Comparative Analysis of Financial Optimization Scenarios for PV and Battery Storage Integration at Heraklion Port

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Abstract: — The rapid expansion of renewable energy, driven by reduced installation costs, technological advancements, and political support, necessitates efficient integration strategies. This study presents a comparative analysis of financial optimization scenarios for the integration of photovoltaic (PV) systems and battery storage at Heraklion Port. By evaluating multiple strategies, the research addresses the economic viability, cost-benefit ratios, and payback periods of different configurations. This analysis considers the broader context of increasing pressure on electricity grids and the need for sustainable solutions to manage dispersed renewable production and energy offsetting. The findings aim to provide insights into optimal investment strategies that balance financial performance with energy efficiency, thereby mitigating costs passed on to consumers and supporting the goals of energy transition and sustainability in port infrastructure.

Key-words: —Renewable Energy Sources, Energy Storage, Ports, Energy investment, Sustainability

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1. Introduction

In the quest for sustainability and resilience, large medium voltage consumers are increasingly pursuing self-sufficiency in energy production. With the rising demand for electricity and mounting concerns about climate change, the integration of electricity storage systems and photovoltaic (PV) generation is emerging as a pivotal solution [1]. This approach not only addresses the need for reliable power supply but also contributes to reducing the carbon footprint associated with traditional energy sources. The adoption of PV and storage technologies enables consumers to manage energy more efficiently, mitigate grid dependency, and enhance overall energy security [1].

Traditional energy grids, while reliable, face challenges related to sustainability, intermittent operation and centralized control. Large installations , with their substantial energy demands, significantly exacerbate these challenges. Additionally, , their reliance on conventional energy sources exposes them to price volatility and supply uncertainties [3]. Consequently, the urgent need for self-sufficiency arises from both environmental and economic considerations. This shift towards self-sufficiency not only aims to enhance sustainability but also to stabilize energy costs and ensure a more resilient energy supply[4].

Photovoltaic technology presents a reliable solution in this context . By capturing solar energy and converting it into electricity, photovoltaic systems provide a renewable and abundant energy source [5]. Large consumer-owned complexes, with their extensive rooftops and available land, are well suited for harnessing solar energy [5]. However, the integration of photovoltaics systems alone is insufficient to effectively meet the diverse and complex energy demands of these facilities.

Storage solutions, such as advanced battery technologies, enable the capture and conservation of excess energy produced by PV systems [6]. By storing surplus energy during peak generation periods, large-scale PV arrays can mitigate the intermittency of solar energy and ensure a continuous supply even during periods of low or no sunlight [7].

Despite its promise, the path to self-sufficiency is fraught with challenges. Complex techniques, including system integration and optimization, require careful planning and execution. Furthermore, regulatory frameworks and economic barriers often hinder the adoption of renewable energy solutions [8]. Overcoming these obstacles requires a holistic approach that considers the specific technological and application needs on a case-by-case basis.

The synergy between electricity storage and photovoltaics has transformational potential for large energy-intensive complexes [10]. Beyond achieving energy independence, the integration enhances resilience, reduce costs, and improves environmental management[11]. By embracing renewable energy and decentralized power generation, these complexes can pave the way to a more sustainable and secure energy future.

2. Materials and Methods

2.1 Electricity Billing Scheme

In this study, the port of Heraklion is analyzed as a large medium voltage consumer.

The consumption period considered is the year 2022. The total consumption was 2307MWh with a maximum peak power of 581.17kW.

The analysis is based on hourly load demand data for the Port of Heraklion in the year 2022 (Fig. 1). The peak value occurred during the morning hour on 30/10/2022 at 4:00 am, with a power demand of 581.17kW, while the average demand value is 263.75kW. However, it is noted that the maximum value depicted in the figure deviates sugnificantly from the typical demand pattern during those hours and will not be considered.Excluding this outlier, the maximum value occured on 19/8/2022 at 22:00 with a demand of 469.59kW.

