Integration of Vanadium Redox Flow Batteries in grid-connected Microgrids

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Abstract -- **Microgrids facilitate the integration of intermittent renewables. They rely on energy management systems to schedule optimally their distributed resources. The incorporation of energy storage assures a reliable and stable electricity supply and enlarges the business opportunities. Vanadium redox flow batteries are among the suitable technologies. This thesis establishes an operation optimization model for a grid-connected microgrid that integrates battery specific characteristics of vanadium redox flow technology as depth of discharge, state of charge dependent power limitations and dynamic efficiencies. To test a hybrid operation, it also defines the model for the more established lithium-ion technology and includes typical features such as degradation. The microgrid energy management is formulated as a non-linear optimization problem. It applies model predictive control to determine the optimal charging cycles and grid power exchange that will achieve the maximum net profit. A case study with real techno-economic input data from the German Island Pellworm has been simulated. The scheduling results for different market applications revealed that the highest revenues from battery operation can be obtained by primary frequency regulation. The second-best option are stacked applications, which combine arbitrage with secondary frequency regulation or grid supportive peak-shaving. A hybridization of vanadium flow with lithium-ion batteries is proposed, since it allows to fulfill market entry barriers in a cost-effective way and can reduce total power losses and degradation.**

Keywords -- Microgrid operation, Vanadium Redox Flow Battery, Energy Management System, Model Predictive Control, Scheduling approach

INTRODUCTION

During the past decades the electricity system has been undergoing major changes: The growth of intermittent renewable energy and distributed energy resources has changed the needs of the electricity system, which now requires more flexibility and a smarter coordination. As an answer to the paradigm change from a centralized and "blind" electricity system to a more decentralized and smarter one, concepts like "Microgrids" (MG) or "energy community" have evolved. They can be understood as clusters of Distributed Energy Resources (DERs) and loads coordinated by an intelligent Energy Management System (EMS) and can operate either islanded or in grid-connected mode [1]. They share features like the ability to integrate demand response, generation of DERs and storage at the distribution level and thus provide a solution to facilitate the expansion of renewables. However, the fluctuating nature of power from renewable energy systems (RES) still involves challenges and in all MGs, there is a need to develop appropriate flexibility options and optimal scheduling to guarantee a reliable microgrid operation.

Consequently, Energy Storage Systems (ESS) are considered critical components for microgrids, assuring a reliable, stable and secure electricity supply and enlarging the potential business opportunities. Tan et al. [2] call for development of proper models and tools which address key integration issues such as optimal sizing, placement and techno-economic operating schemes.

Today, several technologies of ESS have been commercialized, possessing different characteristics concerning power or energy densities, performance, safety, cost and sustainability. The authors Leadbetter and Swan [3] compare storage properties versus application specific requirements. Their research suggests that Vanadium Redox Flow Battery (VRFB) is a promising energy storage system for a wide range of applications including energy as well as power applications. Yet, since commercialization is still young, the literature on VRB-based microgrids is limited. Vanadium flow batteries have unique characteristics compared to other battery types such as a much longer lifetime, non-toxic materials, a flexible energy to power ratio but also a higher control complexity due to active elements like electrolyte pumps. In terms of storage system integration, there is increasing research interest discussing optimal unit sizing [4], [5] or optimal placement within the MG [6]. Another facet deals with how to precisely describe the operation characteristics and determine the optimal operation strategy of the ESS in the MG. The scheduling or unit commitment is a function of the microgrid energy management system (MG-EMS). The MG-EMS tries to dispatch its flexible resources including ESS under a predefined goal, such as minimizing operation costs.

Although research papers propose different energy management systems and strategies [7], few of them study flow batteries or take into account the specific characteristics of VRFB. Accordingly, there is the need to consider storage technology- and application-specific constraints in the control and management strategies. This will allow microgrid operators and investors to estimate the actual economic value of their asset. This thesis seeks to advance the knowledge on the operation of ESS in particular vanadium flow batteries and how to dispatch them economically within microgrids.

BACKGROUND

A. Microgrid concept

A conventional power grid is based on a centralized structure with a few large generation units providing the necessary power, which must be transmitted to loads often located far away from the generation centers. This kind of structure does not allow enough control at lower grid levels and impedes the integration of intermittent RES. To tackle these problems microgrids with smaller generation units distributed at lower grid levels, have gained popularity.

According to the U.S Department of Energy a Microgrid is a “group of interconnected loads and distributed energy resources (DERs) with clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid and can connect and disconnect from the grid” [8].

MGs have been known for decades. Commonly they have been implemented in critical infrastructure such as military bases, hospitals, and data centers, but with the ongoing energy transition and more distributed RES microgrids show advantages over conventional grid structures. As reported by Navigant Research the microgrid market has been growing lately: It passed 4 GW installed capacity and is expected to have tripled the number by 2025 [9].

B. Vanadium redox flow battery

Although flow batteries comprise similar elements as most batteries, they differ from conventional batteries as the reaction occurs between two electrolytes, the anolyte and the catholyte, rather than between an electrolyte and an electrode. The working principle is based on redox reactions: Negative and positive vanadium electrolytes are stored in individual tanks and are circulated with pumps through the power stacks where they are oxidized/reduced (cf. Fig. 1).

