Assessing Economic Constraints and Cost-Benefit Analysis Framework of Solar Parks and Energy Storage Infrastructures

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Introduction

The cost-benefit analysis for solar parks and energy storage infrastructures encompasses multiple components, each with its own considerations. The superstructure of the solar systems, composed of primary and secondary elements, necessitates a multilevel evaluation, inclusive of a geotechnical study to ascertain the foundation methodology. Cost-effective solar systems' foundation types, such as direct ramming, are favored for soft soils, whereas pre-drilling is appropriate for rocky terrains. Corrosion protection is crucial, with Batch Hot-Dip Galvanizing (HDG) offering superior protection for piles in extreme soil corrosion conditions, while pre-galvanized elements provide a more cost-effective, albeit less durable, solution. Inverters, whether centralized or decentralized, should be assessed based on site layout, grid agreement, and owner preferences. Larger transformers in production substations are more cost-effective for projects exceeding 10MWp. The selection of earthing materials is driven by considerations of corrosion between metals, with galvanized steel being cost-effective for pile ramming and copper or copper-plated solutions recommended for concrete micro piles. Cost-efficient earthing solutions are based on the material used; however, local regulations, insurance policies, and owner requirements must be taken into account. Energy batteries are cost-effective for capacity market applications, whereas power batteries are suitable for grid support services. These comprehensive evaluations ensure that each component of the solar park and energy storage system is optimized for cost-effectiveness while maintaining functionality, safety, and compliance with technical standards and local regulations.

The market is trending towards larger storage systems utilizing energy batteries, which are more standardized and cost-effective. Batteries facilitate price stabilization by absorbing energy during low-price periods and releasing it during high-price periods (price arbitrage). This function stabilizes prices during high demand by substituting high-cost thermal units and supports clearing prices by mitigating discharges during overproduction conditions through increased demand. The energy simulation for Greece highlighted the necessity to develop storage stations to absorb the energy produced within the domestic energy system. The supply-demand mismatch caused by high levels of solar-generated electricity, known as the 'duck curve,' can be mitigated by energy storage.

The objective of this research is to evaluate the participation of energy storage infrastructures in energy markets for system balancing and to model the economic relationships engendered by the significant fluctuation of the residual load curve in relation to the performance characteristics of Energy Storage Systems. Ultimately, the characteristics of an economic limit must be defined to prevent the creation of inflation due to energy storage, either at specific times or overall.

Duck curves and energy storage

The "duck curve" is a concept developed by scientists at the California Independent System Operator (Dratsas et al, 2022; Michaelides, 2021; Freeman et al., 2016; CAISO, 2016) to illustrate the supply-demand mismatch caused by high levels of solar-generated electricity. It shows the difference between hourly electricity demand and renewable energy generation in regions with substantial PV (photovoltaic) electricity production.

Energy storage can indeed help mitigate the supply-demand mismatch illustrated by the "duck curve." By storing excess solar-generated electricity during periods of low demand (e.g., midday when the sun is shining brightly), energy storage systems can release this stored energy during periods of higher demand (e.g., in the evening when the sun sets and electricity usage peaks) (see Theodorou & Christopoulos, 2024). This can help smooth out the fluctuations in electricity supply and demand, making the overall grid more stable and efficient (Calero et al, 2021; Wong et al, 2020; Sheha et al, 2020; Kosowatz J, 2018).

Energy storage is not the only solution, though. Other strategies, such as demand response programs (where consumers adjust their energy usage in response to supply conditions) and improvements in grid infrastructure, can also play significant roles in addressing the challenges posed by the duck curve (Debnath et al, 2024), but these strategies are out of scope of this research.

Energy storage systems, regardless of their power and capacity, can participate in various electricity markets, including the day-ahead market (DAM), intraday market, balancing market, and forward derivatives market (Cartuyvels, 2024; Wilkinson et al, 2021). Concurrently, these systems can provide essential services to system operators, thereby enhancing the capacity of congested networks to accommodate Renewable Energy Source (RES) stations and inject otherwise curtailed RES energy.