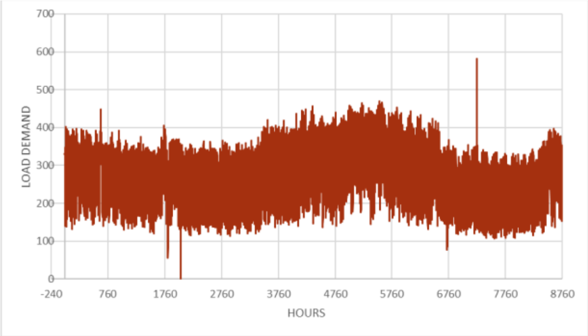

Fig. 1. Hourly time series of cargo demand Port of Heraklion 2022.

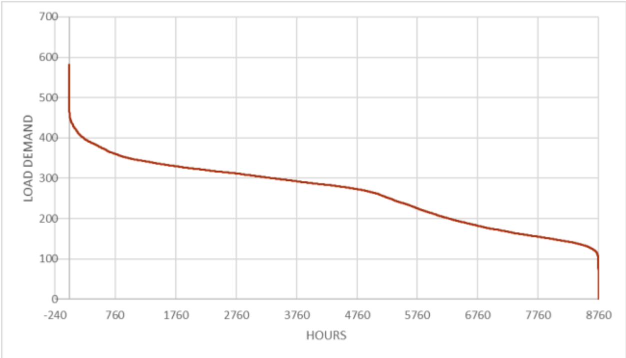

Fig. 2. Duration curve of cargo demand Port of Heraklion 2022.

According to the load demand duration curve (Fig. 2), approximately 53% of the annual demand falls within the range of 270-400kW. It is notable (Fig. 3) that there is a significant increase in consumption during the summer months,particularly in August reaching 235.88MWh attributrd to the tourist season and holiday periods such as Christmas and Orthodox Easter . Conversely, the months with the lowest consumption are April and November registering 160.02MWh and 161.40MWh, respectively.

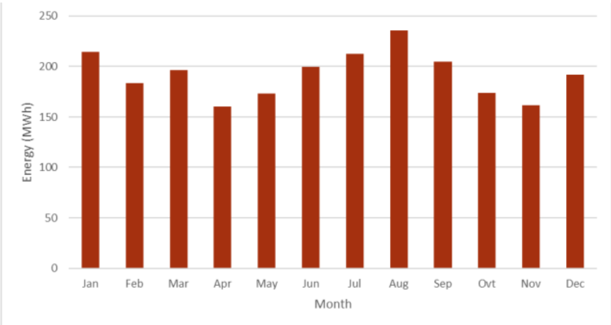

Fig. 3. Monthly energy consumption for the Port of Heraklion.

Throughout the day, peak demand periods coincide with increased power charges. Over the course of the year, it is observed that demand rises from the afternoon and remains at peak levels until the early morning hours. The peak in demand notably occurs at 22:00.

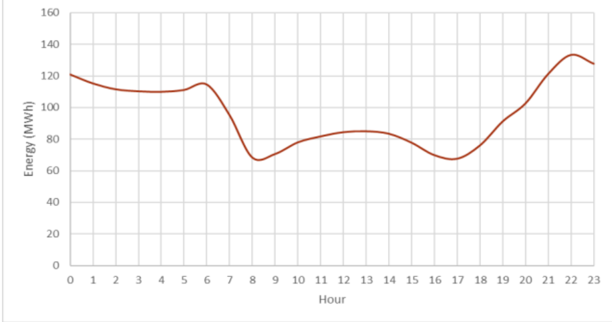

Fig. 4. Energy consumption for each hour of the day.

As per decision of the Regulatory Authority for Energy, as outlined in Government Gazette 198/2023, charges for the utilization of the Greek Electricity Distribution Network (EDNIE) are established. Addiotnally, this decision also specifies the peak hours for each period. According to the regulations, , during the winter months (January, February, November and December), a total 7 hours per day are designated as peak hours, spanning from 10:00 to 14:00 and from 18:00 to 21:00.

During the spring months (March, April, May) peak hours are designated at 4 per day spanning from 10:00 to 14:00. The third peak load period occurs during the summer months (June, July, August), comprising 6 hours per day starting at 11:00 and concluding at 17:00 .

During the autumn months of September and October, the fourth peak period is defined, encompassing 7 hours per day divided into two zones. The first zone extends from 10:00 to 14:00, while the second zone spans from 18:00-21:00.

