Photovoltaics and battery storage— Python-based optimisation for innovation tenders

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Abstract—One of the main concerns in extending variable renewable energy (VRE) is the electric grid stability due to the sources' volatility. Germany is introducing a new auction mechanism within the German Renewable Energy Sources Act called "Innovationsausschreibung" (innovation tender) to grid- and system-supporting VRE-plants operation. The participating hybrid power systems (HPS) must be able to provide one-quarter of their installed power as positive automatic frequency restoration reserve (aFRR). This paper reflects on the optimal operation and design focusing on sizing an HPS consisting of ground-mounted large-scale photovoltaic (PV) and battery energy storage systems (BESS). An optimisation model is developed in Python. It is solved using the Gurobi framework with generation as well as market data for the German spot and balancing market. The optimisation maximises the HPS's revenue under consideration of the BESS costs for the applications energy arbitrage (EA) and aFRR. A case study for a ground-mounted PV reference project verifies the effectiveness of the model. Ultimately, a sensitivity analysis with long-term market prices and BESS costs along with different bit strategies is conducted. The total revenues less annual BESS costs vary from -3.5% for EA to +10.1% for the sequential combination of EA and participation in the aFRR-market compared to a stand-alone PV system. Considering actual BESS costs and market data, a minimum BESS design is the most economical from today's perspective. Due to decreasing BESS costs and increasing market volatility, this is expected to change within the next five years.

Keywords—Battery storage, Photovoltaics, Optimisation, Operation, Sizing, Innovation tender, Energy arbitrage, Balancing market

NOMENCLATURE

Symbols

c	Cost coefficient, €/MW, €/MWh
i	Interest rate, %
int	Integer value, –
max	Maximisation, –
t	Time step, h
AC	Annual costs, €/a
CRF	Capital recovery factor, –
CP	Capacity price, €/MW
DOD	Depth of discharge, %
E	Energy, Wh
EP	Energy price, €/MWh
FC	Full cycles, –
FLH	Full load hours, h
FM	Fixed market premium, €/MWh
LT	Lifetime, a
MP	Market price, €/MWh
OMC	Operation and maintenance cost factor, %
P	Power, W
Rev	Revenues, €
SOC	State of charge, %
$SYNF$	Synergy factor, %
T	Time interval, h
T	Retrieval length, MWh/MW
η	Efficiency, %
σ	Retrieval probability, %

Indices

aFRR	Automatic frequency restoration reserve
ch	Charging
dis	Discharging
init	Initial
max	Maximum
min	Minimum
peak	Peak Power
r	Real
ref	Reference
tot	Total
BESS	Battery energy storage system
CP	Capacity price
E	Energy-related
EA	Energy arbitrage
HPS	Hybrid power system
Inv	Inverter
P	Power-related
PV	Photovoltaic

I. INTRODUCTION

By 2050, renewable energies provide 80% of the electricity generation, according to a German government's goal. One main driver of the energy transition is photovoltaic (PV) with a 10.5% share of the net electricity generation in 2020 [1]. Their main features are simple implementation, a high degree of maturity, and steadily declining levelized cost of electricity.

As a result of nuclear power and coal phase-out in Germany, an increase in electricity generation from variable renewable energy (VRE) is expected, which increases the challenge for grid operators to maintain grid stability. Flexibility options such as grid expansion, storage, and load control are intended to maintain grid stability. A hybrid power system (HPS) is one option to meet this challenge by combining the advantages of generation and storage technologies. For example, seasonally complementary electricity generation from wind and solar energy can be used, which can also reduce grid connection costs. An additional storage system can further increase the utilisation of VRE and provide grid support measures. Various studies [2]–[5] provide an overview of technologies, applications, and combinations of HPS based on VRE.

In the context of the 2020 innovation tender (InnAus) in Germany, the Federal Network Agency (BNetzA) separately tendered such a plant combination for the first time. Until 2028, according to the Renewable Energy Sources Act 2021 (EEG 2021), a cumulative 5.4 GW will be tendered within InnAus. From today's perspective, this funding should be seen as one of the key drivers

for the implementation of battery energy storage systems (BESS) in the German power grid. A market overview of stationary BESS for Germany is presented in [6]. First, energy storage can contribute to grid stability and system security. Second, with appropriate marketing, it is expected that increased revenues for the HPS operator will occur.

