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Profitability analysis of various operational strategies of battery energy storage systems operated with wind power plants

A model-based Austrian case study

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Abstract

High efforts to promote renewable energy systems in Europe have led to fundamental changes in the electricity sector. Consequently, the integration of highly intermittent generation into the energy system is a key task ahead. Energy storage technologies are a promising tool to support this development but current wholesale electricity prices and small price spreads in particular do not allow for profitable operation. Hence, multiple use of energy storage in addition to the traditional field of application (energy arbitrage) can lead to economic efficiency.

This thesis aims to explore options of deployment of battery energy storage systems (BESSs) when operated together with wind power plants (WPPs). Thereby, the BESS is used in three different modes in order to maximize the economic efficiency of the hybrid wind-storage plant: (1) to reduce forecast errors of the WPP and thus reduce payments for balancing energy; (2) to provide ancillary service (positive and negative control energy) to the grid; and (3) to harness excess energy of the WPP by shifting production in moments of low corresponding value of energy to moments of high values. The optimal dispatch strategy of the BESS is obtained from a two-stage linear optimization model which requires perfect foresight of electricity wholesale prices. Moreover, the wind-storage plant is acting as a price taker.

The analysis is based on an existing WPP and data of the Austrian spot and control energy market of the year 2014 and suggests that BESSs are not profitable within the current economic and technical framework conditions. Capital costs of the BESS would have to decrease by 60% in order to allow for profitable operation. Finally, better use of the flexibility provided by a storage unit could be made if it is operated simultaneously on the intra-day and the control energy market and not sequentially as it is implemented in the two-stage framework used in this study. As a result, further research activity should focus on the fusion of the two stages.

Contents

Nomenclature

List of Abbreviations

aFRR	Automatic frequency restoration reserve (secondary control reserve)
BESS	Battery energy storage system
BG	Balance group
CAPEX	Capital expenditures
CE	Control energy
DOD	Depth of Discharge
FCE	Full-cycle equivalent
FE	Forecast error
MW	Megawatt
MWh	Megawatt hour
NPV	Net present value
OM	Operational mode
OPEX	Operational expenditures
PV	Photovoltaics or present value
RES	Renewable energy systems
RMSE	Root-mean-square error
TPC	Total plant cost (of the storage system)
WPP	Wind power plant

Parameters

$FE_{t,T}$	forecast error of WPP generation in moment t (MWh)
$l_{t,T}$	level of storage in moment t of time period T (MWh)
$p^{balance}$	average cost of balancing energy (€/MWh)
p^{spot}	average day-ahead spot market price (€/MWh)

$p_{t,T}^{spot}$	day-ahead spot market price in t (€/MWh)
$p_{t,T}^{CE_{MWh}}$	control energy price in t (€/MWh)
P^{CE}	control reserve power tendered by the generation unit (MW)
$q_{t,T}^{WPP_{actual}}$	actual generation of WPP in hour t (MWh)
$q_{t,T}^{WPP_{schedule}}$	scheduled (predicted) generation of WPP in hour t (MWh)
V^{CE}	penalty factor for unserved control energy call (1)
η^{BESS}	cycle storage efficiency of BESS
$\Theta_{t,T}^{CE}$	Boolean variable that indicates if control energy is requested in t (0,1)
κ^{BESS}	power capacity of BESS (MW)
τ	number of quarters in a time period T
χ^{BESS}	storage capacity of BESS (MWh)

Decision Variables

$d_{t,T}^{CE}$	energy discharged in t in order to provide positive control energy (MWh)
$d_{t,T}^{FE}$	energy discharged in t in order to reduce forecast error (MWh)
$d_{t,T}^{spot_{reduction}}$	reduction of discharge of energy that was scheduled because of day-ahead energy market obligations at the time t to provide negative control energy (MWh)
$d_{t,T}^{spot_{schedule}}$	scheduled discharge of BESS (MWh)
$l_{t,T}$	level of storage at the time t
$q_{t,T}^{shed_{CE}}$	energy shed in hour t to provide negative control energy (MWh)
$q_{t,T}^{shed_{FE}}$	energy shed in t in order to reduce forecast error (MWh)
$s_{t,T}^{CE}$	energy stored at the time t to provide negative control energy (MWh)
$s_{t,T}^{FE}$	energy stored in t in order to reduce forecast error (MWh)
$s_{t,T}^{spot_{schedule}}$	scheduled charge of BESS (MWh); obtained from first stage of optimization

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 thesis aims to explore options of deployment of battery energy storage systems (BESS) when operated together with a wind power plant (WPP). Similar to publications such as Cai et al., 2015, Sioshansi et al., 2011 and Loisel et al., 2011. The novel approach is to use the BESS in three different ways in order to maximize net revenues of the hybrid wind-storage system: (1) to reduce forecast errors of the WPP and thus reduce payments for balancing energy; (2) to provide ancillary service (positive and 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 day considering day-ahead market prices for electricity only. This first optimization leads to a scheduled dispatch of the BESS.
- 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 WPP in Austria. The linear optimization model was implemented in Matlab using Yalmip and Gurobi Optimizer.

1.1 Motivation

The central idea of this thesis is to harness the excess energy of WPPs originating from positive forecast errors in order to provide control energy and increase spot market revenues and can be explained best through a closer examination of the forecast error cost and its components. The cost of forecast error in the moment t results from the multiplication of the energy imbalance price $p_t^{balance}$ and the forecast error FE_t

$$cost_t^{FE} = p_t^{balance} \cdot FE_t. \tag{1.1}$$

Since both factors can be positive as well as negative, four different cases have to be differentiated.

(i) Shortfall in generation (negative forecast error) and positive energy imbalance price: the wind farm has to make a payment to the TSO referred to as *'cost'* in figure 1.1.

(ii) Shortfall in generation and negative energy imbalance price: the WPP receives a payment from the TSO referred to as *'negative cost'*.

(iii) Surplus in generation (positive forecast error) and positive energy imbalance price: the WPP receives a payment from the TSO referred to as *'revenues'*.

(iv) Surplus in generation and negative energy imbalance price: the WPP has to make a payment to the TSO referred to as *'negative revenues'*.

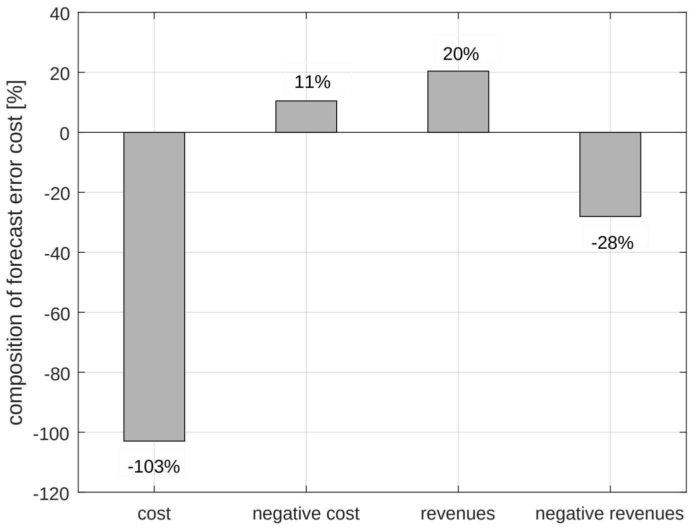


Figure 1.1: Components of forecast error cost of a 20 MW wind power plant in relation to total net cost of forecast errors in the year 2014. *Cost* and *negative cost* occure in case the actual generation exceeds the forecast. *Revenues* and *negative revenues* occur in cast actual generation is lower than the forecast.

Figure 1.1 depicts those four components of forecast error cost in relation to annual total net costs. In case of surplus generation of the WPP, annual *negative revenues* exceed annual *revenues*. Consequently, excess energy, that is fed into the grid, entails costs.

Hence, shedding surplus generation could reduce annual forecast error cost. Furthermore, if a storage unit was available at the wind farm site, excess generation could be stored free of charge and sold later at the spot market. The same is true for excess energy originating from negative control energy requests. This observation forms the basic idea of the analysis conducted within this thesis.

1.2 Structure of the thesis

Chapter 2 gives an overview of storage operational strategies in general and the state of the art of storage modeling. Several studies that aim to analyze operational schemes and economic profitability of storage power plants are discussed in order to address current issues related to storage operation.

Subsequently, the methodology applied in this work is presented in chapter 3, which comprises the two-stage linear optimization framework for storage scheduling, the economic efficiency calculation procedure and the input data necessary for the study.

Generated revenues and incurred cost, based on the optimized operation of the storage system, are discussed in chapter 4, resulting in the profitability analysis of the battery energy storage system for each operational strategy considered. Moreover, chapter 5 aims to identify influencing parameters on storage economics and to assess their impact on the net present value of storage system.

The key results of this work are discussed and interpreted in chapter 6. Finally, conclusions are drawn in chapter 7 and the study is completed with a brief outlook on further research activity required.

2 State of the Art

As of late there is a growing interest in electricity storage technologies and battery energy storage systems (BESS) in particular. Thus, a vast number of scientific papers were published in the past years. This sections aims to provide the reader with a brief overview of research issues related to the subject of electrical storage systems.

2.1 Operational strategies of energy storage systems

Table 2.1 gives an overview of different applications of energy storage systems, referred to hereafter as operational strategies. The summary is subdivided into three clusters: (i) operational strategies from an *end-consumer* perspective, (ii) from a *electricity generation and supply* perspective of either a certain balance group (BG) or the electricity grid operator, as well as (iii) *ancillary services* a storage system can provide to the electricity grid.

Beginning with the end-consumer's perspective, a storage device can be utilized in order to increase the consumption of self-generated electricity (e.g originating from a PV-system) as it was analyzed among others in Merei et al., 2016. In case of time variable electricity prices or grid tariffs at end-user level, deployment of storage systems could further reduce the total electricity procurement cost of consumers. Lastly, a reduction in peak load (respectively in peak generation in case end-users also feed excess self-generation into the grid) through storage deployment can be a reasonable operational strategy according to Lucas and Chondrogiannis, 2016.

From an energy supply company's perspective, storage power plants can be charged in hours with low related electricity wholesale prices and discharged in hours with high prices in order to exploit temporal price differences. This

Table 2.1: Overview of operational strategies of storage systems.

Classification	Operational strategy
end-consumer	- maximize self consumption - minimize electricity procurement cost - minimize peak load/generation
electricity generation and supply	- arbitrage activity at electricity wholesale markets - minimize forecast deviation of volatile generation - provide flexibility to inflexible or intermittent generation - isolated operation (island mode)
ancillary service	- provide regulation reserve (control energy) - voltage stability/ deferral of grid enforcement measures - virtual inertia - black start capacity

operational strategy is commonly known as *energy arbitrage* and constitutes the classical application of storage units. Thus, there are a broad number of studies related to this use case (e.g. Sioshansi et al., 2009).

Additionally, storage power plants provide valuable flexibility that could be utilized in order to compensate for forecast errors of intermittent generation such as wind and PV (Cai et al., 2015) as well as to improve ramping characteristics of stagnant conventional power plants or to even out generation of volatile renewable power plants (Loisel et al., 2011). A more special case of use is isolated operation, when a storage device is used to counteract fluctuations in generation and consumption in a small island grid (Ahadi, Kang, and Lee, 2016).

Last but not least, flexible storage systems can provide all kinds of ancillary services to the electricity grid. Such as regulation reserve (frequency containment reserve resp. frequency restoration reserve) as investigated in Drury, Denholm, and Sioshansi, 2011. Intelligent dispatch of battery units in distribution grids can increase voltage quality[1]. Thus, grid reinforcement measures (reinforcement of power cables and transformers) can be deferred.

A rather novel area of application for storage is to provide virtual inertia. This is considered to become crucial in future power systems if conventional

[1] e.g. to ensure the voltage level to remain within a predefined tolerance range.

bulk power plants (which use synchronous machines and thus provide the power system with inherent inertia) are replaced by distributed generation units that have either a small or no rotating mass (Bevrani, Ise, and Miura, 2014). Finally, it should be mentioned that large storage power plants (such as pumped-storage hydroelectric plants) can be used to carry out a so-called black start after large generators were shut down due to a severe incident of the power system.

In order to increase the economic profitability of storage power plants, efforts regarding the combination of multiple operational strategies (such as arbitrage and ancillary service) to achieve a co-optimized dispatch of the storage facility were made.

2.2 Model based case studies on energy storage profitability

Some scientific publications and the related findings will be discussed briefly in this section in order to provide an overview of existing storage modeling techniques and economic efficiency perspectives of storage systems.

Cai et al., 2015 used a battery energy storage system to compensate forecast errors of wind power generation to realize savings in cost of balancing energy in the year 2050 and concludes that a BESS can be a profitable alternative for short-term balancing of intermittent generation compared to the balancing mechanism in place.

Sioshansi et al., 2011 examined the use of energy storage to mitigate electricity wholesale price suppression of high wind power generation by shifting wind generation from periods with low prices to periods with higher prices applying a two-stage optimization model. While storage operation can significantly increase the value of wind generation, high capital cost of those technologies cannot be justified on the basis of this use.

Li et al., 2015 used a two-step stochastic unit commitment approach with wind power forecast uncertainty to evaluate the potential value of energy storage in power systems with renewable generation. The effectiveness of the proposed battery operation strategy is analyzed on the IEEE 24-bus system, which is a rather small and restricted test system including conventional and renewable power plants. The authors conclude that battery storage can decrease the curtailment of wind generation, reduce load and reserve shortfalls as well as the commitment of thermal units. Total system costs can be reduced, which implies that battery storage is a cost-effective solution[2].