The negative half-cell employs V^{2+}/V^{3+} redox couple whereas the positive half-cell is filled with V^{4+}/V^{5+}. During the discharge cycle, V^{2+} is oxidized to V^{3+} in the negative half-cell and an electron is released to the external circuit. The positive half-cell accepts an electron and V^{5+} in the form of VO_2^+ is reduced to V^{4+} in the form of VO^{2+}(Eq. (1)-(4)). The ion-exchange is enabled with the Proton-Exchange Membrane (PEM), which selectively allows H^+ to pass through. The VRFB is a preferred

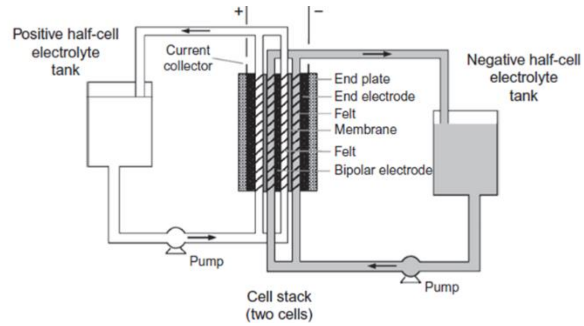


Fig. 1. Schematic structure of a redox flow battery [13].

type of RFB due to its simplicity related to the usage of the same electrolyte in both half cells, avoiding irreversible degradation due to cross contamination.

During charging:

$$(-) \qquad V^{3+}_{(aq)} + e^- \rightarrow V^{2+}_{(aq)} \qquad (1)$$

$$(+) \qquad VO^+_{2(aq)} + H_2O \rightarrow \mathrm{VO}^{2+}_{(aq)} + 2H^+_{(aq)} + e^- \qquad (2)$$

During discharge:

$$(-) \qquad V^{2+}_{(aq)} \rightarrow V^{3+}_{(aq)} + e^- \qquad (3)$$

$$(+) \qquad VO^{2+}_{(aq)} + 2H^+_{(aq)} + e^- \rightarrow VO_{2}{}^+_{(aq)} + H_2O \qquad (4)$$

In contrast to conventional batteries, for VRFB the energy capacity is independent of its power rating, allowing greater flexibility. The stack size determines the power rating (kW) and the amount of electrolyte defines the energy (kWh).

The storage of the active materials in separate tanks makes the battery also safer than conventional batteries. VRFB have a low risk of explosion, the circulating electrolytes facilitate better thermal management and they can be cycled from any state of charge without permanent damage. The long cyclability is a major advantage. More than 20000 charge and discharge cycles have been demonstrated [10].

An existing challenge which limits practical applications to stationary applications is the low specific energy density of 25-30 Wh/kg. Although cost is expected to decrease significantly, the initial battery investment costs per power (~540 €/kW) are still higher than for other battery technologies like lead-acid or lithium-ion based batteries. The initial costs per energy of VRFB

	Generation: Fossil	Generation: RET	Transmission & Distribution	End-consumer
Power Quality		RET Smoothing	Frequency & Voltage Regulation	Endconsumer PQ
Power Reliability	Black Start		Reserve Capacity	Emergency Power
Increased Utilization of Existing Assets	Load Following	RET Firming	T&D Investment Deferral	Increase of Self-Consumption
Arbitrage		RET Arbitrage	Wholesale Arbitrage	Arbitrage with flexible grid tariffs, load shifting

RET Integration: Directly / Indirectly

Fig. 2. Relevant applications for ESS in Microgrids [16].

(~460 €/kWh) can compete with lithium [11].

C. Integration of ESS in Microgrids

Literature suggests various use cases for ESS in microgrids. Here, the classification scheme proposed by Battke and Schmidt [12] is adopted (cf. Fig. 2) , which distinguishes the applications according to the main source of value creation and its location in the power system value chain.

- *Power quality*

Power quality applications include all operations that are necessary to guarantee a stable power supply without deviations from optimal frequency and voltage levels. In grid-connected MGs there is access to the frequency control markets which has three types of reserve products: primary frequency control known as Frequency Containment Reserve (FCR), secondary or automatic Frequency Restoration Reserve (aFRR) and tertiary or manual Frequency Restoration Reserve (mFRR). They differ depending on the required response time, whether they are activated automatically or manually and the delivery duration.

- *Power reliability*

Power reliability applications create economic value by assuring an uninterrupted supply and support during emergencies. In case of power outages storage can enable the black start of other generation devices, or important grid assets. Also, end consumers with critical needs such as hospitals, data centers, security equipment or sensitive industries rely on back-up power.

- *Increased utilization of existing assets*

Increased utilization of existing assets summarizes applications which create value by improving the use of existing generation or transmission capacity. ESS provide dispatchable load and allow RES to follow the load curve, reducing the need and cost for additional fossil generation or RES overcapacities. The main value is created by avoiding RE curtailment and expenses for costly peaker technologies (e.g. diesel or gas). In power networks congestion occurs, which conventionally will require line reinforcement. However, such investments involve long planning, high costs and even lead to public resistance. Congestion management via load leveling or peak shaving with ESS reduce the load factor and thus thermal overload and allow investment deferral.

Moreover, by using ESS for load-shifting, prosumers can increase their self-consumption and make optimal use of their renewable asset. If the cost for customer site-generation is lower than the retail price, it is more economic to maximize self-consumption than feed into the grid.

- *Arbitrage*

For grid-connected microgrids, there is a possibility to trade electricity. Arbitrage applications use price differentials to create economic value. The daily load fluctuations between peak and off-peak times, known as the duck curve in combination with intermittent RES generation in-feed, create fluctuating electricity prices.

The generated electricity i.e. from renewables, *RET arbitrage*, is stored to sell it at times with higher electricity prices. *Whole-sale arbitrage* buys energy at power markets during low prices, stores it and sells it when the prices peak and *end-consumer arbitrage* makes sense for all consumers with contracts that have time flexible energy prices or for those paying a peak-power based demand charge i.e. commercial and industrial customers.

