Optimized Energy Management of a Solar and Wind Equipped Student Residence with Innovative Hybrid Energy Storage and Power to Heat Solutions

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Abstract. Grid-connected Energy Storage Systems (ESS) are vital for transforming the current energy sector. Lithium-Ion Battery (LIB) technology is presently the most popular form of ESS, especially because of its fast response capability, efficiency, and reducing market prices, but is not always preferred for long-term storage, due to its relatively shorter lifetime. A Redox Flow Battery (RFB) on the other hand has a higher lifetime and better long-term storage capability, but has a higher upfront cost and reduced round trip efficiency. A Hybrid ESS (HESS) consisting of LIB and RFB offers the advantages of both technologies, thus making the ESS more economical and flexible to use while also improving the cycle lifetime of individual ESS. Such a grid-connected HESS is planned and installed for a student residence at Bruchsal having 126 apartments for 150 students and equipped with 220 kWp photovoltaics and 10.5 kWp wind-power. Real-time high-resolution data of the residence's electrical load and energy generation are collected and used to optimally control the HESS. Additionally, the RFB is also used as heat storage, which supports partial heating requirements of the residence.

In the present work, an Energy Management System (EMS) is deployed which not only controls this conglomerate but also optimizes its operations in real-time. The HESS is optimized two folds where it is operated with a fixed priority based strategy to improve the operational efficiency. Secondly using solar and load predictions, optimal charging schedules of the individual ESS are estimated. Based on the schedules the ESS are charged at its optimal charging points thus increasing charging efficiency and at the same time it avoids the ESS from staying at high SOC ranges for long time thus reducing ageing. Results based on real life operations based on the proposed methods are provided in this work.

Keywords: stationary energy storage · grid-connected · hybrid energy storage · lithium-ion · vanadium redox-flow · optimization · power-to-heat

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1 Introduction

Rapid growth of global electricity consumption and climate change are the major drivers for shifting the energy sector towards renewable energy sources. Renewable energy generation capacity in Germany alone rose from 36.67TWh in 2000 to 225.58TWh in 2021 and served for about 46% of net public power in year 2021 [1]. Unlike traditional energy sources, non-dispatchable renewable energy sources could be highly localized and uncertain at the same time, causing grid instability. This problem is solved by coupling such energy generation with energy storage technologies, which could act as an energy source when the generation is less or completely absent. In the context of a building coupled with such renewable energy sources, its self-consumption could be increased with energy storage options and energy management, thus leading to reduced energy bills [2]. However, to be economical, it is important that such energy storage options last longer, in order to break even.

Lithium-Ion Battery (LIB) is currently the most popular and often researched form of ESS option for smart grids and buildings. LIB accounts for more than 80% of the technology mix (electrochemical energy storage) serving as stationary storage in 2020 [3]. Although, LIB might not be the best solution for a stationary storage in the long term due to its relatively shorter lifetime, it still dominates this energy sector due to "spill over" from Electric Vehicle (EV) technology developments and market growth [3]. Redox Flow Batteries (RFB) on the other hand is a promising alternative to LIB as a utility scale power grid storage due to its long service life and high cycle stability, operational reliability, and scalability [4]. But RFB in comparison to LIB has significantly less energy density, reduced round trip efficiency and on top of all higher upfront costs majorly due to smaller market penetration making it not a fully commercially viable option.

An ideal utility scale ESS would be the one capable of storing huge amount of energy to last hours (or sometimes even several days), provide instantaneous high power to compensate the highly dynamic renewable energy generation, and at the same time being highly efficient while doing so. But in reality each ESS technology presents characteristic features and is especially well suited for a specific application where nominal power and energy ratings are well known [5]. A Hybrid Energy Storage System (HESS) offers the flexibility of covering a wider range of applications, which is not possible with a single-nature ESS. HESS exploits the advantages of two ESS having two different natures, thus making the system more efficient, economical and flexible to operate [5,6].

With this motivation, a hybrid LIB-RFB ESS is being researched at KIT. Similar HESS have been researched often in the literature [6–12], but most of the times the research scope limits to simulation, designing or experimental development. Unlike most of the literature, this paper describes the structure of a conglomerate consisting of an HESS, two different renewable energy sources: PV and wind, along with three EV Charging Stations (EVCS), installed at a fully functional student residence at Bruchsal, Germany. Additionally, to improve the round-trip efficiency of the RFB, are is aimed to be used as not only electrical energy storage, but also as a heat storage. to do so the electrolytes are re-engineered to be able to store not only the waste heat generated during the RFB operation, but also heat energy converted from surplus electrical energy of PV + Wind. This stored heat is later used to pre-heat the tap water of the building, thus repurposing the waste heat from RFB. To the best of the authors knowledge such a living lab with a combination of a HESS and a thermal coupling has not yet been researched, thus making the whole system a novel one.

