Energy Storage Beyond Arbitrage: Harnessing the Excess Energy of Wind Power Plants

Fabian Moisl[0]

Institute of Energy Systems and Electrical Drives - Energy Economics Group, Vienna University of Technology Gusshausstrae 25-29/E370, A-1040 Vienna, Austria

Abstract

This paper aims to explore options of deployment of battery energy storage systems (BESS) when operated jointly with a wind power plant (WPP). Thereby the BESS is used in three different ways in order to maximize net revenues of the wind-storage system: (1) to reduce forecast errors of the WPP and thus reduce payments for balancing energy; (2) to provide ancillary service (negative control energy) to the grid; and (3) harness excess energy of the WPP by shifting production in moments of low corresponding value of energy to moments of high values. To achieve this, the BESS must operate in both the day-ahead market and the control energy market. The optimal dispatch strategy of the BESS is obtained from a two-stage linear optimization model.

The calculation is based on data from the year 2014 of the Austrian spot and control energy market and was performed using the example of an existing 20 MW WPP in Austria. The linear optimization model was implemented in Matlab using Yalmip and a Gurobi Optimizer.

Keywords:
storage, wind power, ancillary service, forecast error

[0]Nachwuchsautor
E-mail address: moisl@eeg.tuwien.ac.at
Telephone: +43 1 58801 370373
Web: www.eeg.tuwien.ac.at

1. Introduction

High efforts to promote renewable energy systems (RES) in Europe have led to fundamental changes in the electricity sector. Demand minus volatile generation from renewables (the residual load) tends towards zero in few moments during a year and could also become negative at times, which would force RES to shed generation. This is where storage devices could produce relief, but they are currently suffering from low wholesale electricity prices and small price spreads in particular. Consequently, the traditional field of application for storage systems, energy arbitrage, often fails to trigger investment in those technologies.

This paper aims to explore options of deployment of battery energy storage systems (BESS) when operated jointly with a wind power plant (WPP). Thereby the BESS is used in three different ways in order to maximize net revenues of the wind-storage system: (1) to reduce forecast errors of the WPP and thus reduce payments for balancing energy; (2) to provide ancillary service (negative control energy) to the grid; and (3) harness excess energy of the WPP by shifting production in moments of low corresponding value of energy to moments of high values. To achieve this, the BESS must operate in both the (day-ahead) spot market and the control energy market. The optimal dispatch strategy of the BESS is obtained from a two-stage linear optimization model:

- In a first step dispatch of the BESS is optimized for the upcoming period (day) considering day-ahead spot market prices for electricity only. This first optimization leads to a scheduled dispatch of the BEES.
- Subsequently, the second step of optimization takes into account the forecast error of the WPP and the control energy that has to be delivered by the wind-storage system and gives the actual dispatch of the BESS.

Both steps of the optimization model assume perfect foresight and the wind-storage system to act as a price taker. Finally, resulting net revenues from storage deployment are calculated according to the actual dispatch of the BESS using historical data for forecast errors of a WPP and balancing energy prices, spot market prices, control energy calls and control energy market prices.

The calculation is based on data from the year 2014 of the Austrian spot and control energy market and was performed using the example of an existing 20 MW WPP in Austria. The linear optimization model was implemented in Matlab using Yalmip and a Gurobi Optimizer.

2. Method

In order to calculate the optimal employment of the BESS in terms of net revenues, the two-stage linear optimization model described in this section is used. Furthermore, the observed period (year 2014) is divided into shorter time periods T (days), subsequently this short time periods are divided into quarter hours $t \in [0, \tau]$ which reflect the temporal resolution of the optimization problem.

2.1. Two-stage optimization model

The co-optimization problem is split up into two steps: first, employment of the BESS is obtained from a linear optimization problem by considering the day-ahead electricity market (spot market) only. Second, based on the BESS's schedule (according to the first optimization stage) actual usage is obtained from a second linear optimization problem taking into account the forecast error of the WPP and negative control energy requested by the TSO.

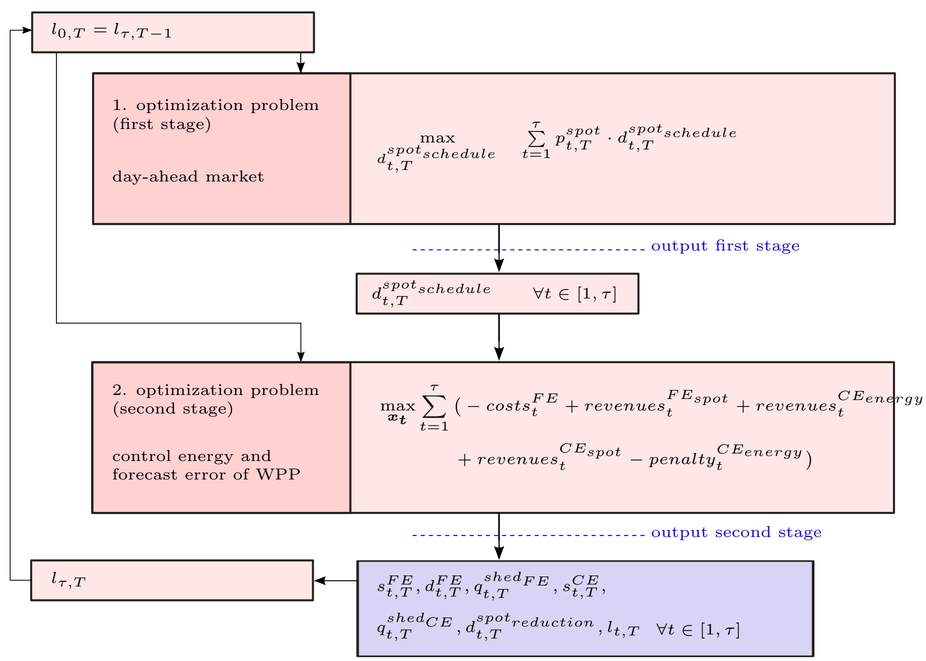


Figure 1: Scheme of two-stage optimization problem. The level of storage at the beginning of a time period T ($l_{0,T}$) equals the level of storage at the end of time period $T-1$ ($l_{\tau,T-1}$)