D. Operation and control of MGs with ESS

To exploit the benefits of microgrids and storage devices, advanced tools and techniques assuring optimal operation are necessary. MG control architectures can be *communication-based* or *autonomous*. In the latter, no information is exchanged but the control actions are implemented based on local measurements. In communication-based structures the operation decisions can be either made *centrally* or *decentralized* at the local control. Since in complex MGs a single control and energy management system would not be sufficient to make all necessary decisions, hierarchical control architectures are widely accepted. Depending on the intelligence of the local controllers, it can be designed as more decentralized or centralized. Literature suggests hierarchies with three to four levels from local power generation control with RESs (first level) to synchronizing activities of the MG with other MGs and the main grid (fourth level). Depending on the applied terminology the energy management functions are placed into secondary or tertiary control [13] .

Whenever there are various energy sources or flexible loads involved in a MG, that need to be "scheduled" an EMS is required [14]. It can control the DERs and BESS by communicating them an optimal operation point (power output, frequency). The EMS core level functions include *Dispatch* and *Transition*. The dispatch function dispatches individual devices in a specific operation mode and with setpoints according to operational requirements. The dispatch must serve the loads in terms of power

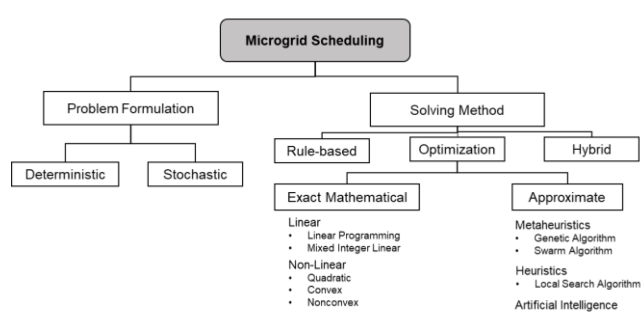


Fig. 3. Techniques for MG scheduling.

while maintaining power quality. The exchange levels (P, Q) at the point of interconnection are also determined by the EMS. The transition function supervises the transformation between "connected" and "islanded" MG state.

To ensure an optimal MG operation, the EMS comprises algorithms, energy management strategies, that optimize the power flows and determine the economic dispatch. Apart from traditional rule-based strategies, various optimization-based techniques have been applied to solve the problem of energy management in microgrids.

Rule-based strategies determine the reference points based on certain input parameters of the present situation and predefined scenarios making use of decision trees. Since no forecasts are used, they are called reactive techniques. Their advantage is the simplicity and runtime performance, which allows real-time control, but they do not generate optimal output results [15].

Optimization-based strategies can identify local and global optima, based on maximization or minimization of an objective function under satisfaction of set constraints. Depending on the mathematical formulation of the objective function and constraints (deterministic or stochastic) and solving methods (mathematical exact or approximate) different cases can be identified (cf. Fig. 3) [16].

PROPOSED EMS SCHEDULING APPROACH

In the following the suggested mathematical formulation of the scheduling optimization problem for a grid-connected microgrid, which will determine the operation regime of the flow battery, is described. The main objective is to provide a tool that optimizes the battery operation in such a way that maximum economic value can be obtained. Different possible applications, of VRFB in a microgrid are integrated in the algorithm. The primary use case addresses the cost reduction for the MG operator by energy arbitrage.

To deal with the uncertainties related to fluctuating renewable power output, demand and price signals, an energy management based on a Model Predictive Control (MPC) strategy is proposed. MPC also known as Receeding Horizon Control (RHC) is an advanced control method for multivariable control problems which accounts for current and future information in the optimization to determine the control action. It minimizes the cost function C_k at time step k over the next N_p steps (cf. Fig. 4).

Only the first element $u_k(t)$ of the output control sequence $u_k \triangleq u_k(t), u_k(t+1) \dots u_k(t+T_p-1)$ is implemented for sampling duration T_s. By repeating this calculation with a receding horizon the control can adapt to changes since the forecasted values are updated every time the prediction window rolls to the next time step $k+1$.Fig. 5 shows the general scheme of the proposed MG-EMS, its inputs data, outputs and restrictions. The problem is formulated as a time discrete non-linear deterministic

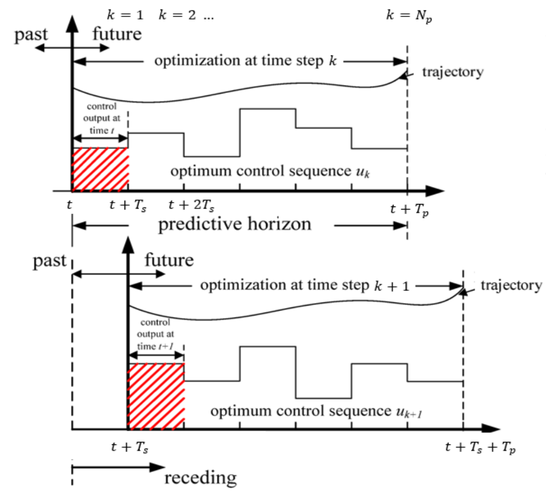


Fig. 4. Schematic diagram of the MPC control [20].

optimization model. The numerical solver fmincon in the Optimization Toolbox of MATLAB is used for the computation.