Loisel et al., 2011 examined the co-operation of a wind farm together with a compressed air energy storage facility in order to reduce the intermittency of its output and to provide flexibility to the system. Results show that under baseline conditions, the hybrid wind-storage system would have negative profits despite price arbitrage operations and ancillary services. But could be improved if the influence of the wind power on the spot price is considered.

2.3 Progress beyond state of the art

The studies cited in the previous section reveal that storage power plants (BESSs in particular) are not profitable at present under most operational schemes due to high capital costs and insufficient electricity price levels[3]. Nevertheless, co-optimized dispatch of storage capacities in order to generate proceeds from different sources simultaneously is the most promising approach towards an economic operation.

In this thesis a two-stage linear optimization model is introduced that aims to explore the economic efficiency of BESSs operated in combination with wind power plants. Consequently, the storage can be used in three different ways in order to maximize net revenues of the hybrid wind-storage system: (1) to reduce forecast deviations of the WPP and thus reduce payments for balancing energy; (2) to provide ancillary service (positive and 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.

[2] However, storage profitability is achieved primary due to the very small test system and thus considerable high scarcity prices.

[3] Especially the traditional field of application for storage systems, energy arbitrage, which is extensively examined and well understood, fails to generate enough revenues to trigger investment in new storage power plants.

The model framework is applied to an existing wind farm in Austria to investigate whether this threefold co-optimized operation of a battery storage system manages to generate revenues that exceed the capital and operational cost of this technology and what are the parameters that have (besides cost) the strongest influence on storage economics.

3 Method

3.1 Energy balance of the hybrid wind-storage plant

The aim of this work is to analyze various operational strategies of battery energy storage system (BESS) when operated in combination with wind power plants (WPP). Hence, the storage unit is operated in three different ways (either exclusively or simultaneously):

(i) it is used to minimize the forecast deviation of the WPP and thus reduces balancing energy costs,
(ii) it provides positive and negative control energy as an ancillary service to the TSO,
(iii) excess energy originating from the first and second application is stored and can be sold on electricity spot markets.

From the system's energy balance perspective (Figure 3.1), the hybrid wind-storage plant is obliged to provide a certain amount of energy in each point of time t (referred to hereafter as q_t^{demand}), which consists of the scheduled (predicted) generation of the WPP ($q_t^{WPP_{schedule}}$), the request for control energy ($q_t^{CE_{demand}}$) and the scheduled discharge of the BESS *'into the spot market'* ($d_t^{spot_{schedule}}$, energy that was sold in the past on electricity spot markets).

The actual amount of energy provided by the wind-storage plant in each point of time t is called q_t^{supply} and consists of the actual generation of the WPP ($q_t^{WPP_{actual}}$), the energy stored or discharged into or from the BESS in order to counteract forecast error and thus reduce forecast deviation (s_t^{FE}, d_t^{FE}), the energy stored or discharged in order to fulfill a control energy request (s_t^{CE}, d_t^{CE}), energy discharged in order to fulfill spot market obligations (d_t^{spot}),

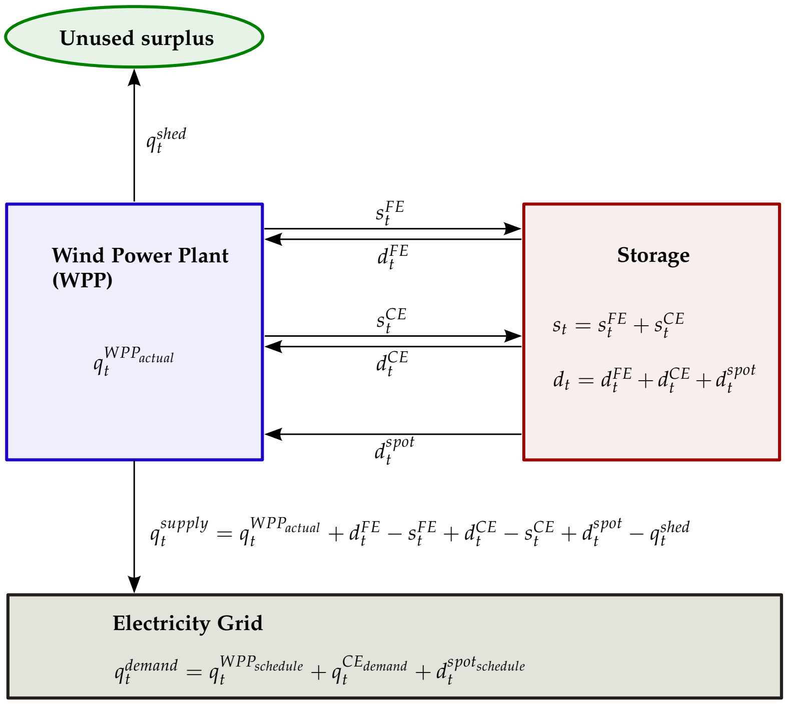


Figure 3.1: Energy balance of overall system. The storage is used to minimize the WPP's forecast deviation, to provide control energy and to shift excess energy of the WPP to the day-ahead market.
(q...quantity, s...store, d...discharge, FE...forecast error, CE...control energy)

and the amount of energy which is shed (q_t^{shed}) in order to accomplish either a negative control energy request, or to reduce (a positive) forecast deviation.

By implication, the optimal operation of the BESS (from the energy balance perspective) attempts to minimize the deviation of q_t^{demand} and q_t^{supply} by adjusting the optimization variables grouped in vector $\boldsymbol{x} = [d_t^{FE}, s_t^{FE}, d_t^{spot}, s_t^{CE}, q_t^{shed}]$

$$\min_{\boldsymbol{x}} \sum_{t \in T} |q_t^{supply} - q_t^{demand}| \tag{3.1}$$

and can be expressed as

$$\begin{aligned}\min_{x} \sum_{t\in T} |(q_t^{WPP_{actual}} + d_t^{FE} - s_t^{FE} + d_t^{CE} - s_t^{CE} + d_t^{spot} - q_t^{shed}) \\ - (q_t^{WPP_{schedule}} + q_t^{CE_{demand}} + d_t^{spot_{schedule}})|\end{aligned} \tag{3.2}$$

respectively as

$$\begin{aligned}\min_{x} \sum_{t\in T} |(FE_t + d_t^{FE} - s_t^{FE}) + (-q_t^{CE_{demand}} + d_t^{CE} - s_t^{CE}) \\ + (-d_t^{spot_{schedule}} + d_t^{spot}) - q_t^{shed}|.\end{aligned} \tag{3.3}$$

The difference between actual and scheduled (forecasted) generation of the WPP is referred to as the forecast error

$$FE_t = q_t^{WPP_{actual}} - q_t^{WPP_{schedule}}. \tag{3.4}$$

Hence FE_t is positive if actual generation exceeds forecast and is negative if actual generation is lower than forecast.

Since the tasks described above affect different electricity markets (day-ahead, balancing and control regulation market) and a real storage system is restricted in its power and energy capacity, the control strategy of the BESS has to take into account different price levels and potential charges in order to find the optimal storage operation. This is done by the linear optimization model described in the section below.

3.2 Two-stage optimization model

To operate the storage system in an optimal way in terms of net revenues, the expected revenues and costs are computed by assigning prices to energy flows depicted in equation (3.3). Furthermore, the observed period (the 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.[1] As a consequence, all time dependent variables and parameters have two indexes. The first index indicates the current quarter hour, the second indicates the current day (e.g. $l_{t,T}$ indicates the level of the BESS in quarter hour t of day T).

This way of indexing is necessary because the co-optimization problem (optimal use of BESS) is split up into two steps: first, operation 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 the control energy requested by the TSO.

The scheme of this two-stage optimization problem is illustrated in figure 3.2. 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 in time period T.

The first stage of optimization 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 operation of the BESS taking into account expected revenues from providing control energy and minimizing the forecast deviation 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 $T+1$.

3.2.1 First stage of optimization: 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

[1] In case the time period T is fixed to one day, τ (the number of quarters within a day) equals 96

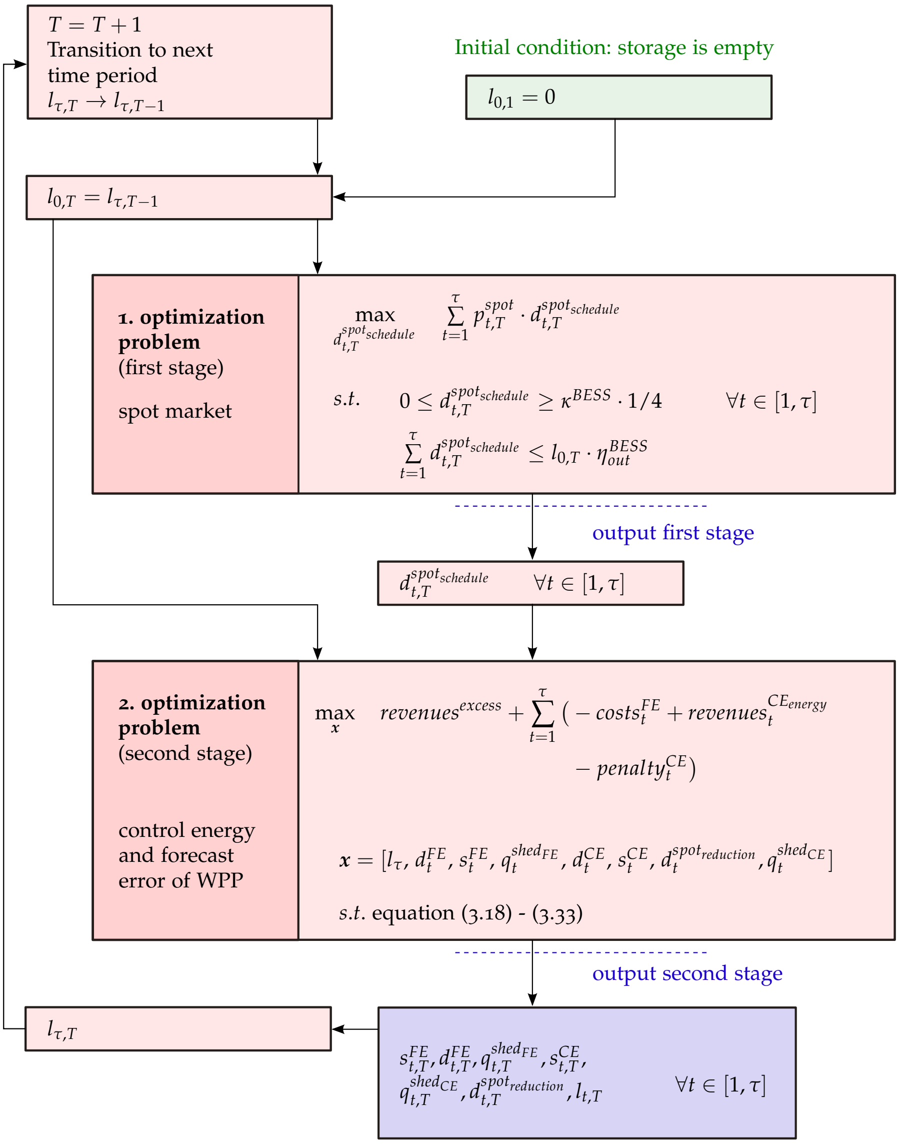


Figure 3.2: Scheme of the two-stage optimization problem. The level of storage at the beginning of a time period T ($l_{0,T}$) equals the level of storage at the end of time period $T-1$ ($l_{\tau,T-1}$). (l...level of storage, s...store, d...discharge, p...price, FE...forecast error, CE...control energy, κ^{BESS}...power capacity of BESS, η_{out}^{BESS}...storage discharge efficiency)

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

$$\max_{d_{t,T}^{spot_{schedule}}} \quad \sum_{t=1}^{\tau} p_{t,T}^{spot} \cdot d_{t,T}^{spot_{schedule}} \tag{3.5}$$

$$\text{s.t.} \quad d_{t,T}^{spot_{schedule}} \geq 0 \qquad \forall t \in [1, \tau] \tag{3.6}$$

$$d_{t,T}^{spot_{schedule}} \leq \kappa^{BESS} \cdot 1/4 \qquad \forall t \in [1, \tau] \tag{3.7}$$

$$l_{t,T} \geq 0 \qquad \forall t \in [1, \tau] \tag{3.8}$$

$$l_{0,T} = l_{\tau,T-1} \tag{3.9}$$

$$l_{t-1,T} - (d_{t,T}^{spot_{schedule}} / \eta_{out}^{BESS}) = l_{t,T} \tag{3.10}$$

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

Note: The storage level at the end of time period $T-1$ ($l_{\tau,T-1}$) equals the storage level at the beginning of the following time period T ($l_{0,T}$). Thus, the energy amount of ($l_{0,T} \cdot \eta_{out}^{BESS}$) can be sold at the spot market in the following time period T.

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)
κ^{BESS}	power capacity of BESS (MW) and
η_{out}^{BESS}	discharge efficiency of BESS.

3.2.2 Second stage of optimization: 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 operation is obtained from the linear optimization problem[2]

$$\max_{x} \quad revenues^{excess} + \sum_{t=1}^{\tau} \left(- costs_t^{FE} + revenues_t^{CE_{energy}} - penalty_t^{CE} \right) \tag{3.11}$$

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 $x = [l_\tau,\ d_t^{FE},\ s_t^{FE},\ q_t^{shed_{FE}},\ d_t^{CE},\ s_t^{CE},\ d_t^{spot_{reduction}}, q_t^{shed_{CE}}]$.

