BUSINESS CASE ANALYSIS OF HYBRID SYSTEMS CONSISTING OF BATTERY STORAGE AND POWER-TO-HEAT ON THE GERMAN ENERGY MARKET

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ABSTRACT

Declining prices on frequency containment reserve (FCR) markets endanger the profitability of battery energy storage systems (BESS). BESS combined with power-to-heat units could improve the profits both by supplying higher power rates on FCR markets and by converting excessive power into heat. Two cases were investigated with a techno-economic model using primary operation and market data of 2018/2019. The system amortises after 12 years with a net present value of two million € operating on the FCR market. No profits were realised by additional arbitrage trading. Taxes, levies and charges frameworks are crucial for the economic success of hybrid systems.

KEYWORDS

hybrid storage, frequency containment reserve, economic analysis

1. INTRODUCTION

Growing shares of electricity provided by intermittent renewable energy sources pose partly unknown challenges to the power transmission grid (Sessa et al., 2018). In this context, ancillary services like frequency containment reserve (FCR) have become increasingly relevant for the power grid to ensure its reliability (Zhang et al., 2019). Due to their fast response capacity, lithium-ion battery energy storage systems (BESS) have proven to be highly suitable for providing FCR from a technical point of view (Stenzel et al., 2019; Thomas, 2017). In addition, they could potentially diminish the overall environmental impact of FCR provision (Koj et al., 2015). Nevertheless, the successful market diffusion of new technologies such as BESS depends not only on their technical suitability or environmental performance but also on their financial profitability and their capacity to compete on the markets. Recently, prices on the FCR market have been decreasing considerably which could endanger the profitability of standalone BESS providing FCR (Kern and von Roon, 2019). Innovative concepts and business models have to be found to safeguard their contribution to reliable power grid operations and to a more environmentally benign FCR provision despite declining FCR returns.

Several studies were carried out investigating the economics of different BESS options. Apart from standalone BESS operating on the FCR market only, two research lines can be identified which are aimed at improving the economic efficiency. The first one relates to increasing revenues by combining FCR operations of BESS with additional applications, e.g. arbitrage trading or peak shaving. Within the second one, hybrid solutions with combined BESS and sector-integrating power-to-heat (PtH) units have been investigated for FCR because they are potentially more cost-efficient than standalone BESS.

Regarding the operation of standalone BESS on the FCR market, research has been conducted considering different technical and economic assumptions. Bühler et al. (2015) investigated large-scale standalone BESS operating on the German FCR market and identified economic viability after 13 years of operation for BESS. Fleer et al. (2016) calculated an amortisation time of 9 years for the same application, assuming lower BESS system costs. In both contributions the calculations are based on relatively high FCR prices from 2012 until 2015. Based on Fleer et al. (2016), Fleer et al. (2018) calculated a break-even period of 13 years, assuming lower FCR prices from 2016. Moreover, they have shown that standalone BESS will become economically unviable if the prices drop to levels much lower than those of 2016. As assumed in their analysis, this price decrease has indeed occurred in the recent years. This suggests that the revenues gained from FCR alone is currently not sufficient for a standalone BESS to be profitable.

Accordingly, extending the operations of BESS to additional applications could be a promising approach to improve the economic performance in the face of decreasing FCR prices. Stephan et al. (2016) conducted an economic analysis of different combinations of BESS applications. Their results indicate the highest net present value (NPV) for the combination of FCR and peak shaving (i.e. levelling demand peaks and thus saving demand charges). Englberger et al.

(2019) came to similar results and identified self-consumption improvement (in combination with an electricity generating unit) as another favourable application to be combined with FCR. The mentioned studies indicate that combining different applications with FCR could increase the economic outcome of BESS. Braeuer et al. (2019), Wankmüller et al. (2017) and Kloess (2012) also considered electricity arbitrage (i.e. the exploitation of price differences on the electricity markets) as an application for BESS. They analysed the German day-ahead and the intraday markets, the MISO (Midcontinent Independent System Operator) electricity market in the United States and the Austrian spot market, respectively. All three studies stated that revenues from this application are too low to justify the battery degradation resulting from cyclic ageing. However, it has to be noted that only electricity prices from 2017 or earlier were analysed.

Combining BESS with a sector integrating PtH unit could be another solution to counteract the FCR price decrease. Compared to standalone BESS, heat can be electrically generated when the BESS is fully charged. In doing so, less BESS capacities for the same FCR power are needed and initial investment costs can be reduced. Additionally, the generation of heat allows for new operational strategies and potential incomes. Melo et al. (2019) observed an increased economic profitability of such systems compared to standalone BESS operating on the FCR market. The analysed system by Melo et al. (2019) amortises within 10 years taking into account the FCR prices of 2015. In contrast, a comparable standalone BESS amortises within 14 years, according to their study. Jomaux et al. (2017) found out that revenues from FCR of a combined BESS and PtH system exceed the costs for 1 MW FCR provided, but they did not carry out an amortisation analysis. In conclusion, the studies show an improved economic viability for BESS on the FCR market, if they are coupled with a PtH unit. However, it is uncertain if such hybrid systems are profitable at recently decreasing FCR prices.

The reviewed research lines indicate to potentially higher profitability of BESS combining other applications or PtH solutions with FCR market operations. However, the results considerably vary between the studies and aggravate drawing reasonable conclusions, especially due to different data and assumptions applied. Particularly, the German FCR market regulations as well as the dynamics and FCR prices have changed considerably. Also, the electricity prices are potentially becoming more volatile (Rintamäki et al., 2017). Regarding additional BESS applications like arbitrage trading, this could challenge the literature trends which have only analysed prices from 2017 or earlier. Moreover, important regulatory cost drivers such as taxes, levies and charges (TLC) were omitted in some studies, but are crucial to be accounted for in economic analyses. Finally, the operation of a hybrid BESS and PtH system in more than one application should be considered.

Against this background, the present contribution applies a holistic view on the economic assessment of a hybrid BESS and PtH system. All relevant costs which accrue during the system's lifetime, like the national regulatory framework's TLC, are included. The market dynamics regarding the decreasing trends of the FCR prices and the changes in the market regulations are considered in this study. Furthermore, the technical layout and the model inputs are based on mostly primary or recent historical price data. They originate from an existing sector-integrating hybrid BESS and PtH system which has been installed in Germany and is investigated in the 'HyReK 2.0' research project (Stadtwerke Bremen AG, 2019). The addressed research questions are, whether the hybrid system can operate economically efficient, providing only FCR and in combination with electricity arbitrage trading, in the face of new FCR regulations and despite declining prices and including the relevant cost factors of an existing system.

The analysed applications of the 'HyReK 2.0' hybrid system in this work are the provision of FCR, arbitrage trading and the generation of heat. In order to represent close-to-reality techno-economic system behaviour, i.e. to process real frequency data and to consider the degrees of freedom of the FCR market as well as battery ageing, a Python-based simulation model of the system and its interactions with the markets was programmed.

Two different business cases of the hybrid system were analysed: The first business case considers the operation only on the FCR market, while the second business case focuses on the FCR market and electricity arbitrage trading on the 15-minute (15-min) intraday continuous market (IDC). Moreover, the influence of the recent changes in the FCR market regulations from the 30-minute (30-min) to the 15-min criterion is analysed for both cases.