1) Objective function

The energy scheduling of the MG is solved as an optimization problem, with the main aim of the EMS is to minimize operational electricity costs. All planning, installation and capital expenditures are sunk costs since they could not be altered by the

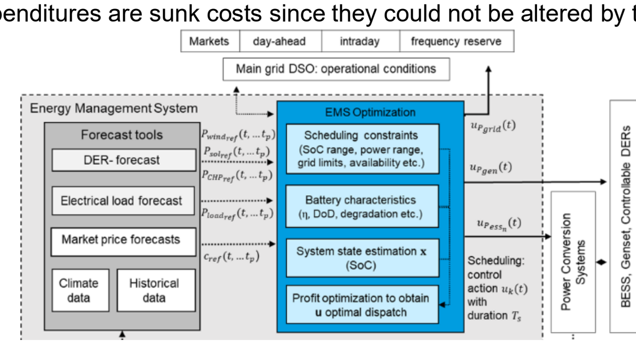


Fig. 5. General scheme of MG-EMS.

energy management strategy and thus are excluded from the optimization. Applying MPC as an approximation this results in the following objective function in Eq. (5), which is subject to equality and inequality constraints.

$$\min_{u_k} \sum_{t=k}^{k+Tp-1} \mathrm{C}(\mathrm{x_k}(t), u_k(t)) \tag{5}$$

$$A(u_k) \leq B$$
$$Aeq(u_k) = Beq \tag{6}$$
$$u_k \triangleq [u_k(t), u_k(t+1) \dots u_k(t+T_p-1)]$$

$$min \sum_{t=k}^{k+Tp-1} (C_{grid}(\mathrm{t}) + C_{gen}(\mathrm{t}) + C_{ess}(\mathrm{t}) - R_{Curt}(\mathrm{t}) - \mathrm{R}_{FR}(\mathrm{t})) \tag{7}$$

The operational costs of a MG in Eq. (7) can be broken down into different components: The first component C_{grid} are the costs from power P_{grid} purchased minus the revenues from delivered power to the main grid at a time-varying market price c_{DA}.

The second term C_{gen} refers to generator fuel costs. The third cost term C_{ess} incorporates battery degradation. Finally, the last two optional components denote revenues from grid supportive operation such as avoided curtailment costs R_{curt} and frequency reserve markets R_{FR}.

The objective function is subject to the following decision variables **u**, the charging/discharging power P_{ess} of each battery, the conventional generator output power P_{gen} and the quantity of power exchange with the main grid P_{grid}. All power variables represent the average power during a time step k.

2) Power balance and grid constraints

A vital constraint is formulated in Eq. (8) It assures the power balance so that supply matches the demand at any time. The power exchange with the main grid can be restricted (i.e. for grid supportive application).

$$P_{PV}(t) + P_{WT}(t) + P_{grid}(t) + \sum P_{ess}(\mathrm{t}) = \mathrm{P_{load}}(t) \quad (8)$$

$$P_{grid}^{min}(\mathrm{t}) \leq P_{grid}(\mathrm{t}) \leq \mathrm{P}_{grid}^{\max}(\mathrm{t}) \quad (9)$$

3) Battery modeling

The battery models include the calculation of the operating state **x**, representing the SoC_n or remaining energy level E_{ess}, variable charging/discharging system efficiencies $\eta_c(t)$ and $\eta_d(t)$ and operational constraints such as maximum charging P_{ess}^{min} and discharging powers P_{ess}^{max}. Separate models are defined for a VRFB and a LiB.

Vanadium redox flow battery

$\mathrm{SoC^{min}}$ and SoC^{max} in Eq. (10) denote the minimal and maximal admissible charging levels to prevent overcharge and overdischarge. The remaining energy is implemented by applying the energy balance.

$$\mathrm{SoC_n^{\mathit{min}}}(\mathrm{t}) \leq SoC_n(\mathrm{t}) \leq \mathrm{SoC_n^{\mathit{max}}}(\mathrm{t}) \quad (10)$$

$$SoC_n(\mathrm{t}) \begin{cases} = SoC_n(t-1) - \eta_{sys,n}^{c}(t) * \dfrac{P_{ess,n}(t)}{E_{nom,\mathrm{n}}} \\ = SoC_n(t-1) - \dfrac{1}{\eta_{sys,n}^{\mathrm{d}}(t)} * \dfrac{P_{ess,n}(t)}{E_{nom,\mathrm{n}}} \end{cases} \quad (11)$$

For the formulation of the battery efficiency there are two main approaches. In the first approach, the efficiency is only determined by the battery state, whether it is in charge or discharge mode and the efficiencies are two constants. The second approach considers that charging and discharging efficiencies depend on the charging/discharging power P_{ess} or current I_{ess} and the SoC. Applying the second concept, to retrieve the system efficiency at different set points $\eta_{sys} = f(P_{ess}, SoC)$, data from repeated cycles with the CellCube (R3) at constant target power is evaluated. The final system efficiency map normalized to the efficiency at rated power and SoC of 50 % is illustrated in Fig. 6. The combination of the real measurement data and the trend identified in [17] has been used to create the efficiency distribution, which also includes pump and inverter losses.

Another distinctive battery property is that during the charging process the battery power is reduced when the SoC is approaching the maximum SoC limits. Instead of continuing to

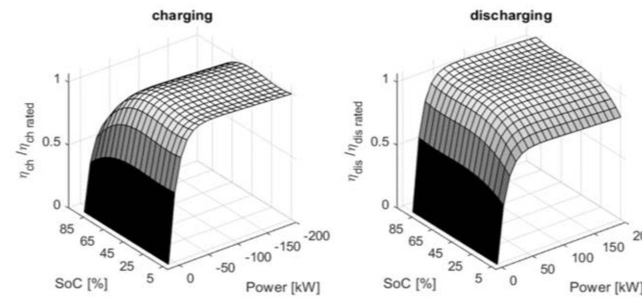


Fig. 6. Normalized system efficiency depending on battery power and SoC.

charge with a constant current or constant power, the current/ power is reduced continuously as in Eq. (12) (tapering/ saturation charge) and finally terminated when the maximum battery voltage is reached.