The participation of storage systems in energy markets predominantly hinges on their technical capabilities to leverage the high fluctuations of hourly market prices in the day-ahead market (arbitrage strategy) or to offer power and energy balancing services (Dratsas et al, 2022).

The burgeoning development of RES production within the Greek energy system, aligned with national targets for 2030 and 2050 as delineated in the National Energy and Climate Plan (NECP) (Hellenic Republic, 2024) and the Long-term Strategy for the evolution of the energy system (Hellenic Republic, 2020), respectively, reduces the residual load (load minus RES production) serviced by dispatchable units during periods of high wind and solar potential. This progression is anticipated to compress energy market clearing prices during peak RES production hours (Hellenic Republic, 2024).

This phenomenon is expected to result in more frequent occurrences of zero or negative prices during congestion periods, potentially leading to economic curtailment of RES production due to the inability to absorb/export it, given the technical minimums of the integrated conventional units providing necessary reserves for system security (Dratsas et al, 2021).

The inability to utilize available RES energy, which essentially incurs almost zero variable costs, is a fundamental issue. Concurrently, persistently low market prices during periods of high RES potential create investment risks regarding the viability of new merchant RES investments and, to a lesser extent, even projects with Contracts for Operational Support of Differential Premium.

Moreover, the increasing penetration of new RES systems, both photovoltaic and wind, is expected to substantially augment the frequency of zero or negative prices in the day-ahead market, as well as the numerical range of hourly price fluctuations in the day-ahead market.

Effective operation of storage systems in electricity markets will contribute to addressing these interrelated issues—RES production curtailments and the consequent zero/negative clearing prices, as well as the increase in hourly price fluctuations in the day-ahead market.

Storage systems facilitate price balancing by absorbing energy during low clearing price hours and injecting it during high price hours (price arbitrage) (Dratsas et al, 2022). This function aids in stabilizing prices during periods of high demand by substituting high-cost thermal units, supports clearing prices, and mitigates curtailments under overproduction conditions through the additional demand created (Theodorou & Christopoulos, 2024).

The day-ahead market, being the most liquid market, reflects the value of electricity to a greater extent compared to other markets, thus providing the most representative price signals for investments in the electricity sector (Cartuyvels, 2024). The ability to effectively operate storage systems in this specific market is crucial for achieving the anticipated system benefits from their operation and the viability of these investments. Additionally, storage systems possess the flexibility to withhold power in the day-ahead market and to use combined buy and sell orders, thereby maximizing their revenues from energy markets with appropriate strategy and planning.

In the context of the intraday market, storage systems can primarily offer sell orders to cover residual production or additional load during relatively high price hours (Cartuyvels, 2024). However, the intraday market is not deemed suitable for purchase orders from storage systems, except in extreme cases of high RES unit participation underestimated during the day-ahead market resolution (Cartuyvels, 2024).

Similarly, the participation of storage systems in the balancing market plays a dominant role in the investment plan, as it can ensure predictable cash flows at the level of cleared balancing power, which are maximized from the cleared balancing energy, particularly during specific hours of production shortage (system short). Additionally, the participation of storage systems, combined with their technical capabilities, ensures nearly zero exposure to deviations.

Due to their nature, storage systems are characterized by very rapid rates of load uptake or rejection, practically determined by the response speed of the inverters. The system's converters will be able to adjust their output power within their full power range (-Pn ÷ +Pn) within 500 milliseconds.

Considering the response speed and flexibility, as well as the advanced control features of batteries and power converters, the systems will be able to provide all the necessary ancillary services to the system, both in terms of power supply and corresponding energy offers.

Battery energy storage systems (BESS) are estimated to possess the capability for optimal and combined participation in energy markets (Michaelides, 2021). Initially, they will utilize their ability to store significant amounts of energy relative to their capacity at repeated times, achieving energy arbitrage from low-price hours to high-price market hours (Cartuyvels, 2024). Subsequently, they will play a particularly important role in the balancing market, where they are expected to earn equivalent, if not higher, revenues.

