

OPTIMISING PV-BATTERY OPERATION FOR GRID DECARBONISATION: A TRADE-OFF ANALYSIS BETWEEN ECONOMIC PERFORMANCE AND ENVIRONMENTAL IMPACT

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ABSTRACT

In the context of electric grid decarbonisation, energy storage systems play an important role by providing the flexibility needed to accommodate high shares of variable renewable energy while ensuring grid stability. This paper evaluates the environmental and economic impacts of grid-connected PV-BESS systems under different optimisation strategies for operations. Specifically, the study investigates the trade-offs between economic profitability (maximising market revenues) and environmental efficiency (minimising the carbon emissions of the electricity mix). The objectives are to determine whether market signals align with low-carbon targets and to compare the carbon reductions achieved under an economic dispatch strategy and an environmental dispatch strategy. Firstly, the operation of the BESS is optimised with a fixed size, focusing on economic performance to maximise revenue through dispatch strategies like peak shaving and energy arbitrage. Secondly, the optimisation targets environmental performance, minimising greenhouse gas emissions by prioritising low-carbon energy sources. The dispatch strategies are implemented using Linear Programming (LP) with the Gurobi solver to ensure global optimality. Following the optimisation, the embodied carbon of the BESS and PV components is evaluated by Life Cycle Assessment (LCA). The techno-economic analysis relies on proprietary industry cost data (CAPEX) for PV and storage components to accurately reflect current market conditions. The methodology is applied to a case study in France (2025 data), characterised by a low-carbon nuclear mix with significant winter peaks and negative summer prices. It is found that the environmental strategy enables the avoidance of 48 % more emissions compared to the economic strategy, with a decrease of 21 % of the revenue compared to the economic strategy. Both strategies achieve a positive environmental balance, with a carbon payback time of 7.6 years for the environmental dispatch strategy and 9.2 years for the economic dispatch.

1. INTRODUCTION

The increasing penetration of intermittent renewable energy sources creates significant challenges for grid stability and energy management [1]. One of the solutions is to associate storage technologies [2,3], the sharp decline in battery costs accelerates the deployment of Battery Energy Storage Systems (BESS). These systems cover a wide range of applications: self-consumption, peak-demand management, and grid support. New services and markets are emerging for battery-connected systems to the electric network, offering opportunities for revenue generation through

market participation. It has been shown that battery storage systems can play a role in decarbonising electricity production with a greater use of renewables in fossil-fuels-based electricity mix [1]. Battery storage systems coupled with renewable plants can displace low carbon emission production from renewable to replace fossil plants production during peak demand and avoid renewable electricity curtailment.

In France, a low-carbon-intensity electric grid, the multiannual energy programme (PPE3) is one of the roadmaps for “French Strategy for Energy and Climate”, targeting to reduce fossil fuel share in final energy consumption from 60 % in 2023 to 30 % by 2035 [4]. With a target of development of solar capacity, the assessment of the benefits of hybridising photovoltaic projects with battery storage becomes important. While the role of BESS in decarbonising fossil-fuel-based grids is well-documented, there is a lack of investigation regarding their environmental added value in already low-carbon electricity mixes. Most existing studies focus on techno-economic optimisation, but few explore the environmental impact and benefits for utility scale systems. In this paper, we aim to assess the environmental and economic performances of adding battery storage systems to photovoltaic systems in the context of a low-carbon electric grid with two operation targets: economic and environmental.

2. METHODOLOGY

2.1. System Architecture

The system studied in the present work includes a PV plant and a BESS connected to the grid, in a front-of-the-meter (FoM) configuration. The solar photovoltaic power plant producing direct current has DC/AC inverters, a BESS composed of battery containers, producing direct current, with power conversion systems with bidirectional AC/DC inverters and a MW transformer. In our study, we consider that both plants, PV and BESS, have their own DC/AC conversion systems. The batteries can be charged either from the grid or from the PV; the PV can export directly to the grid.