The second stage of the optimization problem takes into consideration the following components

- expected revenues from selling excess energy to the day-ahead market ($revenues^{excess}$),
- reduction of forecast deviations and thus reduction of expected forecast error costs ($costs_t^{FE}$) and
- revenues due to fulfilled control energy requests ($revenues_t^{CE_{energy}}$), respectively penalty payments in case of a control energy request violations ($penalty_t^{CE}$).

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

$$costs_t^{FE} = p^{balance} |FE_t + d_t^{FE} - s_t^{FE} - q_t^{shed_{FE}}| \tag{3.12}$$

which can be transformed by means of equation (3.19) and (3.21) to

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

$$costs_t^{FE} = p^{balance}(|FE_t| - d_t^{FE} - s_t^{FE} - q_t^{shed_{FE}}) \tag{3.13}$$

and can be minimized by application of the 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.

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

$$revenues_t^{CE_{energy}} = p_t^{CE^+_{MWh}} \cdot d_t^{CE} + p_t^{CE^-_{MWh}}(-s_t^{CE} - q_t^{shed_{CE}} - d_t^{spot_{reduction}}). \tag{3.14}$$

A positive control energy request (regulation up) can be fulfilled by discharging energy from the BESS (d_t^{CE}), while a negative control energy request (regulation down) 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 ($d_t^{spot_{reduction}}$). Regulation up is fed into the grid at a price $p_t^{CE^+_{MWh}}$, which is positive, resulting in revenues due to the delivery of energy. Regulation down is withdrawn from the grid (therefore it has a negative sign) at a price $p_t^{CE^+_{MWh}}$, which is typically negative during the observed time period.

In case a control energy request cannot be fulfilled, the hybrid wind-storage plant is charged with a penalty payment in the amount of the $V^{CE}-$fold[3] of the control energy price in quarter t ($p_t^{CE_{MWh}}$). The amount of positive control energy requested in t is calculated as $\Theta_t^{CE^+} \cdot P^{CE^+}\frac{1}{4}h$. Where P^{CE^+} is the positive control reserve power in MW tendered by the wind-storage plant, $P^{CE^+}\frac{1}{4}h$ is the control energy required per quarter hour and $\Theta_t^{CE^+}$ is a Boolean value that equals 1 if regulation up is requested in t and 0 otherwise. The same applies for regulation down in analogues manner.

[3]This reflects the fact that the wind-storage plant is obliged to provide control energy.

The requested amount of control energy less the actual provided amount equals the shortfall of control energy and results in a penalty payment of

$$\begin{aligned} penalty_t^{CE} = V^{CE}\Big[&|p_t^{CE^+_{MWh}}| \cdot [\Theta_t^{CE^+} \cdot P^{CE^+}\frac{1}{4}h - d_t^{CE}] \\ &+|p_t^{CE^-_{MWh}}| \cdot [\Theta_t^{CE^-} \cdot P^{CE^-}\frac{1}{4}h \\ &\qquad - (s_t^{CE} + q_t^{shed_{CE}} + d_t^{spot_{reduction}})]\Big]. \end{aligned} \tag{3.15}$$

Finally, to differentiate between the options available to reduce forecast deviations and to provide control energy in order to ensure an optimal operation of the storage device, expected revenues of the energy stored in the BESS at the end of a time period have to be considered[4].

The amount of energy stored in the BESS at the end of a day l_τ (reduced by the discharge storage efficiency η_{out}^{BESS}) can be sold on the spot market and is expected to generate revenues in the amount of

$$revenues^{excess} = l_\tau \cdot \eta_{out}^{BESS} \cdot p^{spot}, \tag{3.16}$$

where p^{spot} denotes the average spot market price in €/MWh.

By substitution of the revenue and cost terms in equation (3.11) the second stage of the optimization model can be expressed as

$$\begin{aligned} \max_x \quad & l_\tau \cdot \eta_{out}^{BESS} \cdot p^{spot} + \sum_{t=1}^{\tau}\Big\{ - p^{balance}(|FE_t| - d_t^{FE} - s_t^{FE} - q_t^{shed_{FE}}) \\ & + p_t^{CE^+_{MWh}} \cdot d_t^{CE} + p_t^{CE^-_{MWh}}(-s_t^{CE} - q_t^{shed_{CE}} - d_t^{spot_{reduction}}) \\ & - V^{CE}\Big[|p_t^{CE^+_{MWh}}| \cdot [\Theta_t^{CE^+} \cdot P^{CE^+}\frac{1}{4}h - d_t^{CE}] \\ & + |p_t^{CE^-_{MWh}}| \cdot [\Theta_t^{CE^-} \cdot P^{CE^-}\frac{1}{4}h - (s_t^{CE} + q_t^{shed_{CE}} + d_t^{spot_{reduction}})]\Big]\Big\} \end{aligned} \tag{3.17}$$

[4]as energy that is stored can be sold on the spot market while energy that is shed is clearly lost and will not gain any further revenues

$$\text{s.t.} \quad s_t^{FE} \geq 0, \quad d_t^{FE} \geq 0, \quad q_t^{shed_{FE}} \geq 0 \qquad \forall t \in [1, \tau] \tag{3.18}$$

$$d_t^{FE} \leq |FE_t| \qquad if FE_t < 0 \tag{3.19}$$

$$d_t^{FE} \leq 0 \qquad if FE_t \geq 0 \tag{3.20}$$

$$s_t^{FE} + q_t^{shed_{FE}} \leq FE_t \qquad if FE_t > 0 \tag{3.21}$$

$$s_t^{FE} + q_t^{shed_{FE}} \leq 0 \qquad if FE_t \leq 0 \tag{3.22}$$

$$d_t^{CE} \geq 0, s_t^{CE} \geq 0, q_t^{shed_{CE}} \geq 0, d_t^{spot_{reduction}} \geq 0 \qquad \forall t \in [1, \tau] \tag{3.23}$$

$$d_t^{CE} \leq \Theta_t^{CE^+} \cdot \frac{P^{CE^+}}{4} \qquad \forall t \in [1, \tau] \tag{3.24}$$

$$s_t^{CE} + q_t^{shed_{CE}} + d_t^{spot_{reduction}} \leq \Theta_t^{CE^-} \cdot \frac{P^{CE^-}}{4} \qquad \forall t \in [1, \tau] \tag{3.25}$$

$$\begin{aligned} d_t^{FE} + d_t^{spot_{schedule}} + d_t^{CE} & \\ -d_t^{spot_{reduction}} - s_t^{CE} &\leq \kappa^{BESS} \cdot 1/4 \qquad \forall t \in [1, \tau] \end{aligned} \tag{3.26}$$

$$\begin{aligned} s_t^{FE} - d_t^{spot_{schedule}} - d_t^{CE} & \\ +d_t^{spot_{reduction}} + s_t^{CE} &\leq \kappa^{BESS} \cdot 1/4 \qquad \forall t \in [1, \tau] \end{aligned} \tag{3.27}$$

$$d_t^{spot_{reduction}} \leq d_t^{spot_{schedule}} \qquad \forall t \in [1, \tau] \tag{3.28}$$

$$q_t^{shed_{CE}} + q_t^{shed_{FE}} \leq q_t^{WPP_{actual}} \qquad \forall t \in [1, \tau] \tag{3.29}$$

$$l_{0,T} = l_{\tau, T-1} \tag{3.30}$$

$$l_t \geq 0 \qquad \forall t \in [1, \tau] \tag{3.31}$$

$$l_t \leq \chi^{BESS} \qquad \forall t \in [1, \tau] \tag{3.32}$$

$$\begin{aligned} l_{t-1} + \eta_{in}^{BESS}(s_t^{FE} + s_t^{CE}) & \\ - \frac{(d_t^{FE} + d_t^{CE} + d_t^{spot_{schedule}} - d_t^{spot_{reduction}})}{\eta_{out}^{BESS}} &= l_t \qquad \forall t \in [1, \tau] \end{aligned} \tag{3.33}$$

Model variables

s_t^{FE}	energy stored in t in order to reduce forecast errors (MWh)
d_t^{FE}	energy discharged in t in order to reduce forecast errors (MWh)

$q_t^{shed_{FE}}$	energy shed in t in order to reduce forecast errors (MWh)
d_t^{CE}	energy discharged at the time t to accomplish a positive control energy request (MWh)
s_t^{CE}	energy stored at the time t to accomplish a negative control energy request (MWh)
$q_t^{shed_{CE}}$	energy shed in hour t to accomplish a 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 a negative control energy request (MWh)
l_t	level of storage at the time t (MWh)

Model parameters

τ	number of quarter hours per 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)
$\Theta_t^{CE^+}$	Boolean variable that indicates if positive control energy is requested in t (0,1)
$\Theta_t^{CE^-}$	Boolean variable that indicates if negative control energy is requested in t (0,1)
P^{CE^+}	positive control reserve power tendered by the wind-storage plant (MW)
P^{CE^-}	negative control reserve power tendered by the wind-storage plant (MW)
$p_t^{CE^+_{MWh}}$	control energy price for regulation up in t (€/MWh)
$p_t^{CE^-_{MWh}}$	control energy price for regulation down in t (€/MWh)
κ^{BESS}	power capacity of BESS (MW)
χ^{BESS}	storage capacity of BESS (MWh)
η_{in}^{BESS}	charge storage efficiency of BESS (1)
η_{out}^{BESS}	discharge storage efficiency of BESS (1)
$d_t^{spot_{schedule}}$	scheduled discharge of BESS (MWh); obtained from first stage of optimization
$l_{0,T}$	level of storage at the beginning of the time period T (MWh)
$l_{\tau,T-1}$	level of storage at the end of time period $T-1$ (MWh)

3.2.3 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

$$revenues_t^{spot} = p_t^{spot} \cdot d_t^{spot_{schedule}}, \tag{3.34}$$

while revenues due to reduction in forecast deviation are given by

$$savings_t^{FE} = \underbrace{p_t^{balance}(FE_t + d_t^{FE} - s_t^{FE} - q_t^{shedFE})}_{\text{costs with storage}} - \underbrace{p_t^{balance} \cdot FE_t}_{\text{costs without storage}}$$

$$= p_t^{balance}(d_t^{FE} - s_t^{FE} - q_t^{shed_{FE}}). \tag{3.35}$$

The balance group (hybrid wind-storage system) has to make a payment to the TSO when balancing energy costs are negative in t and receives a payment if balancing energy costs are positive. Therefore savings are positive when balancing energy costs without storage exceed costs with storage.

The definition of revenues from provided control energy are equal to equation (3.14). In addition there are revenues due to tendered control power (like it is customary for automatic frequency restoration reserve). As distinct from all other sources of proceeds, control power revenues are calculated for a whole year

$$revenues^{CE_{power}} = (p^{CE^+_{MW}} \cdot P^{CE^+} + p^{CE^-_{MW}} \cdot P^{CE^-}) \cdot 8760h, \tag{3.36}$$

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

Moreover, a wind power plant is not likely to participate at the control energy market (balancing market) as a single unit, but within a pool of other power plants resulting in a so called virtual power plant (VPP). In this case the VPP aggregator will charge the wind power plant a fee for integrating that certain power plant into the VPP reffered to hereafter as cost of collateralization ($cost^{CE_{coll.}}$). This fee is assumed to amount to a fraction v^{CE} of the hybrid wind-storage plant's revenues related to tendered control energy and power:

$$cost^{CE_{coll.}} = v^{CE} \cdot (revenues^{CE_{power}} + \sum_{T \in \mathscr{Y}} \sum_{t=1}^{\tau} revenues_{t,T}^{CE_{energy}}) \tag{3.37}$$

Consequently, the actual net revenues generated from storage operation for a whole year $\mathscr{Y}$[5] result in

$$\begin{aligned} revenues^{total} &= revenues^{CE_{power}} - cost^{CE_{coll.}} \\ &+ \sum_{T \in \mathscr{Y}} \sum_{t=1}^{\tau} \left(revenues_{t,T}^{spot} + savings_{t,T}^{FE} + revenues_{t,T}^{CE_{energy}}\right) \end{aligned} \tag{3.38}$$

3.2.4 Simplifications and effects not considered in the model

As it is unavoidable when it comes to any kind of modeling, simplification within the model formulation that neglect certain relations of the *'real world'* have to be made.

Some simplifications were made because detailed storage behavior is considered to be beyond the scope of this work. Others were necessary in order to ensure the model formulation to be a linear program. The relevant issues are stated in the hereafter.

- Degradation effects of the battery storage system (a reduction in the storage capacity χ^{BESS} per full-load cycle performed) were excluded in the model formulation.
- Self-discharge mechanisms of the storage unit are not considered.

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

- Wear costs of the BESS are neglected.
- The dispatch of the storage has no influence on historic electricity prices (the hybrid wind-storage plant acts as a price taker).
- Grid charges ara excluded in this work[6].
- Electricity price levels are assumed to remain constant for the whole lifetime of the BESS.

3.3 Economic efficiency calculation

The final step to assess the profitability of the storage unit is a cost-benefit analysis which compares the annual net revenues gained by storage operation with the total plant cost (TPC) and the operating expenses using the discounted cash flow method. Firstly, the lifetime of the battery storage system (in years of operation) has to be estimated. Subsequently, the yearly net revenues of storage have to be calculated and its present value (PV) has to be compared to the total plant cost of the storage system and the PV of its operational expenditures.