The scheme of this two-stage optimization problem is described in Figure 1. Each iteration starts with the level of storage at the beginning of the current time period T ($l_{0,T}$), which equals the level of storage at the end of the previous period ($l_{\tau,T-1}$) and states the amount of energy (decreased by the BESS's discharge efficiency factor η_{out}^{BESS}) that can be sold at a day-ahead energy market (spot market).

The first optimization stage yields the scheduled discharge of the BESS during the time period T ($d_{t,T}^{spot_{schedule}}$), which is an input parameter of the second stage. This second optimization problem yields the actual employment of the BESS taking into account expected revenues from providing control energy and minimizing the forecast error of the WPP.

Once the second stage is accomplished, all model variables are fixed for the considered time period T and the iteration loop starts over with the subsequent time period $T+1$.

2.1.1. First stage: spot market

Excess energy of the time period $T-1$ (either from positive forecast error, or from a negative control energy call) is stored in the BESS and can be sold to the spot market. This results in a scheduled discharge of the BESS in time period T, which is described by the variable $d_{t,T}^{spot_{schedule}}$ and represents an input parameter for the second stage. The maximum possible revenues from energy sales at the spot market is derived from the simple linear optimization problem

$$\max_{d_{t,T}^{spot_{schedule}}} \sum_{t=1}^{\tau} p_{t,T}^{spot} \cdot d_{t,T}^{spot_{schedule}} \tag{1}$$

$$
\begin{aligned}
\text{s.t.} \quad && d_{t,T}^{spot_{schedule}} &\geq 0 && \forall t \in [1,\tau] && (2)\\
&& d_{t,T}^{spot_{schedule}} &\leq \kappa^{BESS} \cdot 1/4 && \forall t \in [1,\tau] && (3)\\
&& l_{t,T} &\geq 0 && \forall t \in [1,\tau] && (4)\\
&& l_{0,T} &= l_{\tau,T-1} && && (5)\\
&& l_{t-1,T} - (d_{t,T}^{spot_{schedule}} / \eta_{out}^{BESS}) &= l_{t,T} && && (6)
\end{aligned}
$$

which is referred to as the optimization model's first stage.

The optimization variables of the model's first stage are

$d_{t,T}^{spot_{schedule}}$	scheduled discharge of BESS in moment t in time period T (MWh),
$l_{t,T}$	level of storage in moment t (MWh),

while model parameters are

$p_{t,T}^{spot}$	day-ahead energy price at the time t (€/MWh),
$l_{0,T}$	level of storage at the beginning of time period T (MWh); amount of energy that can be sold at the day-ahead market
κ^{BESS}	power capacity of BESS (MW) and
η_{out}^{BESS}	discharge efficiency of BESS.

2.1.2. Second stage: considering forecast error and control energy

Since the fist stage of the optimization model yields only a scheduled use of the BESS in each time period T, the actual employment is obtained from the linear optimization problem[1]

$$\begin{aligned}\max_{\boldsymbol{x_t^2}} \sum_{t=1}^{\tau} \big(- costs_t^{FE} + revenues_t^{FE_{spot}} + revenues_t^{CE_{energy}} \\ + revenues_t^{CE_{spot}} - penalty_t^{CE_{energy}} \big),\end{aligned} \tag{7}$$

which is referred to as the optimization model's second stage. It aims to maximize expected net revenues of storage operation by adjusting the optimization variables grouped in vector $\boldsymbol{x_t^2} = [d_t^{FE}, s_t^{FE}, q_t^{shed_{FE}}, s_t^{CE}, d_t^{spot_{reduction}}, q_t^{shed_{CE}}]$.

The second stage optimization problem takes into consideration

- expected revenues due to reduction of forecast errors ($-costs_t^{FE}$),
- expected revenues from spot market sales ($revenues_t^{FE_{spot}}$, $revenues_t^{CE_{spot}}$),
- revenues due to fulfilled control energy requests ($revenues_t^{CE_{energy}}$) and

[1] The second index T, which indicates the time period, was omitted mostly in this section for better legibility

- penalty payments due to non-fulfillment of control energy requests ($penalty_t^{CE_{energy}}$).

To begin with, WPP's forecast errors cause balancing energy costs by

$$\begin{aligned} costs_t^{FE} &= p^{balance}|FE_t + d_t^{FE} - s_t^{FE} - q_t^{shed_{FE}}| \\ &= p^{balance}(|FE_t| - d_t^{FE} - s_t^{FE} - q_t^{shed_{FE}}) \end{aligned} \tag{8}$$

which can be minimized by employment of BESS or by shedding energy.

If the forecast error FE_t is negative (less generation than predicted) energy can be discharged (d_t^{FE}) from the BESS, if FE_t is positive this excess energy can be either stored (s_t^{FE}), or shed ($q_t^{shed_{FE}}$). $p^{balance}$ denotes the average cost of balancing energy per MWh. Energy that is stored could be sold later on day-ahead electricity markets and therefore has to be valued higher than energy that is shed and thus lost. This is taken into account by the additional revenue term

$$revenues_t^{FE_{spot}} = p^{spot} \cdot s_t^{FE} \cdot \eta^{BESS}, \tag{9}$$

which valuates stored energy by the expected spot market price p^{spot} multiplied by the BESS's roundtrip efficiency η^{BESS}.