$$P_{ess}(t) \leq \frac{P_{ess}^{min}}{1 - SoC_n^{rc}}(1 - SoC_n(t)) \quad (12)$$

$$P_{ess}(t) \leq \frac{P_{ess}^{max}}{SoC_n^{rd}} SoC_n(t) \quad (13)$$

Lithium-ion battery

In contrast to VRFB for LiB aging in the form of capacity fade is significant. Aging processes can be divided into two groups: aging related to cycle life and aging related to calendar life. As calendar aging cannot be altered by the operation mode, it is not comprised in the optimization. The degradation Φ is the inverse function of the number of cycles (cf. Fig. 7).

$$\Phi_k = 0.5 * \left|\Phi_{reg}(SoC(t)) - \Phi_{reg}(SoC(t-1))\right| \quad (14)$$

$$c_{\mathrm{deg}k} = \Phi_k * \Delta C_{rp} \quad (15)$$

The factor 0.5 in Eq. (14) indicates that a charging/discharging process only stands for half a regular cycle. If the battery is cycled from 80 % SoC to 40 % SoC during one step, the degradation is $0.5 * |0.0031\,\% - 0.012\,\%| = 0.0044\,\%$. The degradation is translated into costs with the help of the LIB replacement

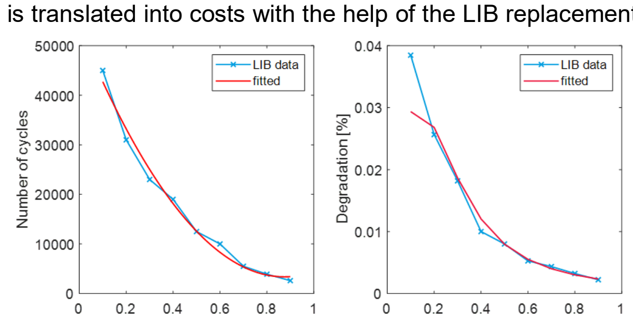


Fig. 7. Cycle life versus DoD curve for NMC LiB (left) Degradation versus SoC curve (right)

cost ΔC_{rp}.

CASE STUDY

A. Case description and input data

The case of study is a grid-connected microgrid on the island of Pellworm in the North-Sea in Germany. It has around 1100 inhabitants and its economy is dominated by tourism and agriculture requiring 8.5 GWh of electricity annually. The island has a high RES generation of 32 GWh/a, primarily from wind but also solar PV and a biogas CHP. The hourly load and consumption profiles required for the optimization have been derived from the consumption distribution and reference PV and wind assets on the island. For the duration of the SmartRegion Pellworm demonstration project, the island had been equipped with two large scale battery energy systems, a CellCube FB200-1600, with a rated power of 200 kW and with an energy capacity of 1600 kWh and a Saft Intensium Max20M LiB with an energy capacity of 560 kWh. Both batteries were connected to the AC grid via an individual battery inverter.

Tab. 1. Battery specifications for VRFB (1) and LiB (2).

Variable	Lower boundary	Upper boundary
P_{ess_1}	-200 kW (charge)	200 kW
P_{ess_2}	-560 kW (charge)	1000 kW
SoC_1	5 %	85 %
SoC_2	20 %	90 %
η_{sys_1}	80 % (charge @ P_{ess_1})	80 %
η_{sys_1}	93 % (charge)	91 %

Since 2012 Germany moved away from guaranteed feed-in tariffs and more RES energy is marketed directly via the exchange. Hence, the buying and selling price for electricity is set equivalent to the hourly EPEX day-ahead market price (EPEX Spot Phelix Day Ahead).

B. Case results

1) Scenario 1: energy arbitrage

Scenario 1 runs the optimization with the single purpose minimizing the cost by exploiting price spreads. Fig. 8 illustrates the dispatch results of a typical day with high wind production fluctuations. The maximum BESS discharge correlates with the peak electricity price, whereas the maximal charge occurs simultaneously to the lowest price at night. It can be noted that due to the large RES generation within the microgrid, the BESS are primarily used to store the overproduction and sell it at times with higher prices, maximizing the revenues from sold electricity. Peak prices occur frequently during the morning (8-10 am) or afternoon (4-8 pm). It can be called generation arbitrage, whereas the typical load shifting occurs as well but only when there is an energy deficit and electricity must be procured.

The simulation of the arbitrage operation strategy for one year, excluding LiB degradation cost, results in additional profits of around 5544 EUR compared to Scenario 0 without storage. Self-consumption and self-sufficiency can be increased slightly. Contrary to expectations, the throughput of VRFB is lower than

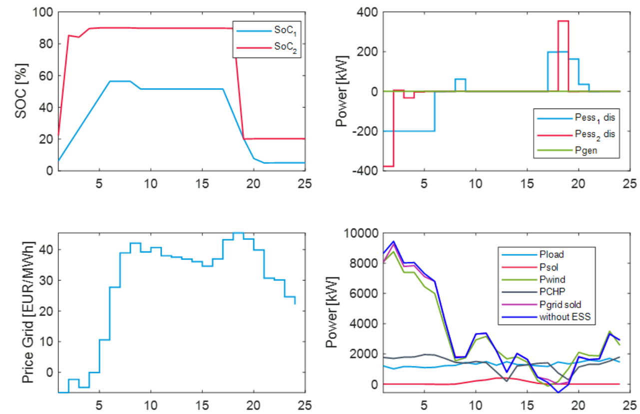


Fig. 8. Scenario 1 - dispatch results for winter day.

for LiB, although the energy capacity of the VRFB is higher. This result can be traced back to the lower system efficiency of VRFB and the requirement for higher price gaps. The LiB degradation of cycle life for one year is 13.5 % or 540 regular cycles. In fact, with this cycling behavior the LiB will not reach the 13 years of average shelf life but only 7-7.5 years. Therefore, for arbitrage only operation, it makes sense to include additional degradation factors to avoid intense cycling.