3.3.1 Expected lifetime of the BESS

Assuming the *Depth of Discharge* (DOD) has no effect on the lifetime of the battery as long as it does not fall below a predetermined minimum level, which is useful for some battery technologies (according to International Renewable Energy Agency, 2015), the intensity of storage utilization is described by its yearly full-cycle equivalent (FCE)

$$FCE^{BESS}_{yearly} = \frac{\sum\limits_{T} \sum\limits_{t=1}^{\tau} (s^{FE}_{t,T} + s^{CE}_{t,T} + s^{spot_{schedule}}_{t,T}) \cdot \eta^{BESS}_{in}}{\chi^{BESS}}, \tag{3.39}$$

[6]This simplification is considered to have little effect on the results because the BESS is located at the site of the wind power plant, thus the public grid is not utilized in case excess energy is stored.

which is nothing more than the accumulated energy charged into the BESS in a year (either to reduce a forecast deviation $s_{t,T}^{FE}$, to provide control energy $s_{t,T}^{CE}$, or to obtain electricity from the spot market $s_{t,T}^{spot_{schedule}}$) diminished by the storage charge efficiency η_{in}^{BESS} and divided by the storage capacity χ^{BESS}.

Since battery storage systems can only be fully discharged a limited number of times, referred to as total cycles of the battery, the expected lifetime of the BESS (in years of operation) is calculated by dividing the total number of cycles by the yearly full-cycle equivalent the storage actually performs

$$lifetime^{BESS} = \frac{cycles_{total}^{BESS}}{FCE_{yearly}^{BESS}}. \tag{3.40}$$

The optimization model's period of observation is only one year (2014), but it is assumed that all revenues and costs related to the BESS will remain constant for the whole lifetime of the battery.

3.3.2 Net present value of the BESS

In order to assess the BESS' profitability the present value (PV)

$$PV(revenues, i, n) = \sum_{t=1}^{n} \frac{revenues}{(1+i)^t} = revenues \cdot \frac{(1+i)^n - 1}{i \cdot (1+i)^n} \tag{3.41}$$

of future annual *revenues* gained by storage operation is calculated (given a lifetime of n years and a fixed interest rate i)

Since the sole contribution of the BESS itself is of interest, revenues of the WPP have to be subtracted. Based on the total revenues obtained per year (see equation (3.38)), the net revenues of the BESS can be expressed as the difference between the revenues gained from operating the wind-storage plant with a BESS of the storage capacity of χ^{BESS} and the revenues gained from operating the WPP without any storage ($\chi^{BESS} = 0$), resulting in

$$net\_revenues^{BESS} = revenues^{total}(\chi^{BESS}) - revenues^{total}(\chi^{BESS} = 0). \tag{3.42}$$

The present value of the net revenues related to the operation of the BESS (PV^{BESS}) is obtained applying equation (3.41)

$$PV^{BESS} = PV(net\_revenues^{BESS}, i, lifetime^{BESS}), \tag{3.43}$$

while the present value of the battery's operational expenditures ($OPEX^{BESS}$) is calculated by

$$PV^{OPEX^{BESS}} = PV(OPEX^{BESS}, i, lifetime^{BESS}). \tag{3.44}$$

Finally, The net present value of the BESS (NPV^{BESS}) is calculated as follows

$$NPV^{BESS} = PV^{BESS} - PV^{OPEX^{BESS}} - TPC, \tag{3.45}$$

where the total plant cost of the BESS (TPC) equal the present value of the capital expenditures ($CAPEX^{BESS}$), the shipping charges and the installation cost.

3.4 Input data

3.4.1 Wind farm

The evaluated wind farm is located in Burgenland (Austria) and is operated by the company *WEB Windenergie AG*[7]. Although it has a physical nominal power of 18 MW the considered time series of predicted and actual generation on quarter-hourly level originating from the year 2014 were converted to a nominal power of 20 MW because of improved comparability.

3.4.2 Electricity markets

All evaluations regarding wholesale electricity markets in this thesis rely on EXAA[8] day-ahead prices. As a consequence, p_t^{spot} denotes the EXAA day-

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

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

ahead price in a quarter hour resolution[9], while p^{spot} denotes the average EXAA day ahead price for the year 2014.

Control energy evaluations rely on automatic frequency restoration reserve (aFRR) data of the control area APG (Austria). $p_t^{CE^+_{MWh}}$ denotes the weighted average energy price of activation of positive aFRR in €/MWh. $p_t^{CE^+_{MW}}$ denotes the average demand rate for positive aFRR per hour in €/MW·h in the year 2014. The same applies to negative aFFR (Table 3.1).

The Boolean variable $\Theta_t^{CE^+}$ indicates if the wind-storage plant is obliged to deliver positive control energy in quarter hour t and is obtained as

$$\Theta_t^{CE^+} = \begin{cases} 1 & \text{if } q_t^{CE^+} > q_{threshold}^{CE^+} \\ 0 & \text{otherwise} \end{cases} \tag{3.46}$$

It is assumed that the wind-storage plant must deliver positive control energy in quarter t whenever the activated positive frequency restoration reserve in the control area APG ($q_t^{CE^+}$) exceeds a certain threshold ($q_{threshold}^{CE^+}$), which was set in order to achieve a probability of 10% of being obliged to deliver aFRR when it is needed within the control area.

Table 3.1: Electricity market data of the year 2014 used for assessment in chapter 4.

Symbol	Parameter	Unit	Value
p^{spot}	average spot market price	€/MWh	32.80
$p^{CE^+_{MW}}$	average price for positive control power	€/MW·h	8.88
$p^{CE^-_{MW}}$	average price for negative control power	€/MW·h	14.29
$p^{balance}$	average cost of balancing energy	€/MWh	39.59
$q_{threshold}^{CE^+}$	threshold for positive aFRR	MWh	25.37
$q_{threshold}^{CE^-}$	threshold for negative aFRR	MWh	36.68

[9]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.

Balance energy market data is obtained from the Austrian balance group coordinator APCS[10]. $p_t^{balance}$ 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 the WPP would have to pay if forecast deviations were not minimized by operation of storage (Table 3.1). It is calculated by

$$p^{balance} = \frac{\sum\limits_{T} \sum\limits_{t=1}^{\tau} -p_t^{balance} \cdot FE_t}{\sum\limits_{T} \sum\limits_{t=1}^{\tau} |FE_t|}. \tag{3.47}$$

3.4.3 Operational and economic parameters of BESS and WPP

Operational parameters regarding the BESS and the WPP which are used as inputs for the optimization problem are summarized in Table 3.2 and Table 3.3.

Table 3.2: Operational and economic parameters of lithium-ion battery storage systems.

Symbol	Parameter	Unit	Reference Case/ [Sensitivity Range]
χ^{BESS}	storage capacity of BESS	MWh	1
$\chi^{BESS}/\kappa^{BESS}$	Hours of energy storage at rated power capacity	h	1
η_{in}^{BESS}	Charge efficiency of BESS	1	0.9 / [0.7 - 1]
η_{out}^{BESS}	Discharge efficiency of BESS	1	0.9 / [0.7 - 1]
-	Maximal depth of discharge (DOD)	%	80
$cycles_{total}^{BESS}$	Total number of life cycles of the BESS	1	7000 / [4000 - 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); (Statista, Inc., 2016)

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

Table 3.3: Further parameters of wind-storage plant assessment.

Symbol	Parameter	Unit	Reference Case/ [Sensitivity Range]
-	Nominal power of WPP	MW	20
P^{CE}	Control reserve power tendered by the wind-storage plant	MW	1
ρ^{CE}	Probability of CE request when it is needed in the control area	%	10 [2.5 - 20]
V^{CE}	Penalty factor for violation of control energy request	1	3
v^{CE}	Fixed rate for collateralization	%	30 / [0 - 50]
τ	Number of quarter hours per time period T	1	96 / [24 - 96]
i	Interest rate	%	10 / [2.5 - 15]

4 Results and Discussion

In this chapter the economic efficiency of different operational strategies of battery energy storage systems is analyzed based on the mathematical model described in section 3. In a first step the WPP - its proceeds at the spot market and its forecast error cost - is analyzed. Subsequently, the battery storage system is evaluated in *arbitrage-only* and *minimum forecast deviation operational mode* (section 4.2 and 4.3) and finally, the co-optimized operation of the WPP and the BESS is examined where it is either used to ensure for the collateralization of the negative control reserve tendered by the WPP or to provide positive control reserve in addition to the negative control reserve tendered by the WPP (section 4.4). This chapter concludes with an overview and a comparison of the profitability of all operational modes analyzed.

4.1 Assessment of WPP only

Revenues and costs related to storage operation must be seen in perspective of proceeds the WPP is able to generate as a separate unit (without a joint storage system) by selling energy to the day-ahead market and providing negative regulation reserve (regulation down). Tis section comprises

- revenues of WPP generation placed on day-ahead markets
- annual cost due to forecast errors (cost of balancing energy)
- revenues of negative CE provided by the WPP

4.1.1 Proceeds of WPP on day-ahead markets

Revenues of the WPP obtained from energy sold at the day-ahead market are calculated by the multiplication of predicted generation of the wind farm in a certain quarter hour t by the day-ahead market price of the related time period. Thus, total revenues resulting from energy generated by the WPP within a year can be expressed as

$$revenues^{day-ahead_{WPP}} = \sum_{T} \sum_{t=1}^{\tau} (p_{t,T}^{spot} \cdot q_{t,T}^{WPP_{schedule}}) \tag{4.1}$$

and 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 4.1). The actual annual 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.

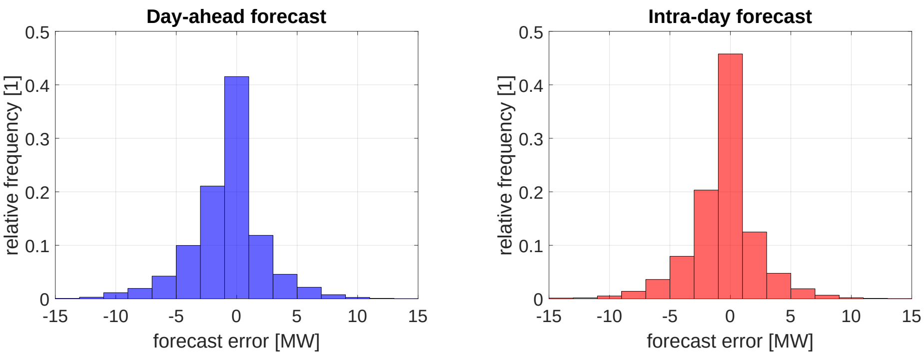
Table 4.1: Assessment of 20 MW wind power plant.

Scheduled annual generation [GWh]	Actual annual 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

Full-load hours of the wind farm are obtained by dividing the actual annual generation by the nominal power of the WPP (20 MW) and amount to 2188 hours for the year 2014, which is very close to 2150 h/yr, the average full-load hours of wind farms in Austria according to Winkelmeier, Krenn, and Zimmer, 2014.

4.1.2 Cost of forecast error

For the examined WPP two different qualities of generation forecasts are available: (i) day-ahead, generation forecast is provided at 10:30 in the morning for the upcoming day; (ii) intra-day, generation forecast is provided four times a day (08:00, 10:30, 18:00 and 21:30).The root-mean-square error (RMSE) in case of day ahead forecast results in 3.1 5MW (= 15.8% of the rated capacity) while the RMSE in case of intraday forecast yields 2.82 MW (14.1%).



(a) Day-ahead forecast (b) Intra-day forecast

Figure 4.1: Histograms of forecast errors of 20 MW wind power plant (interval wigth: 2MW).

Figure 4.1 depicts the histograms of the WPP's forecast error for both, day-ahead and intraday 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%. The systematic error[1] described in section 4.1.1 becomes visible in Figure 4.1, where the relative frequency of forecast errors is higher in the interval [-3MW, -1MW] compared to the interval [1MW, 3MW] for both, the day-ahead and intra-day forecast.

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. Whenever a BG deviates from the scheduled generation (resp. consumption) it has to compensate for its imbalance by either obtaining energy from the balancing mechanism (in case of a shortfall of generation) or by disposing energy (in case of excess generation). Hence, the BG has to obtain balancing energy in the amount of its imbalance at the price $p_t^{balance}$ and the forecast error costs in a certain quarter hour t are calculated as

$$cost_t^{FE} = p_t^{balance} \cdot FE_t \tag{4.2}$$

[1]generation of the WPP is tendentially overestimated because planed shutdowns are not considered for forecasts

The energy imbalance price, also referred to as *Clearing Price 1* is calculated retroactively by *APCS Power Clearing and Settlement AG* based on the control area's imbalance and the spot market price[2]. Since $p_t^{balance}$ can be either positive or negative, four different cases, depicted in Figure 4.2, have to be differentiated.

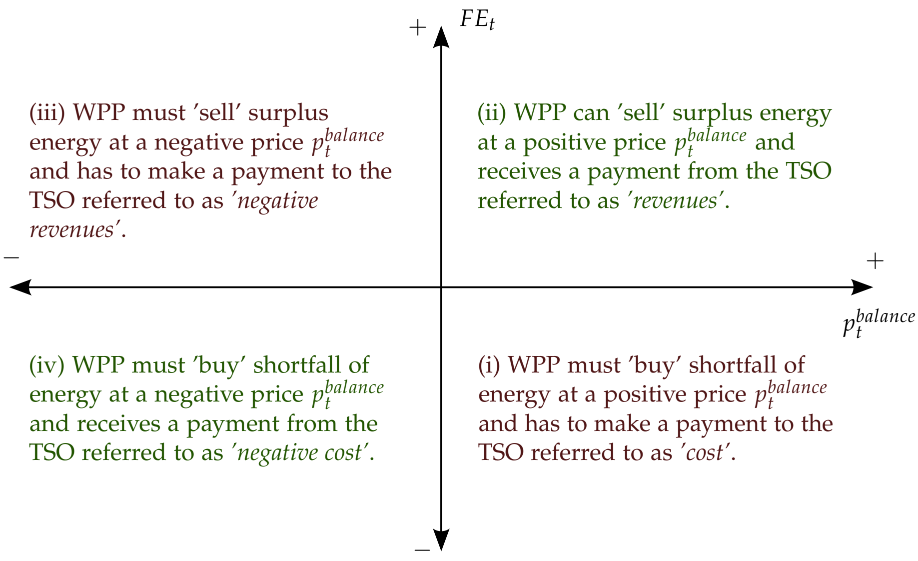


Figure 4.2: Composition of forecast error costs.

