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Determining the minimal Battery Storage System subsidy: The Internal Rate of Return-based optimisation approach

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***Abstract*—Decarbonization efforts aimed at tackling the climate change issues rely on increasing use of renewable energy sources (RES) in the power system. In order to maximise their integration, significantly higher rollout of the battery storage systems (BSS) is necessary, even in the EU which set ambitious goal of achieving carbon neutrality by 2050. EU goals will be difficult to realize without incentives to battery storage. In this paper direct subsidies reducing the installation cost of BSS are considered. We use German power market data for the 2017 and 2021: intraday prices, day-ahead prices and primary reserve markets in particular. Battery storage is integrated with photovoltaics (PV) in order to provide electricity to small and medium sized industrial plants. In this setup the multi-objective optimisation (MOO) method to optimise the annual BSS operation is applied and internal rate of return is used to assess profitability. Since the BSS cycle lifetime (determined by market conditions) often exceeds the calendar lifetime, a fall in the profitability occurs which is used to calculate the subsidy level. The results suggest that the obtained subsidy range is within the range reported in practice considering the perfect foresight assumption used in the analysis. Also, lower subsidies are obtained for 2021 due to conditions more favourable for BSS operation.**

***Index Terms*—Battery Storage Subsidy, Internal Rate of Return (IRR), Multi-Objective Optimisation, Photovoltaic Systems, Renewable Energy**

NOMENCLATURE

A. Sets and indices

Ω^w	Set of weeks, running from 1 to 52
Ω^h	Set of hours, running from 1 to 168
Ω^q	Set of quarter-hour periods, running from 1 to 4

B. Parameters

μ^{ch}	Charging efficiency coefficient
μ^{dis}	Discharging efficiency coefficient
C^{fees}	Fees for supplying electricity (€/kWh)
p^{peak}	Peak power price (€/kW)
$p^{\text{DA}}_{w,h}$	Day-ahead market price (€/kWh)
$p^{\text{ID}}_{w,h,q}$	Intraday market price (€/kWh)
p^{FCR}_{w}	FCR market price (€/kW)
$P^{\text{pv}}_{w,h}$	Utilized PV generation (kWh)
P^{BSS}	Installed BSS power (kW)
$soe^{\max}$	Installed BSS capacity (kWh)

C. Variables

$C^{\text{el}}_{w,h}$	Cost of purchased electricity (€)
C^{peak}	Cost of peak power (€)
R^{FCR}_{w}	Revenue from FCR (€)
$e^{\text{BSS\_prod}}_{w,h,q}$	Electricity directed from BSS to industrial plants (kWh)
$e^{\text{BSS\_grid}}_{w,h,q}$	Electricity directed from BSS to the grid (kWh)
$e^{\text{pv\_prod}}_{w,h,q}$	Electricity directed from PV to industrial plants (kWh)
$e^{\text{pv\_grid}}_{w,h,q}$	Electricity directed from PV to the grid (kWh)
$e^{\text{pv\_BSS}}_{w,h,q}$	Electricity directed from PV to BSS (kWh)
$e^{\text{grid\_prod}}_{w,h,q}$	Electricity directed from the grid to industrial

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	plants (kWh)
$e_{w,h,q}^{\text{grid\_BSS}}$	Electricity directed from the grid to BSS (kWh)
$e_{w,h}^{\text{grid}}$	Electricity traded in the day-ahead and intraday market (kWh)
$e_{w,h}^{\text{DA}}$	Electricity traded in the day-ahead market (kWh)
$e_{w,h,q}^{\text{ID}}$	Electricity traded in the intraday market (kWh)
P_{w}^{FCR}	Power provided for FCR (kW)
soe_{w}^{FCR}	Capacity provided for FCR (kWh)
$P^{\text{ peak}}$	Peak power (kW)
$P_{w,h,q}^{\text{ch}}$	BSS charging power (kW)
$P_{w,h,q}^{\text{dis}}$	BSS discharging power (kW)
$soe_{w,h,q}$	BSS state of energy (kWh)
CF	Annual cash flow (€)
i	Internal rate of return $(\%)$
$x_{w,h,q}$	Binary variable for (dis)charging constraints
$y_{w,h,q}$	Binary variable for trading constraints