A sensitivity analysis has been performed to assess how different parameters affect the dispatch results:

Tab. 2. Scenario 1 – dispatch results for annual simulation

Annual results	Scen. 0	Scen. 1
Profit [EUR]	911,280	+5544
Self-consumption [%]	24.97	24.98
Self-sufficiency [%]	96.29	96.33
Degradation LiB [Cycles]		541 (13.5%)

Impact of algorithm

To test the outcomes of the MPC approach, it is compared with a day-ahead optimization, which optimizes the schedule for the coming 24 hours at once. The prediction horizon has been set to 24 hours, which means that for the first hours the error should be within the same range. As expected, the MPC can reduce the error in the following hours and thus the mismatch cost. For the simulated day the MAPE of the day-ahead optimization is 12.6 % and 6.2 % for the proposed MPC. Hence the implementation of a receding horizon it is one way, to deal with uncertainty due to intermittent RES and consumption behaviors.

Impact of prediction horizon

The analysis discloses that prediction horizon between 8-12 hours achieve slightly better results (cf.

Tab. 3). Prediction horizons of less than 6 hours lead to only a minimal benefit, since the predicted price spread within the short timeframe is not enough to compensate efficiency losses from cycling or degradation. A longer horizon helps to steer the operation onto a desired path. It avoids the problem that the BESS is empty when prices are high or full when it would be cheap to recharge. However, a very long horizon over 12 hours does not provide an improvement because the forecasts degrade as time increases and the decisions made are based on data with larger errors. Hence in this setting, there is a trade-off between prediction horizon and prediction accuracy. In addition, long prediction horizons larger than 12 hours increase the computation.

Tab. 3. Sensitivity analysis with various prediction horizons for two different weeks.

Prediction horizon [h]		4	8	10	12	18
Jan.	Add. profit [EUR]	142	219	219	221	217
July	Add. profit [EUR]	4	22	18	28	9

Impact of battery system efficiency

The efficiency is assumed to have a significant impact, since it defines the losses which need to be compensated by higher price spreads. The LiB already has a roundtrip efficiency of over 85 %, therefore the investigation focuses on the impact of different rated efficiencies of the VRFB, which still has potential in boosting the efficiency.

Tab. 4. Sensitivity analysis with various VRFB efficiencies.

System rt. efficiency	Add. revenue arbitrage		Total share VRFB
64 %	5544	-	48.1 %
70 %	6710	+21.0 %	56.0 %
76 %	8090	+45.9 %	62.9 %
82 %	9503	+71.4 %	68.1 %

Already during recent years progress has been made and compared to the system installed on Pellworm in 2013, new systems achieve higher roundtrip efficiency of 70-75 %. The simulation demonstrated that with an improved system efficiency of 82 % the revenues can be significantly enhanced by 71.4 %. Subsequently, also the energy throughput of VRFB rises with the efficiency and so does the amount of additional revenue traced to the VRFB.

Impact of degradation cost

The previous simulations were performed without considering a degradation cost factor in the objective function. In this case the LiB life would only last around 7-9 years before the remaining capacity would be less than 70 %. The highest monthly benefit is acquired for the case A where no degradation was incorporated in the objective function as it makes use of the LiB battery more aggressively, generating more energy throughput. Despite this, the case also experiences the highest degradation (1.07 %), concluding in the shortest battery lifetime. In general, rising degradation costs limit the flexibility of the LiB operation, resulting in lower profits but increase battery lifetime. When the spread of the battery replacement increases to 100 EUR/kWh (Case C), the LiB rarely reaches a DoD of more than 40 % and the total profit from power exchange decreases.

Tab. 5. Dispatch results under various LiB replacement costs for one month

Δ Replacement [EUR/kWh]		Δ Mon. benefit [EUR]	Degradation [%, cycles]	Lifetime [years]
A.	-	791	1.07 %, 42.9	7.8
B.	*20*	674	0.79 %, 31.6	10.5
C.	*100*	575	0.37 %, 14.7	>13
D.	*175*	571	0.21 %, 8.4	>>13

Even higher degradation costs (Case D) only lead to minimal changes in dispatch results. Fig. 9 illustrates the consequences of degradation costs over one week during winter. It is difficult to determine an accurate degradation cost value for the objective function. While in winter the revenue losses are acceptable, in summer it often makes the difference whether the LiB operates or is in idle mode.

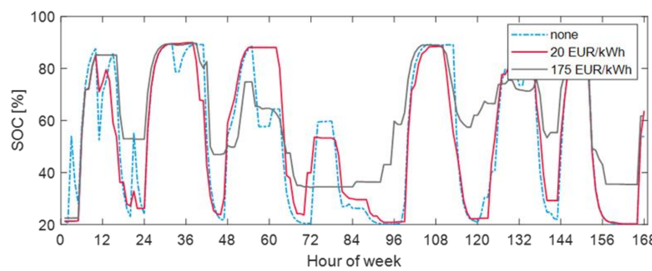


Fig. 9. LiB cycling with different degradation cost factors.

2) Scenario 2: Increased utilization of existing assets

A. Grid supportive peak shaving

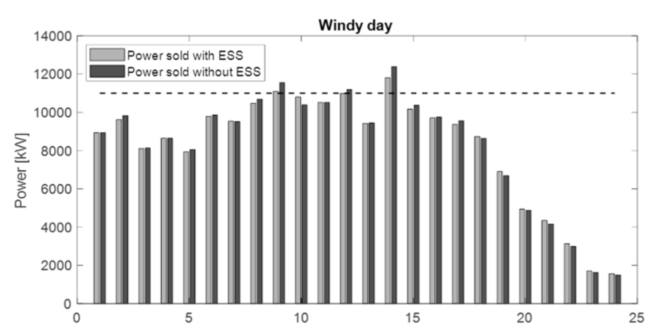


Fig. 10. Scenario 2A - with soft grid limit of 11 MW.