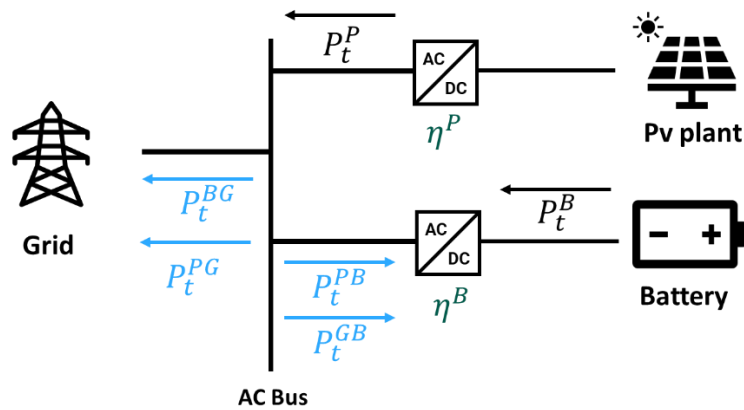


Figure 1. Architecture of a PV-BESS FOM plant

2.2. Problem definition

The primary objective of this methodology is to evaluate and compare the operational dispatch of the PV-BESS system under two distinct paradigms: an economic revenue maximisation strategy

and an environmental impact minimisation strategy. Figure 2 illustrates the different steps needed to conduct the optimisation. The input data are related to the case study and will be detailed in section 3. below. The system operation is simulated over a 15-year project lifetime, discretised into 30-minute time steps ($\Delta t = 0,5$ h), resulting in $T = 262\ 800$ periods. The core problem is formulated as a deterministic linear programming (LP) model. Linear programming is chosen to ensure global optimality and computational efficiency over the long-term horizon.

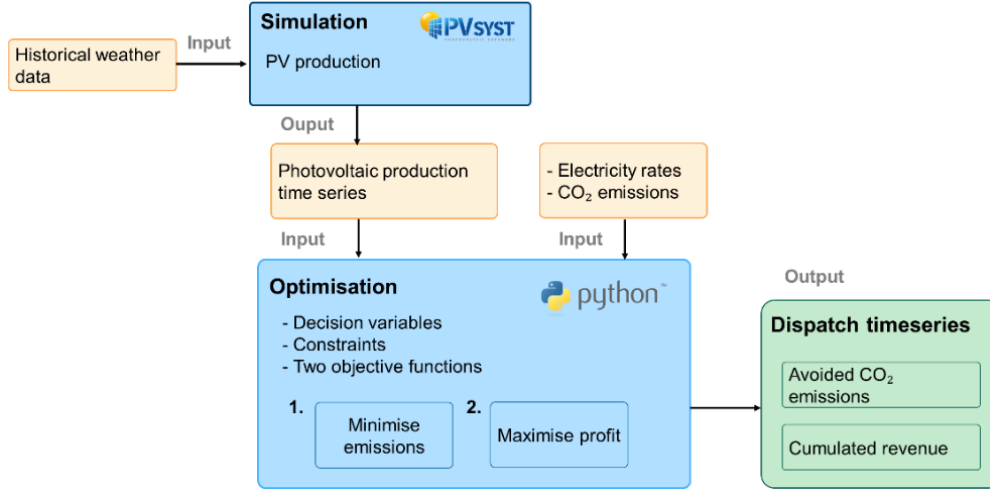


Figure 2. Scheme of the optimisation steps

2.3. Optimization Model

The mathematical model is defined by its operational constraints and the two distinct objective functions that will allow finding the value of the decision variables for each step time.

2.3.1. Decision variables

The four continuous decision variables represent the power flows at each time step t : P_t^{PG} (PV to grid), P_t^{BG} (battery to grid), P_t^{GB} (grid to battery) and P_t^{PB} (PV to battery) shown in blue in Figure 1.

2.3.2. Constraints

The battery system is represented by its nominal capacity, discharge power and limits of state of charge (SoC). The evolution of the battery's SoC is governed by the energy balance equation, which accounts for charging and discharging efficiencies (η_{ch}^B and η_{disch}^B):

$$\frac{E_t - E_{t-1}}{\Delta t} = \eta_{ch}^B (P_t^{PB} + P_t^{GB}) - \frac{P_t^{BG}}{\eta_{disch}^B} \quad (1)$$

To preserve battery health, and comply with manufacturer warranties, the stored energy is strictly bounded between a minimum (α^{min}) and maximum (α^{max}) state of charge:

$$E^{BESS} \alpha^{min} \leq E_t \leq E^{BESS} \alpha^{max} \quad (2)$$

The power that can be injected to the grid or imported are constrained by P^{G_import} and P^{G_export} :

$$0 \leq P_t^{GB} \leq P^{G_import} \quad (3)$$

$$0 \leq P_t^{BG} + P_t^{PG} \leq P^{G_export} \quad (4)$$

The usage of electricity from the PV plant (P_t^P) is constrained by the production at each time step. We consider P_t^P as the usable electricity in AC after the inverter's conversion losses:

$$0 \leq P_t^{PG} + P_t^{PB} \leq P_t^P \quad (5)$$

The nominal capacity of the BESS and PV are respectively subjected to an annual degradation factor, detailed in **3.5. Battery and photovoltaic specifications**, to reflect capacity fade over the 15-year lifetime. Currently, an operational constraint limits the BESS to a maximum of one full equivalent cycle per day. This ensures consistency with exogenous degradation curves and reflects standard industrial practices.

