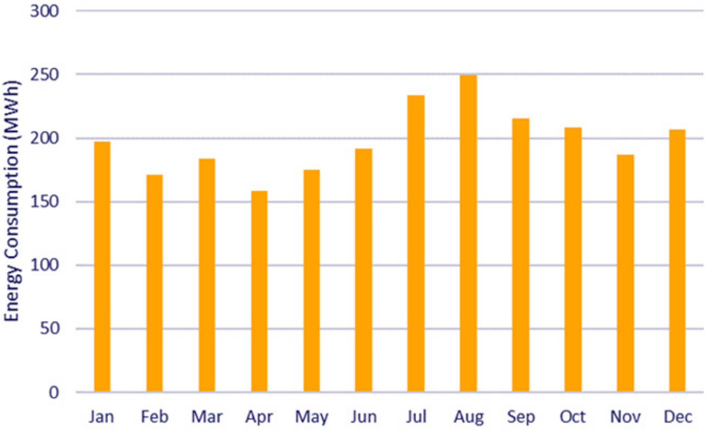

Fig. 1. Monthly electricity consumption of the Heraklion port in 2021.

The seasonal impact is also shown in Figure 1. There is a significant increase in electricity consumption during the summer months due to the tourist season, as well as during the holiday periods of Christmas and Orthodox Easter.

In Figure 2, the average hourly demand is depicted. Peak periods, characterized by higher power charges, are evident during the day. Generally, demand increases in the afternoon and maintains its peak levels until the early morning hours.

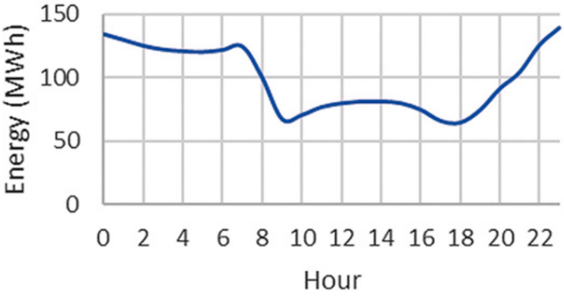

Fig. 2. Average hourly energy consumption for 2021.

2.2 Greek billing system

The Regulatory Authority for Energy (RAE), by a relevant decision (Government Gazette 198/2023), determines the charges for the use of the Greek Electricity Distribution Network (EDNIE). This decision also determines the peak hours per period. According to this regulation, during the winter months (January, February, November, and December), 7 hours per day are designated as peak hours: from 10:00 to 14:00 and from 18:00 to 21:00. Figure 3 illustrates the hourly average energy demand for the port of Heraklion during this period. Although demand is low during the initial peak hours, consumption rises within the peak zone during the afternoon hours. The maximum power recorded is 409 kW, with an average power of 212 kW during peak hours.

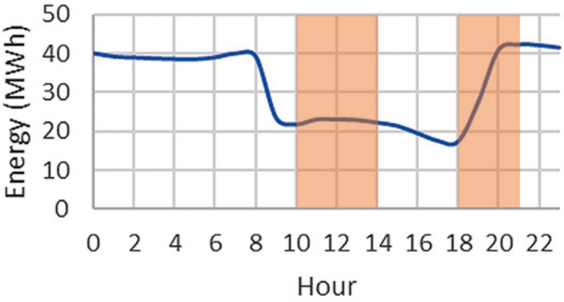

Fig. 3. Average hourly energy consumption during the winter months.

During the spring months (March, April, May) the peak hours are set at 4 hours per day. In this case these hours are from 10:00 to 14:00. Correspondingly the demand from the Port for these months are distributed as shown in Figure 4. Here it is observed that the average peak hours coincide with the lowest demand. During the spring period the maximum power value during peak hours is 287.5kW, while the average power is 174.8kW.

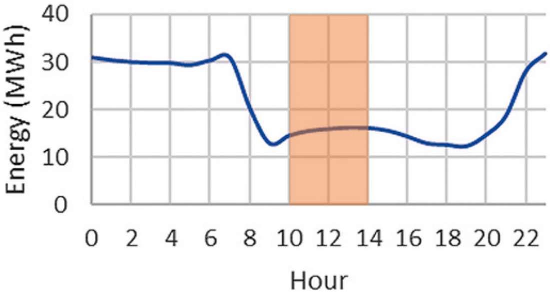

Fig. 4. Average hourly energy consumption during the spring months.