The paper is structured as follows. Section 2 provides a detailed outlook of the system setup, following which the different control levels and optimization strategies are explained in Sect. 3. Based on the optimization strategies the operation result on the real setup are discussed in Sect. 4. Finally an further optimization aims and possibilities are visited in Sect. 5.

2 System Configuration and Components

A Microgrid refers to a self-contained, small scale power grid, consisting of variety of components including distributed generators (DGs), distributed energy storage (DES) options and a single or multiple loads [13]. Thus, the system dealt in this paper could also be defined as an AC-connected microgrid with two different DGs and three different DES (2 electrical and 1 thermal) along with electrical and thermal load from the building, and EVCS load. The system is meant to run under grid-interconnected mode all the time. Figure 1 defines the system layout and the component connections (both physical and digital) with each other. More detailed information on each component is as follows.

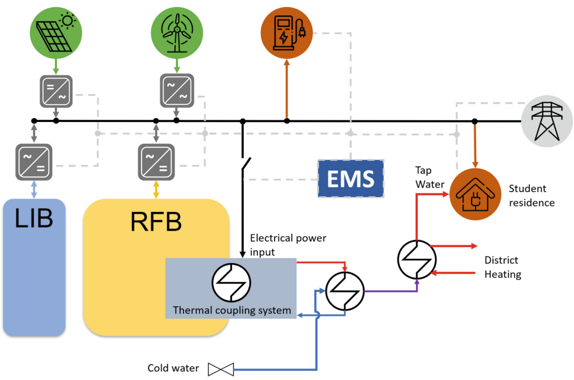

Fig. 1. System layout with solid connection lines depicting the physical connection and dotted lines depicting the communication between the components

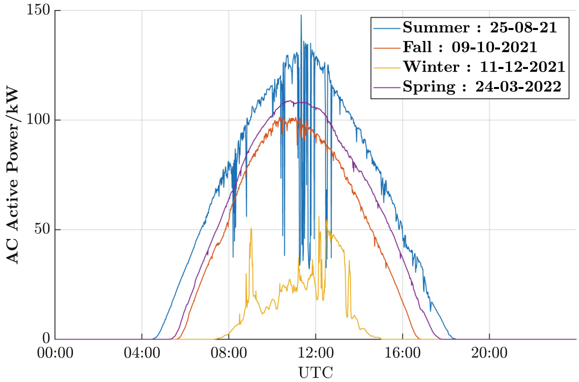

Fig. 2. Power generation measured during different seasons from the PV installation at Student residence (measured after Inverters, courtesy: Stage76 Administration)

2.1 Distributed Generators

2.1.1 Photovoltaic Energy Source

The student residence is installed with a sum capacity of 220 kWp_{DC} Photovoltaic (PV) system. Of this total capacity, roof-top installation accounts for almost 76% and vertical wall mounted installation (i.e. with 90° inclination) accounts for 24%. The installations face different directions, which include east, west and south, thus the energy generation from the whole PV system spans more or less evenly throughout a day, as also seen in Fig. 2.

2.1.2 Wind Energy Source

In comparison to the PV system, the wind energy generation capacity is relatively smaller and limited to 10.5 kWp_{DC}. The vertical axis wind turbines are placed at the highest point of the student residence, i.e. at about 30 m.

2.2 Distributed Energy Storage

2.2.1 Redox Flow Battery - Electrical and Thermal Energy Storage

A 100 kWh_{el} Vandium Redox Flow Battery acts as the first DES of the student residence (see Fig. 3). The peak AC power provided by the ESS during the initial development phase is 14 $\mathrm{kW_p}$. The main motive of the RFB are two folds:

Fig. 3. Vanadium Redox Flow Battery installed at student residence. (Image courtesy: 1st Flow Energy Solutions GmbH)

1) act as a high energy source. Thus it is responsible to cover most of the base load from the building and EVCS.
2) act as a heat storage, where the electrolytes are the medium to store heat. To do so, the electrolytes are re-engineered with the project partner: Fraunhofer, Institute for Chemical Technology, to be stable at higher temperatures (upto 50 °C). The thermal capacity of the tanks could be estimated to around 200 kWh_{th}, when the electrolytes are driven on the range of 40 °C (10°C $\leftrightarrow$ 50 °C) [14].

For the RFB to behave as a heat storage, the source of heat is its own thermal losses during operation, as well as surplus power from PV converted to heat, thus forming a Power-to-Heat solution. The heat is stored and extracted using a Thermal Coupling System (TCS) as defined in Fig. 1. The TCS brings together the district heating system and the RFB. The aim of this setup is to use the heat of the electrolytes to pre-heat the tap water sent further to the residents. The TCS setup developed is aimed at covering only the hot water requirement and not room heating. To ensure safety, the TCS is managed with a dedicated in-house built controller, which is driven by the EMS. This TCS setup is currently under realization phase. The control concept between TCS and EMS is briefed in Sect. 3.