2.3.3. Objective functions

Objective function 1: Economic

For the economic objective function, the algorithm maximises revenue on the Day-Ahead Spot market for the battery and with a fixed value for the photovoltaic electricity sells:

$$Max \sum_{t=0}^T (\pi_t^{pv} P_t^{PG} + \pi_t^{grid} P_t^{BG} - \pi_t^{grid} P_t^{GB}) \Delta t \quad (6)$$

Here, π_t^{pv} is the fixed price paid for photovoltaic production exported to the grid. This price is an incentive added to the wholesale market price by the French commission of energy regulation (CRE). π_t^{grid} is the spot market price. Under this operation mode, the battery will charge with the grid when the prices are negative or low or with the PV and discharge when the prices are the highest on the wholesale market.

Objective function 2: Environmental

For the environmental equation, the algorithm will minimise emissions on the grid; from a life cycle assessment point of view, it will maximise the avoided emissions through the battery operations:

$$Min \sum_{t=0}^T (\varepsilon_t^{grid} P_t^{GB} - \varepsilon_t^{grid} P_t^{BG} - \varepsilon_t^{pv} P_t^{PB} - \varepsilon_t^{grid} P_t^{PG}) \Delta t \quad (7)$$

Under this operation mode, the battery will charge in priority with PV, as the direct emissions are considered zero or with the grid when the emissions are low and discharge when the grid emissions are the highest.

3. CASE STUDY: FRENCH GRID INTEGRATION

3.1. Sizing of the studied system

In the present study, the photovoltaic capacity is fixed to 8 MWp. In real projects, this capacity is often determined by the available area or grid connection limit. And we assume the battery system has a fixed capacity of 10 MWh with a charge/discharge power of 2.5 MW. We consider a 15-year

project lifetime for the PV plant and the BESS. We do not consider grid limit for import and export in this study.

3.2. Photovoltaic production

The photovoltaic system is characterised by its electricity production, simulated on PVSYST® software using typical meteorological year (TMY) input data. It results in a time series of electricity production considering a PV plant located in the Pays de la Loire region, France. This specific area has an irradiance potential of 1450 kWh/m² and a simulated energy yield of 1186 kWh/kW_p on average over the considered lifetime. The average electricity delivered per year over the lifetime is 9 485 MWh.

3.3. Electricity rates

For the electricity rates, we consider that we sell the electricity to the wholesale electricity market (spot market), and we use historical 2025 price data retrieved from the European Network of Transmission System Operators of Electricity (ENTSOE) Transparency Platform [5]. We did not make a scenario for the evolution of electricity prices. Constant prices based on 2025 data for the whole period of simulation have been considered as a first step. The average of the spot market rate in France for 2025 is 61,30 €/MWh, with negative prices in summer that has reach -118 €/MWh and maximal prices that could go above 250 €/MWh.

3.4. Grid emissions

To evaluate the avoided emissions, we used a marginal approach. We use the production data for each type of power plant for 2025, and we sort them according to their merit order to determine the last plants called at each time step. The merit order is an economic ranking system used to determine the order in which different sources of electricity should be used to meet demand [6]. This ranking is based on the marginal cost of the power plants. We consider that the top 10 % of this electricity production constitutes the marginal electricity mix. At each time step, the operation of the battery system thus affects the most expensive dispatchable electricity generation plants and so their related emissions.