2. METHODS AND MODEL FRAMEWORK

2.1. Technical Concept of the hybrid system

In the research project 'HyReK 2.0' a hybrid BESS and PtH system has been installed in Bremen in northwest Germany (Stadtwerke Bremen AG, 2019). The system consists of two components: An 18 MW lithium-ion nickel manganese cobalt BESS with a storage capacity of 14.244 megawatt-hours (MWh) that is combined with an 18 MW PtH unit. If the BESS reaches a state of charge (SoC) of 90%, a high-performance direct current switch allows electricity flows into the PtH unit without disruptions. To avoid cyclic battery ageing, SoC-levels above 90% are avoided. The BESS is additionally connected to the medium-voltage power grid via bi-directional inverters and transformers. The PtH unit is linked to a district heating system.

2.2. The frequency containment reserve market in Germany

2.2.1. Framework

FCR is the first mechanism within the European transmission system to be activated when the power grid frequency deviates from the target value of 50 Hertz (Hz). The transmission system operators (TSO) of Austria, Belgium, Switzerland, the Netherlands, France and Germany organise the procurement of their FCR capacities in a common market (ENTSO-E, 2020). Systems providing FCR are compensated for their service. They have to be prepared for discharging from and supplying to the power grid proportionally to the extent of the frequency deviation (negative and positive FCR). Accordingly, systems are subject to a prequalification process by the TSOs safeguarding their ability to supply and absorb at the specified power rate before being permitted to participate in the market.

The German market regulations of the FCR market have changed as of July 2019. Firstly, a uniform pricing model has been established. Irrespective of the amount of their individual bid, all accepted bids are now compensated with the amount of the last or "highest" accepted bid in the merit-order. Previously, every bidder was compensated with the bid they offered (pay-as-bid). Additionally, the auctions are now carried out on a daily instead of a weekly basis.

Also, prior to these market changes, BESS providing FCR were obliged to maintain the prequalified power output for 30 minutes. The recent change of this requirement to a period of 15 minutes and its effects are part of this contribution and have not been analysed in the previous literature.

The FCR market framework allows the use of the so-called 'degrees of freedom', which allow providers to deviate from proportional frequency control (Thien et al., 2017). Within the deadband, which describes the frequency range between 49.99 Hz and 50.01 Hz, systems are allowed but not required to counteract the frequency deviation ('deadband utilisation'). In addition, FCR providers are permitted to exceed their balancing performance by 20% of the prequalified FCR power ('overfulfilment'). They are also allowed to adjust the BESS SoC by selling or buying electricity on the power markets.

Two price series from the FCR market are publicly available under the previous pay-as-bid pricing scheme ([dataset] regelleistung.net, 2020). The average capacity price represents the weighted average price of all accepted bids. Second, the marginal capacity price is given, which is the price of the last accepted bid in the merit-order. Due to the introduction uniform pricing scheme, only one price series is available since July 2019. The dataset doesn't give any information on the type of technology used by the bidders.

Regarding the frequency and market data used in the present work, the calculations are based on data series from the last 12 months before the new market framework was implemented, i.e. from July 2018 until June 2019. This approach has been chosen because under the new framework no representative market data were available yet.

2.2.2. Battery energy storage systems

BESS are deployed to provide FCR in Germany among other technologies (The German TSOs, 2020). For standalone BESS, the introduction of the 15-min criterion means that less capacity for the same power output has to be kept available, as it is illustrated in Figure 1. The area between the respective curves shows the operational range of BESS. The SoC must be kept within this range to fulfil the 15-min and 30-min criteria. The SoC-limits for the 15-min criterion, represented by the dark green curves, enable the BESS operator to use a larger portion of the available storage capacity without having to adjust the SoC. The minimum BESS capacity to power ratio is 0.5 based on the 15-min criterion and 1.0 according to the 30-min criterion.

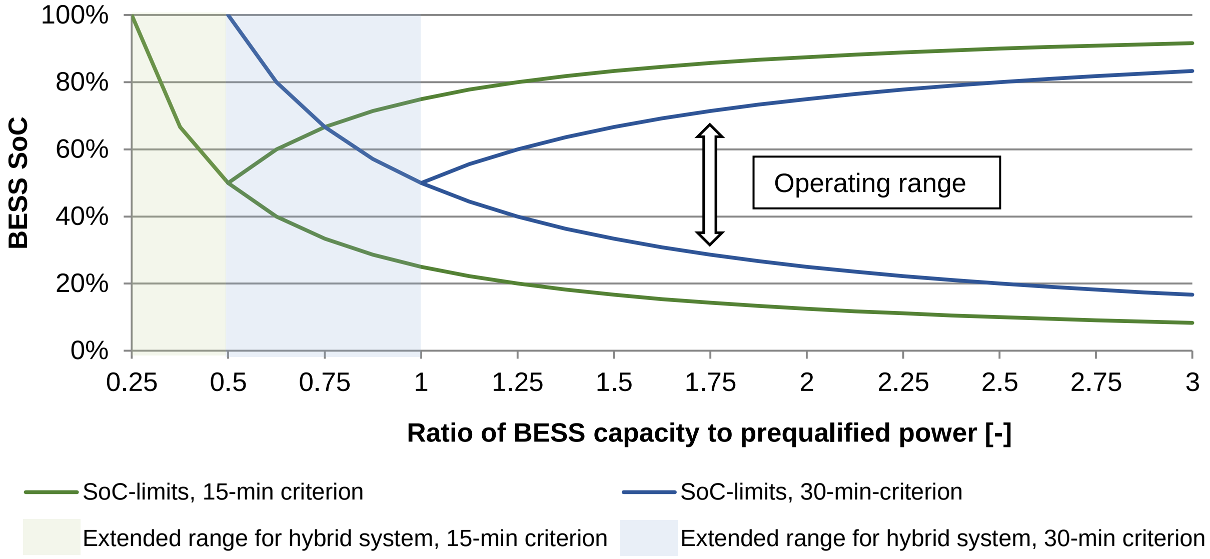

Figure 1: Operating range and SoC-limits of BESS and the hybrid system on the FCR market. The SoC-limits for the 30-min criterion are represented in dark blue and for the 15-min criterion in dark green. For the 30-min criterion, the hybrid system enables capacity to power ratios between 0.5 and 1 compared to a standalone BESS (light blue area). For the 15-min criterion, a capacity to power ratio between 0.25 und 0.5 is possible with a hybrid system (light green area). The upper SoC-limit becomes irrelevant for the hybrid system since electricity intake is unlimited. The operating range lies between the lower and the upper SoC-limits for BESS and above the lower SoC-limit for the hybrid system. [own representation based on regelleistung-online.de (2019) and The German TSOs (2015)]

2.2.3. The battery energy storage system and power-to-heat hybrid system

The prerequisites for standalone BESS on the FCR market apply only partly to the hybrid system examined in this work. Due to the possibility of converting power into heat, the system is not limited in absorbing power. Therefore, the upper SoC-limit becomes irrelevant for the hybrid system, No BESS capacity has to be reserved for negative FCR, so that more BESS capacity can be used to offer positive FCR by holding the SoC at a high level. Consequently, contrary to standalone BESS, the capacity-to-power ratio can be lower than 1.0 and 0.5 for the 30-min criterion and the 15-min criterion, respectively. The extended range of capacity-to-power ratios of a BESS with an additional PtH unit is represented by the light green and blue areas in Figure 1.