2.2 Methodology

The comparison of hourly demand data, as previously analyzed, with corresponding hourly data of electricity production from photovoltaic power plants in a geographical area near Heraklion port, reveals a relative similarity in terms of summer seasonality (Fig. 5). As demand increases, photovoltaic production alo rises. However, this correlation does not hold throughout the day. During midday hours, when the photovoltaic production peaks, consumption decreases at the Heraklion port.

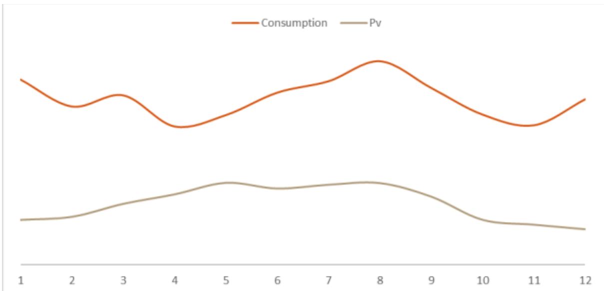

Fig. 5. Timing of summer seasonality of consumption – production.

The asynchrony between production – and demand throughout the day underscores the necessity for energy storage. Another contributing factor for energy storage adoption is the surge in demand during peak periods, notably in the winter and autumn seasons This surge results in escalated charges, which are directly tied to the maximum and average power demand during peak hours.

To implement the algorithm alongside hourly demand data throughout the year, corresponding hourly electricity production from photovoltaic panels is essential. Utilizing actual hourly values from the PV plant, the operational status of thesystem employing battery power is computed.

Hourly demand values are represented as Load[t] where t=1,2,...,8760. Initially, the system is presumed to be fully charged . Losses incurred during charging and discharging, equivalnet to 2% are accounted for. The maximum charging and discharging power are capped at 100kW, with a depth of discharge (DOD) of up to 80%.

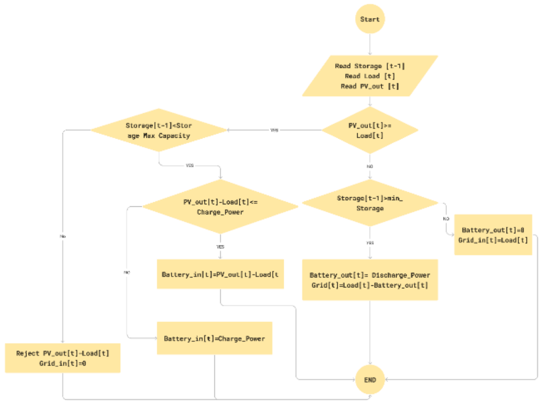

Fig. 6. Calculation per hour of system operation and energy input from the grid.

2.3 PV-Battery Sizing

Given the significant expense associated with electricity storage systems, sizing a system to store all the energy required by the installation during periods of insufficient PV output is not economically viable.. Similarly, installing a system capable of producing annually as much energy as consumed in the facilities at Heraklion Port is not feasible, as surplus energy cannot be stored during peak photovoltaic production hours.

Executing the algorithm in Fig. 6, various combinations of installed PV panel power sizes with differing batterycapacities were examined .

The PV utilization rate is defined as follows:

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

Where Dir[t] represents the annual energy produced by PV and consumed directly, Bat_out[t] denote the annual battery discharge energy fullfilling installation demand,and PV_out[t] signifies the annual production of PV.

The PV utilization rate escalates as the installed power decreases and the battery size increases (refer to Table 1). This phenomenon arises due to the low demand during midday hours, resulting in a diminished absorption rate of the generated energy. Conversely, with larger battery capacities, the absorbed energy diminishes.

TABLE I. PHOTOVOLTAIC EXPLOITATION RATE

PV \ Battery	100kWh	200kWh	300kWh	400kWh
400kWp	86,12%	88,45%	90,42%	92,12%
500kWp	76,33%	78,90%	81,25%	83,43%
600kWp	67,20%	69,67%	72,02%	74,22%
700kWp	59,74%	61,96%	64,09%	66,13%

Simultaneously, the battery utilization rate was computed, as depicted in Table II.

Battery utilization rate is defined:

$$U_{BAT} = \frac{\frac{\sum_{i=1}^{8760} Bat\_out[t]}{365}}{BAT\_cap * DOD} \quad (2)$$

Where BAT_cap represents the capacity of the battery system.