The third peak load period is during the summer months (June, July, August) with 6 hours per day. The period starts at 11:00 and ends at 17:00. According to Figure 5, during this period, the Port of Heraklion, although its highest on average consumption is in the evening hours, has an increased demand during the midday hours, probably due to cruise ship arrivals. The maximum power demand of 453.25kW occurs in August, while the average power demand throughout the period is at 297.75kW. The highest monthly average power value (328.25kW) is once again in August.

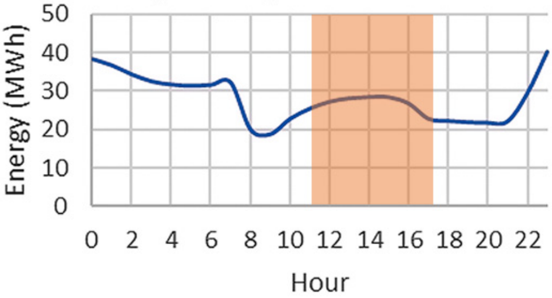

Fig. 5. Average hourly energy consumption during the summer months.

During the autumn months of September and October, the fourth peak period is defined, with 7 hours per day in two zones. The first is 10:00-14:00 and the second 18:00-21:00. In Figure 6, which analyses the demand, it is observed that the second peak zone is identified with an increase in average hourly demand from the facility. In these two zones the average power is 226.15kW, while the peak of 389.15kW occurs in October.

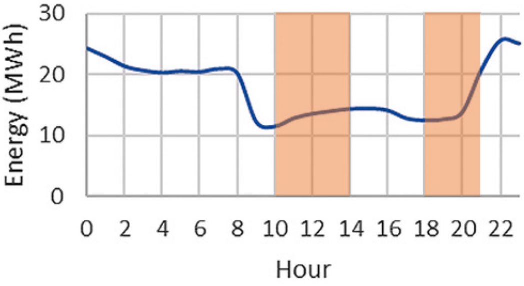

Fig. 6. Average hourly energy consumption during the autumn months.

2.3 Methodology

When comparing the hourly demand data with corresponding PV electricity production data, it's observed that there is a relative alignment in terms of the trend of the time series in summer (see Figure 7). As demand rises, so does PV production. However, the correlation between demand and production distribution throughout the day is not consistent. As previously discussed, during midday hours when PV production reaches its peak, consumption decreases in the port of Heraklion.

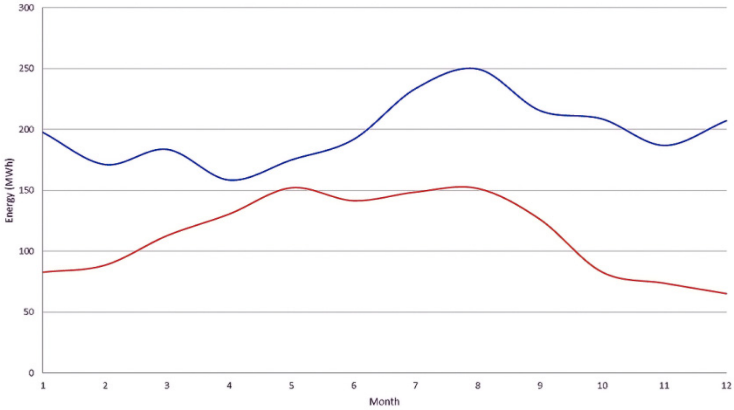

Fig. 7. Trends of PV production and consumption of the system during the summer season.

The mismatch between production and demand throughout the day underscores the necessity for storage solutions. Furthermore, the rise in demand during peak hours, particularly in winter and autumn, emphasizes the importance of energy storage. This surge in demand during peak periods results in increased charges, which are directly linked to both maximum and average power demands during these hours.

In order to implement the algorithm along with the demand data on an hourly basis throughout the year, the corresponding hourly electricity production of photovoltaic panels is required. Using actual hourly values from a photovoltaic station near the Heraklion Port, the operating status of the system using battery power is calculated.