The optimal sizing of an HPS depends on a multitude of marketing opportunities coupled with rapidly changing market conditions. Technical, economic, and regulatory aspects must be considered. In the publications [7]–[10] optimisation approaches for HPS are presented. The studies focus mainly on off-grid and building energy systems. The objective presented in the papers is usually to maximise the systems' reliability or self-sufficiency. Specifically, the optimisation of BESS in combination with PV is addressed in [11]–[13]. Software used for sizing HPS is shown in [3] and [14].

The aforementioned methods have only limited applicability to the problem at hand. Deviations in the objective function and the market constraints, as well as limitations in usability, become apparent. In consequence, an own optimisation model is developed by adapting the methodology published in [15] and [16]. The model fulfils the specific requirements for the hybrid system from InnAus regulation. Furthermore, it offers the user a detailed technical and economic insight into the operation of the hybrid system by providing various applications.

II. SYSTEM DESIGN AND REGULATORY ASPECTS

The tender requires a system combination of VRE-plants, such as PV, and non-VRE-plants or storage facilities. Furthermore, this HPS must be technically capable of providing a minimum of 25% of the installed power capacity ("25%-criteria") as positive automatic frequency restoration reserve (aFRR).

In the case of implementing a storage facility in the HPS, energy must be delivered for at least two hours at nominal power[1]. It must be charged exclusively by the co-located VRE. Consequently, no electricity used in the HPS may be taken from the grid, "green electricity rule". That limits BESS marketing options. For example, without asset pooling, no participation in the frequency containment reserve (FCR) market is possible. The feed-in of the various assets has to take place via the same grid interconnection point.

Using the fixed market premium, the subsidy method varies from regular tenders. However, if the price on the

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[1]This requirement was appended in §13 (2) InnAusV after the first tender.

day-ahead market for certain hourly contracts is negative, the market premium for these hours is reduced to zero. This was the case for 2.4% of the total hours in 2019 and 3.4% in 2020 based on German day-ahead market data [17]. The indicated risk of revenue loss can be reduced by utilisation of a BESS.

In this research, an HPS consisting of a ground-mounted PV array and a BESS is considered. The optimisation utilises an empirical storage model to ensure the applicability of different BESS technologies. Hourly generation data of a PV asset and the referring market prices are used as input data. The model can be adopted with appropriate generation data for any plant outputs in this order of magnitude. The use of other generation profiles, such as an east-west design, is also possible.

An economic operation, the power and energy capacity of the BESS are the key results of the optimisation. In addition, the BESS's and HPS's revenues, full load hours, cycles and opportunity costs are calculated. At an early project stage, the optimisation is an indication for the process design and component sizes. The main assumptions of the model are:

- PV generation and BESS power are constant for the respective hour.
- Day-ahead and aFRR market are considered.
- Sufficient energy demand and capacity are available in the grid.
- Round trip efficiency is assumed for the BESS.
- PV array costs are not considered. The focus is on BESS costs.
- Perfect forecast quality of weather and market data is assumed.

III. Optimal Storage Sizing and Operation

The BESS should be techno-economic optimally sized in relation to a large-scale PV system. Due to the specific costs, the available land area is decisive for the rated power design of PV systems, capped by subsidy limits[2]. The sizing of power and energy capacity of the associated BESS, on the other hand, depends on technical, regulatory, and market aspects.

A mixed-integer linear optimisation is realised within the Python-based Gurobi framework taking into account a full operation year. The objective is the optimal design and operation of BESS to maximise the HPS-revenues considering the BESS costs. Two applications described in the following sections are examined.

[2]The subsidy limit for PV arrays was raised to 20 MW in EEG 2021.

A. Energy Arbitrage

With the first application of energy arbitrage (EA), BESS partially shifts the electricity generated by PV into hours of higher spot market prices.

