

# Speicherregelkraftwerk – Optimization of Self-Consumption by Using Battery Storage

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**Abstract**—In this paper a unique set-up of a battery storage integrated in a wind farm is presented. The wind farm Curslack in Hamburg-Bergedorf and a battery storage with a special controller set-up represent the project “Speicherregelkraftwerk. The wind farm and the battery storage share one grid. This paper presents a simulation model to estimate the potential cost savings for wind farm operators with the optimization of self-consumption of wind turbines by using a battery storage. This is one of multiple use cases that are tested in a research project that aims to make a proof of concept to combine different potentially technical benefits of a battery in a wind park grid. The goal of combining an optimized wind farm operation combined with ancillary services can generate a secure energy system without a dependency on fossil power plants. The battery is charged with wind energy and a locking mechanism assures that no grey energy is stored. When the wind turbines’ rotors are not rotating, the power consumption of the wind turbine for internal processes is mostly covered by the lithium-ion battery. An algorithm was set up to iterate through the second-based input data from the wind farm’s grid of measurement points. The developed simulation calculated savings of energy costs up to 50 % (variable energy costs depending on energy consumption) or total costs up to 39 % (with fixed cost) in comparison to the conventional coverage of the consumption through energy purchase from the grid for the month of May 2019.

**Keywords**— hybrid power plant, battery storage, power quality, ancillary services, “grey electricity locking”, areal grid, battery control methods, optimization of self-consumption

## Nomenclature

EnWG	Energiewirtschaftsgesetz (English: Energy Industry Law)
EU	European Union
MP	Measurement Point
NEW	Norddeutsche Energiewende (English: Northern German Energy Transition)
SoC	State of Charge
StromNEV	Stromnetzentgeltverordnung (English: Electricity Network Fees Regulation)
SRKW	Speicherregelkraftwerk (English: Storage Control Power Plant)

## I. INTRODUCTION

To reach the goals of the United Nations Framework Convention on Climate Change, an increase of renewable energy is necessary [1]. Furthermore, the EU “Clean Energy for Europeans” package requires member states to draw up individual energy and climate plans. One aim is to achieve global leadership in renewable energy and to prioritize energy efficiency [2]. In Germany the net electricity production was 518,13 TWh in the year 2019. Thereby, the share of renewable energy was 238,37 TWh (46 %) [3]. It is expected that Germany's demand for electricity will be approximately 651 TWh in 2030 and approximately 1447 TWh in 2050 (scenario reference), which will have to be covered primarily by renewable energy sources [4]. With the further increase of variable renewable energy, the integration of wind turbines in energy systems is becoming more complex. More and more Energy is provided by decentralized renewable energy systems which feed into the distribution grid instead of the transmission grid. Renewable energy is also dependent on weather, whereby

forecasts are prone to uncertainties. This leads to frequently changing and difficult to predict production and to load flow situations in the transmission and distribution grid [5]. Therefore, wind farms have to supply electricity ancillary services for a safe and secure energy system. In the future, they must compensate the grid stabilizing characteristics of fossil power plants. New control strategies are needed to implement additional system components. This includes balancing out frequency variations in the electricity grid with an inertial response provided by wind turbines. For this purpose the integration of battery storage in wind farms is useful for a joint participation in ancillary service markets [6].

The SRKW aims to provide a synergy of services supplied to support the grid and the wind farm. An important one of these services is to use energy storage capacities to optimize the self-consumption of a wind farm for a reduced energy acquisition from the grid in times of standing rotors.

Thereby, the plant operators can save electricity costs through peak shaving and reduced electricity purchases from the grid [7]. This approach is presented and analyzed in this paper.

The paper presents an innovative research for system integration of renewable energy by using a battery storage. Section 2 gives an overview of the project *Speicherregelkraftwerk* (SRKW – English: Storage Control Power Plant) and its setup. In section 3 the optimization of the wind farm's self-consumption is presented. Finally, a conclusion is given in section 4.

## II. PRESENTATION OF SRKW

The innovative research for system integration of renewable energy of SRKW is part of the NEW 4.0 (Norddeutsche Energiewende, English: Northern German Energy Transition) project which aims to develop a blueprint for the energy transition of northern Germany tackling challenges of a future energy supply with 100 % renewable sources. This accounts not only for the replacement of all conventional sources in the energy production but also for the stabilization and quality conservation of the grid, resulting in the need for ancillary services to be supplied by decentralized renewable sources. The SRKW consists of an onshore wind farm and a lithium-ion battery storage to explore the grid's beneficial potentials for a close collaboration of these technologies.