Hourly demand values are denoted as Load[t] with hour t=1,2,...,8760 the totals hours of the year under study. Initially, the storage system is assumed to be fully charged. Losses during charging and discharging equal to 2% are taken into account. The maximum charging and discharging power are at 100kW with the depth of discharge (DOD) reaching 80%.

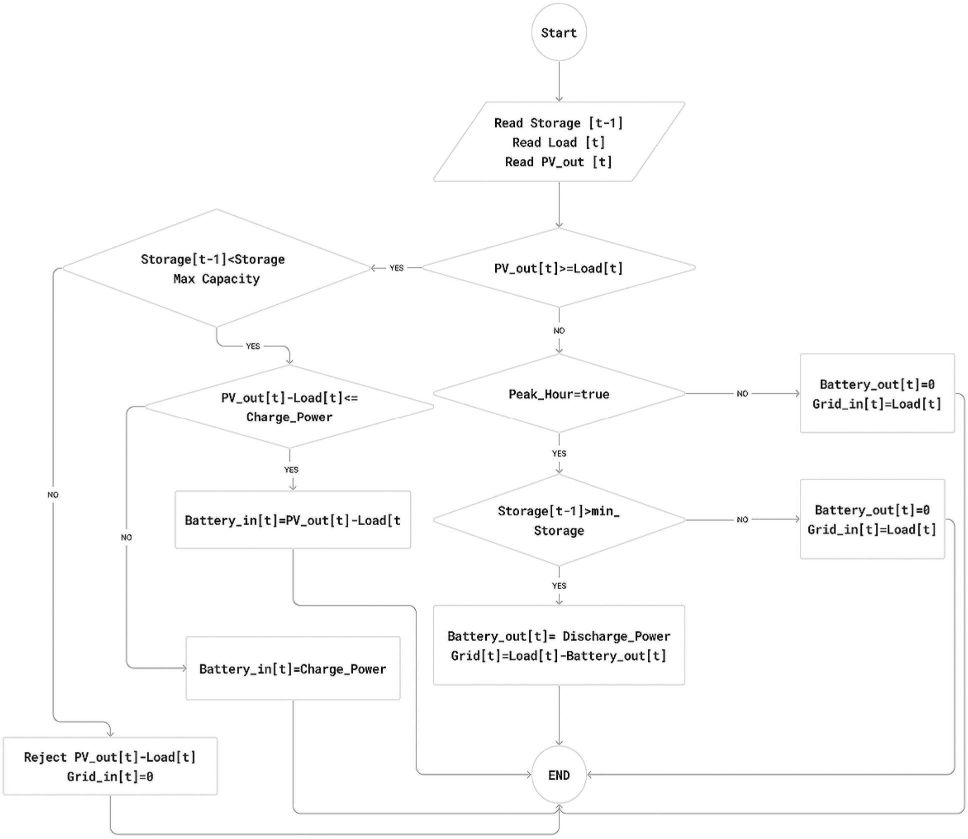

Fig. 8. Calculation of system's hourly operation and energy import from the grid.

In order to maximise the profitability related to the use of the storage system, the battery does not discharge whenever the load is greater than the PV output. The discharge must be required to take place during the predetermined peak hours of the day. The purpose of this condition is to reduce the power quantities subject to billing during peak hours in order to maximize the economic effect of battery use.

2.4 Sizing of photovoltaic - battery

Given the high cost of electricity storage systems, it is not economically feasible to size a system whose capacity is sufficient to discharge when the PV output is not sufficient. Similarly, given that it will not be possible to store the surplus energy during the hours of maximum photovoltaic production, it is also not economically viable to install a system that would produce annually as much energy as is consumed in the Heraklion Port facilities.

After the execution of the algorithm in Figure 8, combinations of different sizes of installed PV panel power with different battery system's capacities were tested.

The utilisation rate of the photovoltaic is defined as follows:

$$\mathrm{N_{PV}}=\frac{\sum_{i=1}^{8760}\mathrm{Dir[t]}+\sum_{i=1}^{8760}\mathrm{Bat\_out[t]}}{\sum_{i=1}^{8760}\mathrm{PV\_out[t]}}, \qquad (1)$$

where Dir[t]: the energy produced by the PV system and consumed directly; Battery_out[t]: the battery discharge energy that met plant demand; PV_out[t]: power production of PV.