1) Objective Function: The objective function of the model is to maximise the difference between the total revenue of HPS and the annual cost of BESS.

$$\max \ (Rev_{\text{HPS}} - AC_{\text{BESS}}) \tag{1}$$

The annual revenue of HPS represents the income from the spot market including subsidies.

$$Rev_{\text{HPS}} = \sum_{t}^{8760} (P_{\text{Feed-in}}(t) \cdot (MP(t) + FM(t)) \cdot T) \tag{2}$$

The fixed market premium *FM* depends on whether the spot market price is positive or negative. The time period of each time step *T* is one hour. The annual expenses for the BESS consist of its annuity and operation and maintenance costs, dependent on the total investment. Due to the co-location of the assets with infrastructure shared, a synergy factor is implemented.

$$AC_{\text{BESS}} = (CRF + OMC) \cdot (1 - SYNF)$$
$$\cdot (c_{\text{E}} \cdot E_{\text{BESS}} + c_{\text{P}} \cdot P_{\text{BESS}}) \tag{3}$$

With the annuity factor of a present value:

$$CRF = \frac{i_{\text{r}} \cdot (1 + i_{\text{r}})^{LT}}{(1 + i_{\text{r}})^{LT} - 1} \tag{4}$$

2) Energy Balance: The feed-in power sums up all of the HPS power streams. In the case of direct grid feed-in from PV, the inverter losses are also taken into account.

$$P_{\text{Feed-in}}(t) = P_{\text{PV}}(t) \cdot \eta_{\text{Inv}} + P_{\text{BESS, dis}}(t)$$
$$- P_{\text{BESS, ch}}(t) - P_{\text{Curtailment}}(t) \tag{5}$$

If the market price becomes negative, the self-regulated curtailment of the HPS is calculated.

$$MP(t) < 0 \longrightarrow P_{\text{Curtailment}}(t) = P_{\text{PV}}(t) \cdot \eta_{\text{Inv}} - P_{\text{BESS, ch}}(t) \tag{6}$$
$$MP(t) \geq 0 \longrightarrow P_{\text{Curtailment}}(t) = 0 \tag{7}$$

3) Constraints: The following constraint is needed to fulfil the 25%-criteria in terms of the minimum BESS power. The denominator takes into account the losses up to the grid interconnection point.

$$\frac{(P_{\text{PV, peak}} + P_{\text{BESS}})}{4 \cdot \sqrt{\eta_{\text{tot}}}} \leq P_{\text{BESS}} \leq P_{\text{PV, peak}} \tag{8}$$

With the minimum and maximum C-rate, a suitable range for power to energy ratio is defined, and the two-hour criteria is fulfilled.

$$C\text{-}Rate_{\min} \leq \frac{P_{\text{BESS}}}{E_{\text{BESS}}} \leq C\text{-}Rate_{\max} \qquad (9)$$

The charging and discharging power is constrained due to the BESS design. The charging power cannot be greater than the power of PV to ensure no power is drawn from the grid.

$$0 \leq P_{\text{BESS, ch}}(t) \leq P_{\text{BESS}} \wedge P_{\text{PV}}(t) \qquad (10)$$

$$0 \leq P_{\text{BESS, dis}}(t) \leq P_{\text{BESS}} \qquad (11)$$

The following equation applies to prevent simultaneous charging and discharging. This relation can be integrated using binary variables to keep the model linear.

$$P_{\text{BESS, dis}}(t) \cdot P_{\text{BESS, ch}}(t) \overset{!}{=} 0 \qquad (12)$$

During operation, the energy limits are defined as follows.

$$E_{\text{BESS}} \cdot (1 - DOD) \leq E_{\text{BESS}}(t) \leq E_{\text{BESS}} \qquad (13)$$

The storage operation is established under the influence of the total efficiency from the PV array's output to the grid connection with respect to an entire cycle.

$$E_{\text{BESS}}(t+1) = E_{\text{BESS}}(t) + P_{\text{BESS, ch}}(t) \cdot \sqrt{\eta_{\text{tot}}} \cdot T$$
$$- \frac{P_{\text{BESS, dis}}(t)}{\sqrt{\eta_{\text{tot}}}} \cdot T \qquad (14)$$

To avoid additional grid connection costs, the maximum simultaneous feed-in power is limited.

$$P_{\text{Feed-in}}(t) \overset{!}{\leq} P_{\text{PV, peak}} \qquad (15)$$

The SOC is specified as a start value. Generally, it is calculated from optimisation results.