Second, the revenues gained by providing negative control energy are calculated as control energy price ($p_t^{MWh_{CE}}$ in [€/MWh]) times provided control energy by

$$revenues_t^{CE_{energy}} = p_t^{CE_{MWh}}(s_t^{CE} + q_t^{shed_{CE}} + d_t^{spot_{reduction}}). \tag{10}$$

A negative control energy request can be fulfilled by either storing or shedding energy ($s_t^{CE}, q_t^{shed_{CE}}$), or by reducing discharge of energy that was scheduled because of day ahead spot market obligations ($d_t^{spot_{reduction}}$). Similar to the considerations above, the options providing control energy have to be valued differently to ensure an optimal employment of the storage device. Energy that is not discharged due to a control energy request ($d_t^{spot_{reduction}}$) can be sold on the spot market and is expected to generate revenues in the amount of $d_t^{spot_{reduction}} \cdot p^{spot}$, where p^{spot} denotes the average spot market price in €/MWh. Energy that is stored in order to fulfill a control energy request can also be sold on the spot market, but is only expected to generate revenues in the amount of $s_t^{CE} \cdot \eta^{BESS} \cdot p^{spot}$. Energy that is shed is clearly lost and will not gain any further revenues. Summing up, expected additional revenues can be stated as:

$$revenues_t^{CE_{spot}} = s_t^{CE} \cdot \eta^{BESS} \cdot p^{spot} + d_t^{spot_{reduction}} \cdot p^{spot} \tag{11}$$

Finally, in case a control energy request cannot be fulfilled, the generation unit is charged with a compensation payment in the amount of the $V^{CE}-$fold. The amount of control energy requested in t is calculated as $\Theta_t^{CE} \cdot P^{CE}\frac{1}{4}h$. Where P^{CE} is the control reserve power in MW tendered by the generation unit, $P^{CE}\frac{1}{4}h$ is the control energy required per quarter and Θ_t^{CE} is a Boolean value that equals 1 if control energy is requested and 0 otherwise. The requested amount of control energy less the actual provided amount equals the shortfall of control energy and results in a penalty payment of

$$\begin{aligned} penalty_t^{CE_{energy}} = V^{CE} \cdot p_t^{CE_{MWh}} \cdot \\ [\Theta_t^{CE} \cdot P^{CE}\frac{1}{4}h - (s_t^{CE} + q_t^{shed_{CE}} + d_t^{spot_{reduction}})]. \end{aligned} \tag{12}$$

By substitution of the revenue and cost terms in equation 7 the second stage of the optimization model can be expressed as

$$\begin{aligned} \max_{\boldsymbol{x_t^2}} \sum_{t=1}^{\tau} \big(& - p^{balance}(|FE_t| - d_t^{FE} - s_t^{FE} - q_t^{shed_{FE}}) + p^{spot} \cdot s_t^{FE} \cdot \eta^{BESS} \\ & + p_t^{CE_{MWh}}(s_t^{CE} + q_t^{shed_{CE}} + d_t^{spot_{reduction}}) \\ & + s_t^{CE} \cdot \eta^{BESS} \cdot p^{spot} + d_t^{spot_{reduction}} \cdot p^{spot} \\ & - V^{CE} \cdot p_t^{CE_{MWh}}[\Theta_t^{CE} \cdot P^{CE}\frac{1}{4} - (s_t^{CE} + q_t^{shed_{CE}} + d_t^{spot_{reduction}})]\big) \end{aligned} \tag{13}$$

$$\text{s.t.} \qquad s_t^{FE} \geq 0, \quad d_t^{FE} \geq 0, \quad q_t^{shed_{FE}} \geq 0 \qquad \forall t \in [1, \tau] \tag{14}$$

$$d_t^{FE} \leq |FE_t| \qquad if FE_t < 0 \tag{15}$$

$$d_t^{FE} \leq 0 \qquad if FE_t \geq 0 \tag{16}$$

$$s_t^{FE} + q_t^{shed_{FE}} \leq FE_t \qquad if FE_t > 0 \tag{17}$$

$$s_t^{FE} + q_t^{shed_{FE}} \leq 0 \qquad if FE_t \leq 0 \tag{18}$$

$$\tag{19}$$

$$s_t^{CE} \geq 0, q_t^{shed_{CE}} \geq 0, d_t^{spot_{reduction}} \geq 0 \qquad \forall t \in [1, \tau] \quad (20)$$

$$s_t^{CE} + q_t^{shed_{CE}} + d_t^{spot_{reduction}} \leq \Theta_t^{CE} \cdot \frac{P^{CE}}{4} \qquad \forall t \in [1, \tau] \quad (21)$$

$$\begin{aligned} & d_t^{FE} + d_t^{spot_{schedule}} - d_t^{spot_{reduction}} \\ & \qquad - s_t^{spot_{schedule}} - s_t^{CE} \leq \kappa^{BESS} \cdot 1/4 \qquad \forall t \in [1, \tau] \quad (22) \end{aligned}$$

$$\begin{aligned} & s_t^{FE} - d_t^{spot_{schedule}} + d_t^{spot_{reduction}} \\ & \qquad + s_t^{spot_{schedule}} + s_t^{CE} \leq \kappa^{BESS} \cdot 1/4 \qquad \forall t \in [1, \tau] \quad (23) \end{aligned}$$