Battery Storage System	Wind Farm
24 Lithium-Ion HV Batteries	5 Wind Turbines – Nordex N 117
Energy Capacity: 792 kWh	1x 3 MW, 4x 2.4 MW
Max. Power: 720 kW	Overall Nominal Power: 12.6 MW
Grid Connection: Existing - Synergy with Wind Farm	Feed-In to public high-voltage grid
Owner: Vattenfall, Joint research operation by HAW HH, Vattenfall, Nordex	Operator: ReTec Zweite Betriebs UG und Co.KG

Table 1: Key Figures of the Battery Storage System and the Wind Farm

Table 1 lists the key figures of the battery storage system and the wind farm. Different control methods of the battery are analyzed on how they can empower the plant with the flexibility to optimize its performance and support the grid with ancillary

services like virtual inertia, frequency containment reserve, volt-ampere reactive support and a stacking of applications.

### A. Schematic System Setup

The schematic system setup of the SRKW is shown in figure 1. The onshore Wind Farm Curslack (1c) in Hamburg consists of five Nordex N 117 Wind Turbines: four 2.4 MW and one 1 MW turbine, making up an overall nominal power of 12.6 MW. The wind farm was commissioned in 2018 and feeds power to the local public high voltage grid. For the formation of the SRKW a 792 kWh lithium-ion battery storage (1a) was integrated into the wind farm. The battery storage has a peak power of 720 kW to discharge in and charge from the wind farm grid with which the SRKW shares its feed-in point to the public grid. Through managing the operation of wind farm and battery storage the central control unit (1b) coordinates their collaboration as a holistic system. Thereby the battery's capacity supports an optimized operation and performance of the wind farm and is used to supply ancillary services (5) to the public electricity grid (4). With the broad spectrum of possibilities for collaboration of battery and wind turbines various business models can be developed (2). The possibility of stacking control methods, as mentioned above, allows for a combination of different business models and the creation of new ones.

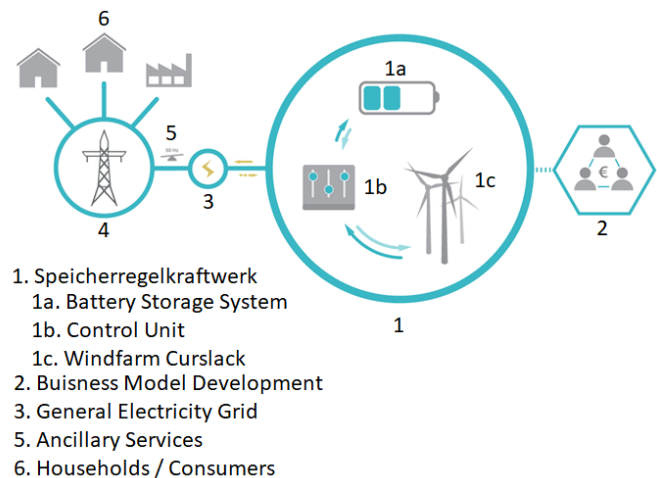


Figure 1: Innovative Research for System Integration of Wind Energy

### B. Measurement and Control Setup

The SRKW's operation is managed through the control of the wind farm and the battery storage. Figure 2 shows the setup of the park grid with these two controllers (2 and 3), the different measurement points (MP) and other major components in it. The transformers (5, 6) connect the 10 kV wind farm grid to the 400 V battery circuit and the 110 kV high voltage public grid (7). The measurement points distributed over different locations in the wind farm grid provide input for the monitoring of the system and the control algorithms executed in the controllers.