$$E_{\text{BESS}}(t=1) = E_{\text{BESS}} \cdot SOC_{\text{init}} \qquad (16)$$

$$SOC(t) = \frac{E_{\text{BESS}}(t)}{E_{\text{BESS}}} \qquad (17)$$

B. Additional Balancing Market Participation

Additional equations are added to the model presented in the previous section. This enables a sequential combination of EA and participation in the aFRR-market. Consequently, the discharge power of the BESS is divided into an EA and an aFRR part.

$$P_{\text{BESS, dis}}(t) = P_{\text{BESS, dis, EA}}(t) + P_{\text{BESS, dis, aFRR}}(t) \qquad (18)$$

Thus, (5) must be adjusted. The share that is retrieved by aFRR is separately considered. The equation describing

BESS operation (14) remains due to the separation in (18).

$$P_{\text{Feed-in}}(t) = P_{\text{PV}}(t) \cdot \eta_{\text{Inv}} + P_{\text{BESS, dis, EA}}(t)$$
$$- P_{\text{BESS, ch}}(t) - P_{\text{Curtailment}}(t) \qquad (19)$$

The marketable power $P_{\text{BESS, aFRR}}$ is an integer value to account for the bid size with increments of 1 MW in the aFRR-market.

$$P_{\text{BESS, aFRR}} \overset{!}{\leq} \text{int}(P_{\text{BESS}}) \qquad (20)$$

The bidding strategy for aFRR-market is integrated in the model. Results are the bids for balancing power and balancing energy. First, the solver decides whether to offer the power in the following product time slice (PTS). Since only positive balancing power is provided, at least one hour of the offered power must be held in reserve, including losses.

$$\frac{E_{\text{BESS}}(t) \cdot \sqrt{\eta_{\text{tot}}}}{P_{\text{BESS, aFRR}}} \overset{!}{\geq} 1\,\text{h} \qquad (21)$$

Penalties paid to the transmission system operator as a result of non-fulfilment are thereby excluded. Besides, the condition applies in the model that PV energy must be generated for at least one hour of the marketing period. Thus, it is possible to charge the BESS during this time to be able to offer again in the subsequent PTS.

$$P_{\text{PV}}(t) \vee P_{\text{PV}}(t+1) \vee P_{\text{PV}}(t+2) \vee P_{\text{PV}}(t+3) \overset{!}{>} 0 \qquad (22)$$

In the case of marketing the BESS power, the profit is calculated for the entire PTS.

$$Rev_{\text{CP}}(t) = P_{\text{BESS, aFRR}} \cdot CP(t) \qquad (23)$$

With marketing, no EA is possible and the complementary discharge power is set to zero for four hours. One of three bidding strategies can be selected in the model to set the energy price. Depending on the strategy, a retrieval probability $\sigma_{\text{Retrieval}}$ is determined. Along with the average retrieval duration of the held power, the retrieved energy can be calculated. It is assumed that balancing energy is retrieved in every PTS where power is marketed to compensate peaks in the price data.

$$E_{\text{aFRR}}(t) = P_{\text{BESS, aFRR}} \cdot \sigma_{\text{Retrieval}} \cdot T_{\text{Retrieval}} \qquad (24)$$

The algorithm created, constantly decides whether EA is carried out or aFRR is marketed. The HPS revenues are calculated as follows.

$$Rev_{\text{HPS}} = \sum_{t}^{8760} ((P_{\text{Feed-in}}(t) \cdot (MP(t) + FM(t)) \cdot T)$$
$$+ Rev_{\text{CP}}(t) + E_{\text{aFRR}}(t) \cdot EP(t)) \qquad (25)$$

The model reflects the fundamental market process. Since November 2020, it is also possible to provide balancing energy without participating in the power capacity auction. If not retrieved, the energy can be offered in the intraday market [18]. This kind of participation is not considered.

