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AAEE PhD-Day 2016



Fifth international PhD-Day of the AAEE Student Chapter in Cooperation with Czech Technical University

Monday, 7th November, 2016

The fifth international PhD Day took place at Czech Technical University at 7th of November. The aim of the event is to give PhD-students the opportunity to present their current scientific work – 1 German, 3 Czech and 4 Austrian PhD Students participated and presented their works. The presentation was followed by a comprehensive feedback of senior and junior researchers. The senior feedback was provided by Jaroslav Knápek, Reinhard Haas, Mario Liebensteiner, Christoph Graf, Julius Bems and Amela Ajanovic.

The feedback of all participants was throughout positive and so we are looking forward to the PhD Day 2017 as part of the 15th IAEE European Conference 2017@Hofburg/Vienna!



Last name	First name	Download presentaton
Haxhimusa	Adhurim	On the Determinants of Electricity Market Integration: Evidence from German and French Electricity Markets
Klamka	Jonas	Solar power self-consumption after the support period: Will it pay off in a cross-sector perspective?
Ortner	André	Modeling competitive equilibrium prices for energy and balancing capacity in electricity markets involving non-convexities
Essi	Andreas	Machine Learning Analysis for a Flexibility Energy Approach towards Renewable Energy Integration with Dynamic Forecasting of Electricity Balancing Power
Holasová	Adéla	Generation adequacy - Impact of RES on the system imbalance
Salaba	Tadeáš	Business strategy of coal-fired power plants at CEZ group
Moisl	Fabian	MBS+ Development of a decentralized small energy storage network to compensate for schedule deviations
Lachmanová	Michaela	Impact of Renewables integration

Working paper: MBS+ Development of a decentralized small energy storage network to compensate for schedule deviations

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Abstract

Despite relatively high cost, more that 30,000 small battery storage devices in combination with photovoltaic (PV) systems were installed in Germany by the end of 2015¹. Investment subsidies and the desire of private households for energy self-sufficiency are the main drivers for this trend, which will most likely increase further in the future. The added value of these battery storage devices for the grid or the energy system is currently low, but could be increased in the future by financial incentives for storage operators or regulatory requirements.

Battery storage systems are predestined to balance fluctuating electricity generation units (such as wind and solar). Thus, this paper aims to identify the potential of a decentralized small storage network to provide flexibility to a balance responsible party (BRP) in order to compensate for schedule deviations.

The potential is assessed economically in terms of avoided schedule deviation cost (imbalance energy cost) for the BRP. Furthermore, repercussion on the load schedule of households that participate in the storage network with their battery system is quantified.

Keywords: battery energy storage system, decentralized flexibility, schedule deviations

Abbreviations

BESS battery energy storage system

BG balance group

¹Speichermonitoring (2016)

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BRP	balance responsible party
IE	imbalance energy
IEP	imbalance energy potential
PV	photovoltaic
R	reference scenario (storage network does not provide imbalance energy)
SI	self-interest of the storage operator (max. PV self-consumption)

Nomenclature

Input (time series)				
$q_{t,n}^{PV}$	Photovoltaic generation of household n in time intervall $t\ (kWh)$			
$q_{t,n}^{load}$	load of household n in time interval t (kWh)			
ΔBG_t	energy imbalance of a balance group in time interval $t \ (MWh)$			
p_t^{IE}	Imbalance energy price in time interval $t~({\ensuremath{\in}}/MWh)$			

Input (parameters)

χ_n	Storage capacity of BESS n (kWh)
κ_n^{in}	Charging capacity of BESS n (kWh)
κ_n^{out}	Discharging capacity of BESS $n~({\rm kWh})$
η_n^{in}	Charging efficiency of BESS n (1)
η_n^{out}	Discharging efficiency of BESS n (1)
au	duration of time intervals $(15min)$

Decision variables

$c_{t,n}$	charging of storage n in time interval t (kWh)
$d_{t,n}$	discharging of storage n in time interval $t \ (kWh)$
$SOC_{t,n}$	state of charge of storage n in in time interval t (1)

1. Introduction

2. State-of-the-Art

The ability of distributed battery storage systems to provide frequency containment reserve was assessed in the research project SWARM (*Storage With Amply Redundant Megawatt*), which is a cooperation between Caterva GmbH (Munich) and N-ERGIE AG (Nuernberg), Steber et al. (2016).

