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ECO-ECONOMIC OPTIMAL SIZING AND OPERATION OF PV-BATTERY SYSTEMS IN BUILDINGS: THE ROLE OF CO_2 PRICE SIGNALS

Laura Maier[1], Matthias Ellinger[1], Dominik Hering[1], Dirk Müller[1]
[1] *Institute for Energy Efficient Buildings and Indoor Climate, E.ON Energy Research Center, RWTH Aachen University, Germany, E-Mail: laura.maier@eonerc.rwth-aachen.de*

Abstract

CO_2 pricing enables building owners to benefit from reduced emissions. Changing power plant mix leads to dynamic CO_2 factors and price signals that PV-battery systems can exploit. The system's size and CO_2 prices influence profitability. So far, no study exists assessing CO_2 pricing's influence on PV-battery systems' optimal sizing and operation. We, therefore, investigate the interaction of PV-battery sizing and operation with CO_2 pricing and combine Design of Experiments with MPC. For a CO_2 price of 100 €/t, the cost-optimal design decreases emissions by 79.7 %. Furthermore, high CO_2 prices yield large PV and medium battery sizing.

Introduction

In February 2022, the second part of the Intergovernmental Panel on Climate Change's (IPCC) Sixth Assessment Report (AR6) was released, highlighting the necessity of "immediate and more ambitious action" to mitigate climate change (Working Group II, 2022). The report states that the establishment of green buildings and the extensive use of renewable energy sources (RES) are crucial measures, in this context. While the aim is defined, there are different ways how to achieve them. One technical solution lies in coupling the building sector with the grid (Umweltbundesamt, 2019). In Germany, the share of RES in the grid has increased from 6 % in 2000 to 42 % in 2020. The coupling of both sectors would consequently lead to an increase in RES in the building sector, too. In this regard, photovoltaic power plants (PV) are key technologies as they generate RES-based electricity. Nonetheless, an increase in RES share on both grid and building-level leads to decreased grid stability. Hence, the need for flexible consumers and generators increases. A promising flexibility option is the installation of storage technologies like battery energy storage systems in decentral systems. However, building owners, who are responsible for the investment decision in such technologies, currently lack economic incentives. Thus, a link between CO_2 emission reduction on building-level and a resulting economic reward is missing. On grid level, the European Emissions Trading System, which regulates CO_2 pricing, was successfully introduced in 2005 with a renewal in the context of the Fit for 55 climate package. Yet, even though building owners and tenants indirectly pay for emissions caused by the grid, a direct incentive to reduce emissions does not exist. In addition, the impact of CO_2 pricing on CO_2 emission is still unclear (Hennes et al., 2021).

A further issue is that even if the investment decision is made, it is unclear what the most cost- and CO_2-effective sizing of PV-battery systems is. Literature proves that the optimal sizing depends on the future operation and vice versa. Moreover, scientists state that a trade-off between cost- and CO_2-optimal sizing of PV-battery systems exists. This is especially true if the whole system's life cycle is evaluated as both technologies. Apart from that, missing standardized international sizing guidelines for PV-battery systems impede the transfer to practice.

In this study, we close these gaps by investigating the following research questions:

- What is a possible way of introducing CO_2 pricing on building level?
- How do the cost and emission optimal sizing and operation of PV-battery systems interact given different CO_2 pricing scenarios?
- Does the integration of CO_2 pricing mitigate the existing trade-off between reducing CO_2 emissions and saving costs?

State of the art

The optimal design and operation of PV-BESS systems have been thoroughly investigated by scientific literature. We categorize the assessed literature in Table 1. As categories, we introduce the objective function, the incorporation of CO_2 pricing scenarios, the method used for sizing, and the battery usages considered. The methods used for optimization are distinguished into deterministic and heuristic optimization methods as well as Design of Experiments (DOE). While the deterministic optimizations simultaneously optimize design and operation and are henced simultaneous approaches, heuristic optimization, and DOE adapt system sizing and subsequently assess the resulting operation. Most of the analyzed studies choose deteministic approaches and apply the concept of mixed-integer linear programs, e.g., (Doroudchi et al., 2015 - 2015; Iria and Huang, 2021 - 2021). MILPs guarantee the calculation of global optima but simplify the system's operation. As literature finds a strong correlation of optimal design and operation, the simplifications might influence the results significantly. To improve operation modeling, heuristic optimization and DOE-based methods are promising. However, none of the studies applying heuristic optimization or DOE consider CO_2 pricing and the environmental costs.