$$d_t^{spot_{reduction}} \leq d_t^{spot_{schedule}} \qquad \forall t \in [1, \tau] \quad (24)$$

$$q_t^{shed_{CE}} + q_t^{shed_{FE}} \leq q_t^{WPP_{actual}} \qquad \forall t \in [1, \tau] \quad (25)$$

$$l_{0,T} = l_{\tau,T-1} \quad (26)$$

$$l_t \geq 0 \qquad \forall t \in [1, \tau] \quad (27)$$

$$l_t \leq \chi^{BESS} \qquad \forall t \in [1, \tau] \quad (28)$$

$$\begin{aligned} & l_{t-1} + \sqrt{\eta^{BESS}}(s_t^{FE} + s_t^{CE} + s_t^{spot_{schedule}}) \\ & \quad - \frac{(d_t^{FE} + d_t^{spot_{schedule}} - d_t^{spot_{reduction}})}{\sqrt{\eta^{BESS}}} = l_t \qquad \forall t \in [1, \tau] \quad (29) \end{aligned}$$

Model variables

s_t^{FE}	energy stored in t in order to reduce forecast error (MWh)
d_t^{FE}	energy discharged in t in order to reduce forecast error (MWh)
$q_t^{shed_{FE}}$	energy shed in t in order to reduce forecast error (MWh)
s_t^{CE}	energy stored at the time t to accomplish negative control energy request (MWh)
$q_t^{shed_{CE}}$	energy shed in hour t to accomplish negative control energy request (MWh)
$d_t^{spot_{reduction}}$	reduction of discharge of energy that was scheduled because of day-ahead energy market obligations at the time t to accomplish negative control energy request (MWh)
l_t	level of storage at the time t

Model parameters

τ	number of quarters in a time period T
FE_t	forecast error of WPP generation in t (MWh)

$q_t^{WPP_{actual}}$	actual generation of WPP in hour t (MWh)
$p^{balance}$	average cost of balancing energy (€/MWh)
p^{spot}	average spot market price (€/MWh)
Θ_t^{CE}	Boolean variable that indicates if control energy is requested in t (0,1)
P^{CE}	control reserve power tendered by the generation unit (MW)
$p_t^{CE_{MWh}}$	control energy price in t (€/MWh)
κ^{BESS}	power capacity of BESS (MW)
χ^{BESS}	storage capacity of BESS (MWh)
η^{BESS}	roundtrip storage efficiency of BESS
$d_t^{spot_{schedule}}$	scheduled discharge of BESS (MWh); obtained from first stage of optimization
$s_t^{spot_{schedule}}$	scheduled charge of BESS (MWh); obtained from first stage of optimization
$l_{0,T}$	level of storage at the beginning of the time period T
$l_{\tau,T-1}$	level of storage at the end of time period T-1

2.2. Actual revenues and costs

Since the two-stage optimization model aims to maximize expected net revenues of BESS operation, actual revenues and costs have to be calculated afterwards (when all variables are fixed). However, the composition of proceeds remains unchanged.

Revenues due to spot market sales are described by

$$revenues_t^{spot} = p_t^{spot} \cdot d_t^{spot_{schedule}} \tag{30}$$

while revenues due to reduction in forecast errors are given by

$$savings_t^{FE} = p_t^{balance}(d_t^{FE} - s_t^{FE} - q_t^{shed_{FE}}). \tag{31}$$

The definition of revenues and penalty payments from provided control energy are equal to equation 10 and 12. In addition there are revenues due to tendered control power. Control power revenues are calculated for a whole year

$$revenues^{CE_{power}} = p^{CE_{MW}} \cdot P^{CE} \cdot 8760h, \tag{32}$$

assuming that control energy is tendered continuously (8760 hours a year). $p^{CE_{MW}}$ is the average price per MW control power tendered for one hour [€/MW·h].

Moreover, a wind power plant is not likely to participate at the control energy market as a single unit, but within a pool of other power plants. In this case the aggregator will charge the wind power plant a fee for integrating that certain power plant into its pool referred to hereafter as cost of collateralization. This fee is assumed to amount to a fraction v^{CE} of the WPP's revenues related to tendered control energy:

$$cost^{CE_{coll.}} = v^{CE} \cdot (revenues^{CE_{power}} + \sum_{T \in \mathscr{Y}} \sum_{t=1}^{\tau} revenues_{t,T}^{CE_{energy}}) \tag{33}$$

Consequently, the actual net revenues generated from storage employment for a whole year $\mathscr{Y}$[2] result in

$$\begin{aligned} revenues^{total} = revenues^{CE_{power}} - cost^{CE_{coll.}} + \sum_{T \in \mathscr{Y}} \sum_{t=1}^{\tau} \big(revenues_{t,T}^{spot} \\ + savings_{t,T}^{FE} + revenues_{t,T}^{CE_{energy}} - penalty_{t,T}^{CE_{energy}}\big) \end{aligned} \tag{34}$$

2.3. Expected lifetime of BESS

The intensity of storage employment is described by its yearly full-cycle equivalent (FCE)

$$FCE_{yearly}^{BESS} = \frac{\sum\limits_{T} \sum\limits_{t=1}^{\tau} (s_{t,T}^{spot_{schedule}} + s_{t,T}^{FE} + s_{t,T}^{CE}) \cdot \eta_{in}^{BESS}}{\chi^{BESS}} \tag{35}$$

The expected lifetime of the BESS is than calculated by dividing the total number of cycles by the yearly full-cycle equivalent the storage actually performs.

$$lifetime^{BESS} = \frac{cycles_{total}^{BESS}}{FCE_{yearly}^{BESS}} \tag{36}$$

[2] $\mathscr{Y}$ represents a certain year as well as a set of time periods T (days) within that year

2.4. Input data

2.4.1. Wind farm

The evaluated wind farm is located in Burgenland (Austria) and is operated by the company *WEB Windenergie AG*[3]. Analyzed time series of predicted and actual generation on a quarter hour level originate for the year 2014.