The existing plant analysed in the present work and described in subsection 2.1 has a capacity-to-power ratio of about 0.8. To fulfil the 15-min criterion and the 30-min criterion, at least 32% (4.5 MWh) and 63% (9MWh) of the total BESS capacity need to be reserved for positive FCR, respectively. Figure 2 gives a detailed insight into the mode of operation of the hybrid system. If the power grid frequency falls below 49.99 Hz, positive FCR has to be provided and power has to be supplied to the grid. This is carried out by the BESS. If the grid frequency increases to a value above 50.01 Hz, negative FCR is necessary. If in this case the BESS SoC is below 90%, the electricity drawn from the grid is supplied to the BESS. However, if the SoC is at or above 90%, electricity flows into the PtH unit and heat is generated. It has been assumed that cyclic battery ageing increases at high SoC-levels, which is the reason why the operating strategy is set to keep the SoC-level below 90%.

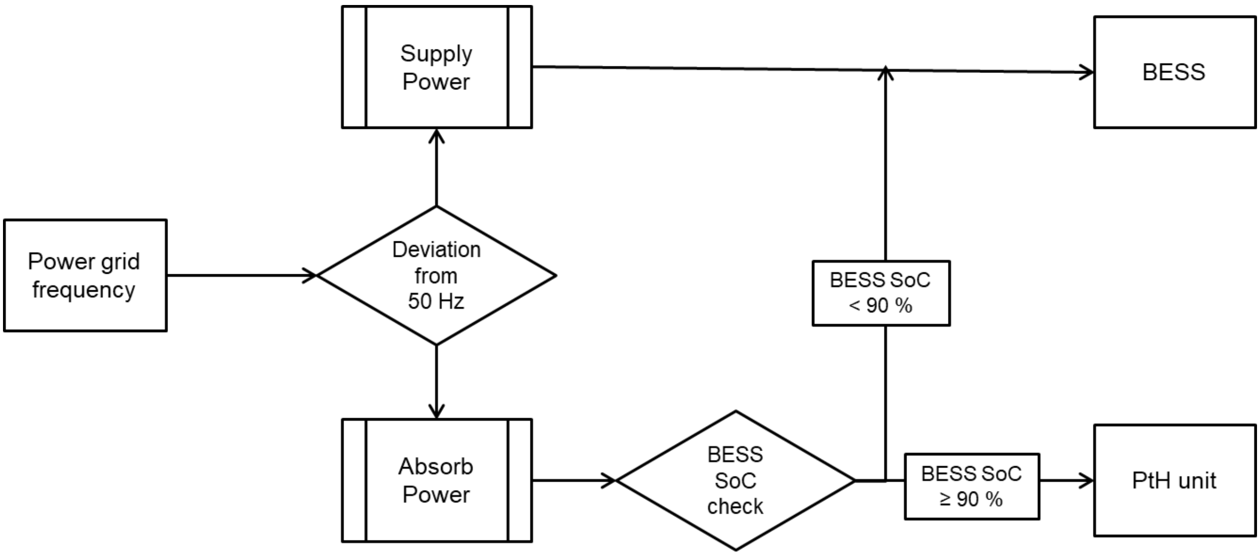

Figure 2: Basic mode of operation of the hybrid system on the FCR market. If positive FCR has to be provided, electricity is supplied from the battery to the grid. If negative FCR has to be provided, the battery is charged until a state of charge of 90%. Then heat is generated by operating the power-to-heat (PtH) unit. [own representation]

2.3. Arbitrage trading on the 15-minute intraday continuous market

The markets of the European Power Exchange (EPEX) were analysed regarding arbitrage trading opportunities for this study. The 15-min IDC is the most short-term market and is subject to strong price fluctuations compared to the day-ahead and the longer-term markets (Braeuer et al., 2019). Thus, it offers the highest revenue opportunities and was chosen for this analysis. Price formation occurs in this market according to the pay-as-bid mechanism and in 15-min time slices. Three price series are available from the 15-min IDC: a weighted average price for the last 24 hours, the last three hours (ID3) and the last hour (ID1) before each time slice ([dataset] EPEX SPOT SE, 2019). In the simulations of the present work, the ID1 price series were used. For each transaction, a 0.09 €/MWh fee applied (EEX-Group, 2019).

2.4. Taxes, levies and charges for battery energy storage systems and power-to-heat

Both the BESS and the PtH unit are legally classified as final consumers in Germany, so that both components are subject to various TLC which incur on electricity consumed. No costs incur for electricity supplied by the BESS. In order to avoid a double burden, previously stored electricity fed into the same grid is exempt from a number of charges, the electricity tax, grid fees and the renewable energy surcharge being the most important. This condition is fulfilled by the BESS, which leads to considerably lower financial burdens of 9.95 €/MWh for the BESS, while 157.78 €/MWh must be paid in TLC for electricity fed into the PtH unit. Figure 3 shows the share of each cost factor concerning BESS and PtH.

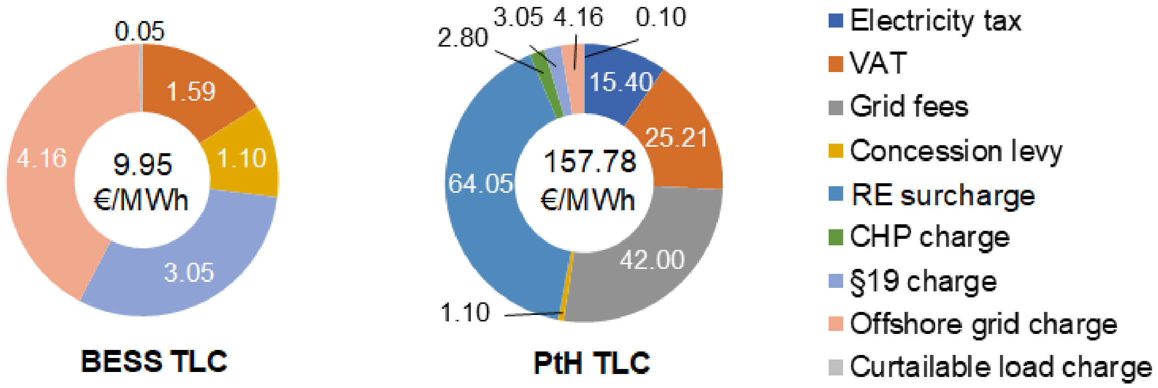

Figure 3: Comparison of variable taxes, levies and charges (TLC) for battery storage systems (BESS, left) and power-to-heat (PtH, right) in €/MWh. VAT: Value added tax, RE: Renewable energy, CHP: Combined heat and power. (Diagram is based on Worschech et al. (2019))

2.5. Python model

2.5.1. General description

The hybrid system has been modelled in Python with its current dimensions of 14.244 MWh energy capacity and 18 MW power (see subsection 2.1). It's charging and discharging processes have been simulated for one year with a time resolution of one second and including efficiency losses from the BESS and the PtH unit. Thus, the total energy throughput of the BESS was determined, which formed the basis for the battery ageing assumptions (see subsection 3.1) and necessary extensions of the BESS capacity due to capacity losses. Also, the amount of generated heat was calculated in the model. The financial outputs of the simulation consist of the revenues from heat sales and arbitrage trading and the costs during the operation (costs and fees for purchasing and selling electricity on the IDC, PtH and BESS TLC). Both the financial and technical outputs were used for the calculation of the NPV (see subsection 2.6.2).
When participating on more than one market, a strategy which determined the conditions of participating in one or the other market has to be chosen and applied in the model (see business case 2 in subsection 3.4).