The utilization rate of the PV grows as the installed power decreases and as the battery size increases. This is because demand during midday hours is low, resulting in a low absorption rate of the energy produced. If there is a large capacity in the batteries, then the dissipated energy decreases. In Table 1, the utilisation rate of the PV panel is calculated for various PV installed capacities (vertical axis) combined with different battery sizes (horizontal axis) is shown.

Table 1. Photovoltaic utilisation rates.

	100kWh	**200kWh**	**300kWh**	**400kWh**
700kWp	58.26%	60.48%	62.63%	64.69%
800kWp	52.36%	54.37%	56.30%	58.17%
900kWp	47.56%	49.36%	51.12%	52.83%
1000kWp	43.58%	45.22%	46.82%	48.38%

The battery utilisation rate is defined as follows:

$$\mathrm{N_{BAT}}=\frac{\frac{\sum_{t=1}^{8760}\mathrm{Bat\_out[t]}}{365}}{\mathrm{BAT\_cap*DOD}}, \tag{2}$$

where BAT_cap: The total capacity of the batteries; DOD: The depth of discharge of the batteries.

Battery utilisation improves as the installed capacity of the PV grows, since the excess power increases, as well as improves as the capacity of the batteries decreases and less excess power is required to charge them.

At the same time, the battery utilisation rate was calculated for the same combinations of PV nominal powers and storage capacities, which is shown in Table 2.

Table 2. Battery utilisation rates.

	100kWh	**200kWh**	**300kWh**	**400kWh**
700kWp	94.90%	92.62%	90.89%	89.17%
800kWp	96.22%	94.64%	93.08%	91.53%
900kWp	97.05%	95.72%	94.51%	93.21%
1000kWp	97.56%	96.28%	95.26%	94.18%

Table 1 shows that for installed capacity greater than 800kWp, the utilisation rate of PV is less than 50%. Due to the low integration rate of these systems, they will not be considered in the economic analysis.

2.5 Economic feasibility

The financial evaluation uses as metrics the Net Present Value (NPV) and Internal Rate of Return (IRR). The annual discount rate is set at 6%, while the evaluation takes into account the installation costs as well as the operation and maintenance (O&M) costs. For the installation of the PV panels, a cost of 800,00 €/kWp and O&M costs of 7 €/kWp is considered. For the installation of the battery (Lithium) a cost of 350 €/kWh is taken, with maintenance costs of 4 €/kWh.

The present average cost of energy is 0.14 €/kWh. The current power charges are 0,987 €/kW average peak power from the providers, 6,66 €/kW maximum power at peak hours, 3,24 €/kW average peak power for the transmission system and 42,826 €/kVA/year average active power at peak hours as unit fixed charge.

Based on the existing legislation on energy billing, and the proposed system's operation, monthly bills were calculated for the new consumptions. The annual profit stemming from the PV nominal power (in kWp) and battery system's capacity (in kWh) is shown in Table 3.

Table 3. Economic profit for the current energy price (0,14€).

	100kWh	**200kWh**	**300kWh**	**400kWh**
700kWp	154,016.29 €	159,904.88 €	165,818.44 €	170,698.12 €
800kWp	158,209.52 €	164,270.91 €	170,332.21 €	175,373.79 €

3 Results and discussion

The internal rates of return for the current energy price range from 18.95% to 22.43% (Figure 9).

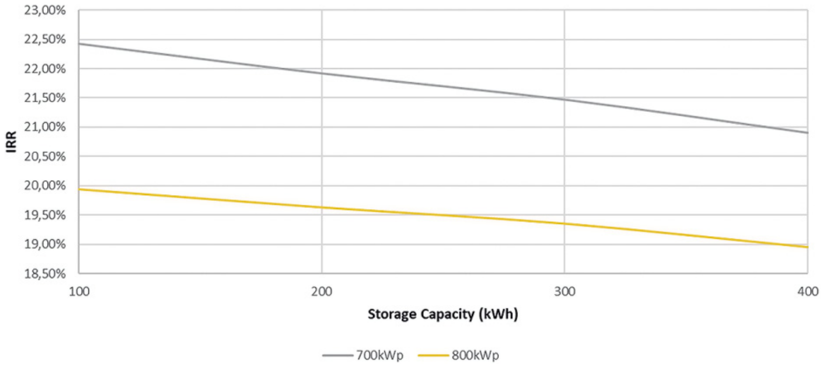

Fig. 9. Internal rates of return for energy cost of 0,14 €.