2.2.2 Lithium Ion Battery - Electrical Energy Storage

A Lithium Ion battery of 60 kWh capacity with 30 kW_p power output is installed at the student residence (see Fig. 4). As described in Sect. 1, the LIB is operated in parallel to the previously mentioned RFB, forming the HESS. The capacity as well as the power output of LIB was carefully chosen after detailed analysis on the efficiency as well as electrical and economic loss of the HESS as a whole

Fig. 4. Lithium Iron Phosphate technology based ESS installed at student residence (Image courtesy: Stage76 Administration)

[15]. The ESS are not connected to each other directly, rather through the AC bus. The main motives of LIB are also two folds:

1) act as a high power source, which could cover up highly dynamic changes in generation (in 250ms range), thus ensuring minimalistic load on the Grid, and
2) avoid partial operation of RFB, thus improving the overall efficiency of the HESS

2.3 Load

2.3.1 Student Residence - Electrical and Thermal Load

The student residence: Stage76, located at Bruchsal, Germany (Fig. 5) was opened up for students to live in at the end of 2019. Unlike other student residences, Stage76 is planned not only for university students but also trainees, which makes it the first of its kind [16]. In terms of modelling the residence's load (both electrical and thermal) it is a challenge as the day to day life of a trainee and normal university student is different. Additionally, a considerable amount of students are seen as a "moving crowd", who live for the minimum rent period of 6 months and leave. The student residence can accommodate 150 students

Fig. 5. Research site: student residence Stage76, Bruchsal, Germany (Image from 22.12.2021, courtesy: Stage76 Administration)

totally, in 102 studio apartments and 24 two room apartments. Since start of 2021, the residence has been running at full capacity all the time. The student residence also has multiple common rooms or utilities, which are regularly used, thus adding up to the total electrical and thermal load.

As evident in Fig. 6, the maximum power requirement of the building averages at ≈31 kW, but some days the short-span peak power requirement could range from 40 kW to 50 kW. The peak power consumption happens mostly between 17:00 UTC and 21:00 UTC. The minimum load on the other hand stays at ≈5 kW, which could be defined as the base load of the building. Based on the measurements the building consumes an average of 320 kWh per day.

On the other hand a typical tap water heating power requirement has no base load, i.e. 0 kW base load, but the peak power requirements could reach upto 100 kW at times. The authors would like to make a note for the readers here that, the power requirement for heating tap water mentioned above are derived values from the energy flow measured between incoming and outgoing water of the community heating setup.

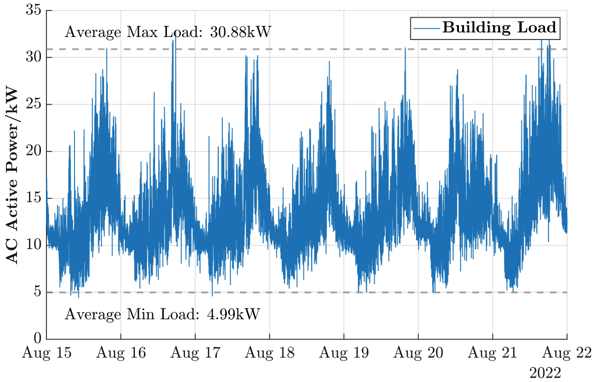

Fig. 6. One week electrical power consumption by the building as measured between 15.08.2022 (Monday) and 21.08.2022 (Sunday). Minimum load requirement was ≈5 kW and maximum load was ≈31 kW (courtesy: Stage76 Administration)

2.3.2 EV Charging Stations - Electrical Load

Given the increasing trend of EV usage currently in Baden-Württemberg state, and also the proximity of the student residence to the city train station, it is expected that the student residence would expect regular visits of EVs for charging. Thus, 3 × 22 kW EVCS are planned for the student residence, making the peak power requirement as 66 kW. It is also expected that the EVCS could work bi-directionally, i.e. with Vehicle-to-Grid (V2G) possibility.

2.4 Energy Management System

As it is evident from the above mentioned micro-grid elements, the whole setup is a combination of a variety of components, making it a complex setup overall. Thus it was important that the architecture of the Energy Management System (EMS) was modular as much as possible, in order to enable flexible control. Open Source Energy Management System (OpenEMS) Association founded on 15.11.2018, as the name suggests is an open source platform for collaborative development of a modular EMS [17]. OpenEMS has various industrial components such as ESS, Inverters, EV Wallboxes and others from multiple firms already integrated into the framework, and at the same time collects the experience from various industry experts in the form of controllers for individual elements of a Microgrid. Thus, it made sense that OpenEMS was used for controlling and optimizing the system defined in this paper. In Sect. 3, more details on the different control levels of OpenEMS and TCS are provided. The operational speed of the EMS has been strategically set to 250 msec, enabling real-time control of the components, and still allowing room for communication delays.