2.5.2. Strategy on the frequency containment reserve market

While providing positive and negative FCR, the hybrid system's charging and discharging processes are based on real frequency data. The operational strategy has been set to use the degrees of freedom 'deadband utilisation' and 'overfulfilment' (see subsection 2.2.1) for maximum electricity charging or consumption. During underfrequencies, only the minimum requirements were fulfilled. Furthermore, energy was purchased on the IDC of the EPEX if the SoC went close to the lower SoC-limit, as described in Figure 1. In doing so, price data and transaction fees as described in subsection 2.3 were used.

2.5.3. Strategy for arbitrage trading

If arbitrage trading on the IDC was done, the prices of one year were analysed. Price differences were identified and ranked accordingly. Additionally, the model tried to pair a buying transaction with a selling transaction and vice versa in order to make earnings without any physical energy flows taking place. Then, taking into account the BESS power and capacity limits, the model executed all transaction pairs exceeding a specific, previously selected price difference. It needs to be low to gain as much revenue as possible. However, if it is too low, too many transactions are realized, resulting in high transaction fees and BESS TLC. Therefore, this price difference has to be optimised for the respective time period under consideration. The PtH unit was neglected for electricity arbitrage operations, because TLC for the PtH unit are considerably higher than the expected benefits from arbitrage trading.

2.6. Investment calculation

2.6.1. Input data

As described in subsection 2.5.1, the costs and revenues from the operational phase of the hybrid system are determined in the simulation model. In addition, the initial and operational investment and the revenues from participating on the FCR market are determined. All input data are then used in a calculation tool in order to carry out an investment calculation, using the NPV approach (subsection 2.6.2).

2.6.2. The net present value approach

Generally speaking, the NPV method is the most common method for investment calculations because it is both easy to apply and to interpret (Schuster and Rüdt von Collenberg, 2017). It is also frequently used for economic assessments of BESS (Fleer et al., 2018; Fleer et al., 2016; Stephan et al., 2016; Bühler et al., 2015). Based on its informative value and to ensure the comparability of the results with existing literature, the NPV method has been chosen as a means to conduct the economic analysis of this work.
The method considers incurring costs throughout the entire life-cycle of an object. Using the NPV method, all cash flows are discounted and their values are determined with respect to the year they incur. The data in this paper are based on the cash flows of one simulated year of operation (see subsection 2.5) which are summed up to a single value, providing a basis for investment decisions. By tracing the NPV development over the project lifetime, the break-even period, at which the NPV turns positive and the initial investment is amortised, can be determined.

$$NPV = -C_0 + \sum_{t=1}^{T} \frac{C_t}{(1+i)^t} \tag{1}$$

C_0 represents the initial investment and C_t the revenues and operational costs occurring in year t. i describes the discount rate, t the year in which the cash flow occurrs and T the lifetime of the object in years.

2.6.3. Sensitivity analyses

Assumptions based on secondary data are subject to uncertainties that have to be taken into account. To understand the influence of the most important assumed parameters used in the model, they were included in the sensitivity analysis. Additionally, according to the results in subsection 4.2, PtH TLC are a major cost factor in the analysed business cases. Therefore, in the sensitivity analysis, PtH TLC were also looked at.

A one-at-a-time sensitivity analysis was applied, varying one of the chosen parameters by ± 50% while all other parameters were kept the same. The sensitivity of each parameter was determined comparing the original results with the results of the varied parameters.

The prices on the FCR German have been decreasing constantly in the past years (Kern and von Roon, 2019). The prices assumed in this work are considerably lower that the prices assumed in similar existing studies which makes a comparison of the results difficult. Therefore, in addition to the one-at-a-time sensitivity analysis, another sensitivity analysis looking at the FCR prices was carried out. The FCR prices assumed in three existing studies of standalone BESS on the FCR market were transferred to the present study. An economic analysis with these prices was carried out for the hybrid system (see subsection 4.3.2). In doing so, a comparison between standalone BESS analysed in literature and the hybrid system analysed in the present study can be done more accurately.

3. CASE STUDY

3.1. Ageing of the battery energy storage system

The lifetime of the BESS was assumed with ten years or 6,000 cycles at 100% depth of discharge (DOD) until a residual SoC of 80% is reached. This is a typical approach applied according to an expert ('HyReK 2.0' Research Project, 2020). In case ten years or 6,000 cycles are exceeded, it has been assumed that the BESS is extended with new cells in order to restore the capacity to the initial 100%. The corresponding costs are recorded in the respective year in the investment calculation.

Fleer et al. (2016) stated that a BESS performs a full cycle equivalent of 7,528 cycles within 15 years on the FCR market for a standalone BESS of a capacity-to-power ratio of 1.0. Prior simulations have shown even less cycles for the BESS in combination with the PtH unit. Thus, if the hybrid system only provides FCR as in business case 1 (see subsection 3.3), calendric ageing was assumed to be more prevalent than cyclic ageing and the BESS cell extension was due once after ten years of operation('HyReK 2.0' Research Project, 2020). For the second business case in which both FCR and arbitrage trading is done (see subsection 3.4), the analyses have shown that the end-of-life criterion of 6,000 cycles is reached after eight years of operation. Therefore, BESS cells are purchased once to recondition the BESS to its full capacity for the 15-year period under consideration.

Capacity losses during the lifetime of the BESS are not represented in the simulation model. Firstly, the ageing behaviour of BESS kept at high SoC-levels have to be analysed. This will be realised within the research project 'HyReK 2.0', but results have to be awaited. However, only 84% of the full BESS capacity is used at most, according to simulations conducted. Since the cyclic and calendric lifetime assumptions refer to 100% DOD usage, the ageing considerations of this work are based on rather conservative figures. Accordingly, it can be assumed that the effects of capacity losses are negligible and were therefore not included.

3.2. Basic model assumptions

Table 1 summarises the assumptions on which the calculations in this work are based on.

Table 1: Basic assumptions for the economic analysis

Parameter	Value	References
Initial investment*	10.5 million €	Primary data ****
Overhead costs	110,000 €/year	Primary data ****
Specific BESS cell extension costs	350 €/kWh	Expert interviews 'HyReK 2.0'
Heat revenues	10 €/MWh	Expert interviews 'HyReK 2.0'
System lifetime except BESS cells	15 years	Primary data ****
Yearly maintenance downtime	2 weeks	Primary data ****
Discount rate	5%	(Melo et al., 2019) (Thorbergsson et al., 2013)
BESS round-trip efficiency **	84.95%	Primary data ****
PtH operation efficiency	96.05%	Primary data ****
BESS calendric lifetime***	10 years	Expert interviews 'HyReK 2.0'

BESS cyclic lifetime***	6,000 cycles	Expert interviews 'HyReK 2.0'
Considered period for frequency and price data (FCR and IDC)	July 2018 – June 2019	-
Notes: * The initial investment includes BESS containers and cells, inverters, transformers, PtH unit, district heating connection, communication and control system as well as groundworks and planning. ** Including battery cells, inverter and transformer efficiencies *** The end-of-life criterion is less than 80% residual capacity at 100% DoD **** Primary data from the research project 'HyReK 2.0'.		