Another distinguishing factor is the objective function. To the authors' best knowledge, Iria et al. (Iria and Huang, 2021 - 2021) are the first to evaluate the effect of CO_2 pricing on the optimal design and operation of PV-battery systems and consider the resulting environmental costs in the form of CO_2 emissions. However, they only consider CO_2 emissions during operation and neglect the system's residual life cycle emissions. They state that CO_2 pricing simultaneously leads to decreased costs and environmental impact, making it a valuable instrument to mitigate the trade-off between cost- and emission-optimal sizing and operation. In addition, they detect that the optimal system always incorporates PV systems while batteries are only installed for some of the use case buildings. Nonetheless, they apply an MILP to obtain their results with simplified controller assumptions. (Iria and Huang, 2021 - 2021)

We close the gaps metnioned above by investigating the following aspects:

- We evaluate both environmental and economic costs as objective functions and compare the resulting design and operation.
- To obtain a realistic operational behavior of the PV-battery system, we choose a DOE-based approach for sizing and combine it with MPC for optimal control.
- To evaluate the effect of CO_2 pricing, we introduce different scenarios as part of our experimental plan.
- We consider the PV-battery system's whole life cycle's emissions.

Method

Research object: Building with PV-battery system

The research object is a former military hospital in Berlin, Germany. It is currently being transformed into a laboratory and office building for start-ups and small businesses called FUBIC. A research project accompanies the transformation process and derives system design and operation recommendations. The

Table 1: Literature overview for PV-battery system optimization. We introduce the following abbreviations: REF:=Reference, ECO:= economic, ENV:=Environmental, D:=Deterministic, H:=Heuristic, P:=Peak load minimzation, S:=Self-consumption maximization, F:=Frequency Reserve Control, Y:=Yes, N:=No

REF	OBJECTIVE		CO_2 PRICING	METHOD			BAT USE
	ECO	ENV		D	H	DOE	
(IRIA AND SOARES, 2020 - 2020)	X		N	X			P, S
(DOROUDCHI ET AL., 2015 - 2015)	X		N	X			S
(LI, 2019)	X		N		X		S
(GABR ET AL., 2021)	X		N		X		S
(TALENT AND DU, 2018)	X		N	X			P, S
(BECK ET AL., 2016)	X		N	X			S
(RUIZ ET AL., 2020 - 2020)	X		N	X	X		P, S
(ASHOURI ET AL., 2013)	X		N	X			S
(LIU ET AL., 2019)	X		N	X			S
(IRIA AND HUANG, 2021 - 2021)	X	X	Y	X			P, S
(GIALLANZA ET AL., 2018)	X		N			X	S
(BANESHI AND HADIANFARD, 2016)	X		N			X	S
(DIAB ET AL., 2016)	X		N			X	S
THIS STUDY	**X**	**X**	**Y**	**X**		**X**	**P, S, F**

project aims at an electricity-based energy concept with zero emissions during operation. For this study, we focus on FUBIC's electrical system. The grid and a PV-battery system cover the building's electrical load. We calculate the electrical load using dynamic Modelica simulations and the open-source modeling library AixLib. The underlying building model is generated using the open-source Python framework TEASER, which bases on a reduced-order model.