First in the merit order comes the renewable energies (PV, wind), with almost no marginal cost, then nuclear plants, hydropower (nearly zero marginal cost but a “usage cost” to reflect that it is a very flexible source of electricity, used for fine load following), and finally fossil-fuelled plants. Based on ADEME data [7], we consider direct and indirect emissions to be consistent with the LCA approach we used for the PV and BESS systems. We consider 1060 gCO₂eq/kWh for fossil hard coal, 420 gCO₂eq/kWh for fossil gas and 730 gCO₂eq/kWh for fossil oil and 3.7 gCO₂eq/kWh for nuclear. France has a low carbon intensity electricity, due to a majority of nuclear in the mix accounting for ~70 % of the total production, 27 % of renewable energy and 3.1 % of gas [8]. The average carbon intensity in 2025 was 46 gCO₂eq per kWh produced [8]. The average marginal mix contains 66 % of nuclear, 31 % of gas, 2 % of oil and 1 % of coal, its carbon intensity is 143.4 gCO₂eq/kWh.

3.5. Battery and photovoltaic specifications

The most common design for utility-scale battery storage systems is batteries coming in 5 MWh DC containers connected with power conversion systems, made of bidirectional inverters and an

MV transformer. These types of systems are proposed by most of the suppliers. We selected the specifications of the model Intensium Flex 5,1 MWh DC from SAFT, a French battery manufacturer. For the specifications, we took 92 % for charging efficiency and 92 % for discharging efficiency at MV level after the power conversion, giving a round-trip efficiency (RTE) of 84.6 %. We set the minimal state of charge (SoC) at 10 % and the maximal SoC at 90 %. The initial SoC of the battery is set to 50 %.

We integrate yearly degradation for the battery system as well as the photovoltaic system. Considering the battery, we took values directly from the supplier specifications for 1 cycle per day, going from 2 % to 1.1 % per year during the lifetime. For the PV modules we assumed a degradation of 0.4% per year given by the formula $P_n = P_1(1 - 0.004)^n$.

3.6. Battery and photovoltaic emissions assumptions

Regarding the CO₂eq emissions factor, we aim to assess the emissions related to each installation, the photovoltaic plant and BESS using a life cycle assessment methodology. LCA is a method for assessing the potential environmental impacts of a product or system throughout its entire life cycle, from raw material extraction to end-of-life waste treatment [9]. As a multicriteria method, it enables the evaluation of impacts across various categories, including climate change, the depletion of fossil and mineral resources, and the broader effects on human health and ecosystems [9]. We only consider the midpoint indicator “Global warming potential at 100 years” expressed in kgCO₂eq. As a first estimate, we only consider the production stage and raw material extraction and processing. We do not consider the use stage, as the assessment of the carbon payback time is conducted independently from the optimisation and we do not consider waste disposal stage for battery and PV due to a lack of standardisation and data. We took values according to ecoinvent database [10] crossed with values from the literature [3,7,8].

For the PV system we took as functional unit 1 kWp installed, we assumed a value of 550 kgCO₂eq/kWp for the photovoltaic modules, based on literature and the carbon footprint limit set by the French commission of energy regulation for their call for tenders [13]. To this value we add the impact of the ground-mounted system, reaching a total value of 1000 kgCO₂eq/kWp [7]. For the BESS, we consider lithium iron phosphate battery cells, currently the most common on the market and showing the smallest environmental impact for their production compared to lead acid and lithium manganate [14]. We take as functional unit 1 kWh of installed capacity. We took the average value of our LCA analysis and literature for the battery cells [15] and added the emissions value related to the complementary equipment such as energy management system, PCS, and steel for containers, resulting in 85 kgCO₂eq/kWh. Our methodology considers the embodied emissions of each system independently of its operational use, enabling an assessment of carbon discounting over the system’s calendar lifespan.

3.7. Economic assumptions

The key economic assumptions adopted in this study are presented in Table 1. Based on supplier’s offers and market trends, the specific capital expenditure (CAPEX) for photovoltaic system is assumed to be 630 €/kWp, for BESS it is 251 €/kWh. The annual operational expenditure (OPEX) for both systems is taken as 1.7 % of their respective CAPEX. We do not consider replacement cost

in this study, as we take a 15-year project lifetime. According to the sizing mentioned in 3.1. Sizing of the studied system, the total cost of the system for 15 years is 9,480,000 €.

Table 1. Economic assumptions

Parameters	Values
CAPEX BESS (€/kWh)	251
Annual OPEX BESS (% of CAPEX)	1.7
CAPEX PV (€/kW _p)	630
Annual OPEX PV (% of CAPEX)	1.7

RESULTS AND DISCUSSION

4.1. Comparison of the two operation modes

The optimisation gives the optimal value for the four decision variables for each 30 min time step. The Figure 3 shows the results for the two operation strategies, the avoided emissions and cumulated revenues through the period of study of 15 years.