(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 4.2.

(ii) However, if the forecast error is positive while the energy imbalance price is positive too, the wind farm 'sells' 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*

[2] For a detailed explanation of the calculation of *Clearing Price 1* see APCS, 2015.

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 4.2 depicts the forecast error costs and the aggregated deviation for positive and negative errors of the 20MW wind farm in the year 2014. 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€. Which constitutes a decrease in forecast error costs of 31% (232 k€).

Table 4.2: WPP forecast error cost in 2014.

		$FE < 0$ Shortfall of energy			$FE > 0$ Surplus of energy		
Forecast quality	Total net cost of FE [k€]	Cost [k€]	Negative cost [k€]	Lack of energy [GWh]	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

Furthermore, the column *'Lack of energy'* in Table 4.2 depicts the amount of energy the WPP has to obtain from the balancing mechanism throughout the year in case the actual generation falls short of forecasted generation ($FE_t < 0$). Column *'Excess energy'* shows the aggregated surplus of energy, which is usually just fed into the electricity grid. The injection of excess energy results in revenues of 152 k€ respectively in negative revenues of -209 k€ per year (in case of day-ahead forecast) and thus in total cost in the amount of -57 k€. As a consequence, the WPP operator has to pay 57 k€ to feed in 6 GWh of excess energy, which corresponds to an average price for excess energy of -9.3 €/MWh. In other words, the WPP operator could save 57 k€ (approximately 8% of annual forecast error cost) by just shedding 6 GWh of generation in case of positive forecast error.

4.1.3 Provision of negative control energy with WPPs

As studies already 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 20 MW WPP demo case are calculated using the two-stage optimization model described in section 3.2. Additionally, savings of balancing energy cost through the reduction of forecast deviation by shedding excess generation is considered in the analysis. Thereby, the storage capacity of the BESS is set to zero (χ^{BESS} = 0). The tendered negative 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 Brauns et al., 2014, while the tendered positive control energy is set to zero ($P^{CE^+} = 0$).

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 3.4.2 it is assumed that the WPP must provide negative aFRR in 10% of all cases when it is needed within the control area, which equals 2877 quarter hours.

Table 4.3 shows the revenues and costs related to 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 equal the sum of *Revenues* and *Negative revenues* in Table 4.2. *Revenues* CE^-_{energy} denote proceeds related to actually provided negative control energy, which make up to more than half of total net revenues, while *Revenues* CE^-_{power} are generated from the provisioning of 1MW of negative control power for a whole year.

Table 4.3: 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€]	Revenues CE^-_{power} [k€]	Cost of collateralization [k€]	Number of CE violations [1]
1.0	287.7	56.6	205.0	125.2	-99.1	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, it can provide balancing energy only in an union with other power plants which entails cost of collateralization for the tendered control power as it is described in section 3.2.3. The *cost of collateralization* is assumed to amount to 30% of all revenues related to control energy and equals 99.1 k€.

The sum of all revenues minus costs result in *total net revenues* of 287.7k€ and represent the proceeds the demo case WPP could realize by minimizing its forecast deviations and 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.

4.2 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 3.2 is considered only. Furthermore, equation 3.5 has to be modified in order to permit the BESS to be charged on schedule, which is achieved by the additional decision variable $s_{t,T}^{spot_{schedule}}$.

The optimization model aims to maximize revenues due to sales of energy at the day-ahead market minus cost incurred for buying energy to refill the storage and can be expressed as

$$\max_{d_{t,T}^{spot_{schedule}}, s_{t,T}^{spot_{schedule}}} \sum_{t=1}^{\tau} p_{t,T}^{spot} \left(d_{t,T}^{spot_{schedule}} - s_{t,T}^{spot_{schedule}}\right). \tag{4.3}$$

Moreover, the model constraints have to be adapted in the following way

$$\text{s.t.} \qquad s_{t,T}^{spot_{schedule}} \geq 0 \qquad \forall t \in [1, \tau] \tag{4.4}$$

$$s_{t,T}^{spot_{schedule}} \leq \kappa^{BESS} \cdot 1/4 \qquad \forall t \in [1, \tau] \tag{4.5}$$

$$l_{t-1,T} + s_{t,T}^{spot_{schedule}} \cdot \eta_{in}^{BESS} - d_{t,T}^{spot_{schedule}} / \eta_{out}^{BESS} = l_{t,T} \tag{4.6}$$

Table 4.4 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€.

Altogether 667.0 MWh of electricity were charged at an average price level of 21.0 €/MWh while 542.7 MWh were discharged at an average price level of 62.1 €/MWh. Thus the average price spread amounts to 41.1 €/MWh and the full-cycle equivalent results in 603 cycles.

Table 4.4: 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

The cost-benefit analysis of the arbitrage-only operational mode is summarized in Table 4.5. Yearly net revenues of 8.7 k€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 -1133.5 k€. Consequently, the net present value of the BESS is highly negative (-1075 k€) when operated in arbitrage-only mode. Hence, investment in battery storage systems is economically not justifiable.

Table 4.5: Net present value of BESS when used for arbitrage only ($\chi^{BESS} = 1MWh$)

Total net revenues of BESS operation [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

4.3 Minimum forecast deviation operational mode of BESS

A second intermediate stage to the co-optimized operation of the battery storage is to use it exclusively in order to minimize the forecast deviation of the WPP. For this purpose the second stage of the optimization model (section 3.2.2) is considered solely and is adapted as shown below[3].

$$\min_{d_t^{FE}, s_t^{FE}} \quad \sum_{t=1}^{\tau} \left(|FE_t| - d_t^{FE} - s_t^{FE} \right) \tag{4.7}$$

$$\text{s.t.} \qquad s_t^{FE} \geq 0, \quad d_t^{FE} \geq 0 \qquad \forall t \in [1, \tau] \tag{4.8}$$

$$d_t^{FE} \leq |FE_t| \qquad if FE_t < 0 \tag{4.9}$$

$$d_t^{FE} \leq 0 \qquad if FE_t \geq 0 \tag{4.10}$$

$$s_t^{FE} \leq FE_t \qquad if FE_t > 0 \tag{4.11}$$

$$s_t^{FE} \leq 0 \qquad if FE_t \leq 0 \tag{4.12}$$

$$s_t^{FE} \leq \kappa^{BESS} \cdot 1/4, \quad d_t^{FE} \leq \kappa^{BESS} \cdot 1/4 \quad \forall t \in [1, \tau] \tag{4.13}$$

$$l_{0,T} = l_{\tau,T-1} \tag{4.14}$$

[3]These adaptions are implemented in the original model formulation by fixing the tendered control reserve power, the energy shed in order to reduce the forecast deviation and the scheduled discharge of the BESS at zero ($P^{CE^+} = P^{CE^-} \overset{!}{=} 0$, $q_t^{shed_{FE}} \overset{!}{=} 0$, $d_t^{spot_{schedule}} \overset{!}{=} 0$).

$$l_t \geq 0 \qquad \forall t \in [1, \tau] \tag{4.15}$$

$$l_t \leq \chi^{BESS} \qquad \forall t \in [1, \tau] \tag{4.16}$$

$$l_{t-1} + s_t^{FE} \cdot \eta_{in}^{BESS} - d_t^{FE} / \eta_{out}^{BESS} = l_t \qquad \forall t \in [1, \tau] \tag{4.17}$$

The model's results of forecast error costs of the WPP in 2014 for both, day-ahead and intraday forecast, under variable storage capacity χ^{BESS} are summarized in Table 4.6. Total net cost of forecast errors at a storage capacity χ^{BESS} minus total cost without a BESS $\chi^{BESS} = 0$ result in total net savings and thus proceeds realized by storage operation.

Table 4.6: 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€]
Day-ahead	0	-744.8	-765.6	78.2	152.3	-208.7
	1	-732.5	-737.7	71.7	125.9	-192.3
	difference	12.3	28.9	-6.5	-26.4	16.4
Intraday	0	-514.6	-581.5	83.2	165.2	-182.5
	1	-505.1	-548.4	75.8	133.2	-165.7
	difference	9.5	33.1	-7.4	-31.9	15.7

The composition of forecast error costs illustrated in Table 4.6 reveals the key problem of this operational strategy, the lack of knowledge regarding the actual balancing price (*Clearing Price 1*) at the moment the imbalance occurs. While the total net savings in case of day-ahead forecast amount to only 12.3 k€, the reduction in cost (when forecast error is negative and the balancing price is positive) is more than twice as high (28.9 k€). Furthermore, the negative revenues, that accrue in case of surplus production in conjunction with negative balancing prices, can be reduced by 16.4 k€ due to storage operation.

Besides the reduction in forecast error costs, the application of storage also reduces revenues generated by forecast errors as elucidated in section 4.1.2. Negative costs are decreased by 6.5 k€ and revenues are 26.4 k€ higher when there is no storage device in operation.

Consequently, the total reduction in forecast error costs of 45.2 k€ is diminished by a decline in revenues of 32.9 k€ resulting in total net savings of forecast error costs of 12.3 k€ (Table 4.7). In total 754.8 MWh of excess energy were charged into the storage in case of day-ahead forecast and a storage capacity of 1MWh resulting in a full-cycle equivalent of 679.3 cycles per year and an expected lifetime of the BESS of 10.3 years.

Table 4.7: Model results for BESS operated in minimum forecast error operational mode in the year 2014 (forecast quality: day-ahead).

χ^{BESS} [MWh]	Total net savings [k€]	Energy stored [MWh]	Energy discharged [MWh]	Full-cycle equivalent [1]
1.0	12.3	754.8	611.4	679.3

Annual net revenues of storage operation of 12.3 k€ over an expected lifetime of 10.3 years yield a present value of 77.0 k€ (see Table 4.7) 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 deviation operational mode to be economically not viable.

Table 4.8: Net present value of BESS when operated in minimum forecast error operationaol mode ($\chi^{BESS} = 1MWh$, forecast quality: day-ahead).

Total net revenues of BESS operation [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

4.4 Multimodal operation of the BESS

4.4.1 Collateralization of negative control energy via BESS

In this section it is assumed that the wind power plant provides 1MW of negative control energy as it was the case in section 4.1.3. In addition a BESS is operated jointly with the WPP in order to provide negative control energy when the WPP is incapable to do so, to reduce forecast deviation of the WPP and thus cost of balancing energy and to harness its excess energy by shifting production to later points in time. Consequently, the storage unit ensures for collateralization of the tendered control energy and the wind-storage plant is not obliged to join a pool of power plants and to pay for collateralization anymore.

The co-optimized operational mode is formulated in section 3.2, but there is no positive control energy tendered by the wind-storage plant ($P^{CE^+} = 0$). 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 and equals $\chi^{BESS} = 1.7MWh$ (as a result, the number of control energy violations by the wind-storage plant is zero compared to 211 in case of no storage). Total revenues of this co-optimized operational mode in comparison to revenues generated by the WPP only are shown in Table 4.9. Total net revenues generated by the WPP only ($\chi^{BESS} = 0MWh$) amount to 287.7 k€ and can be increased to 425 k€ in case a 1.7MWh BESS is applied additionally. Consequently, the storage system's net benefit amounts to 137.2 k€ respectively 80.7 k€/MWh installed capacity.

Table 4.9: Actual revenues and cost of a co-optimized dispatch of the BESS for the *collateralization of control energy operational mode* in comparison to revenues generated by the WPP only, according to section 4.1.3. ($P^{CE} = 1MW$)

χ^{BESS} [MWh]	Total net revenues [k€]	Revenues spot [k€]	Savings FE [k€]	Revenues CE^-_{energy} [k€]	Revenues CE^-_{power} [k€]	Cost of collateralization [k€]
0	287.7	0	56.6	205.0	125.2	-99.1
1.7	425.0	7.5	77.4	214.8	125.2	0
diff.	137.2	7.5	20.8	9.8	0	99.1

Revenues due to provision of negative control energy (CE^{-}_{energy}) and power (CE^{-}_{power}) constitute the largest share in total revenues for both cases, with and without a BESS attached to the WPP. Therefore the net benefit of the storage system is rather low. 9.8 k€ additional revenues due to control energy can be achieved with the storage device while revenues due to tendered control power remain constant.

However, cost of collateralization is omitted in case of a co-optimized dispatch of the BESS resulting in savings of 99.1 k€. Additional revenues from shifting excess energy of the WPP to the day-ahead market (see column *'Revenues spot'* in Table 4.9) are somewhat disappointing yielding only 7.5 k€. Lastly, savings in forecast error costs can be increased from 56.6 k€ (when excess energy is shed only) to 77.4 k€ applying the storage system to reduce both, positive and negative forecast deviations.

The economic efficiency calculation of the co-optimized operational mode is summarized in Table 4.10. All numbers were normalized to a storage capacity of 1MWh. Annual total net revenues of storage operation amount to 80.7 k€/MWh. The lifetime of the storage system is expected to amount to 9.1 years resulting from 762.5 full-cycle equivalents per year. Consequently, the present value of the net revenues amount to 467.1 k€/MWh, while the present value of the operational expenses of the BESS amount to -28.9 k€/MWh and the total plant cost (TPC) to -1100 k€/MWh. Resulting in a net present value of the storage system that is still negative (-661.8 k€/MWh). Thus, economic profitability is not given under this operational strategy.