2.4.2. Electricity markets

All evaluations regarding wholesale electricity markets in this paper rely on EXAA[4] day-ahead prices (spot prices). As a consequence, p_t^{spot} denotes the EXAA day-ahead price in a quarter hour resolution[5], while p^{spot} denotes the average EXAA day ahead price for the year 2014.

Control energy evaluations rely on negative automatic frequency restoration reserve (aFRR) data of the control area APG (Austria). $p_t^{CE_{MWh}}$ denotes the weighted average price of activation of negative aFRR energy in €/MWh. $p_t^{CE_{MW}}$ denotes the average price for negative aFRR power per hour in €/MW·h in the year 2014 (Table 1).

The Boolean variable Θ_t^{CE} indicates if the wind-storage system is obliged to deliver control energy in quarter t and is obtained as

$$\Theta_t^{CE} = \begin{cases} 1 & \text{if } q_t^{CE} > q_{threshold}^{CE} \\ 0 & \text{otherwise} \end{cases} \tag{37}$$

The threshold ($q_{threshold}^{CE}$) was set in order to achieve a probability of 10% of being obliged to deliver aFRR when it is needed within the control area. Balance energy market data is obtained from the Austrian balance group coordinator APCS[6]. $p_t^{balance}$ denotes the energy imbalance price (clearing price 1) in the control area APG (Austria) in quarter t. $p^{balance}$ denotes the average energy imbalance price.

[3]https://www.windenergie.at

[4]EXAA - Energy Exchange Austria, http://www.exaa.at/en

[5]Although EXAA integrated quarter hours for trading in its day-ahead spot market not until September, 3rd, 2014, for the reasons of simplicity, it is assumed that the spot market temporal resolution is one quarter for the whole year 2014.

[6]http://www.apcs.at/en

Table 1: Historical market data of the year 2014

Symbol	Parameter	Unit	Value
p^{spot}	average spot market price	€/MWh	32.80
$p^{CE_{MW}}$	average price for control power	€/MW·h	14.29
$p^{balance}$	average cost of balancing energy	€/MWh	39.59
$q^{CE}_{threshold}$	threshold for negative aFRR	MWh	36.68

2.4.3. Operational and economic parameters of BESS and WPP

Operational parameters regarding BESS and WPP are summarized in Table 2 and Table 3.

Table 2: Operational and economic parameters of lithium-ion battery system

Symbol	Parameter	Unit	Reference Case/[Range]
χ^{BESS}	storage capacity of BESS	MWh	1 / [0 - 261]
$\chi^{BESS}/\kappa^{BESS}$	Hours of energy storage at rated	h	1
η_{in}^{BESS}	storage charging efficiency of BESS	1	0.9 / [0.85 - 1]
η_{out}^{BESS}	storage discharging efficiency of BESS	1	0.9 / [0.85 - 1]
$cycles_{total}^{BESS}$	Life cycles of BESS	1	7000 / [1000 - 10 000][a]
TPC^{BESS}	Total plant cost of BESS	k€/MWh	1100 / [1046 - 1603][b]
$OPEX^{BESS}$	Operational expenditures of BESS	k€/MW-yr	5 / [4.7 - 6.9][b]

[a]Chen et al., 2009; [b]Akhil et al., 2013

Table 3: Further parameters of wind-storage system assessment.

Symbol	Parameter	Unit	Reference Case/[Range]
P^{CE}	Control reserve power tendered by the wind-storage system	MW	1 / [0 - 15]
V^{CE}	Penalty factor for violation of	1	3 / [0 - 10]
v^{CE}	Fixed rate for collateralization	%	30
τ	Number of quarter hours per time period T	1	96 / [24 - 96]
i	Interest rate	%	10 / [5-15]

3. Results and Discussion

In a first step the WPP - its proceeds at the spot market and its forecast error cost - is assessed in this chapter. Then the battery storage system is evaluated in arbitrage only operational mode and finally, the co-optimized employment of the WPP and the BESS is considered.

3.1. Assessment of WPP only

Revenues and costs related to storage employment must be seen in perspective of proceeds the WPP is able to achieve by its own (without a joint storage system) by selling energy to the day-ahead market and providing negative regulation reserve (regulation down).

3.1.1. Proceeds of WPP on day-ahead market

Revenues of the WPP related to energy sales at the day-ahead market add up to 1.62 M€ (respectively 80.8 k€/MW·yr when based on the rated capacity of the WPP) for the year 2014 (see Table 4). The actual yearly generation of 43.8 GWh of the 20 MW wind farm is much lower than the forecasted (scheduled) generation of 50.6 GWh. This is mostly because planed shutdowns of wind turbines (e.g. for maintenance work) are not taken into account for WPP generation forecasts.

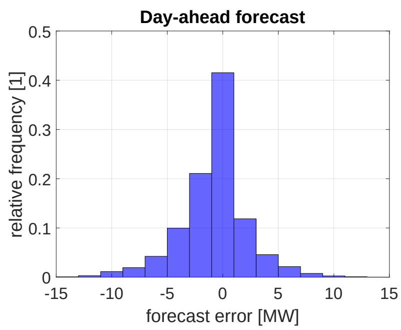
Table 4: Assessment of 20 MW wind power plant.