3. Method

3.1. Energy balance of balance groups

The energy balance (ΔBG_t) of a balance group in each time interval t consists of three parts: (i) energy bought from and sold to utilities and other balance responsible parties (BRPs), (ii) load profiles (and generation profiles) of small consumers that are not metered and (iii) energy generated and consumed by power plants and large consumers within the BG that are metered.

$$\Delta BG_t = \underbrace{SC_t^{procure} - SC_t^{supply}}_{\text{trading with other BGs}} + \underbrace{LP_t^{feed-in} - LP_t^{procure}}_{\text{load profiles of small consumers}} + \underbrace{q_t^{generation} - q_t^{procure}}_{\text{generation and consumption of power plants and large consumers}}$$
(1)

In case of imbalance $(\Delta BG_t \neq 0)$, the BRP incurs costs (C_{IE}) in the amount of the imbalance energy price p_t^{IE} as depicted in equation (2). Thus, BRPs strive to minimize their energy imbalance.

$$C_{IE} = \sum_{t} \Delta B G_t \cdot p_t^{IE}, \qquad (2)$$

3.2. Storage dispatch according to the self-interest of the storage operator

Small battery storage systems are usually operated in order to increase selfconsumption of electricity generated by PV-systems. Therefore, in case PVgeneration exceeds the load of a household n ($q_{t,n}^{PV} > q_{t,n}^{load}$), excess generation is charged ($c_{t,n}^{SI}$) into the household's storage device as long as the BESS is fully charged (as long as it's state of charge (SOC) is < 1).

$$c_{t,n}^{SI} = \begin{cases} \min\left[q_{t,n}^{PV} - q_{t,n}^{load}, \kappa_n^{in} \cdot \tau, (1 - SOC_{t-1,n}) \cdot \frac{\chi_n}{\eta_n^{in}}\right], & \text{if } q_{t,n}^{PV} > q_{t,n}^{load} \\ 0, & \text{otherwise} \end{cases}$$
(3)

On the contrary, in case the load exceeds PV-generation, energy is discharged from the storage $(d_{t,n}^{SI})$ as long as the BESS is fully discharged (as los as SOC > 0).

$$d_{t,n}^{SI} = \begin{cases} \min\left[q_{t,n}^{load} - q_{t,n}^{PV}, \kappa_n^{out} \cdot \tau, SOC_{t-1,n} \cdot \chi_n \cdot \eta_n^{out}\right], & \text{if } q_{t,n}^{load} > q_{t,n}^{PV} \\ 0, & \text{otherwise} \end{cases}$$
(4)

This operational mode is referred to as self-interest (SI) of the storage operator throughout this paper.

3.2.1. Reference scenario

If the storage is exclusively used to increase the self-consumption of the household (self-interest) the state of charge is obtained by:

$$SOC_{t,n} = SOC_{t-1,n} + \frac{(c_{t,n}^{SI} \cdot \eta_n^{in} - d_{t,n}^{SI} / \eta_n^{out})}{\chi_n}$$
(5)

By application of equation 3 to 5 for the whole period under observation (the year 2015), the reference storage dispatch (reference scenario) described by $c_{t,n}^R$, $d_{t,n}^R$ and $SOC_{t,n}^R$ is obtained by:

$$c_{t,n}^R = c_{t,n}^{SI} \tag{6}$$

$$d_{t,n}^R = d_{t,n}^{SI} \tag{7}$$

$$SOC_{t,n}^R = SOC_{t,n} \tag{8}$$

Finally, electricity procured from the grid by the household n in the reference scenario is calculated by:

$$q_{t,n}^{procure,R} = q_{t,n}^{load} - q_{t,n}^{PV} + c_{t,n}^R - d_{t,n}^R$$
(9)

3.3. Imbalace Energy Potential - IEP

The energy balance of a balance group in a time interval t (equation (1)) can be modified by altering the amount of electricity procured from the grid by all metered loads $(q_t^{procure})$. In case the balance group is short (lack of energy), the total load within the balance group should be decreased. In case the BG is long (surplus of energy) the total load should be increased.