3 Approach

3.1 Framework

Energy management framework of a microgrid could be broadly broken down into two types: Centralized Energy Management System (CEMS) and Distributed Energy Management System (DEMS) (such as Multi-agent System based [18]).

In Table 1 some key features of CEMS and DEMS are compared. Both the approaches has its own advantages and disadvantages. Since CEMS has a higher optimization effectiveness, it fits as the best solution for the setup described in the paper, especially since the components (DGs, DES and load) require strong cooperation between each other to operate the system in a secure and reliable way [19]. In accordance to the above, the centralized superordinate control level at the EMS side is showcased in Fig. 7. From the figure, it is clear that the EMS tries to collect the system states from all the components and optimizes the usage of three DES, i.e. LIB, RFB and TCS. As a part of this work, controlling the load in not the aim, rather is to optimize the system according to the availability of DGs and load requirement.

TCS as defined in Sect. 2.2.1, acts as a subordinate controller. It is not only responsible for the operation and safety of the Heat exchanging systems but also ensures the thermal safety of RFB tanks where heat is stored. The EMS directs the TCS with information on how much and which direction the thermal energy has to be exchanged. According to the EMS directives the TCS runs autonomously to achieve these directives. The TCS by itself is not responsible for any optimization of the thermal storage, but at the same time has the authority to override the directives of the EMS, if it detects any irregularities in the system.

Table 1. Comparison between a CEMS and DEMS [19]

	CEMS	**DEMS**
Scalability	Low	High
Flexibility to structural changes	Low	High
Observability of micro-grid components[a]	High	Low
Optimization effectiveness	High[b]	Low
Computation cost	High	Low

[a]Observability here refers to the ability to measure system's current state in real-time, thus making CEMS inherently more observable, [b]Since components are more observable, optimization effectiveness is high

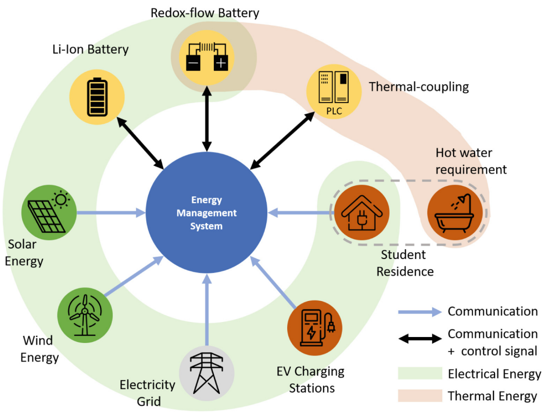

Fig. 7. Electrical and thermal power control concept of the micro-grid based on CEMS

The decision to move the control of the thermal storage out from an EMS to a dedicated TCS was a result of a detailed Failure Mode and Effects Analysis (FMEA). The TCS is currently under realization phase.

3.2 HESS Control Concept

A microgrid system in general offers possibilities of multiple optimization objectives which can be: reduced aging of ESS, improved operational efficiency, thus reduced operation cost and or environmental protection [20]. Obtaining all these objectives together, also commonly referred to as Multi-Objective optimization, is rather a complex process, especially under stringent constraints [21]. For the system defined in this paper obtaining such multi-objective optimization is even more complex due to the fact that there are three DES options offering two different options of energy forms, thus producing a multi-dimensional optimization problem. Additionally, the thermal storage is partly also influenced by the RFB operation, as small amount of heat is accumulated from the waste heat produced when ever the RFB is discharged, thus adding up to the complexity. Thus, to break down the complexity of controlling such a micro-grid, the control strategy and optimization are separated, so as to act as two individual algorithms as briefed further. Both these elements combined form the intelligent CEMS.

3.2.1 Optimal Control Strategy and Regulation

A fixed priority based operation strategy as defined in Fig. 8 is employed for controlling the micro-grid defined in this paper. During surplus availability, i.e. when generation is more than load consumption in the micro-grid, the surplus is channelled to the ESS, starting with RFB and followed by the LIB. If the surplus is still available after being consumed by the ESS then the remaining energy is channelled for the Power-to-Heat application, where the TCS comes