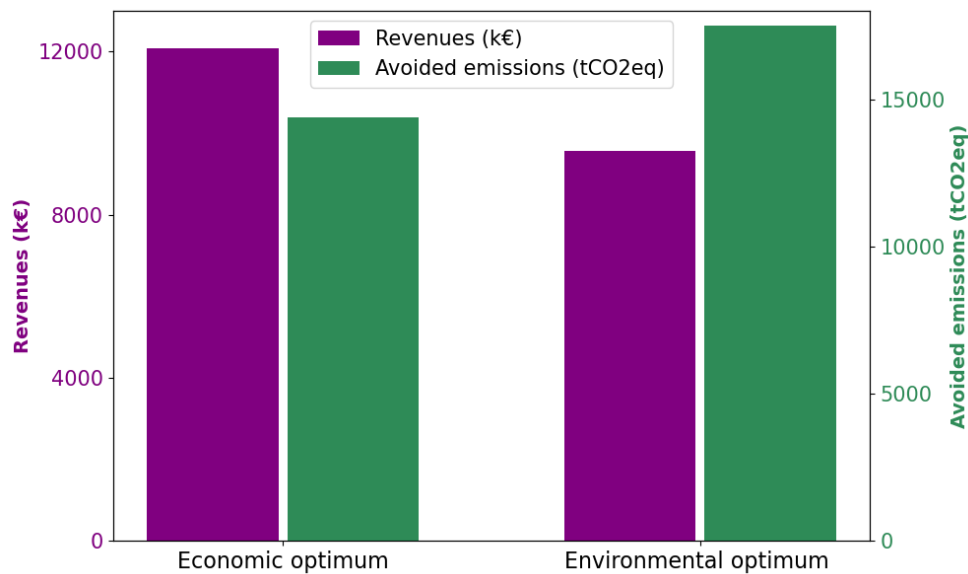


Figure 3. Avoided emissions and cumulated revenues with photovoltaic and BESS system during the period of 15 years

The **Table 2.** Optimisation results for economic and environmental dispatches Table 2 summarises the results obtained for the two different optimisation models. The dispatch strategy with economic objective function obtains a revenue of 12.1 M€ with a total avoided emissions through the lifetime of 11,800 tonnes of CO₂eq emissions. The environmental objective function optimisation obtains a revenue of 9.58 M€ with a total of avoided emissions through the lifetime of 17,500 tonnes of CO₂eq emissions. The environmental strategy enables the avoidance of 48 % more emissions compared to the economic strategy, with in return a decrease of 21 % of the revenue through the studied period. Here the specific location of the case study represents a conservative scenario, the

solar irradiance levels in France result in a lower energy yield than in equatorial climates, thereby restricting the photovoltaic energy revenue generation and availability for storage.

Table 2. Optimisation results for economic and environmental dispatches

Indicators	optimal economic dispatch	optimal environmental dispatch
Cumulated revenues	12.1 M€	9.58 M€
Net avoided emissions	11 800 tCO₂eq	17 500 tCO₂eq

We have seen the results of the two optimisations, now we will look closer to the price and carbon signal for three specific days. Typically, a strong correlation between wholesale market prices and carbon intensity is expected, as fossil fuel plants such as coal and gas have high marginal costs and high emissions. However, in France, this correlation is mitigated by the dominance of nuclear energy (around 70 %) and hydropower (11 %) in the electricity mix. By examining the three specific days shown in Figure 4 **Figure 4**, a clear mismatch between electricity market prices and emissions becomes apparent. This discrepancy arises because French electricity prices are often set by marginal power plants at the European level through interconnections, whereas the emission calculations focus on the domestic French marginal mix. The economic algorithm will discharge the battery to capture the profit, but the actual carbon gain can be negligible.