Battery utilization improves as the installed capacity of the PV system increases (refer to Table II), as it results in a greater surplus of energy available for storage. Conversely, reducing the capacity of the battery system leads to improved utilization, as less surplus energy is needed to charge them.

TABLE II. BATTERY EXPLOITATION RATE

PV \ Battery	100kWh	200kWh	300kWh	400kWh
400kWp	66,07%	60,17%	55,39%	51,37%
500kWp	84,61%	79,73%	75,90%	72,74%
600kWp	91,56%	88,82%	86,58%	84,08%
700kWp	94,41%	92,43%	90,54%	88,58%

Table I illustrates that for an installed photovoltaic capacity of 700kWp, the utilisation rate is less than 60%. Due to the low integration rate of these systems, they will not be considered in the economic analysis.

Additionally, during the winter and autumn months, PV production ceases during the second zone of peak hours. To mitigate power charges, which are computed during peak hours, the algorithm for injectingstored energy can be adjusted to inject energy exclusively during these peak periods.

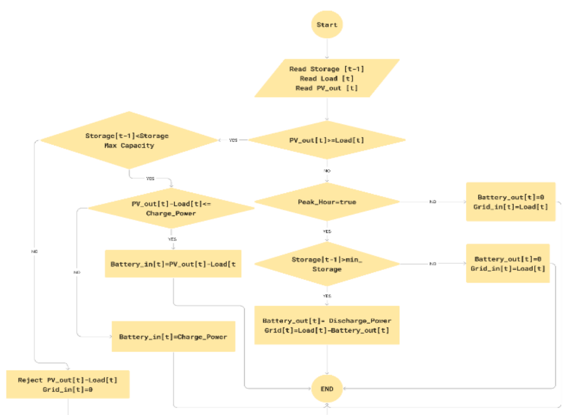

Fig. 7. Optimized stored energy injection algorithm.

3. Results

In the winter months (Fig. 8), as well as in the autumn months (Fig. 9), delaying the injection of stored power leads to a reduction in the power demanded from the grid after 18:00, coinciding with the onset of the second peak zone, which extends until 21:00. Particularly during the winter months, the optimized algorithm appears t to offer prolonged benefits. Subsequent the economic analyses will present the outcomes of both algorithms.

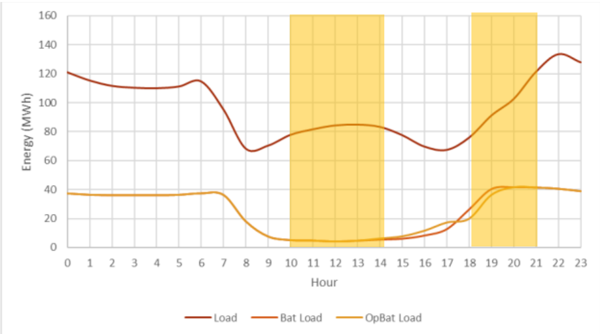

Fig. 8. Battery optimisation in the winter months.

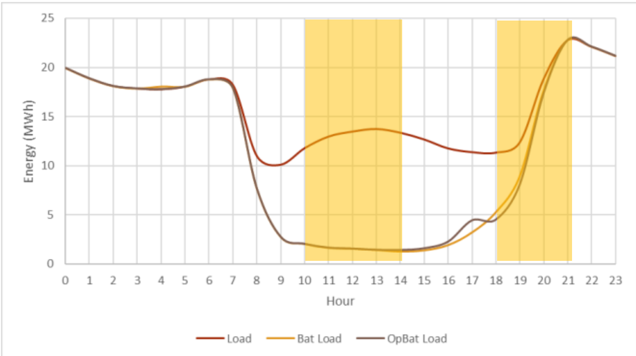

Fig. 9. Battery optimisation in the autumn months.

3.1 Economic Feasibility

The economic evaluation employs the criteria of Net Present Value (NPV) and Internal Rate of Return (IRR). The annual discount rate is set at 6%, considering installation costs along with operation and maintenance expenses. For the installation of PV panels, a cost of 800,00€/kWp is assumed with operational and maintenance (O&M) costs of 7€/kWp. For the installation of the lithium batteries, a cost of 350€/kWh is considered , with maintenance costs of 4€/kWh.