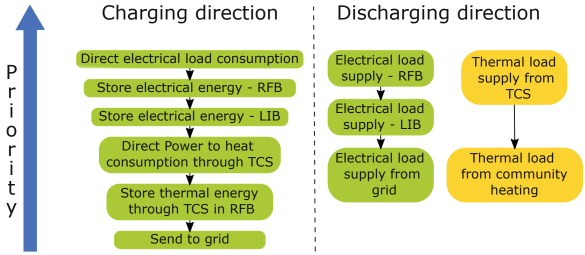

Fig. 8. Fixed priority based operation optimization of HESS for consuming the generated energy of PV and Wind. Each step has its own boundary conditions as explained in Sect. 3.2.1

into play. With the TCS the surplus power is first converted to heat and directly used to pre-heat the incoming tap water. If there is no heat requirement at that point, or the heat requirement is already satisfied, then the remaining energy is converted and stored as heat into the RFB. When available the rest of the surplus is sold to the grid. Similarly, during discharging phase, i.e. when no surplus power is generated from the grid, the electrical load is compensated with the energy stored in the ESS with the priority of RFB and LIB accordingly. If the ESS could not compensate the load requirement, then power is taken from the grid. In this paper the Power-to-Heat energy channel, shown in red background in Fig. 7, is omitted as the TCS responsible for it is under realization phase. Simulative results from this operation strategy has already been discussed in [15]. The target set points of the individual components are calculated every 250ms, while ensuring that they lie within the operation boundaries respectively. The operation boundaries taken into consideration are as follows:

1) RFB
   a) cannot be operated if the electrolyte temperature reaches 47 °C.
   b) Once the above boundary is reached the RFB goes into cooling down phase, where again it is not operable till the temperatures falls down to 46 °C
   c) max allowed power point is 14 kW in both charging and discharging direction.
   d) ESS is not operated between 0 kW and ±7 kW, as the RFB is considered to have low operation efficiency in this range. This ensures optimal control of RFB.
   e) once the electrolyte temperature reaches 45 °C, the ESS is operated at a limited maximum power output of 10 kW.
2) LIB
   a) can be operated to a maximum of 30 kW in both charging and discharging direction
   b) the target values are de-rated at the extreme SOC regions, i.e. between 80-100% and 10-0% SOC.

The defined fixed priority based optimization explained above, enables the RFB to be operated at almost constant power point, irrespective of disturbances in the grid. The disturbances are compensated by the components in the lower end of the priority, such that of LIB. This is done so because the RFB has major auxiliary requirements, in comparison to LIB. Thus optimizing it while also dynamically adjusting the auxiliary requirements is difficult in comparison to operating it at a constant power point.

In order to ensure stable operation of the individual ESS based on the above priority the target set points are then filtered through a moving average filter before sending the request to the ESS. The filtering is done to suppress the influence of the measurement noise in controlling the HESS, such that of continuos on and off switching of the systems. The focus behind this operation strategy has been to improve the self sufficiency of the building consumption and optimize the RFB. This strategy mentioned does not ensure optimal control of the HESS as a whole. To do so optimal control scheduling algorithms are implemented as defined further.

3.2.2 Optimal Control Scheduling

In order to improve the operation efficiency and still operate with the above defined strategy optimal control scheduling has been implemented. This optimization could be done for both charging and discharging direction, but in this paper only the charging direction is focused. The optimization steps are as follows:

1) predict the generation and load of the micro grid in a given day. With the prediction the hourly average surplus availability is determined.
2) based on the prediction, and while moving back in time from the end of the day, the time point is determined, where the generation would be greater than the load. This is called as a the predicted cross-over point. Thus it is important the individual ESS must be ideally full by this time of the day.
3) a buffer time of 30mins are subtracted to the predicted cross-over to accommodate the uncertainty of the predictions errors. The new time point is called as aimed cross-over point.
4) Hourly SOC predictions of individual ESS are done from the aimed cross-over point and backward in time, till the current time of the day, while applying a defined power. The iterations happen from the optimum power point till the max power point possible as per the surplus power.
5) During the iterations in the previous step, if the current SOC of the ESS are predicted in a future time from the current time, it means that the ESS has enough time to be fully charged if it starts charging later, i.e. in future time point. This future time point is considered as the scheduled start of charging of the individual ESS. The power point used during the respective iteration is defined as the optimum power point of the day. The iterations start from the optimum power point of the individual ESS which are 14 kW and 22 kW for RFB and LIB respectively. These points are where the AC to DC conversions are the lowest.

This optimization method is inspired from the implementation in [22]. As an improvement of the method the last step of finding the optimum charging point is proposed in this paper. This optimization enables the individual ESS to be operated at the best optimum power point on a respective day, thus reducing charging losses. On the other hand it also ensures that the ESS dont stay at higher SOC ranges, i.e. ≥90%, for a long time, which increases ageing [23–25]. In order to realize the optimal control scheduling PV and Load forecasting algorithms are necessary. The PV power is forecasted one day ahead with an hourly resolution based on Online Numerical Weather Prediction (NWP) Data [26]. In order to know how the prediction process works out please refer to [27]. The NWP based forecasting are nearly accurate for a clear sky day, but it not reliable on a rainy, cloudy or foggy days [27], as can also be seen in Fig. 9.