I. Introduction

A. Background and Motivation

The European Union (EU) clean energy policy promoted by the Renewable Energy Directive adopted in 2009 has led to a significant increase in total energy subsidies in the EU which has been driven by growing subsidies to Renewable energy sources (RES). According to [1] in the 2008-2018 period the share in total energy subsidies related to RES has grown from approximately 29% to 46% (22 billion euros to 73 billion euros in absolute terms). At the same time the share of fossil fuels subsidies decreased steadily from approximately 54% to 31%. However, it has to be noted that in absolute terms the total amount of fossil fuels subsidies in the EU remained relatively stable over the entire period - 51.4 billion euros in 2008 vs. 50.2 billion euros in 2018. Although the [2] does indicate a decline in fossil fuels subsidies in 2020 this is likely due to the Covid outbreak since the reported drop was related to the transport sector. The EU does seem to perform much better in this regard than the world in general since according to [3] share of fossil fuels subsidies in the world stood at 70% in 2017 and RES subsidies accounted for only 20% of the total. Nevertheless, according to [4] the fossil fuels subsidies do represent one of the biggest hurdles to transition to the RES-based power system.

However, unlike the rest of the world the EU seems undeterred in reaching the Paris Agreement goals of climate neutrality by 2050 since it has demonstrated, as shown in [5], that greenhouse gas emissions can be significantly reduced while maintaining strong GDP growth. The European Green Deal framework is therefore financially backed by the new EU budget and NextGenerationEU recovery and resilience package with 30% of funds designated to address the climate change issues as reported in [6]. Nevertheless, according to [7], apart from the previously mentioned fossil fuels subsidies issue, serious concerns exist regarding acknowledging the pivotal role of battery storage in the pursuit of 100% renewable energy system. Namely, based on the widely-recognized benefits of battery storage in the decarbonisation process [7, p. 6] stressed that "by providing flexibility and fast balancing services battery storage technologies provide all the conditions that are vital for maximising the integration of high shares of variable renewable energy sources". Therefore, the same source calls for leveling the playing field for battery storage by securing NextGenerationEU funds to facilitate the battery storage roll out and the national recovery and resilience plans for financing the support measures. It can be noted that only 5 European countries with large residential solar market were credited with over 90% of new battery storage installations. Out of those five, three are EU member states and have established direct financial incentives in the form of subsidies (Germany, Austria and Italy). Due to the fact that, according to [6], photovoltaics (PV) are viewed as the dominant power generation source in the climate neutral EU, battery storage paired to a PV is analysed in this research.

The goal of this paper is therefore to determine the minimal level of subsidy for a battery storage paired to a PV based on market prices. We apply linear mixed-integer multi-objective optimisation (MOO) model to maximise profitability of operations of such battery storage system (BSS) which is generating cash flows by providing cost reduction to industrial plants and by participating in ancillary services and arbitrage in the day-ahead and intraday markets. The internal rate of return (IRR) is used as a profitability measure in order to calculate the required subsidy. The methodology employed allowed the calculation of cash subsidies based on kWh of storage capacity by reducing the cost of installation. This follows the recommendation in [7, p. 6] which argues against flat subsidies which have proven ineffective since they lead to suboptimal storage capacities. The results of our model show that under perfect foresight assumption used in this analysis the proposed level of subsidies remains within range adopted in the EU member states practice.