Methodology

To estimate the revenues that the system will obtain from its participation in electricity markets, a simulation of the electricity market operation, especially the day-ahead and balancing markets, was conducted (see Figure 1). It is anticipated that the system will derive the largest share of its revenues based on the variable operating costs of the participating units.

To perform the electricity market simulation, data from the National Energy and Climate Plan for 2030 (Hellenic Republic, 2024) and the Long-term Strategy for 2050 (Hellenic Republic, 2020) were considered. This includes the installed capacity and technical characteristics of thermal units, the evolution of the installed capacity of wind and photovoltaic systems and their production time series, the production of hydroelectric systems and other RES technologies according to their capacity evolution, the quantities of electricity imports and exports, and estimates of load prices, natural gas prices, and CO_2 prices.

Specifically, according to the National Energy and Climate Plan for 2030 (Hellenic Republic, 2024), achieving the ambitious targets requires approximately 14.7GW of wind and photovoltaic systems to be installed and operational, producing around 29TWh annually from wind and photovoltaic parks and about 9TWh from all other RES, including large hydroelectric plants. Similarly, for 2050, it is projected that 17.2GW of wind systems and 26.2GW of photovoltaic systems will be installed and operational, according to the NC2 scenario of the Long-term Strategy for 2050 (Hellenic Republic, 2020).

Regarding demand and total load, the data on load evolution presented in the NECP (Hellenic Republic, 2024) and the long-term strategy until 2050 (Hellenic Republic, 2020) were considered (every 5 years until 2040 and for 2050), with linear interpolation per year for the period 2025-2050. For CO_2 emission rights prices, higher values than those of the NECP were adopted (Hellenic Republic, 2024), approximately €50/tnCO_2 for 2025, about €70/tnCO_2 for 2030, €80/tnCO_2 for 2034, €118/tnCO_2 for 2045, and €148/tnCO_2 for 2050, considering current CO_2 emission prices and corresponding studies in the context of EU reports.

Similarly, for natural gas prices, the NECP prices (Hellenic Republic, 2024) were adopted based on the updated EU reference scenario.

It should be noted that post-2050, all energy magnitudes considered for the storage system's operation simulation are assumed to remain stable. Consequently, the annual operation simulation for 2050 is essentially considered stable until the end of the examined period, i.e., 2058.

The energy simulation of energy demand and the participation of RES stations yielded demand curve and residual load curve outcomes, underscoring the necessity of developing storage systems within the domestic energy system to absorb the produced energy from RES stations.