The building load consumption pattern is more or less similar irrespective of the day. Figure 10 depicts a box plot analysis of hourly load measured between June and August 2022. The box plot provides information on maximum, 75th percentile, median, 25th percentile and minimum through each boxes and its whiskers. The outlier data points are marked in red. Greater the gap between the median and its respective 75h and/or 25th percentile data, higher is the variation of load occurrence. From Fig. 10, it is evident that consumption between 0-7 UTC and 21-23 UTC is more or less similar and with low variation. Whereas the load consumption between 7-21 UTC is dynamic, and has huge variations. Nevertheless, the load patter still remains the same, i.e. peak between 17 and 21 UTC. Based on this information it is safe to assume that every day load would more or less replicate the previous day. Thus, the previous day's hourly average data is used as load prediction for the current day in this paper.

Using the above predictions, the charging of individual ESS are optimally scheduled. Based on the optimization and operation strategy discussed here, the operation results are discussed further.

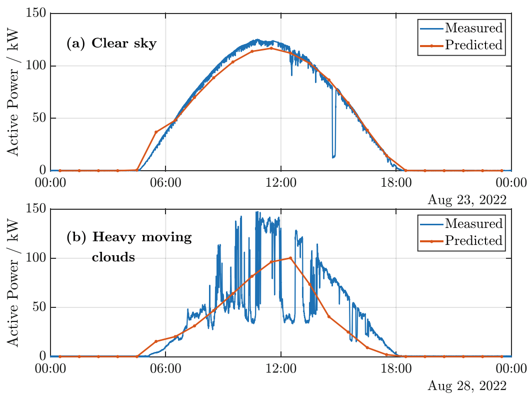

Fig. 9. PV prediction performance for: (a) clear sky day - 23.08.22, and (b) day with heavy moving clouds - 28.08.22

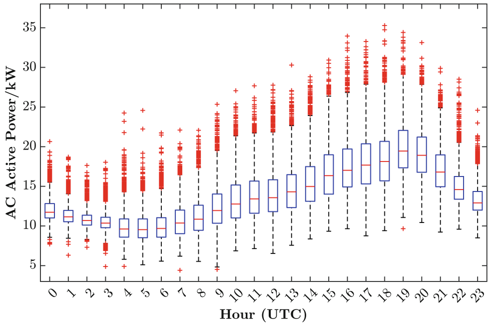

Fig. 10. Box plot of hourly average load requirement of the building. Measurements between June and August 2022

4 Results and Discussion

To provide a better comparison between operation with just fixed priority based optimization and the one along with optimal charge scheduling two different types of days are considered, and the findings are noted as follows. The results are not one on one comparable, as the weather conditions and system states are not exactly the same, but they are more or less similar. Since the microgrid is a real setup which is continuously operated and is reliant on naturally occurring renewable energy generation, reproducing exactly similar conditions for performance comparison is not possible. The examples considered here are clear sky days, i.e. with very minimum to no moving clouds.

4.1 Only Priority Based Optimization

An example operation day (see Fig. 12) of 04.08.22 is considered for the case of charging operation of the HESS without optimal scheduling on a clear sky day. Here the fixed priority based optimization (refer Sect. 3.2.1) alone were in action, i.e. the HESS tries to charge as soon as surplus is available. In the figure the HESS is depicted by the blue (RFB) and orange (LIB) lines. Until 5:30 UTC the LIB tries to maintain the grid (black line) at 0 kW. Once the available surplus exceeds 7 kW RFB starts charging, thus the LIB gives up part of the charging power to RFB. The HESS as a whole has enough time to be fully charged on the given day, but without optimization the time frame was not optimally selected. Especially the LIB, due to its smaller capacity and larger power capability, had enough time to charge at the most efficient power point, i.e. around 22 kW where the inverter efficiency is around 97%. But almost from 0-60% of the charging happened at charging power with lower efficiency thus resulting in higher operational losses. Later on the charging power of LIB stabilized at maximum power of 30 kW, which also is not the optimal operation point of the LIB inverter. Additionally, due to the suboptimal charging schedule both the ESS remain at higher SOC range, i.e. $\geq$95% SOC for a long time, which also leads to partial health degradation of the ESS.