Optimal Control Method: Hierarchical Model predictive control

In contrast to other studies dealing with similar research questions, we optimize the battery's operation using a hierarchical MPC (HMPC) approach. An MILP optimizes the battery's charging and discharging power. The battery is used to maximize self-consumption, reduce peak loads or offer frequency control reserve for primary grid control. As these revenue sources all depend on different time horizons and require varying model accuracies, three optimization layers with different prediction horizons are introduced, resulting in a hierarchical structure. A simulation model is used as the building is still in the renovation phase. In (Maier et al., 2021), the authors describe the optimization in more detail. So far, the objective function only considers the system's economic costs focusing on the battery's annuity. We extend the model by integrating environmental costs for the PV-battery system's life cycle. In addition, even though the model permits the exploitation of dynamic price signals, CO_2 pricing has not yet been considered, which is part of this study.

Key performance indicators

We evaluate how different CO_2 pricing scenarios interact with the profitability of investments in PV-battery systems of different sizes. In addition, we want to assess the environmental impact of the investment. To include the economic and the ecological perspective, we use the annuity as an economic and the overall CO_2 emissions as an ecological indicator.

Economic objective: Annuity

Regarding the annuity, we follow the assumption of the German guideline VDI 2067. The annuity comprises the capital-related, the demand-related and the operating-related costs. For the capital-related costs, we focus on the PV-battery system as the use case is a retrofit building whose other components are no objective of this study. Consequently, the capital-related costs depend on the PV-battery system's sizing. We assume the operation-related costs to depend on the capital-related costs based on predefined ratios. Finally, the demand-related costs derive from the building's electricity demand and additional costs for the grid-related CO_2 emissions.

For the CO_2-depended part of the demand-related costs, we derive the specific CO_2 emissions for each time step t $f_{CO_2,\mathrm{marg},t}$ of the grid and multiply it with the electricity demand $P_{\mathrm{Grid},t}$ of the respective time step (cf. Equation 1). In addition, we assume that the standard electricity price already considers CO_2 pricing due to the ETS. Hence, we subtract a reference CO_2 price $p_{CO_2,\mathrm{ref}}$ from the CO_2 pricing scenario p_{CO_2}. We set the reference price to 5,76 €/t being the average ETS CO_2 price of the year 2017 (European Energy Exchange AG, 2022).

$$c_{CO_2,t} = -\left(p_{CO_2} - p_{CO_2,\mathrm{ref}}\right) \cdot f_{CO_2,\mathrm{marg},t} \cdot P_{\mathrm{Grid},t} \qquad \textbf{(1)}$$

Environmental costs: Life cycle CO_2 emissions

One method to evaluate a system's environmental costs is life cycle assessment (LCA). The method aims to not only consider a system's enviromental impacts during operation but from “cradle to grave”. We adopt this approach and apply it to the PV-battery system under consideration. The CO_2 emissions during operation comprise the emissions caused by the interaction with the electrical grid. In practice, averaged CO_2 emissions per kWh of electricity are listed. Nevertheless, the average is based on a dynamic CO_2 factor as the power plant mix differs for each time step. Consequently, a building energy system with a PV-battery system can adapt its operation and exploit the spreads of the dynamic CO_2 factor. To estimate the dynamic CO_2 factors, a detailed power plant mix model for Germany is needed. Following (Pellow et al., 2020), we assume that the interaction of the battery with the grid causes the marginal power plant to adapt its power. Consequently, we only consider the CO_2 factor of the marginal power plant rather than an averaged one based on (Stinner et al., 2022).

The integration of a battery does not necessarily lead to reduced overall emissions due to emissions caused during production and disposal (Ryan et al., 2018). We, therefore, use literature-based values for production (0.11 kg_{CO2}/Wh (Peters et al., 2017)) and disposal (0.010456 kg_{CO2}/Wh (Hischier, 2021)). In contrast to the battery, the PV power plant does not emit CO_2 during operation. However, its production and disposal cause CO_2 emissions. We use the calculations of an LCA conducted by the PV system's manufacturer. The manufacturer's data comprises the emissions during resource exploitation, the module's production, as well as its disposal. Recycling information is not available. The study states that specific CO_2 emissions per kWh are 0.0295 kg_{CO2}. We transfer this to a peak power reference to 1.385 kg_{CO2}/Wp. (Hanwha Q CELLS GmbH)