Scheduled yearly generation [GWh]	Actual yearly generation [GWh]	Full-load hours [h/yr]	Revenues day-ahead [k€/yr]	Normalized revenues [k€/MW·yr]
50.6	43.8	2188	1615	80.8

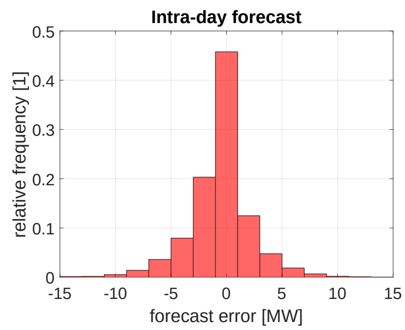
3.1.2. Cost of forecast error

The root-mean-square error (RMSE) in case of day ahead forecast amounts to 3.15MW (= 15.8% of rated capacity) while the RMSE in case of intra-day forecast yields 2.82 MW (14.1%). Figure 3.1.2 depicts the histograms of forecast errors for both, day-ahead and intra-day forecast where an interval width of 2 MW was applied. For day-ahead prognosis ca. 42% of all forecasts are within an error interval of [-1MW,1MW], while in case of intra-day prognosis this number rises to over 45%.

In this section the WPP is considered to be a separate balance group (BG). Consequently, the forecast error of the wind farm is equal to the imbalance of the BG. Hence, the WPP has to obtain balancing energy (positive



(a) Day-ahead forecast



(b) Intraday forecast

Figure 2: Histograms of forecast errors (interval wigth: 2MW).

or negative) in the amount of its imbalance at the price $p_t^{balance}$ and the cost of forecast error in a certain quarter hour t are calculated as

$$cost_t^{FE} = p_t^{balance} \cdot FE_t \tag{38}$$

Since $p_t^{balance}$ can be either positive or negative, one has to distinguish between four different cases:

(i) In the intuitive case when the forecast error is negative (actual generation is lower than predicted) and the energy imbalance price is positive, the wind farm has to obtain energy from the balancing mechanism and has to make a payment to the TSO referred to as *'cost'* in Table 5.

(ii) However, if the forecast error is positive while the energy imbalance price is positive too, the wind farm can 'sell' its excess energy and receives a payment from the TSO referred to as *'revenues'*.

(iii) In case the forecast error is positive while the energy imbalance price is negative, the WPP must 'sell' its excess energy at a negative price and therefore has to make a payment to the TSO referred to as *'negative revenues'*.

(iv) Finally, if both the forecast error and the energy imbalance price are negative, the WPP must obtain energy from the balancing mechanism at a negative price and thus receives a payment from the TSO referred to as *'negative cost'*.

Table 5 depicts the forecast error costs and the aggregated deviation for positive and negative errors of the 20MW wind farm in the year 2014.

Table 5: WPP forecast error cost in 2014.

Forecast quality	Total net cost of FE [k€]	$FE < 0$ Lack of energy Cost [k€]	Negative cost [k€]	Lack of energy [GWh]	$FE > 0$ Surplus of energy Revenues [k€]	Negative revenues [k€]	Excess energy [GWh]
Day-ahead	-745	-767	78	12.8	152	-209	6.0
Intraday	-515	-581	83	10.6	165	-182	5.9

Total net costs of FE in 2014 add up to -745k€ when forecast is provided day-ahead (which is equal to 46% of the proceeds derived from energy sales at the day-ahead market), comprising -767k€ resp. -209k€ cost and 78k€ resp. 152k€ revenues. By comparison, the total net cost of FE in case of intraday forecast add up to only -515 k€, 232 k€ or 31% less than in case of day-ahead forecast.

3.2. Provide Negative aFRR with WPP

As studies had demonstrated (*Brauns et al., 2014*) and effective demonstration has shown, wind power plants are able to provide negative control energy by actively shedding generation. In this section revenues from providing negative automatic frequency restoration reserve (aFRR) by the 20MW WPP demo case are estimated using the two-stage optimization model described in section 2.1. Thereby, the storage capacity of the BESS is set to zero ($\chi^{BESS} = 0$) in order to suppress its effect. The tendered control energy is chosen to be 1MW (5% of the WPP's rated capacity), which is a reasonable assumption in line with the findings of **?**.

Balancing-market data for Austria show that there was a need for downward regulation of aFRR in 28774 quarter hours in the year 2014 (82.1% of all quarter hours a year). As described in section 2.4.2 it is assumed that the WPP is requested to provide negative aFRR in 10% of all cases when it is needed within the control area, which equals 2877 quarter hours.

Table 6 shows the revenues and costs through the provision of negative aFRR by the WPP for the year 2014. Savings in forecast error (column *Savings FE*) result from shedding excess energy of the WPP and equals the sum of *Revenues* and *Negative revenues* in Table 5. *Revenues* CE_{energy} denote proceeds related to actually provided control energy, which make up to more than half of total net revenues, while *Revenues* CE_{power} are proceeds generated from provisioning 1MW of control power for a whole year.

Table 6: Revenues and cost through the provision of negative aFRR by the WPP in 2014

P^{CE} [MW]	Total net revenues [k€]	Savings FE[a] [k€]	Revenues CE_{energy} [k€]	Penalty CE_{energy} [k€]	Revenues CE_{power} [k€]	Number of CE violations [1]
1.0	357.1	56.6	205.0	-29.7	125.2	211 (7.3%)

[a]day-ahead forecast

The wind farm is not able to fulfill a negative aFRR request in 211 cases (7.3% of all 2877 downward regulation calls). Thus a penalty payment in the amount of -29.7k€ has to be made to the power supply company that ensures for the collateralization ot the tendered control power.