Consequently, imbalance energy can be provided actively by charging or discharging storage units or passively by the prohibition of charging and discharging storage units due to self-interest.

The imbalance energy potential (IEP) of a certain storage n for negative imbalance energy (which equals an increase of the households load) therefore consists of the planned discharge (due to self-interest) that can be prohibited and the amount of energy that could be charged additionally to the self-interest as shown in equation (10).

$$IEP_{t,n}^{-} = \underbrace{d_{t,n}^{prohibited}}_{\text{prohibit discharging}} + \underbrace{c_{t,n}^{IE}}_{\text{enforce charging to}}$$
(10)
due to self-interest provide imbalance energy

The potential for positive imbalance energy (which equals a decrease of the households load) consists of the planned charge that can be prohibited and the amount of energy that could be discharged additionally to the self-interest.

$$IEP_{t,n}^{+} = \underbrace{c_{t,n}^{prohibited}}_{\text{prohibit charging}} + \underbrace{d_{t,n}^{IE}}_{\text{enforce discharging to}}$$
(11)

3.3.1. Static Imbalance Energy Potential - sIEP

The static potential of a storage network to provide imbalance energy is obtained from the storage dispatch according to the reference scenario. The static potential for negative imbalance energy (which equals an increase in total load) is calculated by:

$$sIEP_{t,n}^{-} = \underbrace{d_{t,n}^{R}}_{\text{planned discharge that}}_{\text{could be}} + \underbrace{\min\left[\frac{(1 - SOC_{t-1,n}^{R}) \cdot \chi_{n}}{\eta_{n}^{in}}, \kappa_{n}^{in} \cdot \tau\right] - c_{t,n}^{R}}_{\text{could be}}_{\text{prohibited}}$$
(12)

The household's load can be increased either by prohibition of discharging the storage, or by enforcement of charging the storage. The BESS can only be charged if the state of charge is < 1 and if it is not already discharged due to self-interest.

Similarly, the static potential for positive imbalance energy (which equals a decrease in total load) is calculated by:

$$sIEP_{t,n}^{+} = \underbrace{c_{t,n}^{R}}_{\text{planned charge}} + \underbrace{\min\left[SOC_{t-1,n}^{R} \cdot \chi_{n} \cdot \eta_{n}^{out}, \kappa_{n}^{out} \cdot \tau\right] - d_{t,n}^{R}}_{\text{that could be}}$$
(13)
maximum amount of energy that
could be additionally discharged

The household's load can be decreased either by prohibition of charging the storage, or by enforcement of discharging the storage. The BESS can only be discharged if the state of charge is > 1 and if it is not already discharged due to self-interest.

The static potential only indicates to what extent the storage could be used to modify the household's load without actually changing the storage dispatch according to the reference scenario. Consequently, no imbalance energy is provided by the storage network.

3.4. Imbalance energy utilized - IEU

In the previous section the static imbalance energy potential was calculated but not used to reduce a balance group's imbalance. Utilization of the imbalance potential changes the state of charge of the storage and thus has an effect on the remaining potential of the future time intervals.

In case the balance group is short ($\Delta BG_t^R < 0$, lack of energy), positive imbalance energy is needed. Thus, the positive imbalance energy utilized is calculated by:

$$IEU_{t,n}^{+} = c_{t,n}^{SI} + \min\left[SOC_{t-1,n} \cdot \chi_n \cdot \eta_n^{out}, \kappa_n^{out} \cdot \tau\right] - d_{t,n}^{SI}$$
(14)

Consequently, charging due to self-interest is prohibited:

$$c_{t,n}^{prohibited} = c_{t,n}^{SI},\tag{15}$$

while discharging is enforced:

$$d_{t,n}^{IE} = \min\left[SOC_{t-1,n} \cdot \chi_n \cdot \eta_n^{out}, \kappa_n^{out} \cdot \tau\right] - d_{t,n}^{SI}$$
(16)