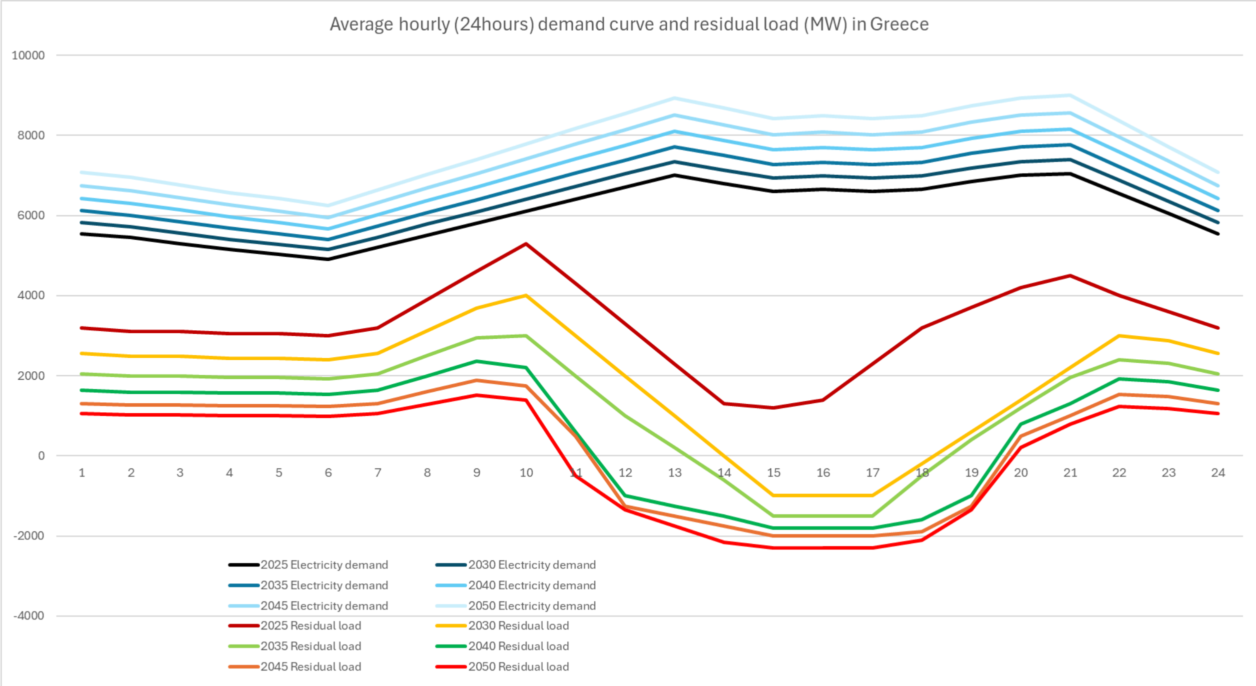

Figure 1 Average hourly (24hours) demand curve and residual load (MW) in Greece

The residual load curve represents the hourly imbalances in energy supply and demand, highlighting the necessity for system flexibility. By subtracting inflexible supply from baseload demand, the curve reveals residual demand (shortages) and residual supply (surpluses). A negative value on the curve indicates energy surplus, whereas a positive value signals a shortage. This imbalance showcases the critical need to dynamically balance the energy system.

The incorporation and functioning of storage facilities within the next-day market settlement exploit the significant variability of the residual load curve. This is based on the operational characteristics of the storage units and the hourly marginal cost in the day-ahead market. According to the simulation, the marginal cost is established during periods of low marginal DAM price by the marginal cost of imports or renewable energy sources, and during periods of high marginal DAM price by the marginal cost of thermal units.

It is important to highlight the consistent contribution and involvement of storage facilities in the electricity market, particularly in providing balancing services through the supply of power for frequency restoration reserves (EAS)

The simulation of the balancing market operations for EAS yields results that substantiate this theoretically anticipated significant contribution. Specifically, the involvement of storage facilities in delivering EAS services accounts for an average annual hourly mean ranging from 20% to 45% of the total capacity of the said project over the examined 35-year period.

Battery Energy Storage System (BESS) Project in Greece

The cost of solar parks varies by location and scale. Considering the design elements presented in the introduction, on average, the total installed cost of utility-scale solar PV ranges from €618/kW to €2,117/kW in Europe, with an average of €1,191.5/kW. On average, the total installed cost of utility-scale solar PV in Greece is around €1,000 to €1,500 per kW.

The cost of grid-scale lithium-ion batteries is typically measured in $/kW or $/kWh (Michaelides, 2025). A good rule of thumb is that grid-scale lithium-ion batteries have a cost of around $749/kW in Europe. The cost of grid-scale lithium-ion batteries in Greece is typically around €600 to €800 per kW. Earnings from solar parks depend on various factors, including location, solar irradiance, and electricity prices. On average, solar parks can generate earnings of around $0.10 to $0.15 per kWh in Europe.

Earnings from energy storage units come from various revenue streams, including price arbitrage, frequency regulation, and capacity payments. The revenue potential can vary significantly based on market conditions and regulatory frameworks.

Technical Specifications: The BESS project incorporates advanced battery technology to store and release electrical energy. Let's assume that we have a battery system designed to manage energy equal to 196 MWh per full charge-discharge cycle, delivering 98 MW of power to the grid (so we can have a reference point per ~100 MW). This performance metric accounts for electrical losses in both the transformer and the connection line.

Figure 2: Example of 25MW/50MWh Battery Energy Storage System in the UK (Lightsource bp, 2024)

Installed Capacity: The installed capacity of the system is determined by the chosen battery technology at the time of final design. For the purpose of this analysis, the capacity is estimated to be 113.4 MW, consisting of 36 inverter modules, each with a capacity of 3,150 kVA. The total installed capacity of the accumulators is approximately 247,680 MWh, achieved through 72 battery units, each with a capacity of 3,440 MWh. The quantization of equipment is a key factor in determining these values.