B. Literature Review

The problem of lack of subsidies for battery storages, although they do provide benefits to RES, has been pointed out by [8] who also note that battery storages are not being rewarded for their higher accuracy and faster response when providing ancillary services. [9] note that the cost of battery storage subsidies could be compensated by the savings generated by lower grid investment need and stress that battery size and cost have significant impact on profitability. [10] point out the role of RES for the European Green Deal and highlight the PV as attractive decarbonisation solution if it is paired with battery storage to help mitigate the drawback of variable power generation. Their paper focuses on tax depreciation incentive which allows tax deductions for battery investment in Italy. Based on the Net Present Value (NPV) method they conduct break-even point analysis in order to evaluate the levels of self-consumption which determine profitability since it is known that PV profitability depends largely on that factor. [11] show that battery storage subsidy of 100 €/kWh for energy storage capacity makes the investment feasible for a prosumer relying on a PV. They find that the proposed subsidy reduces the battery cost 2.5 to 3 times, however, they do not rely on any economic viability method or optimisation model for the system. [12] provide a metric for the cost of energy storage in order to determine the optimal size of energy storage. Again, based on a battery storage paired to a PV they conclude that the system is viable in Germany due to the difference between the retail and feed-in tariff while in California the existing subsidies present the main investment incentive. [13] assess the attractiveness of pairing a battery storage and a PV by applying NPV and IRR as profitability measures. In the analysis different market electricity prices are considered as well as different price increase rates installation costs and subsidies for 13 European countries. The results suggest that the battery storage can be cost-effective without subsidies in the rising electricity prices environment.

The approach adopted in this research proposes several enhancements relative to the papers listed above. In relation to the work of [10] the IRR is used as profitability measure which makes the break-even point analysis redundant since the IRR represents the rate at which the NPV is zero. Additionally, direct incentive in the form of cash subsidy which reduces the cost of battery storage installation is analysed unlike in [10] and as suggested by [9]. Furthermore, unlike in [13] MOO model is applied to maximise the profitability of operations of analysed battery storage system (BSS) while relying on the IRR as profitability measure. Finally, in contrast to [12] we vary c-rate and storage capacity in order to assess the subsidies for various storage power and capacities.

The paper is further organised as follows; Section II describes the data and methodology and also presents the findings, while Section III concludes the research and provides guidelines for the future research by addressing the limitations of the performed analysis.

II. Data and Methodology

A. Data

In this research we used German wholesale electricity price data for 2017 and 2021. More specific, available day-ahead prices (one-hour resolution) and intraday prices (15-minutes resolution) were obtained from the ENTSO-e webpage and the EPEX-Database. However, the 2021 intraday prices were not publicly available, thus we ran a stochastic simulation to generate a time-series of those prices. The frequency containment reserve (FCR) prices (6-hour interval resolution for 2021 and weekly resolution for 2017) were downloaded from the ENTSO-e webpage. The peak power price and the electricity supply fee are set as the average for SMEs in Baden-Württemberg.

The battery price is assumed to be 400 *€/kWh* and 400 *€/kW*, while the PV price is assumed to be 1750 *€/kW*. Data for the PV electricity production were obtained from the renewables.ninja website. Finally, the load profiles (observed 15-minutes resolution) were related to the 50 different German small and medium sized enterprises (SME) (industrial plants) in 2017 available at: https://zenodo.org/record/3899018.YqOJmxrP2Um.

B. Battery Storage System Operation

Battery storage is paired with PV to provide energy supply for industrial plants. Throughout the analysis the PV power is maintained at the same level as the battery storage power. A battery can be charged from the grid (buying on day-ahead and intraday markets) or from the PV and can be discharged back to the grid or to the industrial plants. The battery storage can also provide primary reserves. Finally, the electricity from PV can be stored in the battery, used for the demand of industrial plants or sold to the grid.

Revenue is generated by industrial plants' lower electricity costs (which also include peak shaving), arbitrage in day-ahead in intraday markets and providing primary reserves.