Scenario 2 runs the optimization as a combined application of energy arbitrage and provision of services to the grid by reducing the peak value of the power flow to the main grid. This type of peak-shaving prevents congestion and improves the optimal usage of the existing grid assets deferring the necessity for large investments. The combined storage application is simulated by adding the additional constraint Eq. (9), which limits the power exchange to the main grid to a predefined level. Nevertheless, when choosing an unreachable low grid limit the optimization becomes infeasible. Therefore, soft limits, which penalize any surpassing by a comparatively high cost in the objective function, can be implemented instead.

For the 11 MW soft limit, a drop of the peak by 4.75 % is realized (cf. Fig. 10). If a lower limit is chosen, the arbitrage model will not function accurately. Therefore, it will be a tradeoff, between minimizing the peak grid exchange and maximizing arbitrage revenues. Hence, if the benefits of the DSO, which are avoidance or deferral of grid investments, lower grid losses and lower curtailment compensation, are to be monetarized by service agreements, the payment needs to exceed these losses.

According to SH Netz curtailment had to be performed on Pellworm during 648 hours in 2018. Within the DSO region for 77.5 % of the time curtailment had been necessary. The owner of the generation asset is to be compensated by its DSO. In 2018 the average compensation cost was 117.6 EUR/MWh [18]. With the Pellworm HESS the maximum peak reduction is approximately 600 kWh/h. If we assume that the full reduction is not always manageable and consider an average reduction of 70 %, this would generate an additional profit of around 20000 EUR. This kind of service can be based on bilateral contracts but in the past encountered regulatory issues, since DSOs are highly regulated and limited in their activities how to deal with congestion.

Tab. 5. Scenario 2A - peak shaving for grid.

	Estimation for 2018
Avoided curtailment	648 hours
Average reduction	0.7*600 =430 kWh
Cycle losses	20-25 %
Additional profit	20203 EUR

B. Increased self-consumption

Peak-shaving can also be performed to increase self-consumption and sufficiency, optimizing the utilization of the existing generation assets in the MG. There is incentive for increasing self-consumption due to the normal spread between the price for buying and selling electricity. The electricity price for end-consumers is significantly higher. In Germany, households pay 30 ct/kWh and industrial customers pay 15 ct/kWh, which is up to 10 times the day-ahead prices. Hence, a case is simulated, promoting local use of energy, where the spread between power sold and power purchased is set to 5 ct/kWh.

Tab. 6. Scenario 2B - local consumption.

Annual results	Scenario 0	Scenario 2B
Additional profit [EUR]	-	+30590
Self-consumption [%]	24.97	25.31
Self-sufficiency [%]	96.29	97.60

3) Scenario 3: Power quality – frequency regulation

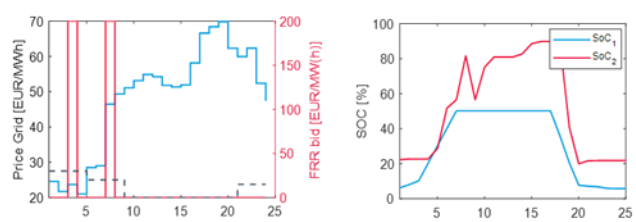
A. Frequency restoration reserve (FRR) & arbitrage

With the previously studied services, a stacked application is created where secondary frequency control and arbitrage are offered in parallel. If successfully prequalified, the asset owner can choose between offering positive, negative or both types of aFRR. For each 4 hour-block a bid in the form of a capacity price (EUR/MW) and an energy price (EUR/MWh) is submitted. Any BESS has to prove that it can supply the aFRR power for 60 min without recharging measures and for the whole 4 hours with measures such as spot market intraday transactions.

The HESS system on Pellworm is not able to provide the minimum of 1 MW FRR power. Still, the system can become part of a pool. Taking into consideration the necessity to adjust the charge limits, an aFRR power of 0.5 MW is assumed. In reality, the duration of one activation is far less and can be reduced by choosing a bidding strategy with a high energy price.

The prices for aFRR are highly volatile and are fraught with risk [19]. For the simulation two combinations of capacity and energy prices are tested, based on the analysis of historic bid data: The first option is to offer negative aFRR at capacity price of 15-30 EUR/MW allowing the battery to be recharged for free. Another option is to offer positive aFRR at 15-40 EUR/MW with a relative high energy price (1000 EUR/MWh) to reduce the chance of activation to avoid the risk of interfering with the arbitrage model

Fig. 11. Scenario 3A - SoC curve for negative aFRR and arbitrage application.



In the negative aFRR scenario, around 7450 EUR come from the reserve and 4500 EUR from the activation at an energy bid of 200 EUR/MWh. Although the SoC is more restricted the losses can be compensated due to the free electricity for recharging the battery when activated. Fig. 11 shows a typical day, where negative aFRR is activated.

For positive aFRR a higher activation bid has been chosen to avoid discharge when spot prices peak, and revenue is generated from arbitrage. Still, the activation happened 82 times. Assuming on average the maximum energy is required for 15 minutes more than 10000 EUR can be obtained from the provision. In contrast to negative aFRR this leads to a reduction of revenues from arbitrage. It should be noted that revenues are likely to be larger if the bidding strategy is adapted more frequently and with more market knowhow.