Economic Analysis: The project's annual net revenue is derived from participation in energy and system balancing markets, alongside income generated from a capacity remuneration mechanism in Greece (economic assumptions based on Papavasiliou, 2021). Graphical representations depict the revenue streams throughout the system's 25-year operational period (see Figure 3).

Fixed Cost Analysis

The initial investment cost components of the system, including the cost of battery replacement at the end of the 4th, 11th, and 18th years of operation, the cost of equipment dismantling in the 25th year of the review period (with the expected operational lifespan of the production facility being 25 years), as well as the annual fixed operating and maintenance costs, are detailed in Table 1.

Specifically, regarding the investment cost, an agreed supply price for the upcoming year was considered. The estimated average supply and installation cost of accumulators is €150/kWh, while the cost for the station's power systems is €200/kW. The total investment cost, inclusive of connection and total development costs for the storage station of this application, is approximately €66.73 million.

The annual operating costs (OPEX) of the station are estimated, based on international literature and evaluations by global agencies, to be roughly 2.75% of the project's construction cost. Within this percentage, 1.25% represents the project's warranty and insurance expenses (≈€834k), while the remaining 1.5% accounts for the operational and maintenance costs.

Table 1: Fixed Investment & Operation and Maintenance Costs for 100 MW

CAPEX (€)	€66,732,000
Batteries	€37,152,000
Control and Power Systems	€22,680,000
Connection Cost	€5,500,000
Others (landscaping, permits)	€1,400,000
OPEX (€)	€1,835k
Warranty Costs	€834k
Operating and Maintenance Costs	€1,001k
Other Costs	
First Battery Replacement Cost (34.4 MWh)	€4,196,800
Second Battery Replacement Cost (34.4 MWh)	€2,924,000
Third Battery Replacement Cost (34.4 MWh)	€2,064,000
Dismantling Cost	€1,098k
Average Annual Inflation	1%

Variable Cost Analysis

The battery station does not incur variable production costs, as it does not directly consume fuel for its operation. The station's production cost is contingent upon the cost of purchasing the charging energy and the efficiency of the full charging-discharging cycle. The station will charge by drawing energy from the system through its participation in the various markets of the target model. The cost of energy absorption by the station cannot be determined directly or unequivocally, as it is influenced by market equilibrium based on participants' bids, market product availability, and the prevailing competitive conditions among participants in the electricity markets.

Analysis of Electric Energy Sales and Revenue Generation

The project's annual net revenues, arising from its involvement in energy markets and system balancing, as well as the annual revenues generated from the capacity adequacy mechanism, are graphically depicted in the ensuing figures. This representation spans the entire 25-year operational lifespan of the station (see Figure 3 and Figure 4).