IV. CASE STUDY

A 10 MW PV reference project is being studied based on 2019 data. The plant is located in northern Germany. On site, an HPS participating in InnAus is planned. The power generation depicted in Fig. 1 is simulated based on weather data [19] with a yearly DC-generation of 1,081 MWh/MW.
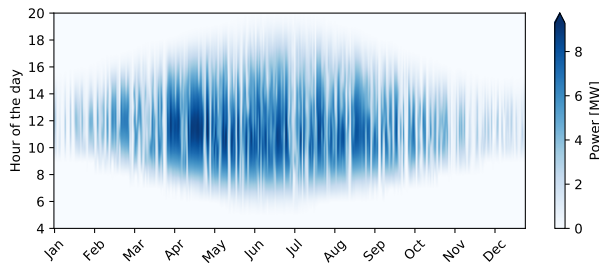

Fig. 1. Power generation from PV, 2019

Additionally, day-ahead spot market prices [20] and aFRR-market prices [21] are used. Comparing generation and day-ahead market data shows that approx. 3% of the total PV energy is generated in hours with negative prices. The calculated revenue streams are compared to a single PV system that could also participate in the first tender ("PV only scenario").

A. Energy Arbitrage

The input parameters are shown in Table I. Including battery module replacement costs, the higher operation and maintenance factor justifies 20 years BESS lifetime. The cost factors cover the investment costs for a turnkey BESS, converted with the 2019 exchange rate. A yearly price decrease of 5% is assumed [22]. Future market premiums may be higher because a two-hour BESS was not obligatory in the first tender.

Table II presents the results using BESS for EA. The optimal BESS size is the minimum allowable design, using the assumptions from Section II. The supplementary revenue generated by BESS does not cover the additional investment for a more extensive system. This is also indicated by the power-related and energy-related BESS revenues. A compensation by EA is not achievable with the current price spreads on the day-ahead market. In

TABLE I
CASE STUDY INPUT PARAMETERS, EA ONLY

Parameter	Value	Unit	Source
η_{Inv}	97	%	[23]
DOD	1	[-]	[22], [24]
η_{tot}	85	%	[25], [26]
LT	20	a	[27], [28]
SOC_{init}	0.5	[-]	-
$C\text{-}Rate_{\text{max}}$	0.5	[-]	[29]
$C\text{-}Rate_{\text{min}}$	0.25	[-]	[24]
$P_{\text{BESS, min}}$	3.72	MW	[29]
$E_{\text{BESS, min}}$	7.44	MWh	[29]
c_{P}	226[a]	T€/MW	[25], [26]
c_{E}	257[a]	T€/MWh	[25], [26]
OMC	2.5	%	[28]
$SYNF$	4	%	[22]
FM	45[b]	€/MWh	[30]
$FM_{\text{PV only}}$	26.5[b]	€/MWh	[30]
i_{r}	2	%	-

[a] Degressive 2021 value
[b] Weighted average awarded bid-level first tender

addition, the full potential of the storage can not be utilised because of the green electricity rule. Thus no charging during the night with lower market prices is feasible, which is also demonstrated in Fig. 2.

Here, a characteristic pattern of the economically optimal BESS operation can be recognised by means of the blue and white areas. Charging usually proceeds in the afternoon, when the relation of PV energy generation and the market price is opportune. With rising market prices, the BESS discharges primarily in the early evening.

TABLE II
RESULTS FOR EA

Parameter	Value	Unit
Optimal BESS power	3.72	MW
Optimal BESS energy	7.44	MWh
Revenues per BESS power	28.50	T€/MW·a
Revenues per BESS energy	14.25	T€/MWh·a
Total HPS revenues	851.93	T€/a
Annual BESS costs	-227.62	T€/a
Optimisation result	624.30	T€/a
Revenue increase to PV only	-3.51[a]	%
EA revenues	106.10	T€/a
Opportunity costs direct feed-in	93.62	T€/a
Equivalent full cycles over lifetime	3,234	[-]
PV full load hour increase	1.2	%/a

[a] Including cost for the BESS

A seasonal correlation can also be noticed. Two superimposed effects lower the number of cycles in winter. On the one hand, there is less charging potential due to the decrease in PV generation, see Fig. 1. On the other hand, there are lower price spreads on the market. When activating BESS, efficiency losses are always considered. These are accompanied by a loss of the proportionate spot market price as well as the fixed market premium.
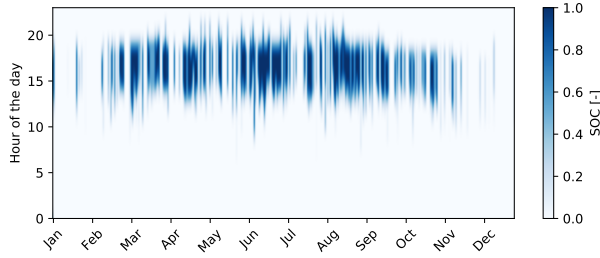
Fig. 2. Optimal storage operation for EA

Thus, a charging cycle can become uneconomical even with advantageous price differences.