Our model is specified in the following way. First, the cost function and its components are defined:

$$cost = \sum_{w} \left(\sum_{h} C^{\text{el}}_{w,h} - R^{\text{FCR}}_{w} \right) + C^{\text{ peak}} \tag{1}$$

$$C^{\text{el}}_{w,h} = e^{\text{DA}}_{w,h} \cdot p^{\text{DA}}_{w,h} + \sum_{q=1}^{4} \left(e^{\text{ID}}_{w,h,q} \cdot p^{\text{DA}}_{w,h,q} \right) + \sum_{q=1}^{4} \left(e^{\text{grid\_BSS}}_{w,h,q} + e^{\text{grid\_prod}}_{w,h,q} \right) \cdot C^{\text{ fees}}, \quad \forall w,h \tag{2}$$

$$R^{\text{FCR}}_{w} = P^{\text{FCR}}_{w} \cdot p^{\text{FCR}}_{w}, \quad \forall w \tag{3}$$

$$C^{\text{ peak}} = P^{\text{ peak}} \cdot p^{\text{ peak}} \tag{4}$$

$$P^{\text{ peak}} \geq e^{\text{grid}}_{w,h,q} \cdot 4, \quad \forall w,h,q \tag{5}$$

In (1) the objective function is defined. Cost of electricity, cost of peak power and revenues from primary reserves are considered.
Equation (2) computes the cost of electricity with fees.
In (3) weekly revenue from primary reserves is defined.
In (4), (5) the cost of peak power and the peak power itself are defined respectively.

$$soe^{\text{FCR}}_{w} = n \cdot P^{\text{FCR}}_{w}, \quad \forall w \tag{6}$$

$$soe^{\text{FCR}}_{w} \leq soe^{\text{ max}}, \quad \forall w \tag{7}$$

$$P^{\text{FCR}}_{w} \leq P^{\text{ BSS}}, \quad \forall w \tag{8}$$

$$soe_{w,h,q} \leq soe^{\text{ max}} - soe^{\text{FCR}}_{w}, \quad \forall w,h,q \tag{9}$$

$$P^{\text{ch}}_{w,h,q} \leq P^{\text{ BSS}} - P^{\text{FCR}}_{w}, \quad \forall w,h,q \tag{10}$$

$$P^{\text{dis}}_{w,h,q} \leq P^{\text{ BSS}} - P^{\text{FCR}}_{w}, \quad \forall w,h,q \tag{11}$$

Equations (6) through (11) implement restrictions on the available battery capacity and power with respect to capacity and power reserved for primary reserves market and with respect to installed battery capacity and power.

$$soe_{w,h,q} = soe_{w,h,q-1} + \frac{P^{\text{ch}}_{w,h,q} - P^{\text{dis}}_{w,h,q}}{4} \quad \forall w,h,q \setminus q_1 \tag{12}$$

$$soe_{w,h,q} = soe_{w,h-1,q_4} + \frac{P^{\text{ch}}_{w,h,q} - P^{\text{dis}}_{w,h,q}}{4} \quad \forall w,h,q_1 \setminus h_1 \tag{13}$$

$$soe_{w,h,q} = soe_{w-1,h_{168},q_4} + \frac{P^{\text{ch}}_{w,h,q} - P^{\text{dis}}_{w,h,q}}{4} \quad \forall w,h_1,q_1 \setminus w_1 \tag{14}$$

$$soe_{w_1,h_1,q_1} = \frac{P^{\text{ch}}_{w,h,q} - P^{\text{dis}}_{w,h,q}}{4} \tag{15}$$

$$P^{\text{ch}}_{w,h,q} \leq x_{w,h,q} \cdot M, \quad \forall w,h,q \tag{16}$$

$$P^{\text{dis}}_{w,h,q} \leq (1 - x_{w,h,q}) \cdot M, \quad \forall w,h,q \tag{17}$$

Equations (12) through (15) define the battery state of charge in the current period in relation to (dis)charging from the previous period while (16) and (17) use binary variable x to deny the simultaneous charging and discharging of the battery.