The current average cost of energy is 0.14€/kWh. The prevailing power consist of 0.987€/kW for average peak power from suppliers, 6.66€/kW for maximum power at peak hours, 3.24€/kW for average peak power for the transmission system, and 42.826€/KVA/year for average active power at peak hours as a unit fixed charge.

Based on the existing legislation on energy charges, monthly bills were computed for the new consumptions. The annual benefit derived from the optimised algorithm (Table IV) exceeds that fom the conventional method (Table III) in every combination.

TABLE III. ECONOMIC BENEFIT FOR THE CURRENT ENERGY PRICE (0,14€) WITHOUT THE OPTIMIZED ALGORITHM

PV \ Battery	100kWh	200kWh	300kWh	400kWh
400kWp	118,936.69 €	121,700.42 €	124,132.14 €	126,205.20 €
500kWp	131,616.51 €	135,448.59 €	139,066.71 €	142,401.41 €
600kWp	139,267.17 €	143,699.24 €	148,130.89 €	152,273.25 €

TABLE IV. ECONOMIC BENEFIT FOR THE CURRENT ENERGY PRICE (0,14€) WITH THE OPTIMIZED ALGORITHM

PV \ Battery	100kWh	200kWh	300kWh	400kWh
400kWp	119,262.60 €	122,203.20 €	124,711.18 €	126,763.57 €
500kWp	132,009.30 €	136,055.41 €	139,835.84 €	143,140.23 €
600kWp	139,591.50 €	144,245.83 €	149,170.94 €	153,191.62 €

The financial disparity resulting from the algorithm considering peak hours during the winter and autumn months can reach up to 1.040,05 €. This amount corresponds to a 7.55% increase in added value provided by the storage system. Consequentlythe subsequent economic analysis will focus on systems employing the optimized algorithm.

The internal efficiencies across the current energy price range vary from 23.69% to 33.14% (see Fig. 10).

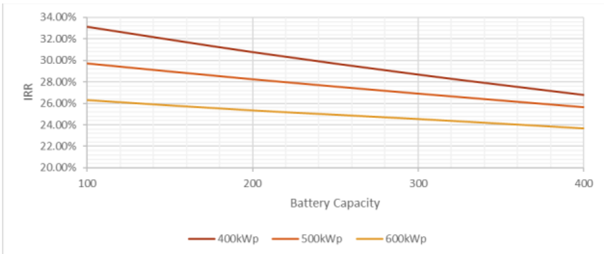

Fig. 10. Internal efficiency for energy charge 0,14€.

Similarly, the net present values range from from 682.604€ to 763.167€ (Fig 11).

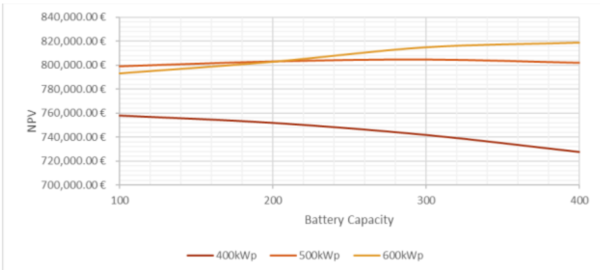

Fig. 11. Net present value for energy charge 0,14€.

Upon comparing both criteria, systems with an installed PV capacity of 500kWp and 600kWp emerge as superior investments. Specifically, for a 500kWp system, the optimal matched battery capacity is 200kWh, while for a 600kWp PV system, a battery with a capacity of 300kWh appears preferable.

3.2 Sensitivity Analysis

Admist a period of fluctuating energy costs, the impact of reducing energy costs to 0.12€/kWh and increasing them to 0.16€/kWh is examined.

During changes in energy costs the internal efficiency of the system with an installed capacity of 400kWp proves superior.