Similarly, the net present values range from 682.604 € to 763.167 € (Figure 10).

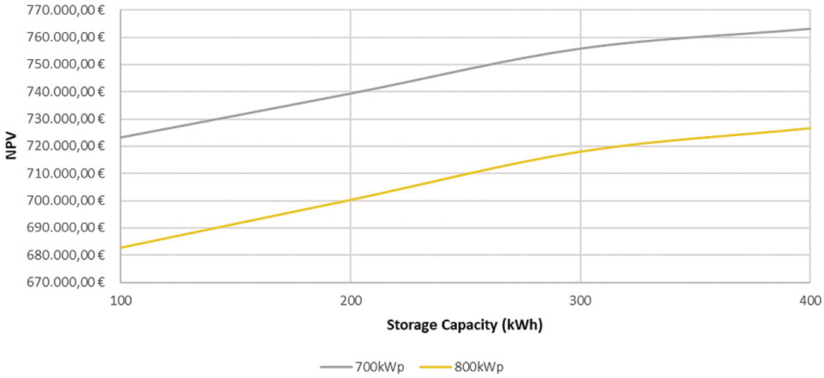

Fig. 10. Net present value for energy cost equal to 0,14 €.

Comparing both criteria, the preferred installed capacity of PV system is 700kWp. The net present value's slope decreases after 300kWh capacity, marking the specific capacity value as the optimal.

3.1 Sensitivity analysis

Since the cost of energy is constantly changing, the effect of a reduction in the cost of energy to 0.12 €/kWh and an increase to 0.16 €/kWh are examined.

For altered energy costs, the internal rate of return of the system with installed capacity equal to 700kWp is greater, as shown in Table 4 and Table 5, for a range of energy costs (in €) and storage system capacity (in kWh).

Table 4. Internal rate of return for 700kWp PV.

	100kWh	**200kWh**	**300kWh**	**400kWh**
0.12 €	19.83%	19.36%	18.95%	18.42%
0.14 €	22.43%	21.92%	21.48%	20.91%
0.16 €	24.97%	24.42%	23.94%	23.34%

Table 5. Internal rate of return for 800kWp PV.

	100kWh	**200kWh**	**300kWh**	**400kWh**
0.12 €	17.52%	17.24%	16.98%	16.60%
0.14 €	19.94%	19.63%	19.35%	18.95%
0.16 €	22.29%	21.96%	21.66%	21.23%

For the same values, a similar observation applies to net present values. The economic valuations are consistent with the utilisation rate of the photovoltaic system, as can be concluded by Table 6 and Table 7.

Table 6. Net present value for 700kWp PV.

	100kWh	200kWh	300kWh	400kWh
0.12 €	596,354.86€	607,814.55 €	619,810.32 €	622,690.90 €
0.14 €	723,104.12 €	739,301.61 €	755,881.58 €	763,167.47 €
0.16 €	849,853.38 €	870,788.68 €	891,952.84 €	903,644.05 €

Table 7. Net present value for 800kWp PV

	100kWh	200kWh	300kWh	400kWh
0.12 €	552,407.46 €	565,165.89 €	578,249.67 €	582,312.10 €
0.14 €	682,604.80 €	700,243.32 €	718,044.10 €	726,662.61 €
0.16 €	812,802.14 €	835,320.75 €	857,838.54 €	871,013.12 €

In any case, the system with an installed capacity of 700kWp and a storage capacity of 300kWh yields better financial results.

3.2 Results of the sensitivity analysis

Applying to the installation the PV system with an installed capacity of 700kWp using storage capacity of 300kWh, the demand to be covered by the grid is reduced as shown in Fig. 11.