$$d_{w,h,q} = e^{\text{BSS\_prod}}_{w,h,q} + e^{\text{grid\_prod}}_{w,h,q} + e^{\text{pv\_prod}}_{w,h,q}, \quad \forall w,h,q \tag{18}$$

$$P^{\text{pv}}_{w,h} = \sum_{q=1}^{4} \left(e^{\text{pv\_prod}}_{w,h,q} + e^{\text{pv\_grid}}_{w,h,q} + e^{\text{pv\_BSS}}_{w,h,q} \right), \quad \forall w,h \tag{19}$$

$$e^{\text{grid}}_{w,h,q} = e^{\text{grid\_BSS}}_{w,h,q} + e^{\text{grid\_prod}}_{w,h,q} - e^{\text{BSS\_grid}}_{w,h,q} - e^{\text{pv\_grid}}_{w,h,q}, \quad \forall w,h,q \tag{20}$$

$$\sum_{q=1}^{4} e^{\text{grid}}_{w,h,q} = e^{\text{DA}}_{w,h} + \sum_{q=1}^{4} e^{\text{ID}}_{w,h,q}, \quad \forall w,h \tag{21}$$

In (18) the demand from industrial plants is met by buying from the grid, discharging previously stored electricity from the battery or using PV's electricity.
In (19) the usage of electricity from PV is defined.
Equations (20) and (21) describe the electricity traded with the grid.

$$P^{\text{ch}}_{w,h,q} = \mu^{\text{ch}} \cdot 4 \cdot (e^{\text{grid\_BSS}}_{w,h,q} + e^{\text{pv\_BSS}}_{w,h,q}), \quad \forall w,h,q \tag{22}$$

$$P^{\text{dis}}_{w,h,q} = \frac{1}{\mu^{\text{dis}}} \cdot 4 \cdot (e^{\text{BSS\_grid}}_{w,h,q} + e^{\text{BSS\_prod}}_{w,h,q}), \quad \forall w,h,q \tag{23}$$

$$P^{\text{ch}}_{w,h,q} + P^{\text{dis}}_{w,h,q} \leq P^{\text{BSS}}, \quad \forall w,h,q \tag{24}$$

$$e^{\text{DA}}_{w,h} \leq y_{w,h} \cdot M, \quad \forall w,h \tag{25}$$

$$e^{\text{DA}}_{w,h} \geq (y_{w,h} - 1) \cdot M, \quad \forall w,h \tag{26}$$

$$e^{\text{ID}}_{w,h,q} \leq y_{w,h} \cdot M, \quad \forall w,h,q \tag{27}$$

$$e^{\text{ID}}_{w,h,q} \geq (y_{w,h} - 1) \cdot M, \quad \forall w,h,q \tag{28}$$

$$e^{\text{BSS\_total}} = \sum_{w} \left(\sum_{h} \left(\sum_{q} \left(e^{\text{grid\_BSS}}_{w,h,q} + e^{\text{PV\_BSS}}_{w,h,q} \right) \right) + P^{\text{FCR}}_{w} \cdot f^{\text{FCR}} \right) \tag{29}$$

Equations (22) through (24) define the charging and discharging power for each period considering the charging and discharging inefficiencies and battery power.
Equations (25) through (28) use binary variable y to deny the simultaneous buying at the one market and selling at the other. Finally, (29) computes annual cycle degradation as total energy that went through the battery.

C. Research Methodology

Battery storage purchase represents the largest capital expenditure (i.e. cash outflow) for any investor. Therefore, the level of battery storage subsidy greatly defines system size, operational settings and business efficiency. To estimate the minimal level of battery storage subsidy we used the IRR as a key economic metric to capture the BSS' financial performance. Namely, IRR represents the compounded annual profitability rate of a project with respect to capital expenditures and expected net cash flows over the project's lifetime. Thus, IRR is the key variable in the process of linear mixed-integer multi-objective optimisation.