Table 4.10: Present value of net revenues due to co-optimized operation of the storage system ($\chi^{BESS} = 1.7MWh$, $P^{CE^-} = 1MW$, $P^{CE^+} = 0MW$).

Total net revenues of BESS operation [k€/MWh·yr]	Expected lifetime of BESS[a] [years]	PV of revenues [k€/MWh]	PV of $OPEX^{BESS}$ [k€/MWh]	PV of TPC^{BESS} [k€/MWh]	NPV of BESS [k€/MWh]
80.7	9.1	467.1	-28.9	-1100	-661.8

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

4.4.2 Provision of negative and positive control energy via BESS

In this section the BESS is operated in a multi-modal way as it is described in section 3.2. It is used to reduce forecast deviations of the WPP, to shift excess generation to the day-ahead market and to provide positive and negative control energy. As it was the case in the previous section, revenues and costs resulting from this different applications are compared to revenues a WPP would be able to generate without a storage device attached. The tendered control power amounts to 1MW for both, regulation up and regulation down ($P^{CE+} = P^{CE-} = 1MW$), while the capacity of the battery energy storage systems is determined to 1 MWh.

Table 4.11 depicts revenues and costs related to the co-optimized dispatch of the WPP and the BESS and compares the wind-storage plant with a storage capacity of 1 MWh with the sole 20 MW WPP ($\chi^{BESS} = 0$). Revenues from excess energy that is shifted to the day-ahead market equal 4.3 k€ which corresponds to 50% of revenues achieved when the BESS used for arbitrage only (see Table 4.5) compared to 0 k€ in case no storage device is used. Revenues from reduced forecast deviations amount to 56.6 k€ without storage and can be only increased by 1 k€ by means of the battery. This result suggests that excess energy stored is only used to fulfill positive control energy requests rather than to reduce negative forecast deviations because of higher control energy prices and high penalties in case a control energy request is violated.

Table 4.11: Actual revenues and cost of a co-optimized dispatch of the BESS in 2014 when positive and negative control energy is provided by the wind-storage plant in comparison to revenues generated by the WPP only, according to section 4.1.3 ($P^{CE+} = P^{CE-} = 1MW$).

χ^{BESS} [MWh]	Revenues spot [k€]	Savings FE [k€]	Revenues CE^+_{energy} [k€]	Revenues CE^-_{energy} [k€]	Revenues CE^+_{power} [k€]	Revenues CE^-_{power} [k€]	Cost of coll-ateralization [k€]
0	0	56.6	0	205.0	0	125.2	-99.1
1	4.3	57.6	52.6	214.7	77.8	125.2	-141.1
diff.	4.3	1	52.6	9.7	77.8	0	-42

Revenues derived from provided positive control energy (CE^+_{energy}) amount to 52.6 k€ and are significantly lower than revenues gained from provided negative control energy (CE^{-}_{energy}) 214.7 k€. This is because the wind-power plant is able to fulfill most of the regulation down requests and only fails 8 times (0.28%) to do so, while regulation up requests were not met in 1433 cases (62.6%). Compared to the sole wind power plant revenues due to the provision of negative control energy are even higher in case a storage is attached to the WPP. This is again because of a higher fulfillment rate of control energy requests - the WPP fails to provide negative control energy 211 times a year (7.3%) as it is requested by the TSO.

Revenues related to tendered negative control power (CE^{-}_{power}) are identical regardless of the storage capacity available, because the amount of control power which is made available is unchanged, while in case there is no storage device available there is also no tendered positive control power and hence no related revenue component. The costs of collateralization are assumed to amount to 30% of all revenues obtained from control energy and power as it was the case in all previous sections. Since revenues of control reserves are higher when a storage device is operated in addition to the WPP, also costs of collateralization are.

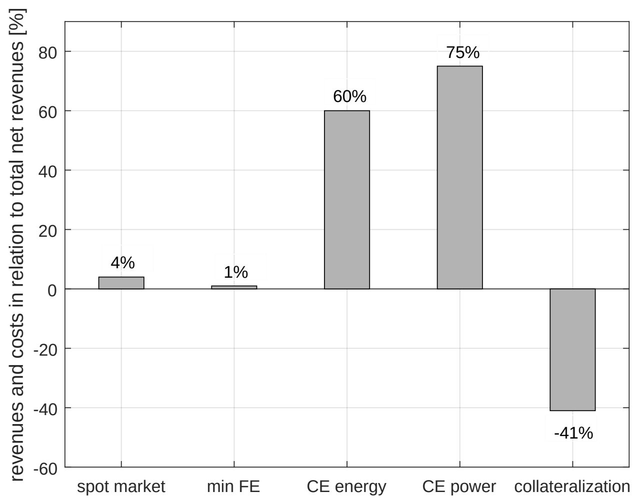


Figure 4.3: Revenue streams and costs in relation to the total net revenues of BESS (103.4k€) in case the BESS is used to provide negative and positive control energy (CE).

The total amount of all additional revenues and costs (row *'diff.'* in Table 4.11) come to 103 k€ and constitute the *total net revenues of BESS operation* per year. The relative order of magnitude of the various additional revenue and cost components in relation to the total net revenues is visualized in figure 4.3. Proceeds due to tendered control energy and power represent the highest share in total net revenues (60% resp.75%), but entail also cost of collateralization which amount to -41% of total net revenues. While revenues originating from spot market sales and reduced forecast deviation have only small impact on the total net revenues (4% resp. 1%). Suggesting once more that the battery storage system us mostly used to fulfill control energy requests and hardly used to reduce forecast deviations.

Since the storage unit is utilized more heavily when positive and negative control energy is provided (the full-cycle equivalents amount to 1034, see Table 4.12) compared to previous operational modes, its lifetime in years is considerably lower, only 6.8 years (compared to 9.1 years in the previous mode).

Therefore the present value (PV) of the total revenues are only slightly higher (491.4 k€ compared to 467.1 k€ in the previous case), while the present value of the operational expenditures are similar to the values obtained in the previous cases. The total plant costs are only dependent on the storage capacity. The net present value of all revenues and cost accrued over the lifetime of the storage device amount to -632.4 k€ and is again negative as is was the case in all other operational strategies assessed. Consequently, the battery storage unit is economically not viable due to its high investment cost.

Table 4.12: Present value of net revenues due to co-optimized operation of BESS when positive and negative control energy is provided by the wind-storage plant ($\chi^{BESS} = 1MWh$, $P^{CE^+} = P^{CE^-} = 1MW$).

Total net revenues of BESS operation [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€]
103.4	6.8	491.4	-23.8	-1100	-632.4

[a]Resulting from 1034 full-cycle equivalents per year.

4.5 Comparison of examined operational strategies

The storage operational strategies examined in this work have a revenue structure bases on (i) proceeds originating from energy sales at the spot market, (ii) savings of balancing energy costs by a reduction of forecast deviation of the WPP and (iii) revenues due to tendered control power and provided control energy. Depending on the operational strategy applied, the various revenue and cost components yield different outputs as it was shown in the previous sections.

Firstly, shifting excess energy to the day-ahead market result in rather low revenues due to the following reasons:

- The weighting factor for excess energy stored at the end of a day - the average day-ahead market price in 2014 (p^{spot}) is rather low. Thus, the storage is more likely to be used for other purposes (reduction of forecast deviation and provision of control energy), than for shifting excess energy to the day-ahead market.
- Further on, comparatively low day-ahead market prices naturally result in low proceeds. Even in the arbitrage-only operational mode revenues originating from electricity sales at the spot market amount to only 8.7 k€ per year.

Secondly, savings of balancing energy due to reduced forecast deviations is mainly obtained by shedding excess energy. Only 12.3 k€ net savings at *minimum forecast deviation mode* (section 4.3) and at most some additional 20.8 k€ savings in case of *collateralization of negative CE via BESS* (with a storage capacity of 1.7 MWh, section 4.4.1) could be achieved. This can be explained as follows:

- As it was the case with revenues due to shifted excess energy, the provision of control energy is valued higher than the reduction of forecast deviation (also because of penalty cost incurred in case of control energy request violation).
- Moreover, forecast errors can also result in revenues if it is beneficial for the whole control area in a certain moment in time, as explained in section 4.1.2. Hence, a reduction in forecast deviations can also entail cost in addition to proceeds.

Lastly, the largest part of total revenues is generated by the provision and supply of control energy (80% in case of *collateralization of negative CE mode* and 84% when positive an negative control energy is provided). Consequently, the net present value of the battery storage is considerably higher for operational strategies that include provisioning of control energy (figure 4.4). While the arbitrage only and the minimize forecast deviation operational mode yield in a net present value of the BESS that is highly negative (-1075 k€ respectively -1054 k€), a significant improvement of annual revenues and thus the storage system's NPV can be achieved in case the BESS is also use to provide control energy (-662 k€resp. -632 k€).

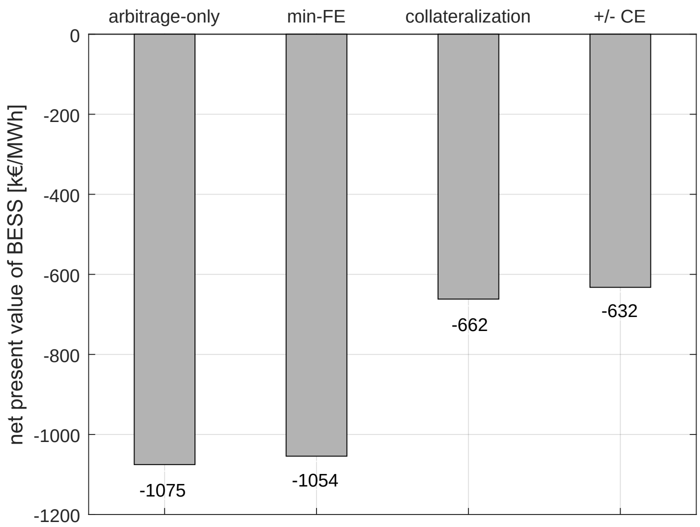


Figure 4.4: Comparison of the BESS' net present value of all operational strategies examined (min-FE...minimum forecast deviation oerational mode, collateralization of negative CE operational mode, +/- CE...provision of negative and positive CE operational mode).

Since the net present values of all operational strategies assessed are negative, none of them is profitable. Consequently, the NPV indicates the reduction in investment cost per MWh storage capacity that is necessary in order to achieve economic efficiency of the battery. The total plant cost of the storage unit were assumed to amount to 1100 k€/MWh. Thus the BESS' cost would have to decrease by 98% - 96% in case of arbitrage-only and minimum forecast deviation OM, respectively by 60% - 57% in case of collateralization or +/- CE operational mode to justify such investments.

5 Sensitivity Analysis

Since various operational and economic parameters of the optimization model and the BESS depend on assumptions (such as the battery technology used and the framework conditions of the electricity markets considered), it is crucial to examine the influence of those parameters on the model outcomes. Table 5.1 shows an overview of all parameters used for sensitivity analyses in this section and the examined range.

Table 5.1: Operational and economic parameters of the optimization model that are used to operforme sensitivity analyses.

Symbol	Parameter	Unit	Reference Case/ [Sensitivity Range]
τ	number of quarter hours per time period T	quarter hours	96 / [12 - 96]
ρ^{CE}	request probability of control energy	%	10 / [2.5 - 20]
η_{in}^{BESS}	charge efficiency of BESS	1	0.9 / [0.7 - 1]
η_{out}^{BESS}	discharge efficiency of BESS	1	0.9 / [0.7 - 1]
$cycles_{total}^{BESS}$	total number of cycles of BESS	1	7000 / [4000 - 10 000]
v^{CE}	fixed rate of collateralization	%	30 / [0 - 50]
i	interest rate	%	10 / [2.5 - 15]

While the sensitivity of the number of quarter hours per time period is examined regarding the collateralization of CE operational mode (section 4.4.1), all further parameters and their influence on yearly revenues and cost as well as the net present value of the storage system are analyzed within the second multi-modal operational mode when the BESS is used to provide positive and negative control reserve.

This section concludes with a comparison of the model parameters and their influence on the relative change of the battery's net present value.

5.1 Collateralization of negative control energy via BESS

5.1.1 Variation of quarter hours per time period

Quarters per time period (τ) define the duration of the two stages of the optimization model (see section 3.2). After τ quarter hours the excess energy of the WPP stored in the BESS is sold to the day-ahead electricity market. In the initial state τ is set at 96 quarter hours. Consequently, the time period per stage of optimization equals one day. By shortening the time periods the energy content of the BESS is sold to the spot market more frequently (e.g. two times a day in case τ equals 48 quarters). Hence, excess energy is rather used to generate revenues at the spot market than to reduce negative forecast deviations of the WPP. This assumption is confirmed by Table 5.2, while revenues from spot market sales rise as τ decreases, revenues due to the reduction of forecast error costs decrease. Furthermore, revenues and costs related to control reserve energy and power remain constant, as they are not affected by the number of quarter hours per time period.

Table 5.2: Actual revenues and cost of a co-optimized dispatch of the BESS under variation of quarter hours τ per time peiod ($\chi^{BESS} = 1.7MWh, P^{CE^-} = 1MW, P^{CE^+} = 0MW$).