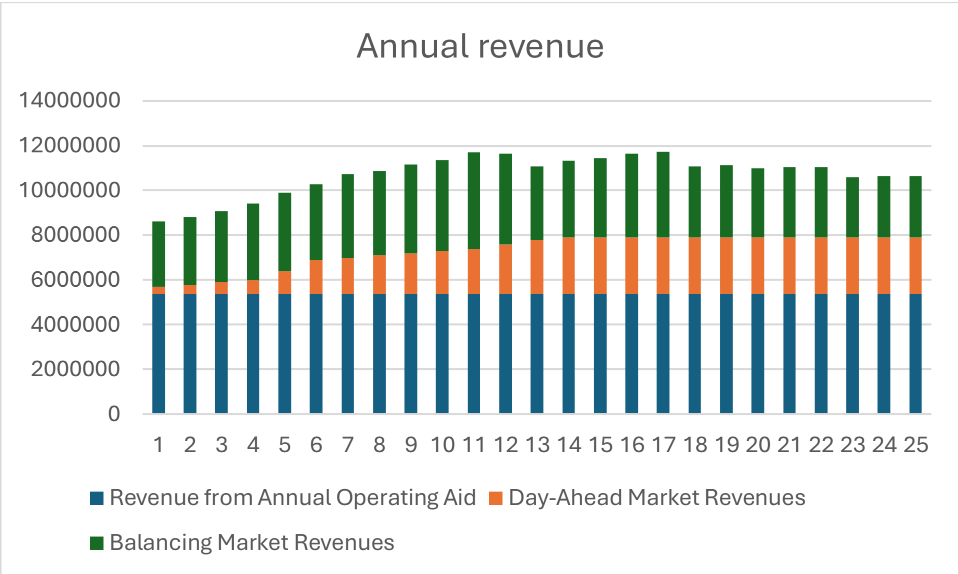

Figure 3: Annual revenue for 100 MW BESS project

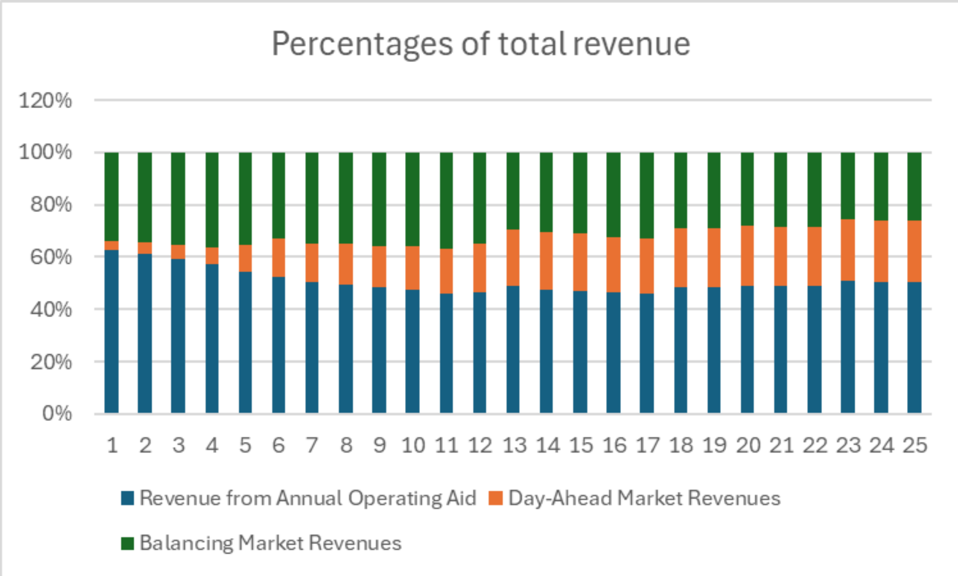

Figure 5: Percentage of total revenues for 100 MW BESS project

The annual reference revenue from the anticipated auction is projected to be €55,000 per MW, resulting in an estimated annual income of €5,390,000 for a ~100 MW station.

Policy and Regulatory Context: The National Recovery and Resilience Plan (NRRP) in Greece includes distinct actions to support the development of storage systems. A competitive process aims to install a total capacity of approximately 700 MW (European Commission, 2023). Concurrently, a Ministerial Decision outlines procedures for competitive bidding, targeting a total capacity of 1,000 MW (European Commission, 2023). Selected storage stations will receive both investment and operational support (European Commission, 2023).

Conclusion

BESS projects in Greece represent a significant step towards enhancing the stability and efficiency of the national power grid. By leveraging advanced battery technology and aligning with national policies, the project aims to deliver substantial economic and environmental benefits. Future developments and regulatory frameworks will play a critical role in the successful implementation and operation of such energy storage initiatives to cover residual load of 2500 MW by 2050.

The profitability analysis of BESS projects in Greece indicates significant market potential but also highlights various challenges that need to be addressed. NECP has established ambitious targets for energy storage, and recent tenders for storage systems have incorporated support mechanisms to stimulate investment. This initial support is essential as the market is still evolving and may not fully capture the value of energy storage. While there is a clear effort to make BESS projects financially viable without government aid, current market conditions and regulatory frameworks continue to play a crucial role in their support. Transitioning to a fully self-sustaining market for BESS will likely require ongoing innovation and adaptation.

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