4.2 Priority Based Optimization + Optimal Charging Schedule

Based on the aimed cross over at 15:30 UTC as shown in Fig. 11, delayed charging schedule was defined for the HESS. The operation results could be seen in Fig. 13. As per the optimization the LIB was scheduled to be charged from 10:00 UTC at its most optimum operation point, i.e. 22 kW. On the other hand due to lower power capability of RFB the optimizer (refer to Sect. 3.2.2) could not find an optimal schedule for the RFB, thus it started charging as soon as possible. In this case the LIB was able to be fully charged and while doing so was operated almost all the time at the defined efficient operating power point of 22 kW, except few times it had to adjust itself due to dynamics of the surplus availability. Thanks

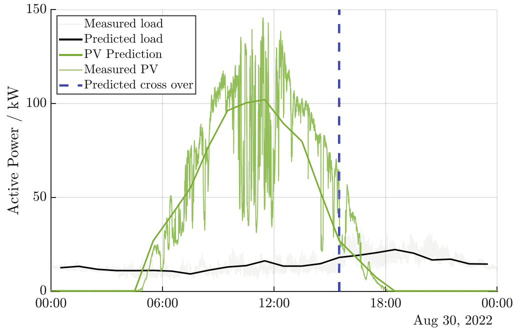

Fig. 11. Aimed cross-over point for a normal day with moving clouds day of 30.08.22. Based on the predictions the operation could be witnessed in Fig. 13

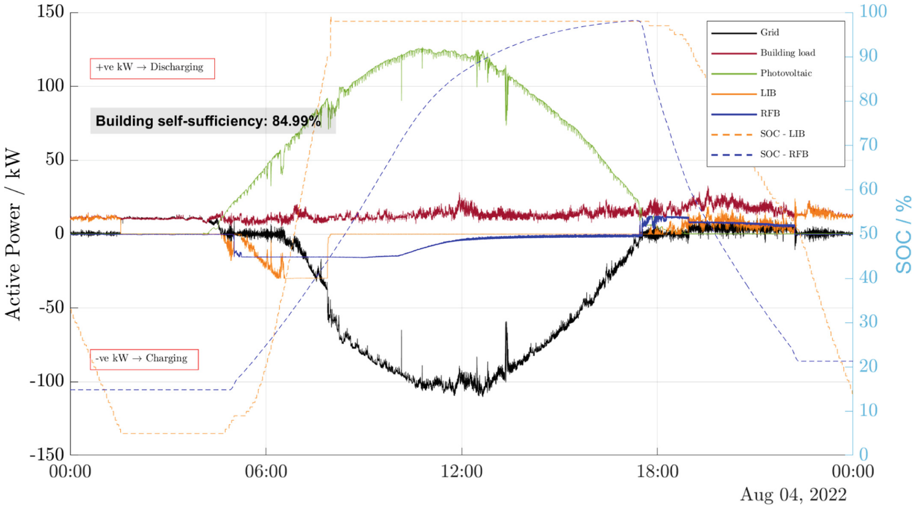

Fig. 12. Real operation of the micro grid without optimization on a clear sky day - 04.08.2022. Building achieved a self sufficiency of 84.99% on this day

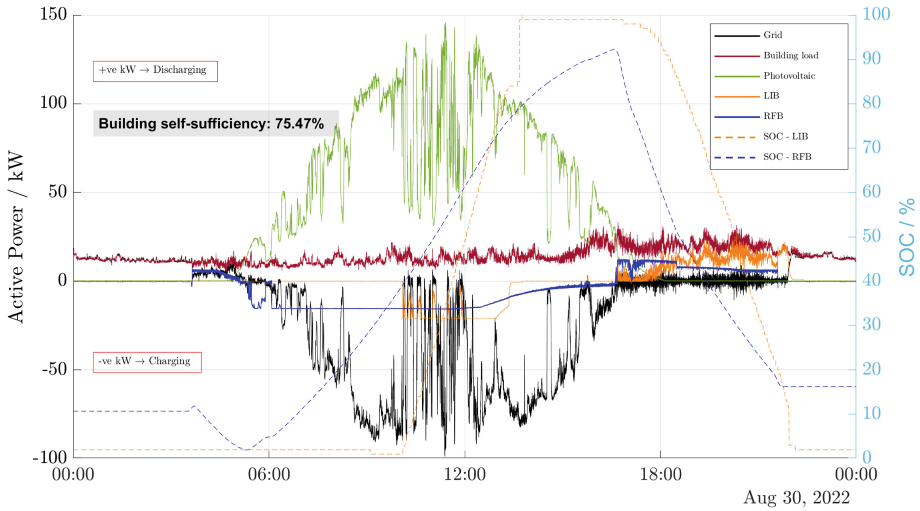

Fig. 13. Real operation of the micro grid with optimization on a normal day with minimum moving clouds - 30.08.22. The Microgrid achieved a self sufficiency of 75.47% on this day.