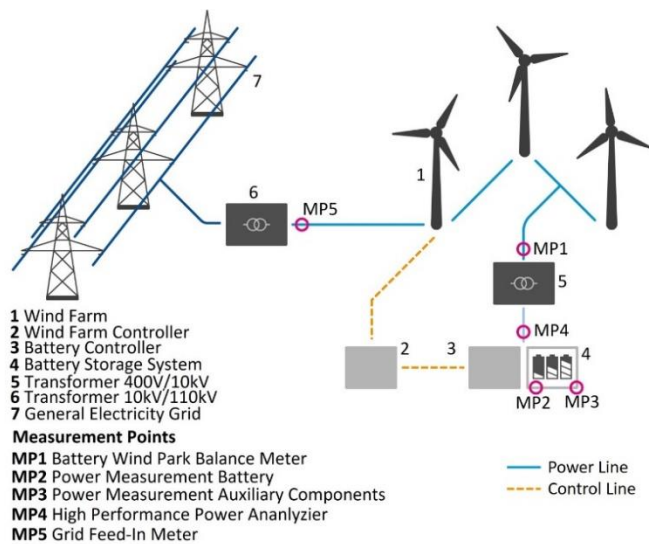


Figure 2: Measurement and Control Setup of the SRKW's areal grid

In order to maintain the plant's status as a producer of fully renewable energy according to German law [8] a locking mechanism assures that no energy is fed to the battery from the public grid and is potentially later fed back into the grid as green energy. Consequently, the battery can only be charged by the local wind power which imposes restrictions and challenges for its operation. To assure that no energy finds its way from the grid into the battery, the locking mechanism monitors the power flow at the Grid Feed-In Meter (MP5) and prevents any charging procedures of the battery in times when the grid feed-in is below a certain threshold or even negative. As this locking is unidirectional, the battery can still supply loads like self-consumption in the wind farm (see section 'Optimization of Self-Consumption') with its available capacity in these times. The high performance power analyzer (MP4) captures different power quality characteristics of the park grid at the connection point of the battery in high resolution and accuracy. This allows to determine and analyze the impacts that different operations of the wind farm and the battery have on the local power quality. MP2 and MP3 monitor the battery and its auxiliary components to assess the battery's condition and readiness at any time.

### III. OPTIMIZATION OF SELF-CONSUMPTION

### A. Problem settings

A wind farm always has a certain amount of self-consumption of power in standby and feed-in mode. May it be for active procedures like the pitching of the blades or the yaw drive of the nacelles or for plant control, cooling of transformers and air conditioning [9]. In times of absent or low wind speeds these self-consumptions turn a wind farm from an energy producer into a consumer drawing power from the grid. This has influences on the grid and can result in significant expenditures for the amount of energy drawn from the grid (depending on the windpark set up). Also, the energy being taken causes costs for system operators.

In Germany larger electricity consumers pay a reduced working price which considers the total purchased electrical energy.

Additionally, a price for the power value is calculated. This price depends on the maximum power occurring in the billing period (monthly or annual). The averaging interval for the power value is 15 minutes [7], [10]. A smooth load profile means lower costs for the grid usage fees according to StromNEV (Stromnetzentgeltverordnung English: Electricity Network Fees Regulation) and § 20 EnWG (Energiewirtschaftsgesetz English: Energy Industry Law) [11]. It is a fee paid to the grid operator by every grid user who transmits electricity or gas through the supply grid [12].

Hence, in the investigated case costs can be reduced by two points:

- peak shaving
- use of self-produced wind energy. (is considered in simulation)

The legal framework for energy storage and self-supply is the deciding factor for the final economic efficiency. For the first time in the EU package “Clean Energy for all Europeans“, concrete regulations for the use of energy storage as an essential instrument for achieving the necessary flexibility in the electricity market are set up [13]. Storage systems are becoming an integral part of the electricity market. For the regulatory implementation various regulations refer explicitly to energy storage. Also, energy storage systems which use renewable energy for self-supply are described. EU-Member states should remove legal and commercial barriers for consumers who store their own generated electricity. These include the payment of disproportionately high fees. A double payment obligation and also a double grid fee may not be applicable if the stored electricity is used for self-consumption or flexibility services to grid operators are provided. Additionally, consumers with storage systems may offer several ancillary services simultaneously [14].

In the approach of optimized self-consumption, the battery storage's energy capacity is used to cover these self-consumptions and to prevent or mitigate the purchase of energy from the public grid. The energy is fed into the battery in times of sufficient wind speeds beforehand. The unidirectional locking mechanism (see above) allows for a discharge of the battery to support the self-consumption of the farm in times of no production from the turbines. The amount of energy available from the battery depends on its State of Charge (SoC) and therefore its operation before the shortfall of the turbines production.

A simulation is designed to give insight on the applicability and constructiveness of different control approaches for the battery in this matter. In the simulation only the use of self-produced wind energy is considered, thereby peak shaving has no part.

### B. Simulation description

The actual capacity of the lithium-ion storage is fixed through the properties of its components and doesn't allow for dynamical modifications. Through the use of the battery

management, the usable energy storage capacity and the discharge limit can be modified in real time [15]. With this control energy can be fed into or out of the battery depending on whether the power production from the wind turbines is higher or lower than the power consumption of the plant itself. To simulate the working principles of the whole system a mathematical model has been implemented in Python which is described below.

#### - Simulation software

The programming language Python was selected for the simulation in this paper. The Python code is sometimes significantly shorter and easier to read, compared to the program code of other frequently used programming languages. The object-orientated paradigm was chosen to structure the code.