TABLE V. INTERNAL RATE OF RETURN FOR 500KWP PV

	100kWh	200kWh	300kWh	400kWh
0.16 €	32.85%	31.26%	29.81%	28.44%
0.14 €	29.74%	28.26%	26.91%	25.64%
0.12 €	26.57%	25.83%	23.97%	22.79%

TABLE VI. INTERNAL RATE OF RETURN FOR 600KWP PV

	100kWh	200kWh	300kWh	400kWh
0.16 €	29.12%	28.10%	27.25%	26.33%
0.14 €	26.29%	25.34%	24.55%	23.69%
0.12 €	23.41%	22.53%	21.80%	21.00%

Despite this, in terms of net present values, the 600kWp system appears more favorable, although it is closely competes with the 500kWp system.

TABLE VII. NET PRESENT VALUE FOR 500KWP PV

	100kWh	200kWh	300kWh	400kWh
0.16 €	917,811.81 €	925,788.27 €	930,984.96 €	931,555.59 €
0.14 €	799,157.73 €	803,211.32 €	804,830.64 €	802,088.24 €
0.12 €	680,503.65 €	705,556.06 €	678,676.32 €	672,620.90 €

TABLE VIII. NET PRESENT VALUE FOR 600KWP PV

	100kWh	200kWh	300kWh	400kWh
0.16 €	918,496.61 €	932,631.82 €	949,048.13 €	956,892.38 €
0.14 €	793,157.92 €	802,784.38 €	814,891.77 €	818,712.39 €
0.12 €	667,819.23 €	672,936.93 €	680,735.40 €	680,532.39 €

Once more, the aforementioned two systems appear preferable preferable. Summarizing the results based on the net present value (Fig. 12), the system with an installed PV capacity of 500kWp and a battery capacity of 200kWh is selected due to smaller variations in energy cost fluctuations.

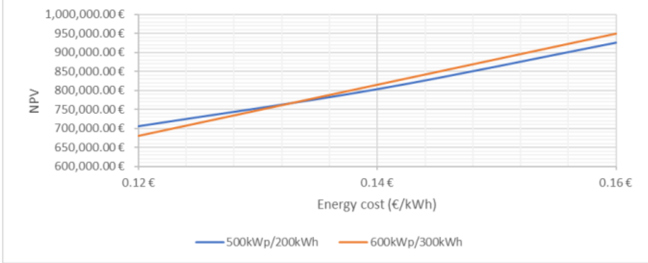

Fig. 12. Comparison of 500kWp-600kWp systems.

During the summer months the energy demand of Heraklion Port can be supplied by 37.5% through the combination of PV and Battery (Fig. 13).

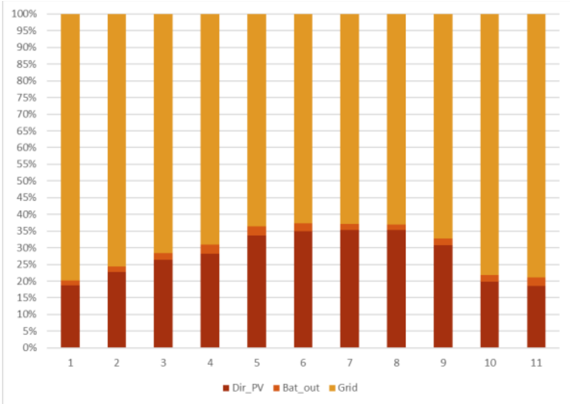

Fig. 13. Power distribution in the installation.

The optimization in the use of the energy generated by the battery in the installation has a significant benefit on the costs imposed on the power demand (Fig. 14), which annually reaches 28.814,34 €.

Fig. 14. Impact on power costs.

4. Conclusion

The global energy landscape is experiencing a profound transformation, propelled by the pressing demand for sustainable solutions. Large medium-voltage consumers, encompassing diverse structures from high-rise residential to commercial office spaces and healthcare facilities, represent a substantial portion of global energy consumption. Historically,these buildings have heavily depended on the utility grid to fulfill their energy requirements. However, this dependency poses a multifaceted challenge - fluctuating electricity costs can strain budgets and reliance on fossil fuel production contributes to environmental pollution.

In the case study the benefits to energy costs are notably significant, amounting to €136,055.41 per year. This underscores the pivotal role of storage as a critical component in maximising the utilization of solar energy.

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Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

The authors equally contributed in the present research, at all stages from the formulation of the problem to the final findings and solution.

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Conflict of Interest

The authors have no conflicts of interest to declare that are relevant to the content of this article.