τ [quarters]	Total net revenues [k€]	Revenues spot [k€]	Savings FE [k€]	Revenues CE^-_{energy} [k€]	Revenues CE^-_{power} [k€]	Cost of collateralization [k€]
12	445.1	45.5	60.2	214.8	125.2	0
24	433.1	25.5	67.5	214.8	125.2	0
48	426.3	16.4	69.9	214.8	125.2	0
72	428.6	12.2	76.4	214.8	125.2	0
96	425.0	7.5	77.4	214.8	125.2	0

Since additional revenues on spot markets rise stronger than cost savings of forecast errors decline when τ is reduced, the total net revenues of BESS operation increase (Table 5.3). However, shorter duration of the time periods per optimization step lead to an increase in storage utilization and therefore to a considerable decline in expected lifetime of the BESS (from 9.1 years in

Table 5.3: Present value of net revenues due to co-optimized use of the BESS under variation of quarter hours τ per time peiod ($\chi^{BESS} = 1.7MWh$, $P^{CE^-} = 1MW$, $P^{CE^+} = 0MW$).

τ [quarters]	Total net revenues of BESS operation [k€/MWh·yr]	Expected lifetime of BESS [years]	PV of net revenues [k€/MWh]	PV of $OPEX^{BESS}$ & TPC^{BESS} [k€/MWh]	NPV of BESS [k€/MWh]
12	92.6	5.7	386.4	-1120.9	-734.5
24	85.5	7.4	431.6	-1125.3	-693.3
48	81.5	8.6	456.8	-1128.0	-671.2
72	82.9	8.9	472.9	-1128.6	-655.6
96	80.7	9.1	467.1	-1128.9	-661.8

case $\tau = 96$ to 5.7 years in case $\tau = 12$). This is why the present value of the net revenues is actually lower in case of lower τ. Since the toal plant cost (TPC) of the BESS depend on the storage capacity only and the decrease of the present value of the operational expenditures at declining τ is rather low, the net present value of the BESS is smaller in case of lower τ although yearly revenues are higher compared to the initial state of 96 quarters per period.

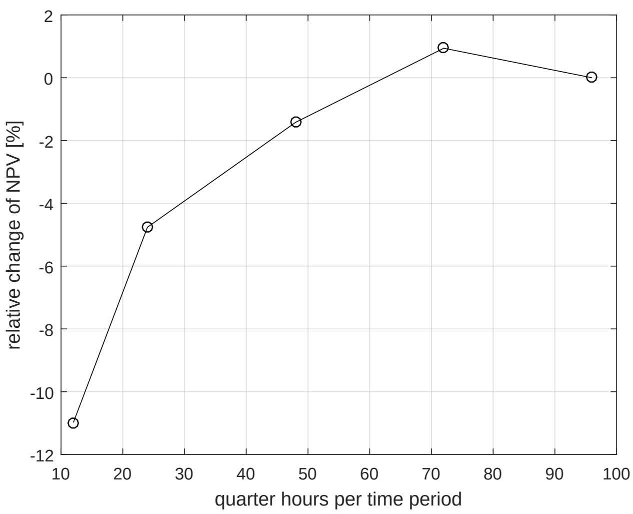


Figure 5.1: Sensitivity of quarter hours per time period τ in regards of the net present value (NPV) of the storage system.

However, as depicted in figure 5.1, there is an optimal value for quarter hours per time period at approximately 72 quarters where revenues due to spot market sales can be increased while the expected lifetime of the BESS is diminished only slightly.

In conclusion, increased usage of the BESS (because of lower τ) result in higher revenues from energy sold at day-ahead markets, but also dramatically shortens the lifetime of the storage system and thus result in a worse economic performance.

5.2 Provision of negative and positive control energy via BESS

5.2.1 Variation of control energy request frequency

Since provisioning of control reserve is the main source of proceeds generated from storage operation, the frequency of control energy requests is considered crucial for economic evaluation of the storage unit. As described in section 3.2.3 revenues due to tendered control power (*Revenues* CE_{power}) do not depend on actual control energy requests while revenues due to provided control energy (*Revenues* CE_{energy}) naturally do as illustrated in Table 5.4.

Table 5.4: Actual revenues and costs of co-optimized dispatch of the BESS when positive and negative control energy is provided by the wind-storage plant under variation of the request frequency of control energy ρ^{CE} ($\chi^{BESS} = 1MWh, P^{CE+} = P^{CE-} = 1MW$).

ρ^{CE} [%]	Revenues spot [k€]	Savings FE [k€]	Revenues CE^{+}_{energy} [k€]	Revenues CE^{-}_{energy} [k€]	Revenues CE^{+}_{power} [k€]	Revenues CE^{-}_{power} [k€]	Cost of coll-ateralization [k€]
2.5	4.0	67.5	19.9	60.2	77.8	125.2	-124.2
5	4.1	62.4	33.5	116.4	77.8	125.2	-124.2
7.5	4.2	59.2	44.1	167.0	77.8	125.2	-124.2
10	4.3	57.6	52.6	214.7	77.8	125.2	-141.1
15	4.4	54.1	69.5	296.6	77.8	125.2	-170.7
20	4.6	52.8	86.9	365.4	77.8	125.2	-196.6

Table 5.5: Present value of net revenues due to co-optimized operation of the storage system under variation of the probability of control energy requests ρ^{CE} ($\chi^{BESS} = 1MWh, P^{CE+} = P^{CE-} = 1MW$).

ρ^{CE} [%]	Total net revenues of BESS operation [k€/MWh·yr]	Expected lifetime of BESS [years]	PV of net revenues [k€/MWh]	PV of $OPEX^{BESS}$ & TPC^{BESS} [k€/MWh]	NPV of BESS [k€/MWh]
2.5	84.0	9.1	486.3	-1129.0	-642.6
5	89.7	8.2	486.8	-1127.1	-640.4
7.5	96.0	7.4	485.7	-1125.3	-639.6
10	103.4	6.8	491.4	-1123.8	-632.4
15	116.1	5.7	486.5	-1120.9	-634.4
20	133.2	4.9	493.9	-1118.5	-624.7

As the CE request frequency ρ^{CE} decreases - based on the initial value of 10% - the proceeds gained from provided control energy drop, while revenues from spot market sales are hardly influenced but tend to decrease too as less excess energy originating from negative control energy demand can be stored.

The opposite is true for savings in forecast error cost, as the CE request frequency decreases utilization of the limited storage capacity is shifted in order to reduce forecast deviations and thus cost of balancing energy. Since costs of collateralization of tendered control energy are assumed to amount to 30% of proceeds related to tendered reserve energy and power (which decline as the request frequency drops), that cost component decreases in case of decreasing control energy request frequency.

Altogether, the *total net revenues of BESS operation* decrease with a decreasing request frequency of control energy as illustrated in Table 5.5. Similar to the analysis in the previous section (5.1.1) the expected lifetime of the BESS decreases dramatically with increasing usage as it is the case when the CE request frequency rises. Consequently, the increase of the present value of generated net revenues with increasing CE request probability is rather moderate. Thus, the change in net present value of the BESS is very low, as also shown in figure 5.2.

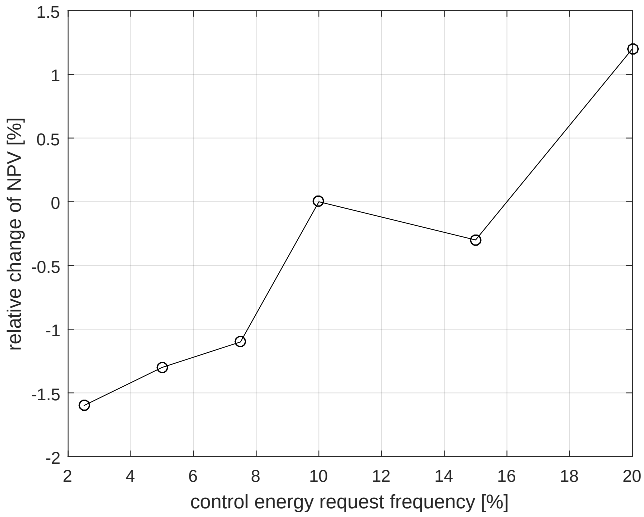


Figure 5.2: Sensitivity of control energy request frequency ρ^{CE} in regards of the net present value (NPV) of the storage system.

5.2.2 Variation of storage charge/discharge efficiency

The storage charge efficiency as well as the discharge efficiency were set to 0.9 in the initial state ($\eta_{in}^{BESS} = \eta_{out}^{BESS} = 0.9$). Naturally, a decline in efficiency causes storage revenues to drop, but the effect is rather modest as parts of proceeds, such as revenues for tendered control power, are not affected by the storage efficiency and some proceeds even increase with decreasing efficiency[1].

An increase of the storage charge/discharge efficiency from 90% to 100% increases the net present value of the BESS only by 1.2% (see figure 5.3), while a decrease to 70% decreases the NPV by 2.7%.

[1]A downward regulation request can also be fulfilled by consuming energy. The lower the storage efficiency, the more energy is needed in order to charge the BESS.

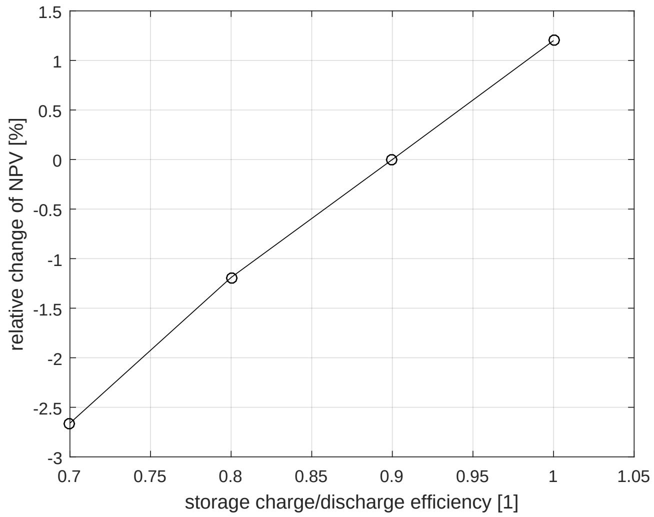


Figure 5.3: Sensitivity of storage charge/discharge efficiency ($\eta_{in}^{BESS} = \eta_{out}^{BESS}$) in regards of the net present value (NPV) of the storage system.

5.2.3 Variation of total life cycles of BESS

According to equation (3.40) the expected lifetime of the BESS in years of operation is dependent linearly on the number of total cycles it can perform until the storage capacity decreases dramatically $cycles_{total}^{BESS}$. Thus, it has a great impact on the economic efficiency of the storage unit.

Table 5.6 depicts the relation of total life cycles of the BESS and the expected lifetime in years of operation in a rage of 4000 to 10000 cycles, as well as the present value of net revenues gained from storage operation. Since the yearly net revenues are assumed to remain constant over the lifetime of the BESS, the net present value of the storage unit rises with increasing life cycles.

An increase of the total life cycles of the BESS from 7000 cycles, which is the reference value for all analyses, to 10000 cycles increases the battery's net present value by 19.7%, while a decrease to 4000 cycles reduces the NPV by 26% as it is illustrated in figure 5.4. Even at an increased number of 10000

Table 5.6: Present value of net revenues due to co-optimized operation of the storage system under variation of the total number of cycles (lifetime) of BESS $cycles^{BESS}_{total}$ ($\chi^{BESS} = 1MWh, P^{CE+} = P^{CE-} = 1MW$).

$cycles^{BESS}_{total}$ [1]	Total net revenues of BESS operation [k€/MWh·yr]	Expected lifetime of BESS[a] [years]	PV of net revenues [k€/MWh]	PV of $OPEX^{BESS}$ & TPC^{BESS} [k€/MWh]	NPV of BESS [k€/MWh]
10000	103.4	9.7	622.4	-1130.1	-507.7
9000	103.4	8.7	582.7	-1128.2	-545.5
8000	103.4	7.7	539.1	-1126.1	-587.0
7000	103.4	6.8	491.4	-1123.8	-632.4
6000	103.4	5.8	439.0	-1121.2	-682.2
5000	103.4	4.8	381.6	-1118.5	-736.8
4000	103.4	3.9	318.7	-1115.4	-796.7

[a]Resulting from 1034 full-cycle equivalents per year.

full-load cycles the net present value of the storage system is still highly negative and thus economically not viable.

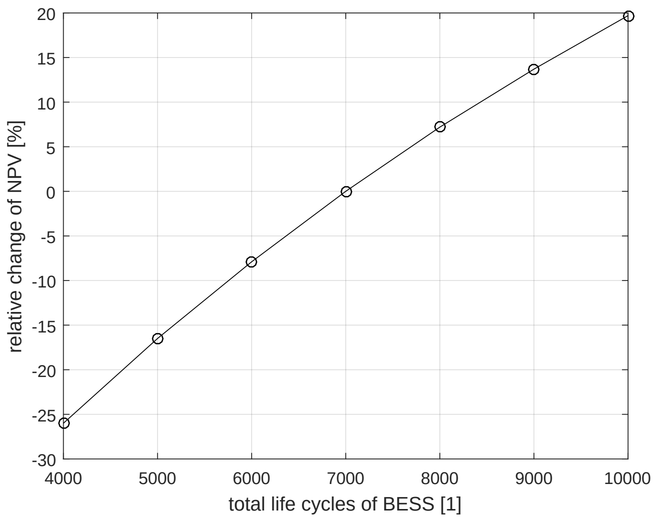


Figure 5.4: Sensitivity of total life cycles of the BESS in regards of its net present value (NPV).

5.2.4 Variation of collateralization cost

Since proceeds originating from control reserve energy and power constitute the highest share in total revenues, cost of collateralization have a strong impact on the profitability of the BESS (see figure 5.5). A decrease of cost of collateralization from 30% of revenues related to control energy and power (reference value) to 0% (no cost of collateralization) leads to an increase of the battery's net present value of 31.6%, while an increase of cost of collateralization to 50% of related revenues reduces the net present value by 21.1%. As a consequence, even in the case of no collateralization cost the net present value of the battery storage is negative.