Negative imbalance energy would increase the BG's imbalance and is set to zero:

$$IEU_{t,n}^{-} = 0 \tag{17}$$

$$d_{t,n}^{prohibited} = 0, \quad c_{t,n}^{IE} = 0 \tag{18}$$

In case the balance group is long ($\Delta BG_t^R > 0$, surplus of energy), negative imbalance energy is needed.

$$IEU_{t,n}^{-} = d_{t,n}^{SI} + \min\left[\frac{(1 - SOC_{t-1,n}) \cdot \chi_n}{\eta_n^{in}}, \kappa_n^{in} \cdot \tau\right] - c_{t,n}^{SI}$$
(19)

Consequently, discharging due to self-interest is prohibited:

$$d_{t,n}^{prohibited} = d_{t,n}^{SI},\tag{20}$$

while charging is enforced:

$$c_{t,n}^{IE} = \min\left[\frac{(1 - SOC_{t-1,n}) \cdot \chi_n}{\eta_n^{in}}, \kappa_n^{in} \cdot \tau\right] - c_{t,n}^{SI}$$
(21)

Positive imbalance energy would increase the BG's imbalance and is set to zero:

$$IEU_{t,n}^+ = 0 \tag{22}$$

$$c_{t,n}^{prohibited} = d_{t,n}^{IE} = 0 \tag{23}$$

Finally, the storage dispatch is a combination of usage according to the selfinterest and the imbalance energy provided. Thus, the amount of energy charged or discharged from the storage is calculated as follows:

$$c_{t,n} = c_{t,n}^{IE} + \left(c_{t,n}^{SI} - c_{t,n}^{prohibited}\right)$$
(24)

$$d_{t,n} = d_{t,n}^{IE} + \left(d_{t,n}^{SI} - d_{t,n}^{prohibited}\right)$$

$$\tag{25}$$

Consequently, the battery's state of charge results from:

$$SOC_{t,n} = SOC_{t-1,n} + \frac{(c_{t,n} \cdot \eta_n^{in} - d_{t,n}/\eta_n^{out})}{\chi_n}$$
 (26)

and the amount of energy procured from the grid by the household n results in:

$$q_{t,n}^{procure} = q_{t,n}^{load} - q_{t,n}^{PV} + c_{t,n} - d_{t,n}$$
(27)

3.5. Savings in imbalance energy costs

The total cost for imbalance energy of a balance group in the reference scenario²³ (C_{IE}^R) is calculated from the balance group's imbalance ΔBG_t^R and the imbalance energy price p_t^{IE} according to:

$$C_{IE}^{R} = \sum_{t} \Delta B G_{t}^{R} \cdot p_{t}^{IE}$$
⁽²⁸⁾

Usage of the storage networks aims to modify the imbalance of the reference scenario. The modified imbalance is obtained by:

$$\Delta BG_t = \Delta BG_t^R + \sum_n \left(q_{t,n}^{procure,R} - q_{t,n}^{procure} \right)$$
(29)

Hence, the total cost for imbalance energy in case the storage network is used to compensate for schedule deviations result in:

$$C_{IE} = \sum_{t} \Delta BG_t \cdot p_t^{IE}, \qquad (30)$$

and total Savings (S_{IE}) in imbalance energy costs can be calculated by:

$$S_{IE} = C_{IE} - C_{IE}^{R}$$

$$= \sum_{t} \left(\left(\Delta B G_{t}^{R} + \sum_{n} \left(q_{t,n}^{procure,R} - q_{t,n}^{procure} \right) \right) - \Delta B G_{t}^{R} \right) \cdot p_{t}^{IE}$$

$$= \sum_{t} \sum_{n} \left(\left(q_{t,n}^{procure,R} \right) - \left(q_{t,n}^{procure} \right) \right) \cdot p_{t}^{IE}$$

$$= \sum_{t} \sum_{n} \left(\left(q_{t,n}^{load} - q_{t,n}^{PV} + c_{t,n}^{R} - d_{t,n}^{R} \right) - \left(q_{t,n}^{load} - q_{t,n}^{PV} + c_{t,n} - d_{t,n} \right) \right) \cdot p_{t}^{IE}$$