In the research we assume that BSS will provide investors with a continuous and constant level of benefits (cash flows from energy savings and revenues from ancillary services and electricity prices arbitrage trading) over all years of operation. Thus, the IRR can be defined as:

$$\frac{(1+i)^T - 1}{(1+i)^T \cdot i} = \frac{I}{CF}\,, \tag{30}$$

where i is the internal rate of return of BSS, T is the battery cycle lifetime, I is initial investment in battery and CF are cash flows which are assumed constant for the whole lifetime T.
Cash flows are defined as the difference between the cost without BSS, $cost_{w/ob}$ and the cost with the BSS, $cost$:

$$CF = cost_{w/ob} - cost\,. \tag{31}$$

TABLE I
MOO EFFECTS FOR C-RATES 0.4 AND 0.5 (CAP. 3 MWH AND 4MWH) IN 2017

Capacity	c-rate	Investment	BSS cash flows	Optim. points	T	IRR	T'	IRR'
			531 144	op_1	15.64	8.79%	15.64	8.79%
			531 060	op_2	17.60	9.62%	17.60	9.62%
			530 783	op_3	20.11	10.34%	20.00	10.31%
			530 219	op_4	23.46	10.93%	20.00	10.29%
3000	0.5	-4 425 000	529 203	op_5	28.16	11.39%	20.00	10.27%
			527 087	op_6	35.20	11.67%	20.00	10.21%
			508 867	op_7	46.93	11.43%	20.00	9.69%
			463 718	op_8	70.39	10.47%	20.00	8.39%
			410 028	op_9	140.79	9.27%	20.00	6.76%
			569 140	op_1	16.57	8.26%	16.57	8.26%
			569 005	op_2	18.64	9.04%	18.64	9.04%
			568 580	op_3	21.30	9.72%	20.00	9.42%
			567 866	op_4	24.85	10.28%	20.00	9.40%
4000	0.4	-5 040 000	566 558	op_5	29.82	10.70%	20.00	9.37%
			564 224	op_6	37.27	10.96%	20.00	9.31%
			559 204	op_7	49.70	11.03%	20.00	9.18%
			510 663	op_8	74.55	10.12%	20.00	7.93%
			445 884	op_9	149.10	8.85%	20.00	6.18%

We used the multi-objective optimisation method known as epsilon constraint method presented in [14]. Two objective functions we optimized were the cost function and the $e^{\text{BSS\_total}}$ function which computes the depletion of battery cycles. This method yields a Pareto optimal front for each battery capacity and power parameter. For every point of the Pareto front the IRR is computed and the point with the highest IRR is chosen as optimal for that particular capacity and power.

The results of the multi-objective optimisation can be seen in Table I. With each step op_n, the optimisation has stricter constraints with regard to lower amount of cycles to work with annually resulting in higher costs but longer battery lifetime. In example in Table I the offset is paying off until optimisation points op_6 and op_7 when the IRR begins to decrease. The results of MOO are T and IRR for optimal optimisation point op_n.

However, if battery calendar lifetime of 20 years is assumed (which is closer to real-world scenario than the optimisation output in some cases), new results are obtained and denoted