B. Additional Balancing Market Participation

In the following, participation in the positive aFRR-market is assumed. Table III provides the vital additional parameters. The values are listed per PTS, which is four hours[3] in this case. All input parameters already presented in Table I remain unchanged. The parameters $T_{Retrieval}$ and CP are always used, and EP with regarding $\sigma_{Retrieval}$ is based on the chosen bid strategy. The reference case results with average power and energy prices are displayed in Table IV. As in the simulation with EA only, the economically optimal case is a minimum design. Nevertheless, revenues can be increased by 14% compared to EA.

TABLE III
CASE STUDY INPUT PARAMETERS, EA AND aFFR

Parameter	Value	Unit	Source
$T_{Retrieval}$	0.287[a]	MWh/MW·PTS	[21]
CP	Avg. value[b]	€/MW·PTS	[21]
$\sigma_{Retrieval, ref}$	7.2	%	[32]
EP_{ref}	Avg. value[b]	€/MWh	[21]
$\sigma_{Retrieval, low}$	21.8	%	[32]
EP_{low}	Min. value[b]	€/MWh	[21]
$\sigma_{Retrieval, high}$	2.2	%	[32]
EP_{high}	0.75·Marg. value[b]	€/MWh	[21]

[a] Average value based on 2019 aFRR-market
[b] Tender results from the grid operators

The reduced opportunity costs, along with the reduced number of cycles, indicate a lower BESS utilisation. This is particularly evident in Fig. 3. The blue areas show a high SOC over most of the year. Here, power is held in reserve to participate in the aFRR-market. Since the minimum energy requirement, in terms of marketed power, is one hour, SOC is not consistently one during periods of marketing. In the evenings, additional EA can be observed in analogy to the first case.

[3]The PTS will be reduced to 15 minutes in Q3/2021 [31]

TABLE IV
RESULTS FOR EA AND ADDITIONAL aFRR-MARKETING

| Parameter	Value	Unit
Optimal BESS power	3.72	MW
Optimal BESS energy	7.44	MWh
Revenues per BESS power	40.10	T€/MW·a
Revenues per BESS energy	20.05	T€/MWh·a
Total HPS revenues	940.23	T€/a
Annual BESS costs	-227.62	T€/a
Optimisation result	712.61	T€/a
Revenue increase to PV only	10.13[a]	%
EA revenues	54.84	T€/a
aFRR revenues	94.32	T€/a
Opportunity costs direct feed-in	46.04	T€/a
Equivalent full cycles over lifetime	1,795	[-]
PV full load hour increase	1.15	%/a

[a] Including cost for the BESS
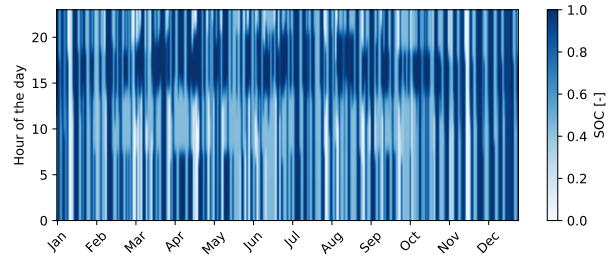
Fig. 3. Optimal storage operation for EA and additional aFRR-marketing

V. SENSITIVITY ANALYSIS

Three different input variations are applied: future spot market prices, bid strategies, and a "Scenario 2025".

A. Future Market Prices

To quantify possible scenarios in the future, the optimisation is subsequently carried out with simulated market data [33] for the years 2030 and 2040. The same generation data and input parameters are used to ensure comparability of the results. According to the internal analysis, both the price level on the wholesale market and the volatility increase. This can be seen notably in a total revenue increase in Table V. Furthermore, a higher storage operation can be observed.