$$= \sum_{t} \sum_{n} \left(c_{t,n}^{R} - d_{t,n}^{R} - \left(c_{t,n} - d_{t,n} \right) \right) \cdot p_{t}^{IE}$$

$$= \sum_{t} \sum_{n} \left(c_{t,n}^{R} - d_{t,n}^{R} - \left(c_{t,n}^{IE} + c_{t,n}^{SI} - c_{t,n}^{prohibited} \right) + \left(d_{t,n}^{IE} + d_{t,n}^{SI} - d_{t,n}^{prohibited} \right) \right) \cdot p_{t}^{IE}$$
(31)

 $^{^{2}}$ Reference scenario means that the storage network in not used to minimize the imbalance of the balance group but only to satisfy the self-interest of the storage operator.

 $^{{}^{3}}C^{R}_{IE}$ is negative in case of costs and positive in case of revenues.

Obviously, the savings are zero if the storage dispatch in case of imbalance energy provision of the storage network $(c_{t,n}, d_{t,n})$ equals the storage dispatch in the reference case $(c_{t,n}^R, d_{t,n}^R)$.

3.5.1. Repercussion on the load schedules of households

Assume there is no repercussion on the schedule of a household in case storage devices are used to provide imbalance energy, the savings in imbalance energy costs could be calculated according to:

$$S_{IE}^{gross} = \sum_{t} \sum_{n} \left(IEU_{t,n}^{+} - IEU_{t,n}^{-} \right) \cdot p_{t}^{IE}$$
$$= \sum_{t} \sum_{n} \left(c_{t,n}^{prohibited} + d_{t,n}^{IE} - \left(d_{t,n}^{prohibited} + c_{t,n}^{IE} \right) \right) \cdot p_{t}^{IE}$$
(32)

The difference of total savings and gross savings (in case reactions on the schedules are neglected) is obtained by:

$$S_{IE} - S_{IE}^{gross} = \sum_{t} \sum_{n} \left(c_{t,n}^{R} - d_{t,n}^{R} - c_{t,n}^{SI} + d_{t,n}^{SI} \right)$$
(33)

Consequently, repercussion come about because storage usage due to the selfinterest of the storage operator defer in the reference case and in case the storage network is used to reduce schedule deviations.

3.6. Input Data

Time series for the year 2015 of PV-generation and the load of various households located in Austria were provided by *neovoltaic AG*. The time series for the year 2015 regarding energy balance of a balance group was provided by *Energie Burgenland AG*, and the imbalance energy price for the control area APG is published by the Austrian Balance Group Coordinator, *Austrian Power Clearing and Settlement*⁴ (APCS).

4. Discussion

4.1. Imbalance energy costs

The duration curve of the imbalance energy price p_t^{IE} of the year 2015 is depicted in figure 1. For a significant number of hours per year it is much higher

⁴http://www.apcs.at/en

(or lower) than the average EXAA spot price in 2015. High imbalance energy prices occur in case the total load within the control area exceeds the total generation (the control area is short). This is when a BRP could instruct the storage network to stop charging and start discharging to benefit from the hight prices (respectively avoid high costs).

On the contrary, in case of negative imbalance energy prices, which occur if total generation within the control area exceeds the total load (the control area is long), the BRP will instruct the storage network to stop discharging and start charging, because additional consumption is rewarded in case of negative electricity prices.



Figure 1: Duration curve of the imbalance energy price p_t^{IE} in the year 2015 in comparison to the average EXAA spot price in 2015.

4.2. Storage dispatch in the reference scenario

Storage dispatch in the reference scenario is depicted in figure 2 for two representative days in July 2015. The storage is charge in the morning as soon as electricity generated by the PV-system exceeds the household's load and is discharged in the evening as the load exceeds the PV-generation.



Figure 2: Storage dispatch in the reference scenario for two representative days in July 2015 (storage energy capacity: $\chi_n = 5MWh$, storage charging/discharging capacity $\kappa_n^{in} = \kappa_n^{out} = 5MW$, storage charging/discharging efficiency $\eta_n^{in} = \eta_n^{out} = 0.9$).

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