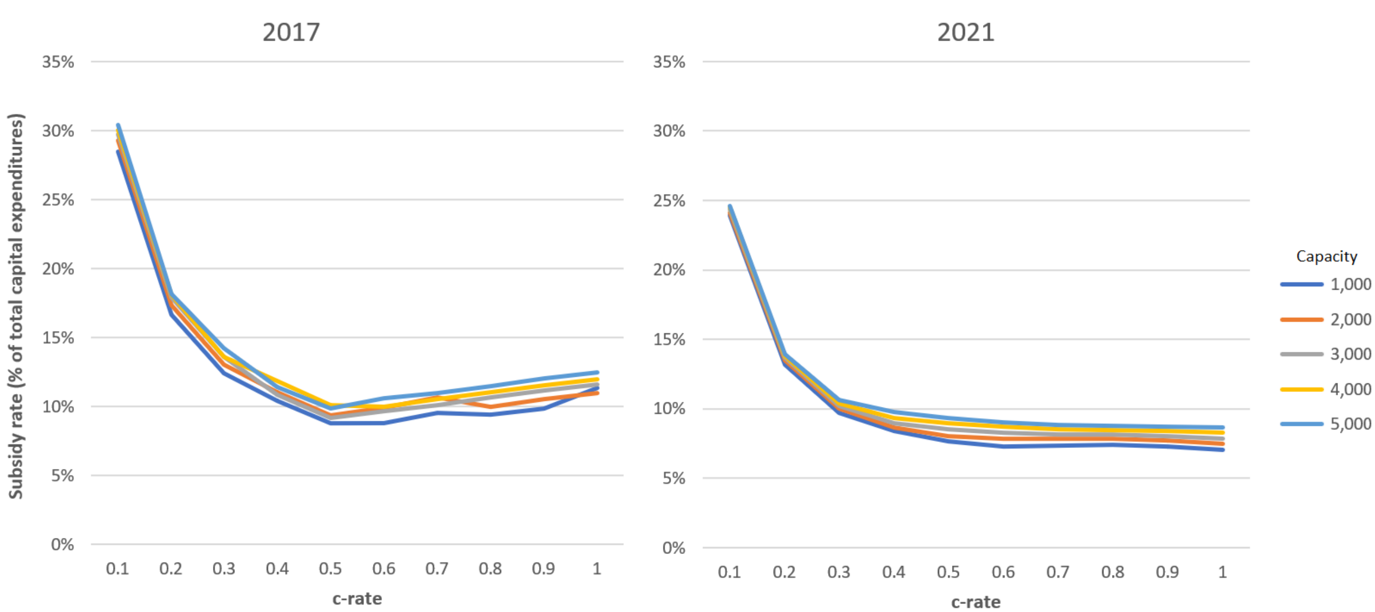

Fig. 1. Minimal subsidy levels for various c-rates and capacities in 2017 (left) and 2021 (right)

TABLE II
SUBSIDIES IN €/KWH FOR VARIOUS CAPACITIES AND C-RATES IN 2017

	Capacity				
c-rate	**1 000**	**2 000**	**3 000**	**4 000**	**5 000**
0.1	175	180	183	185	187
0.2	138	144	149	150	150
0.3	130	136	142	142	148
0.4	131	139	136	149	144
0.5	130	137	135	149	146
0.6	148	167	163	169	179
0.7	182	203	193	200	209
0.8	199	211	225	234	243
0.9	230	245	260	269	280
1	289	280	295	306	318

by T' and IRR', where T' is the minimum of battery calendar lifetime (20 years) and cycle lifetime (5000 cycles) and IRR' is the internal rate corresponding to the new lifetime T'.

The fact that investors are bounded by (more realistic and reasonable) number of calendar lifetime years of BSS' exploitation means that they are facing suboptimal IRRs relative to available market opportunities. This fact can be also seen as a reasonable basis for determining the minimal level of battery storage subsidy. Thus, in the process of determining the minimal level of subsidy we determined the maximal acceptable level of investment costs, which assures the optimal (higher) levels of IRR (IRR instead of $IRR^{'}$) within calendar lifetime years of BSS' exploitation:

$$I_0^{\max} = CF \cdot \frac{(1+i)^{T'} - 1}{(1+i)^{T'} \cdot i}\,, \tag{32}$$

where T' is the minimum between battery calendar lifetime (20 years) and cycle lifetime (5000 cycles).

In order to obtain the minimal level of battery storage subsidy as a percentage of overall capital expenditures we compared the maximal acceptable level of investment costs with the actual ones:

$$\text{subsidy}_{\%}^{\min} = 1 - \frac{I_0^{\max}}{I_0}\,. \tag{33}$$

Also, we calculated the minimal level of battery storage subsidy in monetary terms per capacity of BBSs installed (*€/kWh*):

$$\text{subsidy}_{\text{€/kWh}}^{\min} = \frac{I_0 - I_0^{\max}}{soe^{\max}}\,. \tag{34}$$

Since the optimisation is based on real-time market data, no forecasts are used in the optimisation procedure, i.e. the analysis assumes perfect foresight. Therefore, we refer to the obtained results as the minimal BSS subsidy level.