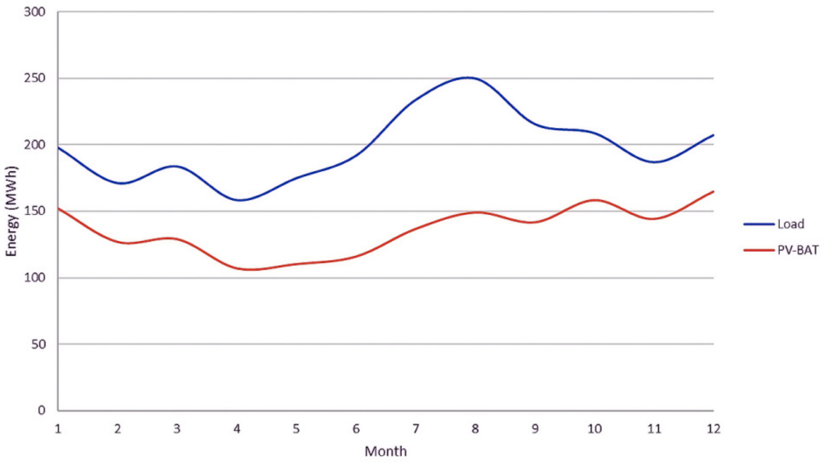

Fig. 11. Impact on monthly energy demand before and after installation of PV – Battery.

During the summer months, 40% of the energy demand of Heraklion Port can be satisfied from the PV – Battery coupling (Fig. 12).

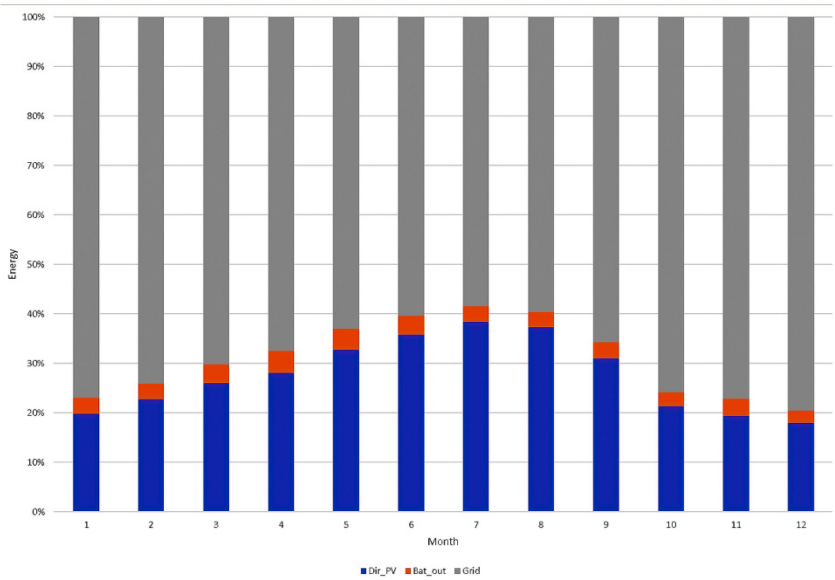

Fig. 12. Optimal monthly energy mix.

There is a significant decrease, on average, in hourly power imported from the grid during peak hours, which reaches zero from March to August, therefore decreasing significantly the associated cost (Fig. 13).

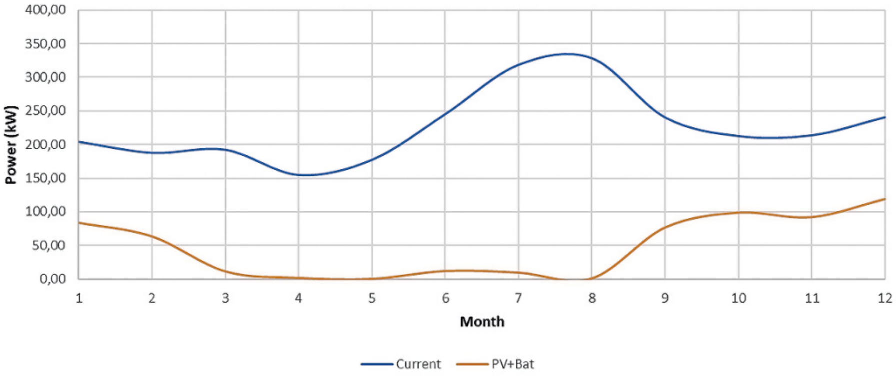

Fig. 13. Average hourly power imported from the grid in peak hours.