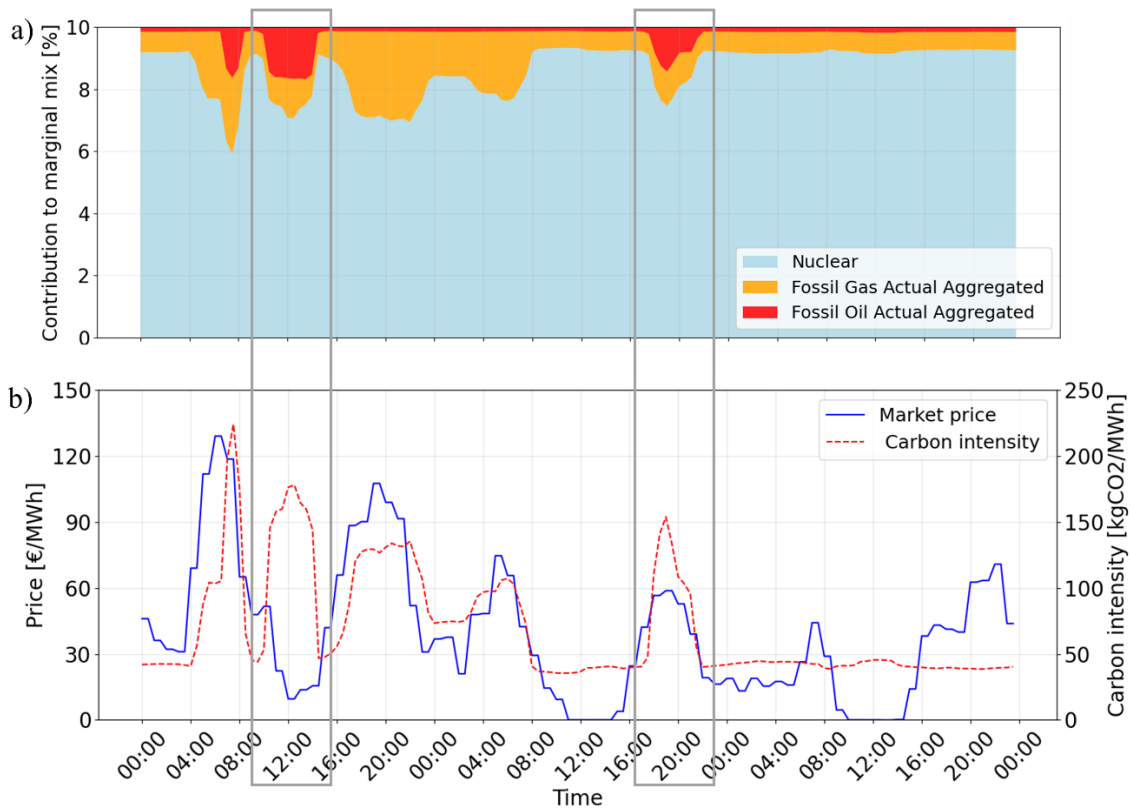


Figure 4. Power plant proportion in merit order (a) and associated emissions and market prices (b)

As a result of these divergent signals, both algorithms behave differently, as illustrated in Figure 5 (a) and (b). For the environmental strategy, the algorithm prioritizes charging when carbon emissions are lowest to discharge when grid emissions are at their highest, regardless of the price signal. For the economic strategy, the algorithm charges when market prices are low (or negative) to discharge when prices peak, independently of the carbon signal. These two strategies lead to distinct carbon intensities associated with the battery operation (Figure 5c). Since the direct emissions of the BESS are dependent on the carbon intensity of the source used for charging, the environmental dispatch ensures that the "carbon debt" at charging is low enough to be offset by the emissions avoided during discharge.