3.3. Business case 1

In the first business case the operation of the hybrid system on the FCR market from July 2018 until June 2019 was considered. The operating strategy described in subsection 2.5.2 was applied. It was assumed that the operators were compensated with the average capacity price, representing an average bidding behaviour (Fleer et al., 2016). In order to examine the effects of the new market framework based on the 15-min criterion (see subsection 2.2.1), a comparison between the 15-min criterion and the former 30-min criterion has been conducted.

3.4. Business case 2

In order to determine a strategy for business case two, a fixed bidding price for the FCR market was selected throughout the entire year. For an average bidding strategy, the average of the 52 marginal capacity prices of the considered period (2,114 €/MW*week) was calculated. It has been assumed bidding this price in every week. If the bid was accepted, revenues from FCR flowed in this week and the operating strategy described in subsection 2.5.2 was applied. If the bid was rejected, electricity arbitrage trades were done on the IDC as described in subsection 2.5.3. A market analysis of the IDC in the period considered prices has shown that a minimum arbitrage price difference of 23 €/MWh renders the highest annual profits for the time period considered. As in business case 1, this business case was analysed for both the 15-min criterion and the 30-min criterion.

4. RESULTS

The results of the simulation model are presented and the NPV development of the two considered business cases over the system's lifetime is illustrated in the following subsections. Furthermore, the lifetime cost elements are analysed and their shares of the total costs are shown. In a last step, several parameters are investigated in a sensitivity analysis.

4.1. Net present value analysis

Figure 4 shows the development of the NPV of the first considered business case over the time period of 15 years. For the 15-min criterion as well as for the 30-min criterion, the business case breaks even after 12 years, reaching a NPV of about 2.4 and 2 million € in year 15, respectively. For both scenarios, the NPV increases steadily. One exception can be recognized of year 10, in which additional costs for new BESS cells to restore the initial BESS capacity incur due to calendric ageing.
As demonstrated in Figure 5, the NPV of business case 2 does not turn positive, neither for the 15-min criterion nor for the 30-min criterion. Except for year 8, in which BESS cells have to be purchased due to cyclic ageing, the NPV improves continuously. However, this business case does not break even within the 15 year lifetime and therefore represents an unfavourable investment decision. With the bidding strategy applied (see subsection 3.4), the bids offered on the FCR market are accepted in 26 weeks of the year, mainly from August 2018 until January 2019. Accordingly, arbitrage trades are executed during the rest of the year in July 2018 and from February until June 2019.
In comparison to single market operations on the FCR market, the economic outcome of the hybrid system deteriorated when adding arbitrage trading as a second application. According to the results presented, the FCR market is the most favourable market for the hybrid system.
Possible reasons explaining the different outcomes for the 15-min criterion and the 30-min criterion will be specified in the next subsection, where the cash flow structure of both business cases are analysed.

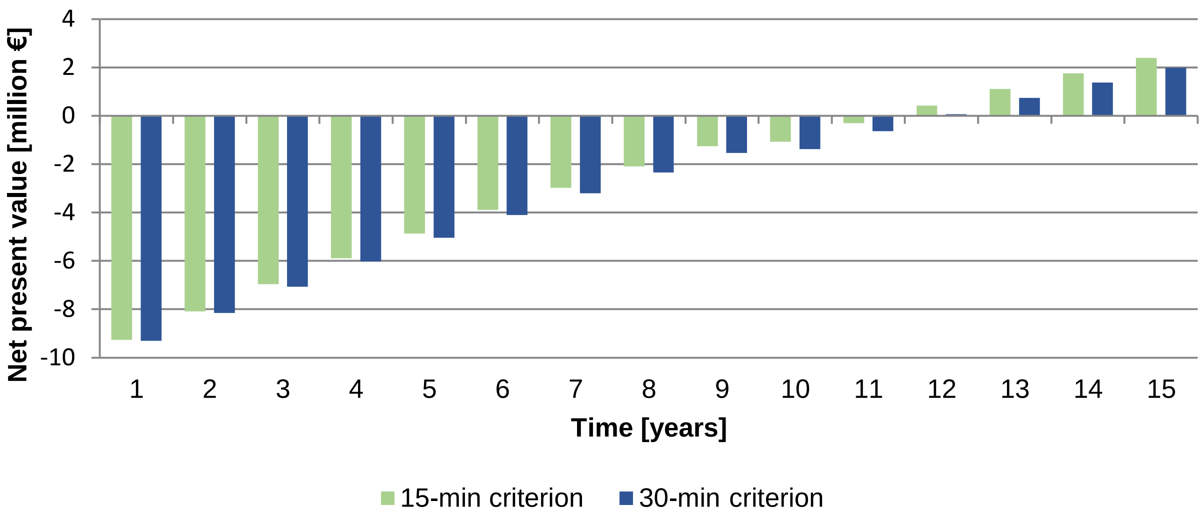

Figure 4: Net present value development of business case 1 (FCR) for the 15-min criterion and the 30-min criterion assuming a 5% discount rate [Diagram is based on own calculations]

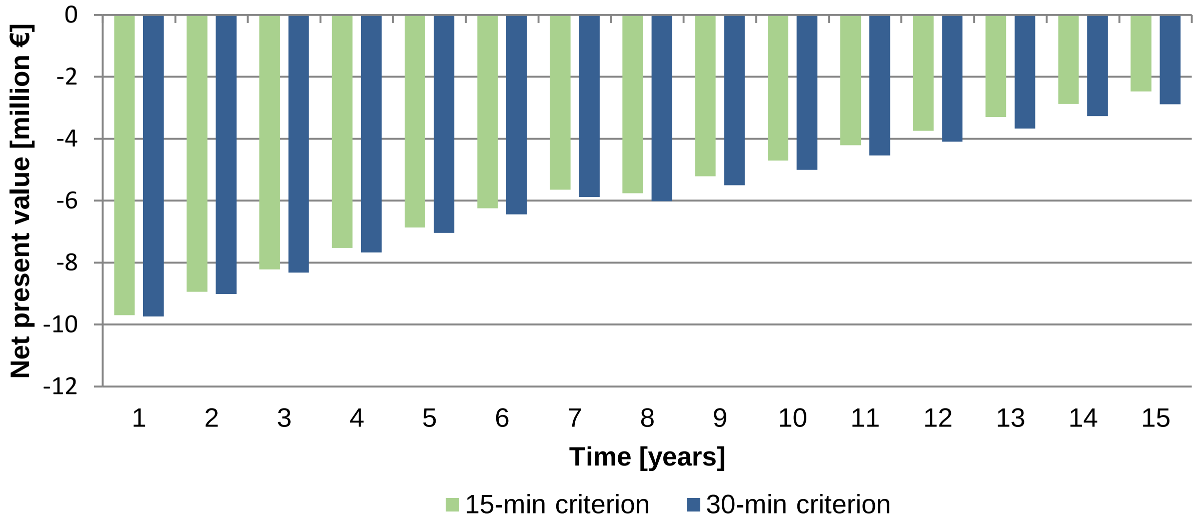

Figure 5: Net present value development of business case 2 (FCR and arbitrage trading) for the 15-min criterion and the 30-min criterion, assuming a 5% discount rate [Diagram is based on own calculations]

4.2. Cash flow structure analysis

Figure 6 illustrates the cash flow structures of both business cases considered for the 15-min criterion and the 30-min criterion.