Tab. 8. Scenario 3A - results of of aFRR and arbitrage.

Bidding strategy	**Revenue aFRR**		**Arbitrage**	**Total**
	Cap.	Energy		
Negative	7452	4500	4302	16254
Positive	7987	10375	2813	21175

B. Frequency containment reserve (FCR)

FCR is a power-based application, requiring high power for maximum 15 minutes, and thus not the primary choice for VRFB. Notwithstanding this, FCR is an attractive option for batteries and several large-scale batteries already take part in the German FCR market. Unlike FRR, a stacked service with FCR is difficult, since FCR is activated several times an hour and any arbitrage transaction would hardly comply with the absolute power and direction required for FCR.

The auction for FCR takes place weekly and it is a symmetric product. The prequalified power P_{FCR} depends on the maximal charge P_{ess}^{min} and discharge power P_{ess}^{min} as well as the nominal energy capacity E_{nom} since the requirements also define upper and lower boundaries for the charge level. According to the current regulations around 500 kW could be prequalified for Pellworm, without the necessity of becoming part of pool. The findings show that FCR market has a high attractivity for batteries. With regard to VRFB which has a high CAPEX per power the FCR market is more suitable in the form of a hybrid storage system.

Tab. 7. Scenario 3B - revenues from FCR.

	FCR primary reserve
Average price $c_{FCR_{res}}$	2170 EUR/MW/week
Additional revenue C_{FCR}	56320 EUR/year

CONCLUSION

The paper developed a data driven operation optimization tool, which allows to simulate different applications with battery-technology specific characteristics and is able to determine a beneficial schedule for the MG under uncertain conditions. It provides an analytical tool for the operator to facilitate and schedule the VRFB battery operation, either as a single technology or paired with LiB.

In addition, the use of model predictive control was explored. It was demonstrated that the MPC approach can counteract undesired impacts due to uncertain factors, like large power mismatches, which would occur in offline optimizations. The proposed formulation includes the equipment power constraints, variable bounds in power rates, state of charge constraints, efficiency criteria, and degradation to prevent early BESS failure while economically allocating the system demand and maximizing revenues from power exchange with the main grid. To test the proposed operation strategies and to quantify the economic benefits from the VRFB, a case study has been conducted with data from the Island Pellworm (cf. Fig. 12).

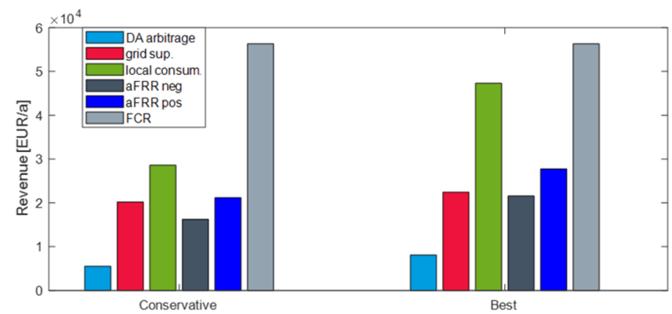


Fig. 12. Summary of case results - annual revenues for different applications

The analysis concluded that for single value streams such as arbitrage the VRFB does not have sufficient economic merit yet. Energy arbitrage has low technical requirements, but the revenues are limited by the daily price spread, which in the German spot market is not enough. For the VRFB the price gap is often not enough to cover the storage losses, leading to long times of no usage. A smaller E/P ratio of the VRFB and additional intraday arbitrage might improve the economic outcomes.

A future focus should be improving the system efficiency from VRFB, which as observed, has a high impact on the economic viability. In comparison with other papers [20], the obtained revenues from energy trade are lower. Yet, most other techno-economic studies use simulations with perfect foresight resulting in an overestimation of the benefits of BESS.

The findings suggest that by combining revenue streams from different applications the integration of VRFB has a potential to result in total gains. Adding additional revenues by peakshaving as a congestion management service for the DSO to avoid curtailment and high grid losses, demonstrated to be a very suitable use case for VRFB paired with LiB. Despite this, any cooperation with DSO/TSO is very limited due to strict regulations and the unbundling requirement.

It has been shown that local consumption should always be considered if the price for selling electricity is lower than the one for consumption. In particular, for industrial or campus microgrids, where the owner structure and regulatory issues are clearer, this is the main business case.

The available frequency reserve markets are characterized by higher technological entry barriers but also higher revenues. The future attractivity of frequency regulation market highly depends on price evolvement. Whereas many researchers predicted falling prices [21], for 2019 this is only the case for FCR. The FRR market demonstrates an increasing demand and a rise in prices. A stacked model with negative aFRR and arbitrage can be beneficial since the free energy from activation can be sold via the day-ahead market. In addition, by combined business models the risk of bidding is reduced, since the battery can be operated fully for arbitrage in case the bid is not accepted. The results of this study correspond to research on combined business models for batteries which demonstrated additional profits by stacking applications [22].

Moreover, the case results strongly point out that VRFB and LiB can and should be used complementarily as a hybrid storage system. Many applications require high power but also the certainty that it can be provided for a time duration of up to 4 hours without notice in advance to adjust SoC beforehand. Here, a LiB with increased energy capacity would become very expensive. Especially, since 1 kWh of rated energy capacity for VRFB and LiB are not equivalently utilizable. For LiB the useful SoC range is smaller since the DoD should be restricted to avoid fast degradation. The optimization with LiB degradation revealed that in order to reach shelf-life a DoD of 60 % would rarely be exceeded.

The case study showed that vanadium redox batteries are a versatile solution for MGs, able to generate additional revenues. Their economic feasibility for future investments in MGs highly depends on the MG ownership and tariff structure, battery size and scale and realization of future cost reductions.

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