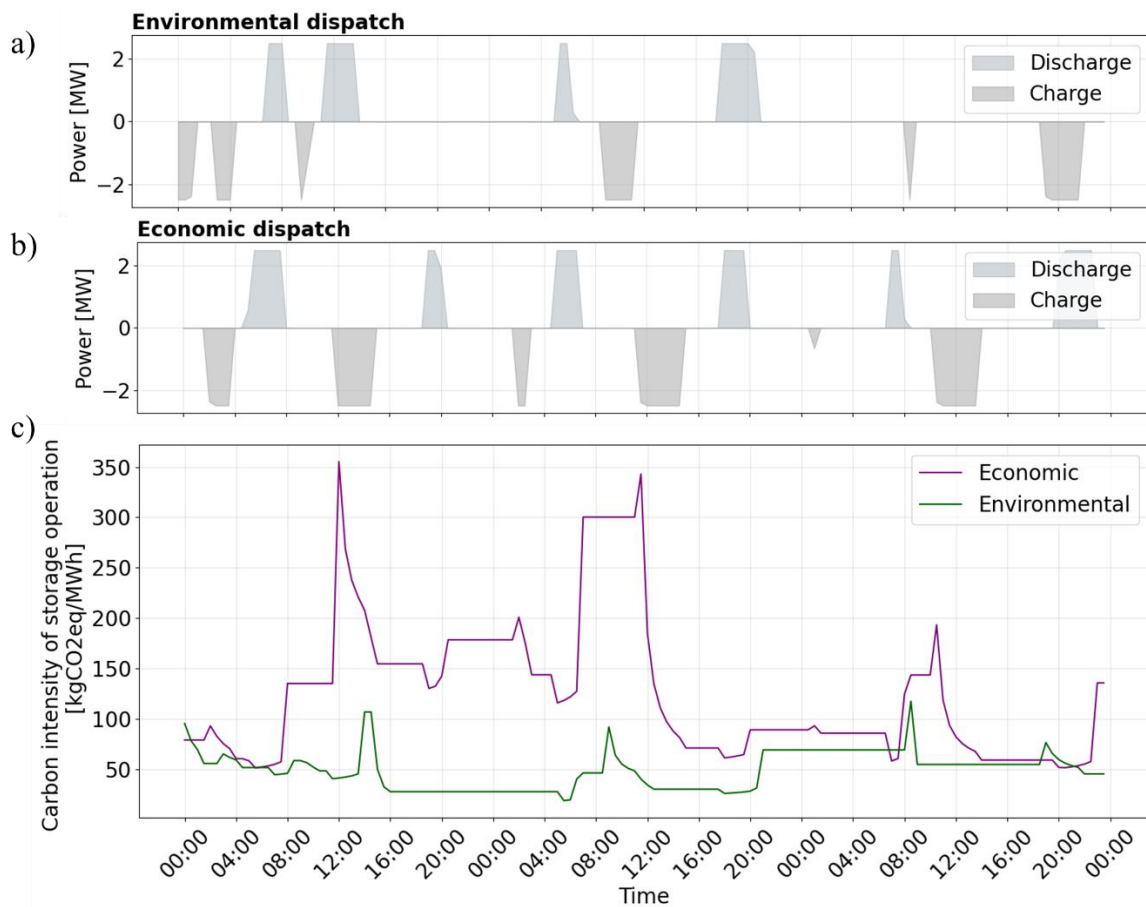


Figure 5. (a) Charge and discharge operation for environmental strategy (b) Charge and discharge operation for economic strategy (c) Carbon intensity of storage operation

4.2. Cost and revenue analysis

Regarding the cost of the project of 9.476 M€ (Table 1) and the cumulated revenues obtained (Table 2), the dispatch strategy will affect the system's financial viability. The economic optimal dispatch strategy generates 12.08 M€ in cumulative revenue. This results in a net profit of 2.60 M€ over the 15-year period. The environmental optimal dispatch strategy results in cumulative revenues of 9.58 M€, leaving a marginal surplus of only 0.10 M€. The conclusion on this analysis is limited by the period of assessment, as the PV-BESS project generally lasts longer than 15 years, with a replacement of the batteries to match the PV lifetime. Furthermore, fees related to project

development are not considered here. The aim of this analysis is to have an order of magnitude between the costs and revenues generated by the two operation strategies.

4.3. Carbon payback time for both operation strategies

To provide a comprehensive environmental assessment beyond operational dispatch, the embodied carbon emissions of the PV plant and the BESS were integrated into the analysis to determine the Carbon Payback Time. This metric defines the period required for the avoided emissions generated by the system's operation to compensate for the greenhouse gas emissions produced during the raw material extraction and manufacturing stages.

The evaluation relies on electricity generation data from 2025 in France. This year serves as a conservative baseline for environmental benefits, as it featured an exceptionally high share of low-carbon electricity, with 95.2% of production coming from nuclear and renewable sources [8]. In such a decarbonized grid, the marginal emissions avoided by the BESS are naturally lower than in fossil-heavy mixes, making the "repayment" of the carbon debt more challenging.

The results shown in Figure 6 demonstrate that both strategies achieve a positive environmental return within the beginning of system's operational life. For the environmental dispatch strategy, the carbon payback time is reached in 7.6 years. This shorter duration is expected, as the algorithm specifically targets the displacement of the most carbon-intensive marginal plants. For the economic dispatch strategy, the carbon payback time is reached in 9.2 years. Although the dispatch is driven by market prices, the underlying correlation between prices and emissions still yields significant net carbon benefits.