TABLE V
RESULTS FOR EA WITH FUTURE MARKET DATA

Parameter	2030	2040	Unit
Optimal BESS power	3.72	3.72	MW
Optimal BESS energy	7.44	7.44	MWh
Revenues per BESS power	57.58	60.14	T€/MW·a
Revenues per BESS energy	28.79	30.07	T€/MWh·a
Optimisation result	851.10	1,087.61	T€/a
Revenue increase EA ref.	36	74	%

B. Bid Strategy Variation

The results using different bid strategies depending on EP and regarding $\sigma_{\text{Retrieval}}$, see Table III, are shown in Table VI. Low EP results in a decrease of the total revenue. Using 75% of the marginal EP leads to a larger sizing as the most economical option, based on the 2019 real-life prices. Here, 17% of PTS with a marginal EP above 10,000 €/MWh can be detected.

TABLE VI
RESULTS USING DIFFERENT BID STRATEGIES

Parameter	EP_{low}	EP_{high}	Unit
Optimal BESS power	3.72	9.76	MW
Optimal BESS energy	7.44	19.52	MWh
Revenues per BESS power	35.37	118.18	T€/MW·a
Revenues per BESS energy	17.68	59.09	T€/MWh·a
Optimisation result	675.57	1,303.90	T€/a
Revenue increase aFRR ref.	-5	83	%

In this case, the share from balancing power is around 19.2%, whereas the reference simulation share is significantly higher at 64.2%. Since January 2021, a price cap of 10,000 €/MWh has been implemented in the aFRR market so that the volatility will decrease in the future. Besides, there is a high degree of uncertainty about the actual retrieval length.

C. Scenario 2025

Finally, an outlook into the future is given, considering a possible design in 2025 with adjusted parameters. The 2025 spot market prices [33], the same generation data [19], and the aFRR market data from the year 2019 [21] serve as input parameters. Due to an uncertain market outlook for the aFRR market, the 2019 data is used representatively for revenues from future flexibility marketing. With further development, especially in cell technologies, higher BESS efficiency assumed at 90% is expected in this scenario. Improvements in cell technology are accompanied by a longer lifetime, which impacts the cost for retrofitting included in the operating and maintenance costs ($OMC = 1.5\%$). In [25] a cost degression of 30% for BESS in the medium scenario is predicted compared to 2019 costs. The maximum FM in 2025 will be around 50 €/MWh [29]; the weighted average value is estimated at 30 €/MWh.

The results are listed in Tab. VII. It can be seen that in this scenario, the optimal design is no longer the minimum BESS design. The possible positive developments from the BESS perspective can therefore affect the optimal BESS design.

TABLE VII
RESULTS FOR SCENARIO 2025

Parameter	2025 Value	Unit
Optimal BESS power	4.22	MW
Optimal BESS energy	8.44	MWh
Revenues per BESS power	57.98	T€/MW·a
Revenues per BESS energy	28.99	T€/MWh·a
Optimisation result	837.93	T€/a
Revenue increase to PV only[a]	30[b]	%

[a] Based on 2019 data
[b] Including cost for the BESS

VI. CONCLUSION

A model was developed to optimise and operate a BESS with respect to an InnAus ground-mounted PV array. The case study results show:

- With opportune BESS marketing, higher revenues minus BESS costs (approx. 10%) can be generated compared to a stand-alone PV asset in InnAus. Operating only with EA results in a revenue reduction (approx. -4%). A minimum BESS design is most economical using current data and parameters. Further applications such as FCR marketing or intraday trading can be appended to the model.

- The operation of the BESS is limited due to the green electricity rule. Thus, the BESS can not exploit its full marketing potential, such as the symmetrical provision of FCR or night-time charging in the case of EA and aFRR.

- InnAus is a suitable approach of VRE integration due to the 25%-criteria. It can be seen as a driver for implementing flexibility options, especially in the form of BESS, in the German power grid. Furthermore, this incentive encourages plant operators to take advantage of new marketing opportunities with the overriding goal of maintaining grid stability.

The balancing market is subject to constant changes in market conditions. Also, the market for BESS is expected to continue its dynamic development. With this optimisation model, an up-to-date evaluation of economic efficiency can be carried out by adjusting the data and parameters. This was shown with the scenario 2025, where the economically optimal design is larger than the minimum design. It turns out that both grid and plant operators can benefit from InnAus, ultimately contributing to the energy transition.

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