Table 2. Results comparison of AC to DC conversion losses pertained during charging of LIB from real operation. The comparisons are done on different days, thus are not directly comparable, but the weather conditions were very similar

Day Type	Without optimal scheduling				With optimal scheduling			
	Date	*Charging efficiency (%)*	*SOC gained (%)*	*Wait period at High SOC (hr)*	*Date*	*Charging efficiency (%)*	*SOC gained (%)*	*Wait period at High SOC (hr)*
Heavy moving clouds	10.07.22	89.05	93	7.3	28.08.22	90.5	99	1.53
clear sky	04.08.22 (Fig. 12)	89.55	93	9.57	30.08.22 (Fig. 13)	90.64	98	2.85

to the fixed priority based optimization, the RFB saw a constant charging power point the whole time, until the electrolytes reached its upper voltage limit, from then onwards the power point had to be de-rated. Thus, while looking at both LIB and RFB as a HESS the overall operation losses are drastically reduced with this strategy.

Although the day without optimization the microgrid was able to achieve a higher self-sufficiency of 84.99% compared to 75.11% with optimization, it does not portray the efficiency gained from the optimization. Rather the result of optimization is hidden in terms of reduction in conversion losses in the inverter of the individual ESS, and especially for LIB in the setup. This is because the RFB is already optimized by the fixed priority based operation strategy, thus does not gain much more from optimal scheduling. Table 2 summarizes the reduction in conversion losses and reduction of wait period at high SOC range for LIB by the optimization. For better understanding two different types of days are selected: clear sky days and days with heavy moving clouds. Clear sky days portray situations where the Individual ESS could be charged stably in a single operation condition with very less to no disturbances, thus providing better optimization possibility. Days with heavy moving clouds define days when the PV output changes dynamically, which corresponds to dynamic change of operation points of the individual ESS. As mentioned earlier in Sect. 3.2.2, moving clouds are difficult to predict thus act as the major factors of optimization failure.

For the case of heavy moving clouds Table 2 provides information on two different days, i.e. 10.07.22 and 28.07.22. Here one can observe that conversion losses are lesser for the case with optimization with optimal scheduling, and the wait time at high SOC is drastically reduced, i.e. about 6 h. Even though optimization on a cloudy day is difficult, the micro-grid was still able to gain from the optimization.

Similarly for the case of clear sky day, both the days chosen, that are: 04.08.22 (check Fig. 12) and 30.08.22 (check Fig. 13) had more or less similar system states, thus a much better comparison could be done. Again the LIB profited by the optimum charge scheduling and was able to reduce the conversion losses, even-though for the fact that the SOC gained was greater on 30.08.22 in comparison to 04.08.22. Again here the wait time for the LIB before discharging is drastically reduced, i.e. about 7 h. Thus, this provides the validation of the optimal scheduling.

5 Conclusion and Outlook

This paper has briefly introduced the setup of a HESS consisting of a 100 kWh RFB and 60 kWh LIB, installed at a student residence in Bruchsal, Germany. The student residence has a total energy generation capacity of 230.5 kWp_{DC} from locally installed PV and Wind energy sources. The main motivation of researching a HESS is its flexibility of operation covering a wide range of applications. Additionally, a novel heat storage system is also introduced, where the re-engineered electrolytes of the RFB are used as a medium to store heat. Along with external heat input provided to the defined heat storage system, even the waste heat generated during the operation of RFB is stored and effectively reused, thus improving the cycle efficiency of the RFB. To control such a conglomerate, a centralized EMS is deployed, due to its advantages of better optimization effectiveness. The EMS acts as a superordinate control and dictates operation to each controllable component, while also optimizing the whole system. This paper focused on the method of optimizing the charging of HESS enabled by solar and load predictions. With the predictions, a cross over point of generation capability and consumption requirements are identified, and thus a delayed charging schedule at the most optimum operation point are defined for the individual ESS. Real-life operations of the micro-grid are compared to analyse the efficiency gained by the micro-grid with the help of the optimization. To do so two different types of days are considered, namely: clear sky day and day with heavy moving clouds. The AC to DC conversion losses during the charging process of the HESS are compared. The optimization enables the micro-grid to intelligently choose the operation conditions and thus reduce the losses which goes unnoticed in normal operation.

Similar to the optimization of charging direction, the EMS could also be optimized for discharging direction. Additionally, the charging and discharging optimization could also be combined for achieving more complex and multi-objectives. With the setup breiefed in this paper further optimizations are being researched, which could be broken down as follows:

1) RFB:
   a) improve round-trip efficiency through reducing pump and inverter losses
   b) reduce standby consumption
   c) reduced ageing at high temperatures
   d) maximize waste heat utilization through TCS
2) LIB:
   a) reduced ageing by controlling the charging and discharging process
   b) improve efficiency through reduced inverter losses
3) LIB + RFB HESS: improve building self-sufficiency (both electrical and thermal load)

As an outlook, various optimization solutions based on heuristic or model-predictive methods would be implemented on the setup to attain the multi-objectives mentioned. Based on the results, a detailed analysis would be done on how far better would such a HESS with Power-to-Heat solution work compared to a system with a single ESS.

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