In business case 1 1.1 GWh and 1.3 GWh heat are generated every year for the 15-min criterion and the 30-min criterion, respectively. For the 30-min criterion, the operational range of the BESS is smaller than for the 15-min criterion. This circumstance results in generally higher SoC-levels of the BESS and therefore higher amounts of electricity converted into heat. The difference of heat generated is visible in the lifetime cost structure, since the share of PtH TLC is higher for the 30-min criterion. Apart from the PtH TLC, all cost factors contribute equally to the cost structure.

Regarding both regulation approaches, the revenues for heat are negligible in comparison to the revenues gained from operating on the FCR market, which amount to roughly 1.7 million € each year.

In business case 2, the revenues from trading are considerably lower than the revenues from FCR (0.2 million € vs. 1.0 million € annually), although the temporal distribution was half and half for the two markets. Since less heat is generated in total (roughly 0.5 GWh and 0.7 GWh for the 15-min criterion and the 30-min criterion, respectively), PtH TLC account for a lower share in the cost structure in business case 2 than in business case 1. Similar to business case 1, the higher total amount of PtH TLC for the 30-min criterion is noticeable in the cost structure due to the smaller operating range of the BESS. The BESS TLC represent the lowest cost factor, whereas roughly half of the total costs can be attributed to the overhead costs and the PtH TLC.

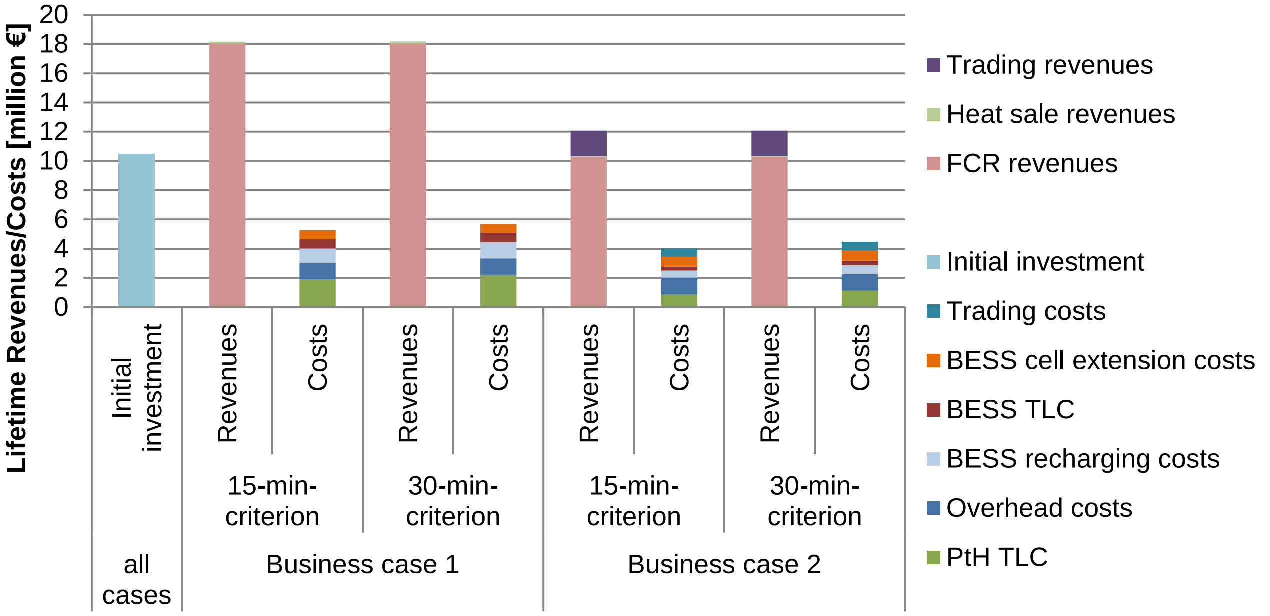

Figure 6: Discounted aggregated lifetime cash flow structure of the two considered business cases, both for the 15-min criterion and the 30-min criterion. [Diagram is based on own calculations]

4.3. Sensitivity analyses

4.3.1. One-at-a-time analysis

A sensitivity analysis has been conducted for the most important parameters assumed for which no primary data were available (cycle stability, BESS cell extension costs and discount rate). Due to their relevance in the total costs (see subsection 4.2), the effect of PtH TLC changes on the NPV results from subsection 4.1 were also investigated. The parameters were varied each by ± 50% and the results were compared to the original results of both business cases for the 15-min criterion in Figure 4 and Figure 5.

Only the results of the 15-min criterion of the two business cases were looked at in the sensitivity analysis. Since the results of the 15-min criterion and the 30-min criterion are similar in both business cases, it was assumed that they would show similar results in the sensitivity analysis as well. For better clearness and comprehensibility, it was therefore decided to exclude the business cases for the 30-min criterion. The results are shown in Figure **7**.

The most sensitive parameter in both business cases is the discount rate. A lower discount rate leads to NPV improvements of about 2.5 million € and 1.5 million € in business case 1 and 2, respectively. The analysis of PtH TLC shows considerable effects on the NPV in business case 1 regarding the relatively small amount of generated heat. In business case 2, these effects are less perceptible since less heat is generated. Due to the fact that in both cases BESS cells have to be purchased once after commissioning, the effect of BESS cell cost variations is similar in both business cases. They could potentially contribute to a more economically viable operation of the system. The cell costs for the BESS extension have minor effects for both cases.

Regarding the parameters analysed, it can be concluded that no scenario in the sensitivity analysis would lead to the economic success of the strategy pursued in business case 2 and only an increase of the assumed discount rate could endanger the profitability of business case 1.