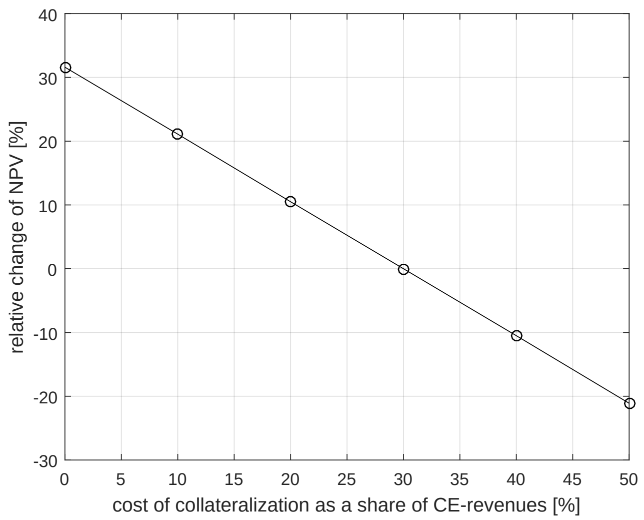


Figure 5.5: Sensitivity of cost of collateralization for control energy in regards of the net present value (NPV) of the storage system.

This result is highly plausible, because revenue streams from spot market sales and forecast error cost can be neglected in comparison to revenues related to control energy and power, as it can ce seen in figure 4.3. Thus, a variation in collateralization cost entail a change in the battery's NPV in the same order of magnitude.

5.2.5 Variation of interest rate

Finally, the influence of the assumed interest rate on the net present value of the battery system is examined. Since future proceeds are discounted with the interest rate, the NPV of the storage system rises with decreasing interest rate (figure 5.6). The impact on the economic efficiency of the BESS is comparatively high, as a decrease of the interest rate from 10% (reference value) to 2.5% leads to an increase of the NPV of 21.8%.

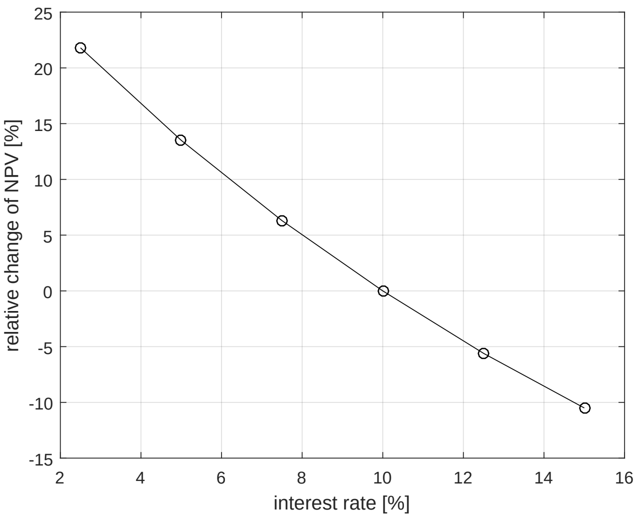


Figure 5.6: Sensitivity of interest rate *i* in regards of the net present value (NPV) of the storage system.

5.2.6 Comparison of sensitivities

In order to establish comparability of sensitivities of the analyzed parameters, the relative change of the battery's NPV is considered in relation to the relative change of the influencing parameters (see figure 5.7). As already mentioned in the sections above, the impact of the request frequency of control energy and the storage charge/discharge efficiency is negligibly small compared to the other parameters. In the case of request frequency this finding can be

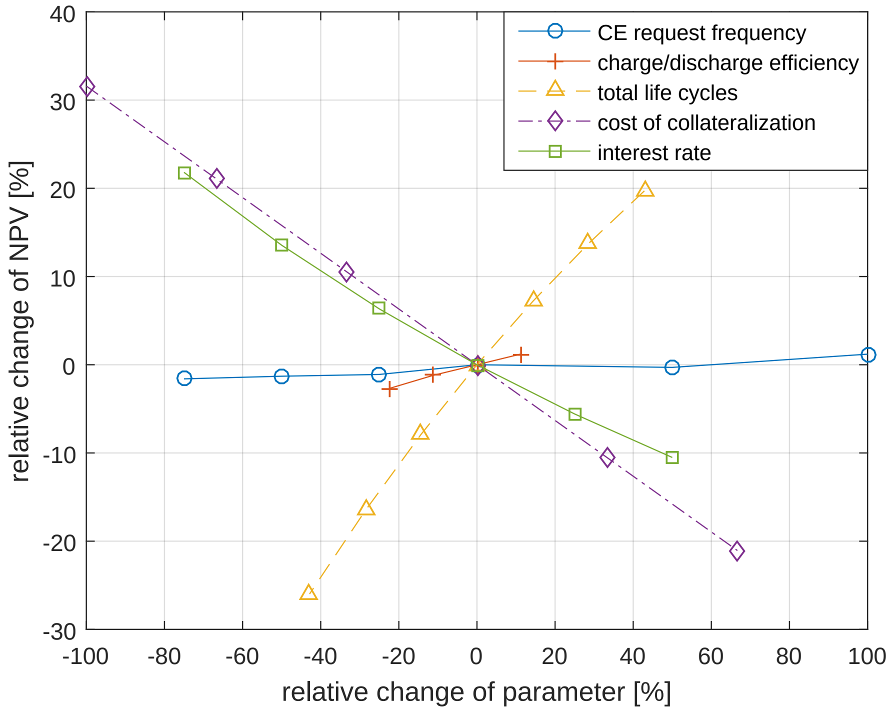


Figure 5.7: Comparison of sensitivities of various influencing parameters in regards of the net present value (NPV) of the storage system in case it is operated to provide positive and negative control energy.

explained by the negative effect a stronger usage of the BESS has on its lifetime. Although higher revenues originating from provided control energy can be generated in case the CE request frequency rises, the decrease in expected lifetime of the battery leads to an opposing effect. Resulting in a net effect on the present value that is rather low.

The influence of variations in the cost of collateralization on the NPV is significant and of the same order of magnitude as the influence of the interest rate. The effect of the total number of life cycles of the battery storage on its profitability is equally strong, but of opposite sign.

6 Synthesis of Results

The economic profitability analysis in chapter 4 as well as the sensitivity analysis in chapter 5 demonstrate that neither of the operational strategies assessed in this work generates enough revenues in the course of the lifetime of the battery storage to compensate for its capital and operational expenditures.

The *arbitrage-only operational mode* yields particularly low profits due to relatively small price spreads of the EXAA day-ahead electricity wholesale price. Consequently, only 2.2% of the BESS' capital expenditures of 1100 k€/MWh can be recovered by storage operation resulting in a highly negative net present value of the BESS (-97.8% of the battery storage system's investment cost, see figure 6.1).

However, the profitability of an operational mode that aims to *minimize the WPP's forecast deviation* is hardly any better, yielding proceeds in the amount of only 4.2% of the BESS' investment cost. As elucidated in section 4.3 this is caused by the lack of knowledge of the balancing energy price in the moment a forecast deviation occurs. Since forecast errors could also yield revenues to the WPP operator, usage of the BESS in this operational mode can be both, beneficial and disadvantageous.

The BESS' NPV in relation to its investment costs depicted in figure 6.1 also indicates the order of magnitude the storage unit's capital cost had to decrease as to achieve profitability. Since that would require a decrease by 97.8%, respectively 95.8% for the operational schemes mentioned above, cost-effective use of storage is not possible in the foreseeable future.

Through a multi-modal operation of the storage unit that aims to minimize the WPP's forecast deviation, to provide regulation reserve and to shift excess energy of the wind power plant, it is possible to increase the generated revenues significantly.

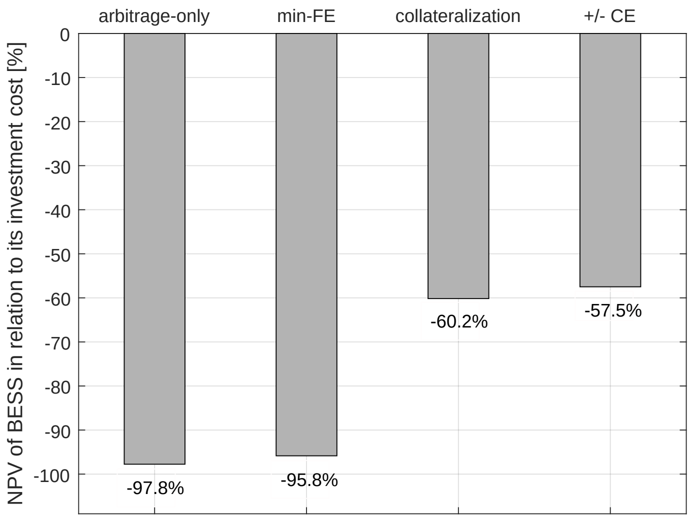


Figure 6.1: Comparison of the BESS' net present value (NPV) in relation to its investment cost (1100 k€/MWh) for all operational strategies examined (min-FE...minimum forecast deviation oerational mode, collateralization of negative CE operational mode, +/- CE...provision of negative and positive CE operational mode).

As a consequence, also the BESS' net present value can be increased but is still negative (-60.2% of the storage system's total plant cost in case it is used to ensure for collateralisation, respectively -57.5% in case the battery is used in order to provide positive and negative regulation reserve). Although investment in battery storage systems is still not justified as it is operated in a multi-modal way, a reduction in total plant cost of approximately 60% would lead to economic efficiency.

Furthermore, this study has shown that, in case the BESS is used to provide positive and negative regulation reserve, the cycle efficiency of storage system has only a minor impact on its profitability (see figure 6.2 respectively section 5). The same is true for the request frequency of control energy. Contrary to expectations, the BESS' net present value decreases only slightly when the request frequency drops. This can be explained by two counteracting effects: while annual revenues decrease in case the request frequency decreases, the

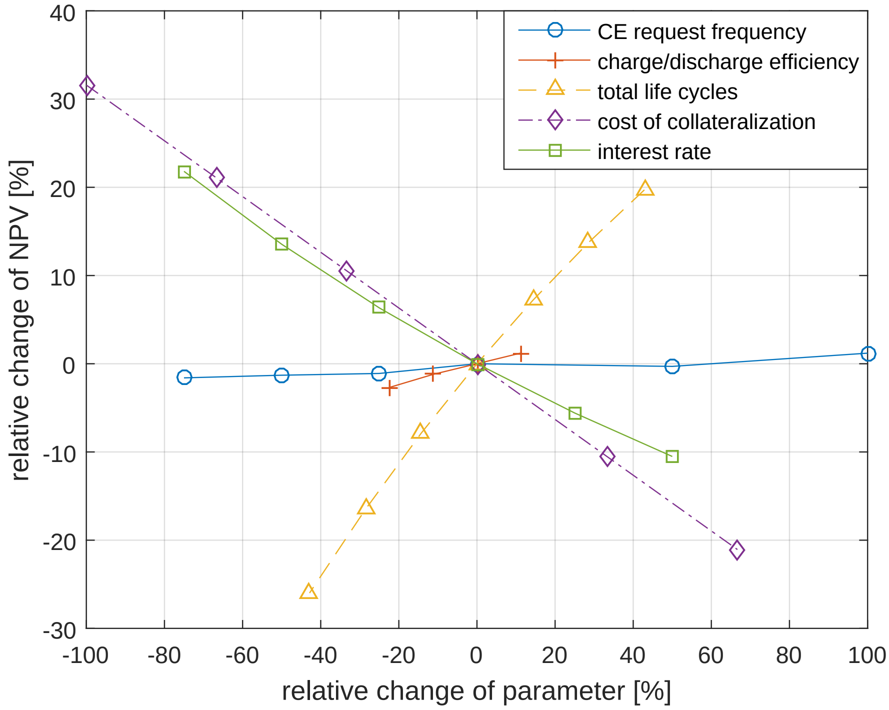


Figure 6.2: Comparison of sensitivities of various influencing parameters in regards of the net present value (NPV) of the storage system in case it is operated to provide positive and negative control energy.

expected lifetime of the battery in years of operation is considerably higher when it is utilized less intensively[1].

The parameters that have great impact on the profitability of the storage are the total full-load cycles of the battery, the assumed cost of collateralization of regulation reserve, as well as the interest rate that is anticipated to discount future cash flows. Nevertheless, modification of model parameters in a wide range led to an increase of the BESS' net present value of approximately 30% (at the most), which is insufficient for a profitable operation of the storage.

[1]Note that it is assumed that the lifetime of the battery storage is limited by a fixed number of full-load cycles.

7 Conclusions and Outlook

The two-stage optimization model introduced in this work has shown that the storage system's net present value is negative for several operational strategies. Thus, the BESS is not profitable within the current economic and technical framework conditions. In comparison to operation schemes that pursue only a single objective (arbitrage-only respectively minimum forecast deviation operational mode) storage revenues could be significantly increased by multi-modal use. However, storage investment cost would still have to drop by approximately 60% in order to establish profitability.

Crucial parameters having a significant influence on the economic viability of battery storage are capital cost and total full-load cycles, while the cycle storage efficiency has a rather low impact. The limited number of full-load cycles a battery storage can perform is particularly problematic since a more intensive use of the storage decreases its lifetime dramatically and thus also total revenues. It is important to note that all model results and derived findings rely on Austrian electricity market data of the year 2014 and do not take into consideration development of electricity and control energy prices.

Moreover, better use of the flexibility provided by a storage unit could be made if it is operated simultaneously on the intra-day and the control energy market and not sequentially as it is implemented in the two-stage framework used in this study. Hence, further research activity should focus on the fusion of the two stages.

Apart from energy storage deployment, the analysis suggests that WPP operators could save some 8% ot total balancing energy cost by shedding excess generation (in the period of positive forecast errors).

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