The sum of all revenues minus penalty payments result in total net revenues[7] of 357.1k€ and represent the proceeds the demo case WPP could make by providing negative control energy (without having a storage device attached). Those net revenues serve as the basis for all further analysis in conjunction with BESS economics.

3.3. Arbitrage-only operational mode of BESS

To get a first idea about the order of magnitude of proceeds a storage system is able to generate when it is used to perform arbitrage on the day-ahead electricity market, the first stage of the optimization model in section 2.1 is considered only. Furthermore, equation 1 has to be modified in order to permit the BESS to be charged on schedule.

Table 7 depicts the model results related to the arbitrage-only operational mode of a BESS with a storage capacity of 1 MWh. The revenues generated in the year 2014 amount to 33.7 k€ while the costs of energy charged into the BESS add up to -14.0 k€ resulting in total net revenues of 8.7 k€.

Table 7: Revenues and cost of BESS used for arbitrage only in 2014.

χ^{BESS} [MWh]	Total net revenues [k€]	revenues [k€]	cost [k€]	Energy stored [MWh]	Energy discharged [MWh]	Full-cycle equivalent [1]
1.0	8.7	33.7	-14.0	667.0	542.7	603

[7]In case of a fixed rate for collateralization in the amount of 30% of the proceeds through provision of negative aFRR, total net revenues amount to 287.7k€.

The cost-benefit analysis of the arbitrage-only operational mode is summarized in Table 8. Yearly net revenues of 8.7 k€/yr result in a present value of 58.2 k€ applying an expected lifetime of the BESS of 11.6 years and an interest rate of 10%. The present value oft the BESS's total plant cost (TPC^{BESS}) and the operational expenditures add up to -1133 k€. Consequently, the net present value of the BESS is highly negative (-1075 k€) when operated in arbitrage-only mode, making investment in batteries economically not justifiable.

Table 8: Net present value of BESS when used for arbitrage only ($\chi^{BESS} = 1MWh$)

Total net revenues of BESS employment [k€/yr]	Exp. lifetime of BESS[a] [years]	PV of revenues [k€]	PV of $OPEX^{BESS}$ [k€]	PV of TPC^{BESS} [k€]	NPV of BESS [k€]
8.7	11.6	58.2	-33.5	-1100	-1075

[a]Resulting from 603 full-cycle equivalents

3.4. Minimum forecast error operational mode of BESS

A second intermediate stage to the co-optimized employment of the battery storage is to use it exclusively in order to minimize the forecast error of the WPP. For this purpose the second stage of the optimization model (section 2.1.2) is considered solely[8]. Model results of forecast error costs of the WPP in 2014 under variable storage capacity χ^{BESS} are summarized in Table 9.

Yearly net revenues of storage employment (total net cost of forecast errors at a certain storage capacity χ^{BESS} minus total cost without a BESS $\chi^{BESS} = 0$) of 12.3 k€ over an expected lifetime of 10.3 years yield a present value of 77.0 k€ (see Table 10) surpassing operational expenditures at a present value of -31.3 k€. However, high total plant costs of the BESS entail a net present value of the storage that is largely negative (-1054 k€) and causing the minimum forecast error operational mode to be economically not viable.

[8]The original model formulation has to be adapted as follows: the tendered control reserve power, the energy shed in order to reduce the forecast error and the scheduled discharge of the BESS is fixed at zero ($P^{CE} \overset{!}{=} 0$, $q_t^{shed_{FE}} \overset{!}{=} 0$, $d_t^{spot_{schedule}} \overset{!}{=} 0$).

Table 9: WPP forecast error cost in 2014 under variable storage capacity χ^{BESS} ($\chi^{BESS}/\kappa^{BESS} = 1h$).

			$FE < 0$ lack of energy		$FE > 0$ surplus of energy	
Forecast quality	χ^{BESS} [MWh]	Total net cost of FE [k€]	Cost [k€]	Negative cost [k€]	Revenues [k€]	Negative revenues [k€]
	0	-745	-767	78	152	-209
Day-ahead	1	-732	-738	72	126	-192
	0	-515	-581	83	165	-182
Intraday	1	-505	-548	76	133	-166

Table 10: Net present value of BESS when employed in minimum forecast error operationaol mode ($\chi^{BESS} = 1MWh$, forecast quality: day-ahead).

Total net revenues of BESS employment [k€/yr]	Exp. lifetime of BESS[a] [years]	PV of revenues [k€]	PV of $OPEX^{BESS}$ [k€]	PV of TPC^{BESS} [k€]	NPV of BESS [k€]
12.3	10.3	77.0	-31.3	-1100	-1054

[a]Resulting from 679.3 full-cycle equivalents

3.5. Co-optimized operational mode of BESS

In this section it is assumed that the wind power plant provides 1MW of control energy as it was the case in section 3.2. In addition a BESS is operated jointly with the WPP in order to reduce its forecast error, to harness its excess energy and to provide control energy when the WPP is incapable to do so. The size of the storage capacity is selected as small as possible such that control energy calls can always be fulfilled by the wind-storage plant: $\chi^{BESS} = 1.7MWh$. Total revenues of this co-optimized operational mode in comparison to revenues generated by the WPP only are shown in Table 11. Total net revenues generated by the WPP only ($\chi^{BESS} = 0MWh$) amount to 357.1 k€ and can be increased to 425 k€ employing a 1.7MWh BESS. Consequently, the storage system's net benefit amounts to 67.9 k€.