Experimental setup and regression

The computational effort of the annual simulation using the HMPC is 26 h for an Intel Xeon© (3.07 GHz; 24 GB RAM; 64-bit operating system). Because of the high computational effort, we apply methods of DOE to efficiently maximize the information gain based on a reduced number of experiments. We follow the Central Composite Design approach, which is an experimental plan enabling the efficient assessment of three factors based on five levels. The consideration of five levels enables the observance of nonlinear behavior. This study defines the battery capacity, the PV power plant's peak power, and the CO_2 price as factors. The experimental plan is shown in Table 2.

Table 2: Simulated experimental plan used for the HMPC model following Central Composite Design

Exp. no.	Battery capacity in kWh	PV Peak Power in kWp	CO_2 price in €/t
1	304	527	41.5
2	1500	1300	102.5
3	750	0	102.5
4	750	2600	102.5
5	750	1300	0
6	750	1300	205
7	1196	527	41.6
8	304	2073	41.6
9	1196	2073	41.6
10	304	527	163.4
11	1196	527	163.4
12	304	2073	163.4
13	1196	2073	163.4
14	750	1300	102.5
15	0	1300	102.5

The battery capacity range of 0 to 1500 kWh derives from an internal calculation of minimum and maximum battery capacities. Regarding the PV plant we choose 0 as lower boundary. The upper boundary bases on the assumption that the PV plant covers the building's whole electrical load. An electrical load of 2372 MWh and an average of 900 full load hours results in a maximum PV peak power of approximately 2600 kWp. In accordance with the battery capacity and the PV peak power, the minimum factor value of the CO_2 price is set to 0 €/t. The upper boundary is set based on an estimation of the German Federal Environmental Agency, which calculates the resulting costs of climate change caused by increasing CO_2 emissions. The Agency calculates the costs for the years 2016, 2030, and 2050. For 2030, the costs are 205 €/t serving as an upper boundary (Bünger and Matthey, 2018). The CO_2 price is part of the HMPC's objective function. Hence, the system's optimal control and overall economic and environmental costs are influenced by the CO_2 pricing scenarios.

Polynomial-based Regression

The simulation results obtained from the experimental plan shown in Table 2 result in discrete values of the objectives. As we aim at analysing functional relations, we apply the concept of polynomial-based, multivariate regression. For both objectives $y(x_i)$, we determine the regression parameters b_i of a polynomial of second degree using the SciPy. Here, $x_i \in \{C_{\text{Bat}}, P_{\text{PVp}}, p_{\text{CO2}}\}$ serve as factors. As metric to evaluate the regression function's accuracy, we use R^2 and the normalized root mean squared error $NRMSE$.

Simulation results

For each experiment shown in Table 2, we perform annual simulations using the HMPC as controller. Based on the results of the 15 experiments, we deduce the polynomial of second-order and calculate its accuracy. We present the results in Table 3.

Table 3: Regression error metrics based on simulation results

Objective	$NRMSE$	R^2
Annuity	-0.0216	0.98
CO_2 emissions	0.0039	0.99

The $NRMSE$ and the R^2 show high accuracies. This is why we also allow the interpretation of interpolated values for the following analysis.

Economic assessment

A mathematical analysis of global optima for the deduced nonlinear regression function shows that the only extremum ($C_{\text{Bat}} = 643$ kWh, $P_{\text{PV,p}} = 3039$ kW, $p_{\text{CO2}} = 132$ €/t) is a saddle point and exceeds the boundaries set by the experimental plan. This is why we only maximize the regression function for two factors, while the residual factor is assumed to be constant in the following analysis. In Figure 1, the results for the optimized annuity with the respective optimal PV peak power and battery capacity are shown. The CO_2 price is varied from 0 to 205 €/t. We detect that an increase in CO_2 pricing supports the investment in larger PV plants. The trend of the optimal battery capacity is slightly decreasing. The overall system annuity reaches its minimum at around 120 €/ t. However, we want to highlight that the optimal sizes of the PV plant and the battery capacity are determined based on a mathematical formulation yielding sizes which exceed the maximum factors. This is why the results for CO_2 prices of 120, 160, and 205 €/t are extrapolations and hence less trustworthy.