#### - Simulation inputs

Second-based measurement series of the wind farm's power production and the battery storage system are used as data inputs to the simulation. In this paper, only the data from the month of May 2019 analyzed and shown. The consumption with and without battery storage can be accurately calculated by a self-consumption simulation. The simulation shows the potential savings in energy purchases through the usage of the battery storage's capacity throughout May. The investment costs of the battery system as well as potential other costs e.g. for maintenance are not considered because it is anticipated that the battery is used for different purposes and the optimized self-consumption is an additional benefit.

Furthermore, in the simulation the accuracy of the models is evaluated by a comparison with actual consumer bills from the energy retailer.

#### - The algorithm

The flow chart in figure 3 shows the generated model and its algorithm. To maximize the economic profits of the combination of battery storage and wind energy generation, the two classes *Battery Control* and *Wallet* have been implemented. The simulation starts with the initialization of the first iteration. This is done with the condition charging: = *false* meaning that the battery was not charged before. With every data point the iteration of both classes begin.

Table 2: Description of parameter/variable

Parameter/Variable	Description
$power_{feed-in}$	Power at grid connection of wind park. [kW] Positive values: energy is fed from wind park in the energy grid Negative values: energy is drawn from public grid
charging	Indicates if battery is charged or not. [True or False].
wallet1	Counts the simulated energy costs for a the wind park without the usage of a battery caused by energy taken from the grid[€]
wallet2	Counts the simulated energy costs for a the wind park including the usage of a battery (including losses in earnings from energy that is used instead of being fed in the grid) [€]
$threshold_{upper}$	Upper threshold for $Power_{feed-in}$ which has to be reached or exceeded to unlock possibility of charging battery. Fixed value[kW] After that charging is possible till $Power_{feed-in}$ falls below lower threshold.
$threshold_{lower}$	Lower threshold for $Power_{feed-in}$ which stops possibility of charging battery if value is fallen below. Fixed value[kW]
max SoC	Maximum SoC – fixed value [%] of the maximum possible energy that can be charged in the battery system.
min SoC	Minimum SoC – fixed value [%] of the minimal energy that can be charged in the battery system. Often differs from 0 to avoid damage of battery cells