Revenues due to provision of control energy (CE_{energy}) and power (CE_{power}) constitute the largest share in total revenues for both cases. Therefore the net benefit of the storage system is rather low (9.8 k€ resp. 0.0 k€). However, penalty payments for unfulfilled control energy calls are omitted in case of a co-optimized dispatch of the BESS resulting in savings of 29.7

Table 11: Actual revenues and cost of a co-optimized dispatch of the BESS in 2014 in comparison to revenues generated by the WPP only, according to section 3.2. ($P^{CE} = 1MW$)

χ^{BESS} [MWh]	Total net revenues [k€]	Revenues spot [k€]	Savings FE [k€]	Revenues CE_{energy} [k€]	Penalty CE_{energy} [k€]	Revenues CE_{power} [k€]	Number of CE violations [1]
0	357.1	0	56.6	205.0	- 29.7	125.2	211
1.7	425.0	7.5	77.4	214.8	0	125.2	0
diff.	67.9	7.5	20.8	9.8	29.7	0	- 211

k€. Additional revenues from shifting excess energy of the WPP to the day-ahead market (see column *'Revenues spot'* in Table 11) are somewhat disappointing yielding only 7.5 k€. Lastly, savings in forecast error costs can be increased form 56.6 k€ (when excess energy is shed only) to 77.4 k€ applying the storage system to reduce both, positive and negative forecast errors.

The economic efficiency calculation is summarized in Table 12 for both considered options of collateralization. Yearly total net revenues amount to 67.9 k€ in case a penalty payment has to be made when the wind-storage plant is incapable to fulfill a control energy call. Furthermore, total net revenues are higher (137.2 k€) in case a fixed rate of 30% of total revenues is charged for collateralization.

The present value of the net revenues amount to 393.1 k€ (penalty factor) respectively 794.1 k€ (fixed rate). In any case, the NPV of the storage system is negative. It has to be put in relation to its storage capacity χ^{BESS} to establish comparability. The NPV amounts to -885.8 k€/MWh in case of a penalty payment respectively -649.9 k€/MWh in case of a fixed payment for collateralization and is therefore considerably higher than it is for the other operational modes.

Table 12: Present value of net revenues due to co-optimized employment of the storage system ($\chi^{BESS} = 1.7MWh$, $P^{CE} = 1MW$).

Collateralization of control energy	Total net revenues of BESS employment [k€/yr]	Expected lifetime of BESS[a] [years]	PV of revenues [k€]	PV of $OPEX^{BESS}$ [k€]	PV of TPC^{BESS} [k€]	NPV of BESS [k€]
Penalty factor	67.9	9.1	393.1	-28.9	-1870	-1506
Fixed rate	137.2	9.1	794.1	-28.9	-1870	-1104

[a]Resulting from 762.5 full-cycle equivalents per year.

4. Conclusion

All of the evaluated operational strategies of the battery energy storage system (arbitrage-only, minimum forecast error and co-optimized operational mode) yield a negative net present value and are thus economically not viable (see figure 4). While generated revenues of each operational mode surpass the operational expenditures of the storage system the BESS's investment costs are still considerably high and would have to decline by 60% to 80% to achieve profitability.

However, the WPP operator could save payments for balancing energy in the amount of several ten thousand Euros by actively shedding surplus generation in case of positive forecast error.

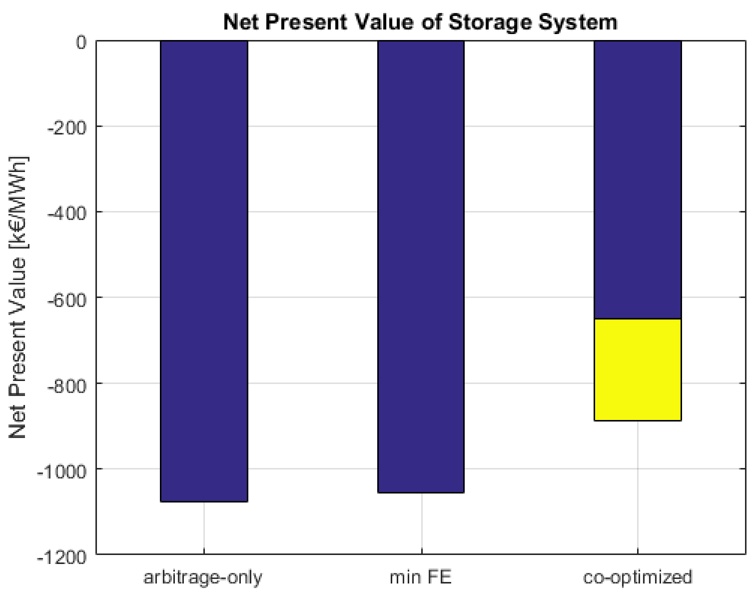


Figure 3: Comparison of net present values of storage systems under different operational modes.

References

Akhil, Abbas A. et al. (2013). DOE/EPRI 2013 electricity storage handbook in collaboration with NRECA. Sandia National Laboratories Albuquerque, NM, USA. url: http://www.emnrd.state.nm.us/ECMD/RenewableEnergy/documents/SNL-ElectricityStorageHandbook2013.pdf

Brauns, Steffen et al. (2014). Regelenergie durch Windkraftanlagen. url: http://www.energiesystemtechnik.iwes.fraunhofer.de/content/dam/iwes-neu/energiesystemtechnik/de/Dokumente/Studien-Reports/20140822_Abschlussbericht_rev1.pdf (visited on 06/09/2015)

Chen, Haisheng et al. (2009). Progress in electrical energy storage system: A critical review. In: Progress in Natural Science 19.3, pp. 291 312. issn: 10020071. doi: 10.1016/j.pnsc.2008.07.014. url: http://linkinghub.elsevier.com/retrieve/pii/S100200710800381X (visited on 12/09/2015)