To better understand the relation between battery capacity and PV plant sizing changes with the resulting annuity, we illustrate their interaction in Figure 2 for a fixed CO_2 price. We select a CO_2 price of 50 €/t as this was the average price in April 2021. As discussed earlier, we detect that an increase in PV plant sizing leads to a higher annuity. This trend results from the decrease in electricity taken from the grid and hence reduced operating costs. In addition, we observe that medium battery capacities lead to the highest annuities.

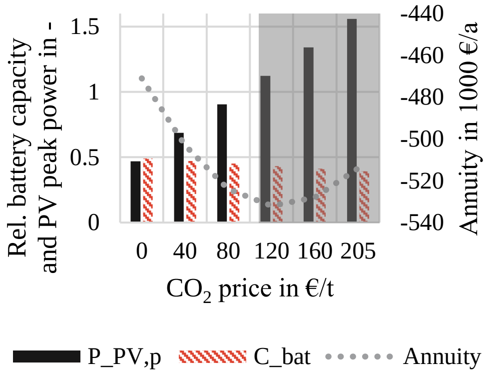

Figure 1: Annuity optima with respective C_{Bat} and PV_p for a CO_2 price of 50 €/t.The grey box marks the extrapolation beyond CCD boundaries.

For the selected CO_2 price and the sizing ranges, we deduce an optimal battery capacity of 702 kWh and an optimal PV plant size of 1909 kWp, yielding an annuity of -509,550 €/a. The annuity is negative for all factor combinations assessed in this study as we focus on investments and operating costs. Nonetheless, if a system without a PV-battery system is taken as a basis, the annuity increases by 22 %. Besides the interaction of PV-battery sizing and the annuity, we analyze the relation between CO_2 pricing, battery capacity, and the annuity. The results are depicted in Figure 3. The annuity decreases with increasing CO_2 pricing due to the resulting higher prices for electricity consumption.

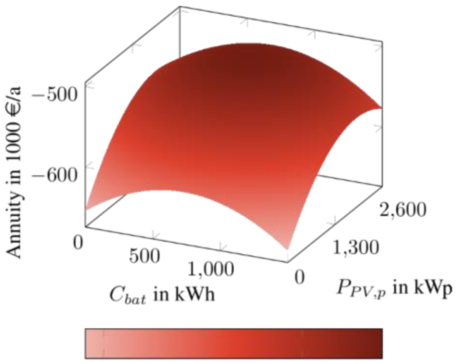

Figure 2: Relation of annuity, battery capacity, and PV peak power for a fixed CO_2 price of 50 €/t.

Ecological assessment

In addition to the economic assessment, we also investigate the effect of PV-battery sizing on the system's overall annual CO_2 emissions. At first, we investigate the relation between the annual emissions, the battery capacity, and the CO_2 price for a fixed PV plant size. Figure 4 shows the simulation results. We obtain minimum emissions when the battery capacity (~1500 kWh) and the CO_2 price (205 €/t) are high. Another effect is that depending on the CO_2 pricing

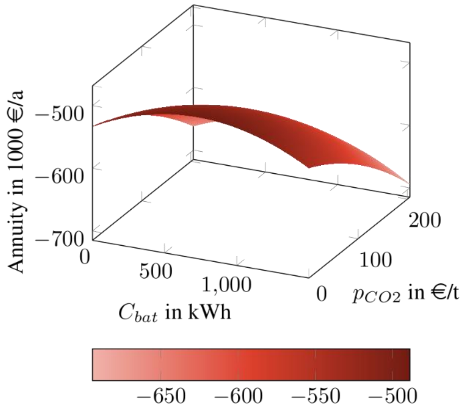

Figure 3: Relation of annuity, battery capacity, and CO_2 price for a PV plant of 2000 kWp.