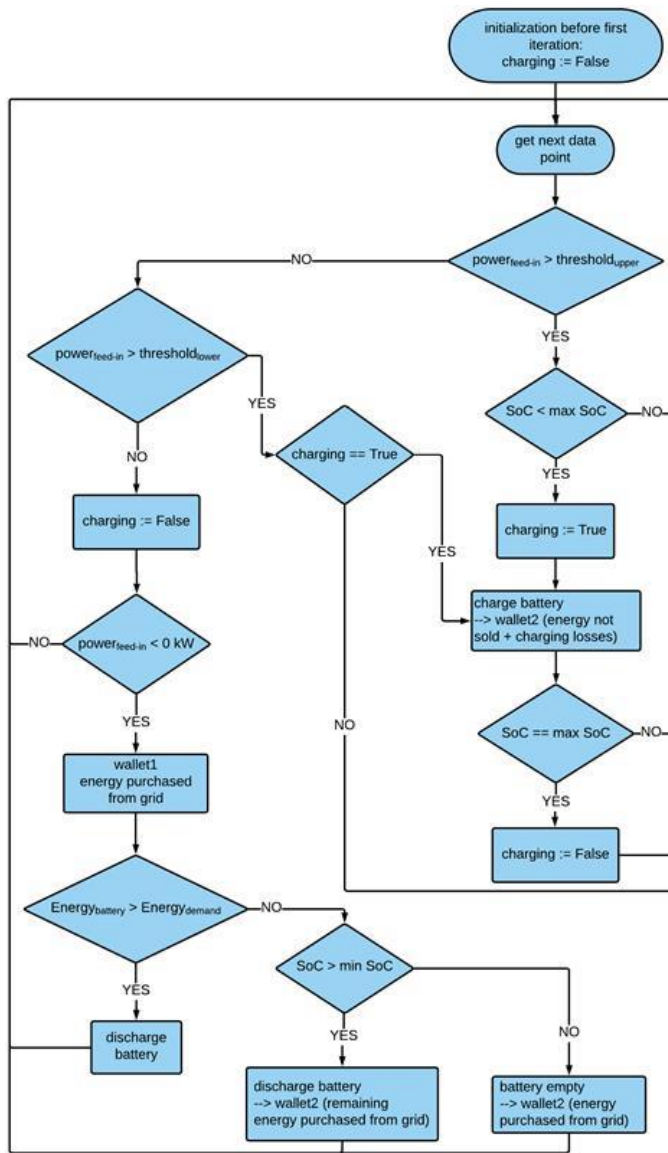


Figure 3: Flow Chart of generated model

### 1) Battery Control

The two main functions of the battery storage are charging and discharging. A certain logic operation is required for when and how the battery can be charged. The initial SoC value in the battery is very important, because it is needed to iterate the SoC change of the entire battery. In the Python simulation, the SoC value can be changed as a variable in the main model, therefore, the initial value of SoC must be estimated based on the battery management prior to the starting point of the simulation. In this algorithm, charging of the battery can only start when the two following conditions are met: Firstly, the SoC value needs to be below either 100 % or a predefined maximum threshold for the SoC. Secondly, the energy resulting from the power production of the farm ( $power_{feed-in}$ ) being present for the given time step may not exceed the vacant capacity of the battery. Upper threshold is defined as twice the nominal active power of the battery storage system (larger value). Lower

threshold is defined as minimal grid safety management Performance for charging operation. To achieve a stable operation, a hysteresis of two thresholds is applied for the charging clearance. This is illustrated in figure 4.



Figure 4: Demonstration of the charging clearance hysteresis

In times of sufficient wind power the lower threshold is crucial for the clearance of the charging. When  $power_{feed-in}$  drops below this lower threshold the charging clearance is revoked until the upper threshold is reached again by production (red area in figure 4). In times when  $power_{feed-in}$  alternates around one of the thresholds the hysteresis prevents the charging clearance from following this alternation which would result in many steep charging peaks.

The amount of energy charged is determined by the charging power and the remaining energy capacity in the battery. When the SoC value has reached the given threshold ( $SoC == max\ SoC$ ), the charging process ends.

One of the technical drawbacks of electro-chemical battery storage systems are their different kinds of energy losses. These losses are normally related to the efficiency of the electro-chemical conversion in the battery cells and the inverter efficiency in the DC/AC conversion, and vice versa [16]. According to the size of the charging current a corresponding loss coefficient is set up as a parameter in the main model. As the amounts of energy lost in this manner cannot be sold to the grid or used to compensate the electricity demand in the wind farm anymore, they result in a respective financial loss/cost.

### 2) The Wallet

The optimization of self-consumption is presented as one of various services which can be realized with the assets of the SRKW system. These assets are assumed as given resources in the financial analysis of this paper which therefore only takes into account the purchase/compensation costs of the energy amounts involved in the coverage of the self-consumption. To cover energy consumption in the wind park during times of energy not being generated from wind, energy normally has to be obtained and therefore purchased from the grid. Accordingly, two modes of consumptions are possible. Either energy is being drawn from the grid or it is taken from the battery storage. The *class Wallet* takes these two procedures into account with their respective costs. While drawing the energy for the self-consumption from the grid entails the respective energy purchase price to be paid to the energy retailer, a coverage

through the battery storage mitigates the amount of energy available to be sold to the grid for compensation. The exact cost can be obtained through the *pay function*. The *pay function* adds up the payments made for energy drawn from the grid. Alternatively, it stores the lost compensation for produced energy being stored in the battery and therefore not sold to the grid. The algorithm iterates through the data and calculates the respective costs for both set-ups for each of the second-based inputs. In each step, it is decided whether the battery will be charged or not and if energy needs to be drawn from the grid or the battery for coverage of consumption. The results and their respective costs are stored in two wallets. wallet1 stores the simulated costs for a system without a battery while wallet2 does the same for a system with battery support. They are compared in figures 7 and 8.

#### IV. RESULTS AND DISCUSSION

The results of the generated simulation are presented in a graphical form.

Figure 5 shows the power production from the wind turbines in percent throughout the days of May 2019, whereby 100 % indicates the highest performance. It gives a vivid visualization of the wind speeds and thereby the wind energy production's fluctuation. In times when the production goes to 0 % (blue line) the battery is supposed to take over the supply of the self-consumption.

The SoC values in percent of the simulated battery is described in figure 6. A comparison with figure 5 shows how the battery's capacity is used in the absence of power production by the turbines. When the production from wind stops the SoC value begins to drop as the battery is used to cover the self-consumption. With the resumption of the production the battery is recharged again and the SoC is brought back up.

Figure 7 compares the energy costs for the systems excluding fixed costs with and without the support of the battery. Hence, only the variable costs, depending on the consumed kWh, are included in the simulation.