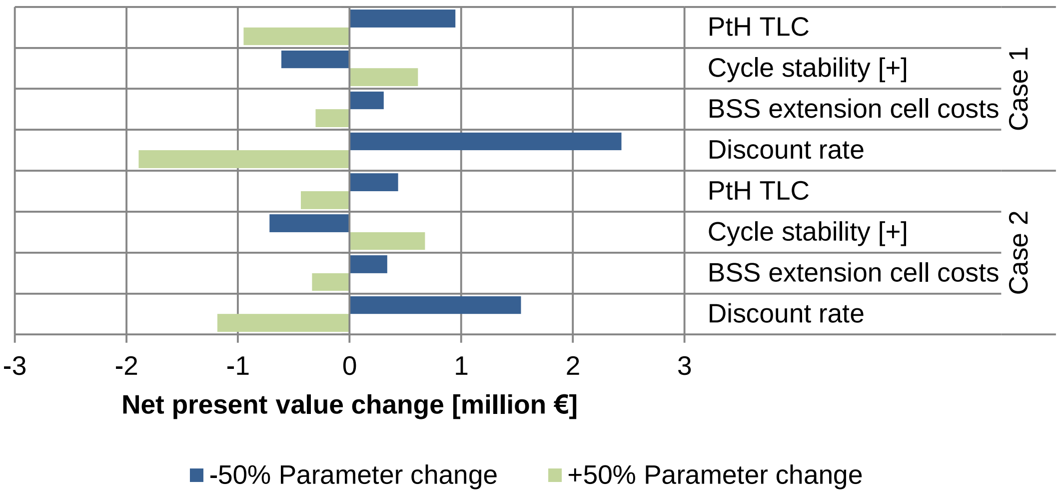

Figure 7: Results of the sensitivity analysis for the business case 1 and 2 for the 15-min criterion. ‚Cycle stability' is the only parameter which improves the NPV when its value is increased and is labelled accordingly with [+]. [Diagram is based on own calculations]

4.3.2. Price analysis of the frequency containment reserve market and comparison with battery energy storage systems

FCR prices have been declining constantly in the recent months and years. The results of the present work are based on FCR prices from July 2018 until June 2019. Since calculations in the existing literature rely on former, higher prices, the results cannot be compared and the benefits of a hybrid system in contrast to a standalone BESS do not become apparent. In order to overcome this constraint, business case 1 was recalculated with FCR prices from three other studies in which BESS on the FCR market were analysed: Fleer et al. (2018), Fleer et al. (2016) and Bühler et al. (2015).

Business case 2 has been omitted from this analysis because studies of combined market operation as in this work are rare in existing literature and difficult to compare due to differing operating strategies. Moreover, subsection 4.1 has already shown that the economic results of business case 1 (FCR only) are considerably more favourable than those of business case 2 (FCR and arbitrage trading) under current market conditions and that arbitrage trading does not contribute to more financially attractive outcomes. For these reasons, the FCR price analysis has been limited to business case 1.

Table 2 gives an overview of the outcomes, if FCR prices from the mentioned studies were transferred to business case 1 of the hybrid system in the present work (line 1). Moreover, the original break-even periods from the BESS of the compared studies are shown in line 2. In order to demonstrate the economic benefits from a hybrid system in comparison to a standalone BESS, line 3 shows the difference of payback period of the hybrid system and the standalone BESS for the varying price assumptions.

The results show that the payback period improves considerably when adopting higher FCR prices and demonstrates that the profitability of the hybrid system is highly dependent on the FCR price development. From the comparison of the hybrid system and the standalone BESS, it can be concluded that the hybrid system operates more economically efficient than standalone BESS. The break-even periods are shortened by five, seven and four years, respectively. These results are in line with a study by Melo et al. (2019), in which a hybrid BESS and PtH system was compared to a standalone BESS for FCR operations. In the study, the calculated payback-period could be reduced by four years with a hybrid system.

Although there is a clear tendency with regard to the results of the comparison between the hybrid system and standalone BESS, it has to be mentioned that not only FCR prices differed between the present work and the compared studies. There are further methodological differences and assumptions which might have effects on these findings. For example, in the mentioned studies the NPV results are based on smaller system sizes and were scaled up for the comparison which might not respect economies of scale. Also, initial investment assumptions were based on higher numbers than in the present work.

Table 2: The effects of a frequency containment reserve (FCR) price sensitivity analysis on the payback period of a hybrid battery energy storage system (BESS) and a power-to-heat (PtH) system compared to standalone BESS in the face of the decreasing FCR price trend. [based on own calculations]

Data and assumptions applied for FCR prices				
Reference	Study at hand	Fleer et al. (2018)	Bühler et al. (2015)	Fleer et al. (2016)
Year of FCR prices	2018/2019	2016	2012-2014	2015
FCR prices [€/MW*week]	1,931	2,451	2,956	3,646
Payback time calculated				
1 Hybrid system (BESS and PtH) [years]	12	8	6	5
2 Standalone BESS [years]	N/A	13	13	9
3 Improvement of hybrid systems compared to standalone BESS [years]	N/A	+5	+7	+4

N/A: not applicable

5. DISCUSSION

This study investigates two business cases of a hybrid system consisting of a stationary BESS and a PtH unit. The results show that the operation only on the FCR market is profitable while strategies including arbitrage trading on the IDC do not allow any economic operation of the hybrid system. The present study indicates that hybrid systems operate more economically efficient than standalone BESS analysed in existing literature.

5.1. Comparison with the state of research

There are only few studies which examined the economics of hybrid systems on the FCR market. Melo et al. (2019) have found that the economics of a BESS on the FCR market are improved when adding a PtH unit, allowing the same power rates to be offered with a lower BESS capacity. This has been confirmed in this contribution with more recent FCR prices and primary economic and technical input data. In doing so, existing literature of BESS operating on the FCR market was compared with the results of this contribution: Fleer et al. (2018), Fleer et al. (2016) and Bühler et al. (2015) investigated the operation of standalone BESS providing FCR in Germany. According to their research, it takes between 9 and 13 years until the initial investment is amortised. In comparison to the present study in which FCR prices from 2018/2019 (1,931 €/MW*week) were assumed, their calculations are based on higher FCR prices (between 2,451 and 3,646 €/MW*week from 2012-2016). By transferring their price assumptions into the present work and comparing the results, it has been shown that the hybrid system performs more economically efficient than the standalone BESS. The recent change of FCR market regulations did only show a negligible effect on the economic operation of the hybrid system.

The study by Jomaux et al. (2017) has concluded that the economic potential for hybrid BESS and PtH systems on the FCR market is promising. Their assumptions were based on higher heat revenues and no TLC were taken into account. However, according to the results of this work, TLC are a decisive factor in the profitability of the system. Since Jomaux et al. (2017) did not carry out an investment analysis, their results cannot be compared to the results of the present paper.

With regards to the second business case combining the operation on the FCR market and electricity arbitrage, Braeuer et al. (2019), Wankmüller et al. (2017) and Kloess (2012) have suggested that the small potential revenues from arbitrage trading on continuous electricity markets cannot make up for the resultant BESS degradation. Although cyclic BESS ageing did not prove to be highly decisive for the systems' profitability in this work, the business case including arbitrage trading is indeed unprofitable.

5.2. Critical reflection of the assumptions and model inputs

With regard to the FCR and IDC market data used in the simulations of both business cases, perfect price foresight was assumed for the time period considered. Since FCR revenues in business case 1 were based on the average capacity price instead of the higher marginal capacity price, this assumption is acceptably close to realistic revenues from FCR. With regards to the arbitrage trading simulations in business case 2, the proceeds on the IDM market are potentially lower in reality due to imperfect price foresight. On the other hand, the calculations are based on average IDM prices. Order book buying and selling prices are likely to be more volatile, possibly offering higher arbitrage potential.

Regarding business case 2, the average of the marginal capacity prices of the FCR market from July 2018 until June 2019 was determined and bidding this price in every week of the simulated year was assumed (see subsection 2.5.3). When the bids were rejected, arbitrage trades were realized if a fixed difference between the selling and buying price was exceeded. This price difference has been determined beforehand and was applied for the whole year in the simulations. Different market strategies should be investigated regarding FCR bidding and arbitrage trading strategies in order to identify the most promising economic outcome.