This proves that a trade-off between the emissions primarily caused by the battery itself and those secundarily caused by the electricity consumption using the grid.

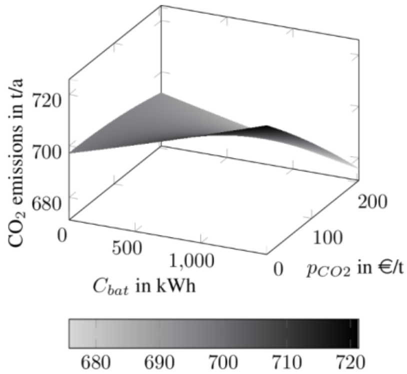

Figure 4: Relation of emissions, battery capacity, and CO_2 price for a fixed PV plant size of 2000 kWp.

scenario, higher battery capacities either cause higher or lower emissions than smaller ones. When analyzing the interaction of annual emissions, PV plant size, and the CO_2 price, there is a clear trend that emissions decrease with increasing PV peak power (see Figure 5). Apart from that, we analyze the economic optimum's effect on the overall emissions. To understand if the introduction of CO_2 pricing leads to decreased emissions, we analyze the economic optimum for given CO_2 prices of 0 and 100 €/t and calculate the resulting CO_2 emissions.

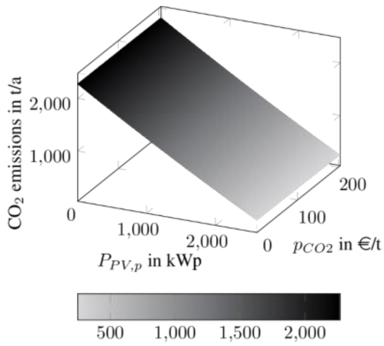

Figure 5: Relation of emissions, PV plant size, and CO_2 price for a battery capacity of 700 kWh.

For 0 €/t, the cost-optimal battery capacity is 737 kWh and the PV power is 1219 kW. If the CO_2 price increases to 100 €/t, the cost-optimal battery capacity decreases to 666 kWh while the optimal PV power equals 2600 kW. The latter, however, results in a decrease of emissions by 79.7 %. Consequently, CO_2 pricing provides incentives to save emissions.

Discussion

We calculate the grid-related CO_2 factors based on a predefined scenario for the power plant mix. However, a change in CO_2 pricing would presumably influence the power plant mix. This interaction would affect the discussed results as the introduction of CO_2 pricing would presumably decrease grid CO_2 factors. In addition, we assume a constant CO_2 and electricity price over the defined system's lifetime. Yet, the CO_2 price will presumably be adapted stepwise. In addition, we calculated the annuity optima in Figure 1 without considering the experimental plan's boundaries. Hence, we cannot conclude that the curve reflects actual relations, especially as the annuity minimum is on the threshold.

Conclusions and outlook

This study investigates the effect of CO_2 pricing on a PV-system's optimal design and operation in buildings. DOE serves as sizing method with PV peak power, battery capacity, and CO_2 price as factors. We yield optimal control by applying model predictive control. As objectives, we consider the annuity and life-cycle-based emissions to understand if CO_2 pricing is a suitable economic incentive for building owners to reduce emissions. Results prove that introducing CO_2 pricing results in higher annuities for large PV systems and medium batteries which simultaneously leads to reduced emissions. Consequently, eco-friendly technologies like PV-battery systems are economically favored. In addition, we detect that PV plants influence emissions more significantly than batteries. The introduction of batteries only leads to CO_2 emission reductions for CO_2 prices exceeding a threshold. The threshold depends on the PV system's size. In summary, CO_2 pricing mitigates the trade-off between emissions and costs. Future studies should include the interaction between integrating CO_2 prices and the resulting power plant mix and add constraints for the optimizations.

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