D. Findings

Table I shows a small fraction of the overall results of the multi-objective optimisation. Namely, a large number of optimisation outputs is a result of numerous observed system setups (battery capacities, c-rates, market data samples, and optimisation points). Further analysis is carried out for each possible setup at an optimisation point with the highest IRR.

Figure 1 shows the minimal level of battery storage subsidy for various c-rates and capacities. It can be seen that maximum subsidies required are achieved for lower c-rates. Since, in the case of lower c-rates, the battery has smaller power, it is not charged and discharged that much annually so the battery cycle lifetime of the optimal MOO optimisation point is longer than for higher c-rates. Therefore, subsidy needs to compensate for a longer time period leading to an increase. Also, general tendency related to higher subsidies for higher capacities can be observed. In 2017, subsidies achieve minimum for c-rate of 0.5 which can be traced back to the fact that c-rate of 0.5 for all capacities gives the maximal internal rate of return. Note that the level of subsidies is higher in 2017 (ranging from slightly below 10% to slightly above 30%) than in 2021 (ranging from slightly below $\sim 8\%$ up to 25%).

Table II shows the subsidies in *€/kWh* for 2017. The subsidization range is $130-318$ *€/kWh* with an average of 189 *€/kWh*. The minimal subsidy levels for 2021 are somewhat lower, with a range of $81 - 221$ *€/kWh* and an average of 129 *€/kWh*. Since these are minimal subsidization ranges, they support the reported subsidy range applied in practice according to [7] ($200 - 300$ *€/kWh*). However, again with the minimal subsidy point in mind, the results do not support findings from [11] which propose only 100 *€/kWh* subsidy.

It can be seen From Figure 1 and also from Table II that the minimal level of battery storage subsidy is always at lower levels in 2021 than in 2017. Market conditions in 2021 were more volatile and the prices were higher, thus creating the more favourable environment for BSS deployment requiring lower subsidies. This corroborates the findings of [13] as they claim that the battery storage can be cost-effective without subsidies in the rising electricity prices environment.

III. CONCLUSION

This research provides analysis based on multi-objective optimisation method and on internal rate of return as a profitability measure. Battery calendar lifetime of 20 years is assumed as constraint and as motivation for determination of minimal level of BSS subsidies since the obtained results show that battery cycle lifetime is often longer than calendar lifetime, due to market conditions. The results imply that the subsidy range in *€/kWh* is $130-318$ in 2017 and $81-221$ in 2021. 2021 requires lower subsidy levels since the prices are more volatile and higher improving the market conditions for BSS operation.

There are a few limitations of the conducted analysis which should be addressed in future research. One such limitation lies in the fact that optimisation of BSS operations is carried out under perfect foresight. Therefore, future research should include electricity prices forecasting which is expected to increase the reported minimal subsidization levels. It remains to be seen if the range of subsidies will remain in $200-300$ *€/kWh* range used in practice as reported in [7]. Another limitation is related to the fact that the installed PV power was constantly kept at the same level as installed battery power. BSS profitability and with that minimal subsidies required probably depend on the PV power to battery storage power ratio. Finally, the optimisation in this research is carried out under no calendar lifetime constraint, which is considered only after optimising for the internal rate of return. Introducing that constraint directly in the optimisation should result in a better use of battery storage and therefore a lower difference between optimal IRR and IRR' (under calendar lifetime constraint). Future research can thus reveal whether abandoning the perfect foresight assumption will prevail over lowering the difference between the IRRs. However, based on our analysis we would expect the effect of the difference in IRRs to be relatively low and the effect of forecasting to be quite significant.

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