The electricity costs with a battery usage are shown in relation to the eventual costs for a system without a battery (blue line) defined as 100 % at the end of the month. The battery is assumed to be charged at the beginning of the simulation. With the first outages of wind power the cost saving potential of the battery become evident. With more wind power outages, the divergence between the two systems' costs keeps increasing.

The comparison of actual energy purchase bills from the energy retailer and the simulated costs of consumption without a battery storage shows a similar result for May. In this month the variable energy costs for the setup with battery storage end up being only around 50 % of the ones without. The same behavior is shown in Figure 8, in which the simulation includes additional fixed cost. The total energy costs for the setup with battery storage end up being around 39 % lower than those of one without. The calculated savings depend on wind farm and cost assumptions. A statement about the overall economy of the battery storage is not given. Only the electricity cost for the operator decrease.

Considering the long life- and operation time of battery storages this shows their potential to save a lot of money in the operation of a wind farm. Additionally, the utilization of stored wind energy from the battery for the wind farm's consumption lessen its dependency on energy supplied from the grid. This does not only disburden the grid but also mitigates the plant's consumption of gray energy from the grid, further strengthening its part in the progression towards a renewable future of energy supply.

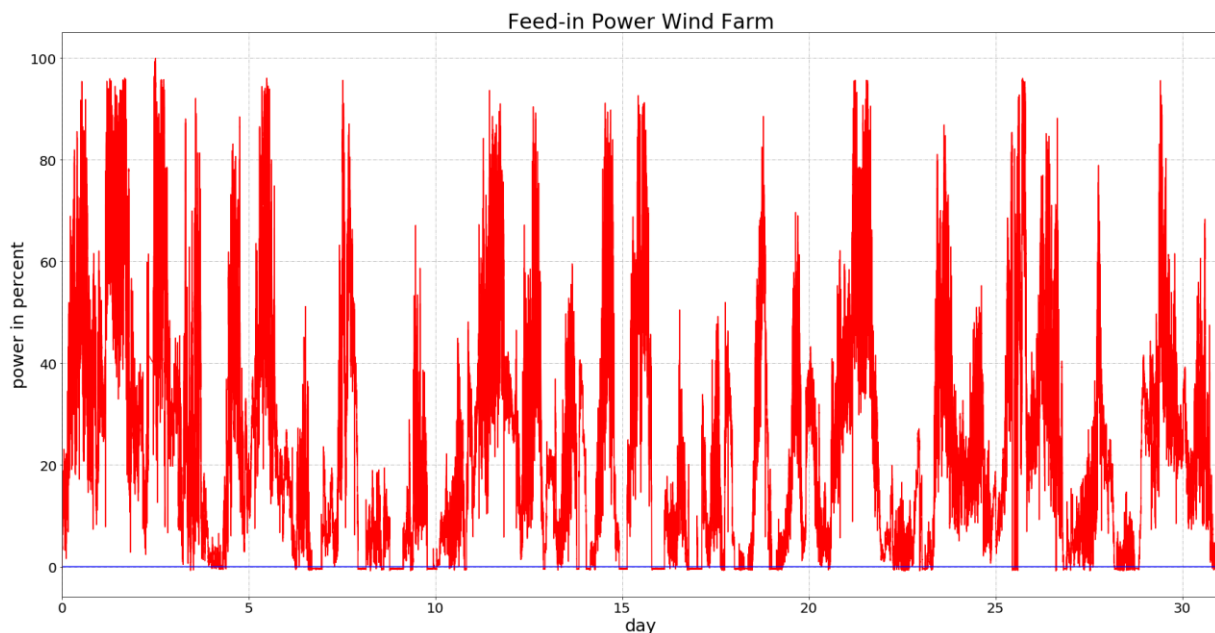


Figure 5: Electricity production delivered to the grid

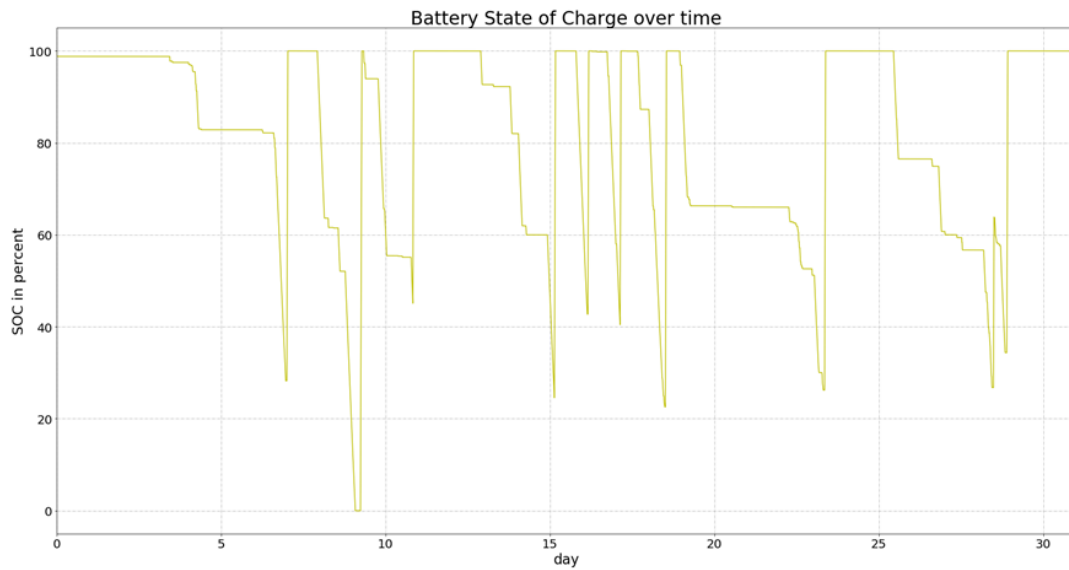


Figure 6: Value in the battery development throughout May

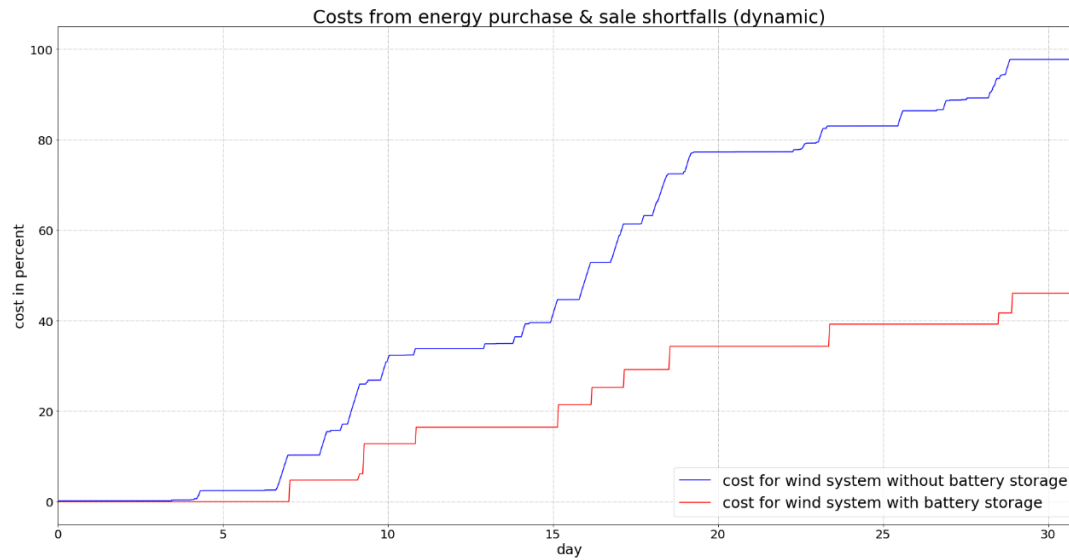


Figure 7: Costs for wind system with and without battery storage (dynamic)