For FCR operations, the chosen operating strategy included using the FCR degrees of freedom for maximum energy intake. For further economic optimisation, different target SoCs which are to be reached by the strategy could be analysed (e.g. by using the degrees of freedom or by buying and selling electricity on the IDC).
Our assessment is based on the results of a Python-based simulation model. In doing so, the performance of the BESS under circumstances based on German frequency data from July 2018 until June 2019 provided detailed and realistic BESS charging and discharging behaviour and rendered reliable outcomes for the techno-economic evaluation of the hybrid system. Furthermore, in contrast to many other studies dealing with similar topics, the economic dataset worked with is widely based on primary data provided from a real project, in which a hybrid BESS and PtH system has been installed. Therefore, the majority of the model parameters are based on highly detailed and accurate primary data.
Addressing the issue of uncertainties regarding secondary data, a one-at-a-time sensitivity analysis for the most important assumed parameters was performed. The contribution of each parameter is determined and the most sensitive parameters were tracked down. The results show that the discount rate had a high impact in both cases and should be monitored critically in future NPV calculations. It also shows that technical improvements regarding the cycle stability of the BESS cells could contribute to more profitable operations.

5.3. Relevance of demand response measures and electricity pricing strategies

Standalone BESS have been prequalified increasingly for the German FCR market and are likely to reduce carbon emissions caused by FCR provision (The German TSOs, 2020; Stenzel et al., 2019; Koj et al., 2015). In addition, the hybrid system analysed in this paper enables sector integration by converting negative FCR into heat. This additionally contributes to the decarbonisation of the heat sector, which still relies heavily on fossil fuels (German Federal Ministry for Economic Affairs and Energy, 2020). With an increasing input of electricity from renewable energy sources, frequency deviations are expected to increase, which will create higher potentials for technologies like hybrid systems and sector integrating solutions on balancing markets (Schäfer et al., 2018).
In combination with heat generated from balancing measures, demand response measures could further contribute to the decarbonisation of the heat sector. By shifting heat demand to times of overfrequencies in the power grid, less heat would have to be generated through fossil energy carriers like gas or coal.
Instead of a PtH unit, a standalone BESS can also be combined with other types of generators, for example an electrolyser or a cooling unit. In these cases, hydrogen or cooling energy could be produced and used for different applications (e.g. mobility, refrigerated storage), which could open more business cases for hybrid systems and reduce the use of fossil energy carriers.
However, electricity pricing regulations in Germany for the conversion of power into products like heat, hydrogen or cooling energy are impeding the dissemination of such innovative technologies (Thomas, 2017). Within the sensitivity analysis of this work, the effects of PtH TLC under current German regulatory frameworks have been looked at. It shows that PtH TLC have a major effect on the outcome of business case 1 (one million € NPV change for 50% more/less PtH TLC), especially considering the relatively low amount of heat generated (1.1 GWh per year). If hybrid systems are to push the energy transition and the electrification of the heat sectors, they will be required to generate substantially higher amounts of heat. However, their profitable operations are endangered at current PtH TLC levels. The reconsideration of these financial burdens is therefore strongly suggested. The grid fees as part of the electricity price could for instance be lowered if the grid is overstressed which would encourage efforts in favour of sector integration. In the specific case of the hybrid system considered in this work, the current TLC rate of 158 €/MWh for the conversion of PtH is much higher than the revenues of 10 €/MWh from selling heat. This pushes the operators towards using operation strategies avoiding the use of the PtH unit and thereby preventing sector integration efforts.

5.4. Further research

In order to improve the simulation results, reliable data on the cyclic and calendric ageing of BESS cells would be beneficial. Such data are generated in the course of the research project ‘HyReK 2.0’. Focal points are BESS cycling tests considering the ageing behaviour regarding the specific application of a BESS in combination with a PtH unit and under various operational strategies, e.g. assuming operations with high average SoCs. Once data are available in this regard, capacity losses during the lifetime can be simulated for instance, yielding better inputs for the economic assessments. Although the results of this work as well as other studies (Braeuer et al., 2019; Wankmüller et al., 2017; Kloess, 2012) indicate that arbitrage trading on spot markets is unprofitable, more volatile prices as well as technical and economic progress regarding the BESS cells could influence these outcomes (Rintamäki et al., 2017). Further investigations and observations are also necessary concerning the development of the FCR prices which are of crucial importance for the economic operation of the system. They fell drastically in the past years in general and by 30% from 2018 to 2019. Furthermore, the recent switch to uniform pricing, smaller time slices and the 15-min criterion as well as the lack of information regarding market participants and the technologies used complicates predicting future market developments. As shown by Englberger et al. (2019) and Stephan et al. (2016) for standalone BESS, combining several applications could also be a promising field of research for hybrid BESS.

6. CONCLUSIONS AND POLICY IMPLICATIONS

The market share of standalone BESS on the FCR market has been increasing in the past years (The German TSOs, 2020; Stenzel et al., 2019; Fleer et al., 2016). However, the recent downward trend in the FCR prices is challenging the financially profitable operation of standalone BESS.

This paper gives insights into the economics of a hybrid system consisting of a BESS and a PtH unit allowing the provision of the same power rate without a lower BESS capacity and therefore potentially improving the economics in comparison to a standalone BESS. Two business cases of the hybrid system using the NPV approach were investigated: In the first business case, only FCR market operations were simulated. In the second business case, both arbitrage trades on the IDC as well as bidding on the FCR market were investigated. Both cases were simulated for the 15-min criterion as well as the 30-min criterion reflecting recent changes in the market regulations. Furthermore, this study exhibits the impact of four input parameters (PtH TLC, BESS cycle stability, BESS extension cell costs, discount rate) in a sensitivity analysis. Considering current market prices and conditions, the results show that the hybrid system amortises within 12 years in the first business case, performing more economically efficient than standalone BESS. In the second business case, no amortisation is achieved within the lifetime due to low proceeds during the arbitrage trading phases. The discount rate and the TLC for the operation of the PtH unit show the highest impact according to the analysis carried out, whereas economic and technological progress of BESS can have a moderate impact on the financial outcome.

In the course of the German project 'HyReK 2.0', in which a hybrid BESS and PtH system has been installed, further primary data for more realistic input parameters of the economic assessment will be generated and insights for the application of superior operational strategies will be gained. Considering the recent price developments, changes in the German FCR market conditions have to be taken into account for future studies. Also, technological and economic progress as well as price developments of BESS cells could potentially improve the economics of the system and have to be tracked. First and foremost, however, it has to be noted that the regulatory framework for sector integrating technologies is rather unfavourable, inhibiting the diffusion of innovative approaches like the one presented in this contribution. If they ought to make the power system more flexible and decarbonise not only the power sector, but also the mobility and heat sectors, politically established financial burdens should be re-evaluated and adjusted accordingly.

ACKNOLEDGEMENTS

This work has been funded by the German Federal Ministry for Economic Affairs and Energy (BMWi) under the grant no. 03ET6147C and is part of the project 'HyReK 2.0 – Hybrid Regulating Power Station'.

DECLARATION OF COMPETING INTERESTS

There are no competing interests to be declared regarding this work.

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