And during the peak hours, the impact on the maximum imported power in each month is significant, yet not as much as the impact on the average values (Figure 14).

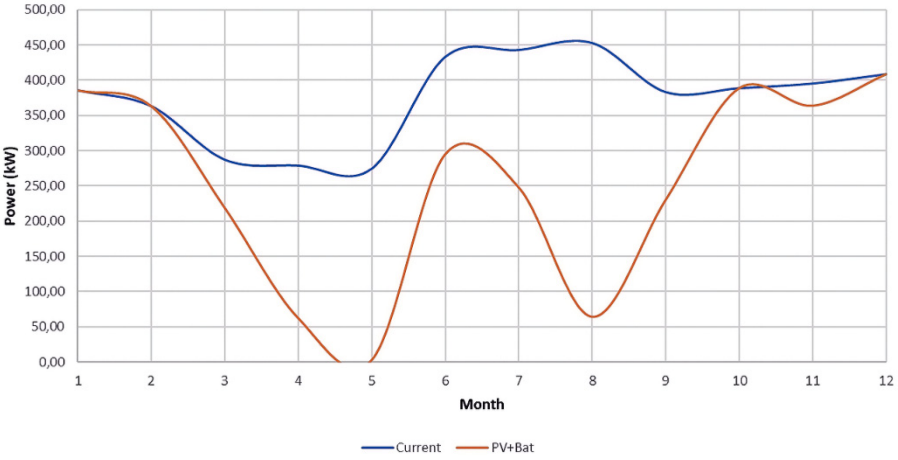

Fig. 14. Maximum power imported during peak hours in each month.

The optimal solution yields a significant reduction on the costs imposed on the power demand (see Figure 15), which annually reaches 25.000,00 €.

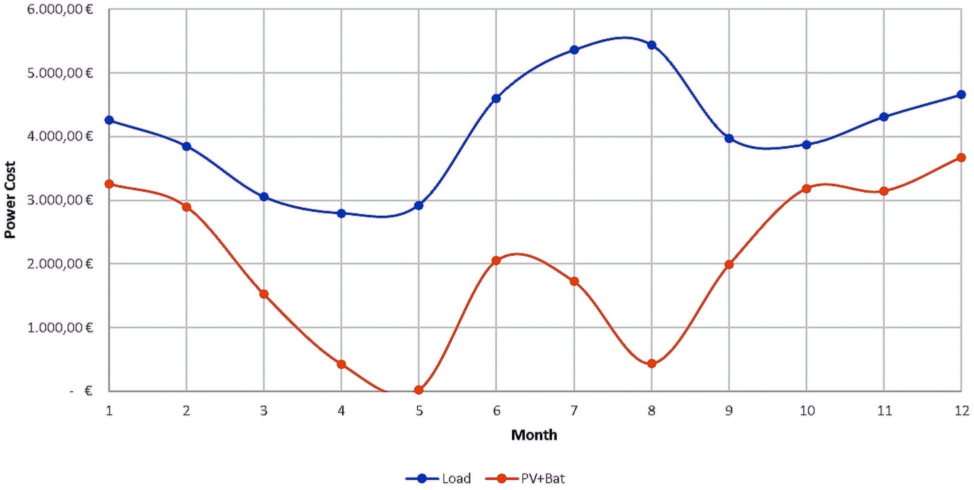

Fig. 15. Impact on costs associated with power import during peak hours.

4 Conclusion

The combination of EU directives, the rising costs associated with increased electricity expenses and ports' growing reliance on electrical power underscores the necessity of integrating RES and electricity storage technologies within port premises. This study specifically proposed the installation of a PV-battery storage system at the port of Heraklion. The methodology employed actual billing schemes for medium voltage customers, alongside an analysis of the port's demand and PV production data in 2021, the technical specifications of each proposed system's component, and financial evaluation metrics such as NPV and IRR. The optimal solution identified for the port was a system with 700 kWp of PV nominal power coupled with 300 kWh of storage capacity. The solution yields a maximum monthly energy coverage of 40% of total demand for the year

2021, and a huge reduction in imported power from the grid in peak hours. For late spring and summer, the reduction levels reached zero energy, contributing greatly to the investment's profit by reducing the associated costs of those imports, projecting a total estimated annual profit of €165,818.44.

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