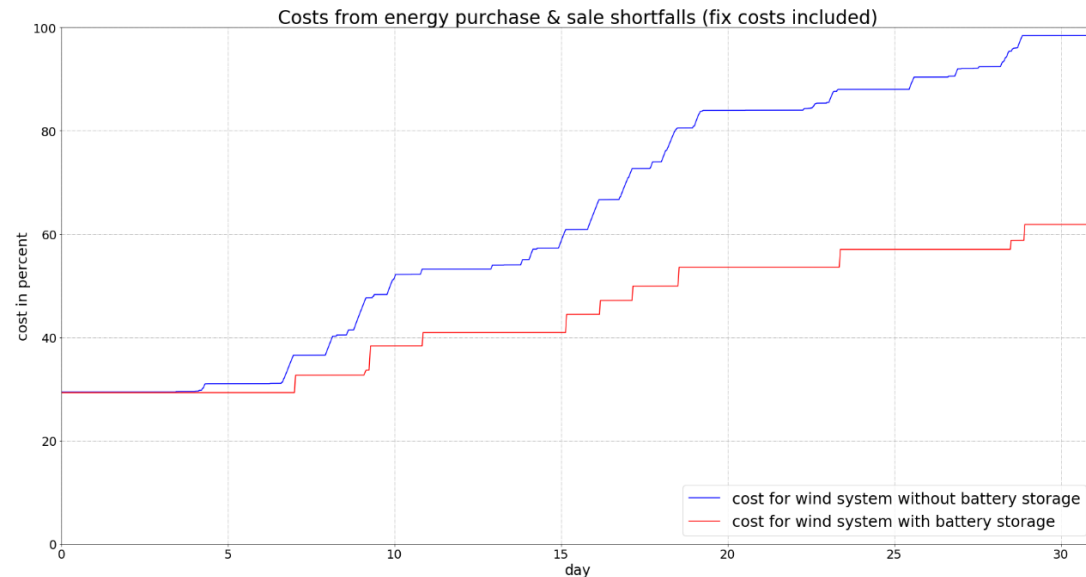


Figure 8: Costs for wind system with and without battery storage (fix costs included)

It is notable that the results presented here for the period of one month cannot simply be projected to a whole year. In Europe the wind speed is depending on the season and weather, which leads to a variation of wind speed throughout the months of the year. That means also varying wind production. Furthermore, maintenance and other interventions with the operation of the plant have major influences on its power production and therefore its need for external coverage of self-consumption. Another point of a long-term view of the savings, is to include the new legal regulations from the EU package “Clean Energy for all Europeans” for energy storage and self-supplies. Accurate calculations should include allocations and fees [14]. A challenge for the optimization of self-consumption lies in the limited predictability of its times of need being linked to the wind speed or other external factors. This makes it demanding to assure the availability of sufficient energy in the battery at all times. This issue becomes even more severe when the battery is used for multiple services simultaneously and its capacity has to be spread among these. This issue can be observed in figure 6 depicting the SoC value of the battery. Around day ten the SoC drops to 0 %. For the respective point in time, figure 5 shows that there was no power produced by the wind farm for a longer period of time. The battery’s energy capacity was consumed entirely for the self-consumption while not being sufficient to cover the whole outage of production. This results in a significant increase in the cost for the wind system with battery storage (red line, Figure 7) as energy was needed to be drawn from the grid for the remaining time of the production outage of the wind turbines.

The battery’s competence to sufficiently support the farm’s consumption is obviously bound to its size. Already at this rather small size it is possible to supply the whole electricity demand of the wind park by the battery in some months of the year. A larger size could lead to a higher share of self-supply. Nevertheless, costs for the installation will rise and an integrated concept for a multiple purpose use of the battery is needed to justify such an investment. Processing further and longer measurement series from the SRKW with the simulation presented in this paper will give valuable input to such an analysis.

## V. CONCLUSION AND FURTHER WORK

For the exemplary period of one month being investigated in this paper cost savings of up to 50 % for variable costs or 39 % for total costs (variable + fixed costs) were calculated. As in this paper only the data for one month was analyzed in the simulation, to demonstrate the project, the findings drawn from the results are limited. Processing longer measurement time series of, for example, a whole year can give a lot more insight into the approach’s performance. Fortunately, the available measurement database is constantly expanded by the SRKW’s measurement grid.

In the simulation carried out in this paper the battery was controlled to compensate any energy acquisition from the grid whenever possible. For the wind farm the price for energy purchased depends significantly on the maximum power drawn from the grid within the billing period (see section 2). This makes it interesting to consider the implementation of a peak-shaving approach for the consumption of the wind farm not only for the sake of grid but also for financial reasons. A respective approach shall be analyzed in future simulations. Also feed-in management measures<sup>1</sup> for wind turbine should be considered in simulation because these measures currently prevent legally the use of the battery storage during the time of management. The wind farm SRKW has in 2020 an over average number of measures which should be integrated in future simulation. Another step in this project is the actual implementation of the simulation at the SRKW. For this purpose, the battery is controlled as suggested by the algorithm in the described way. The measured data obtains input for a more precise calculation. Subsequently, the actual savings generated can be compared to the ones predicted by the simulation.

Moreover, a stacking of the optimized self-consumption with ancillary services like primary control reserve and virtual inertia was developed and will be tested to strengthen the battery’s role as a productive and diverse support for the quality of the grid and the wind farm operation. The different applications can reduce the costs for operation of the battery storage but some as primary control reserve and virtual in are strongly dependent on the legislative framework in the future.

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<sup>1</sup> Network operators regulate renewable energies, e.g. wind power, if sections of distribution or transmission network are overloaded and the security of power supply is at risk.



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