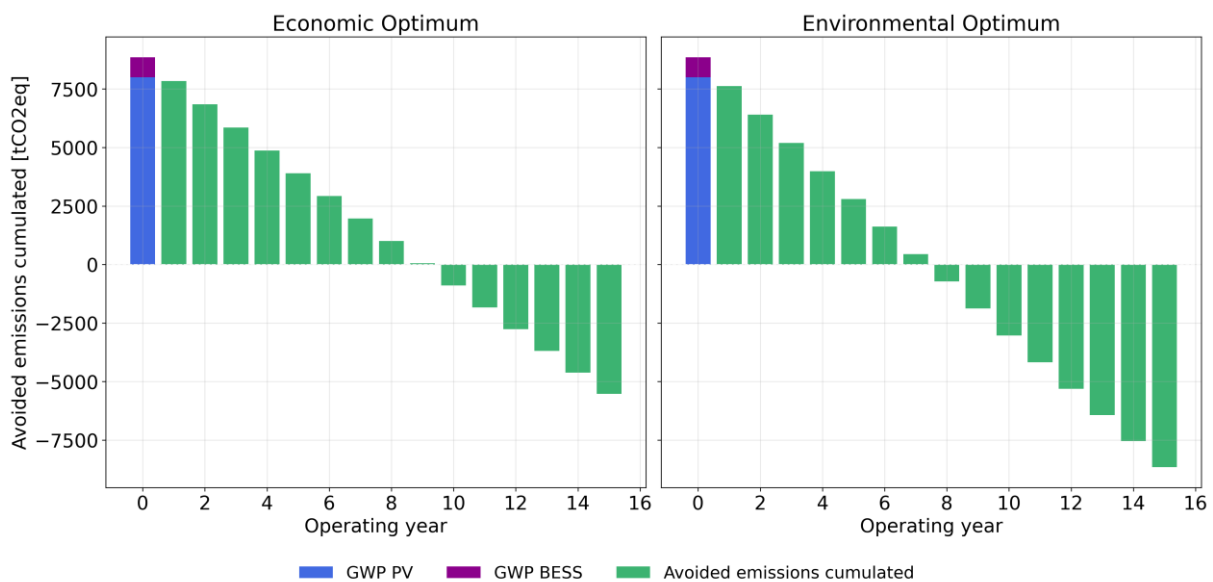


Figure 6. Carbon payback time for environmental and economic dispatch strategies

4. CONCLUSIONS

This study provides a comprehensive analysis between economic profitability and environmental efficiency for grid-connected PV-BESS systems within the specific context of the French low-carbon electricity mix.

By using a deterministic Linear Programming (LP) dispatch model with a marginal approach for grid emissions, we demonstrate that the environmental dispatch strategy enables the avoidance of 48 % more emissions than the economic dispatch strategy. This shows that, although wholesale market prices and emissions are correlated on average, price signals do not serve as a perfect proxy for optimal emissions avoidance, especially in nuclear-dominated mixes. While the environmental strategy prioritises emissions avoidance, it results in a 21 % reduction in revenue, which is significant for project developers.

By applying a Life Cycle Assessment (LCA) framework to operational dispatch, we showed that both economic and environmental strategies achieve a positive environmental balance over the system's 15-year lifecycle. The carbon payback time was found to be 7.6 years for environmental dispatch and 9.2 years for economic dispatch. Both approaches allow to effectively cover the embodied emissions of the system over their lifetime, validating the role of BESS as a net-decarbonisation tool even in low-carbon grids.

While the geographical and systemic characteristics of the French context impose a lower bound on the potential for absolute emission avoidance and revenue generation, the results demonstrate the efficacy of the proposed optimization framework.

NOMENCLATURE

Abbreviations

AC	Alternating Current
BESS	Battery Energy Storage Systems
CAPEX	Capital Expenditure
DC	Direct Current
LCA	Life Cycle Assessment
LP	Linear Programming
MV	Medium Voltage
OPEX	Operational Expenditure
PV	Photovoltaic
RTE	Round-Trip Efficiency
SoC	State of Charge
TMY	Typical Meteorological Year

Greek Symbols

α^{max}	Maximum state of charge [%]
α^{min}	Minimum state of charge [%]
Δt	Time step duration [h]
ε	Carbon intensity [kgCO ₂ _{eq} /MWh]

π	Price [€]
η	Efficiency [%]

Latin Symbols

E	Energy [MWh]
P	Power [MW]
t	Time [-]
T	Total optimisation horizon [-]

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