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OPTIMIZED ENERGY MANAGEMENT OF A PHOTOVOLTAIC-HEAT PUMP SECTOR COUPLING SYSTEM WITH ELECTRICAL AND THERMAL ENERGY STORAGES IN AN OFFICE BUILDING

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Abstract

About 77 % of energy demand in non-residential building is for heating and cooling, highlighting the urgent need for sustainable solutions to decarbonise this sector. A promising approach is the integration of a photovoltaic (PV) system, a reversible power-controlled heat pump (HP) with electrical and thermal energy storage, managed by an energy management system (EMS). Latent thermal energy storage (TES) enables demand flexibility for maximum renewable energy utilisation via HPs. A lithium-ion battery (LIB) is incorporated to dynamically balance load and generation mismatches. Such a PV-HP system operated by a priority-based EMS will be introduced in this paper. The system is used to efficiently regulate energy flows to provide thermal and electrical energy to the office building. The EMS features an optimised LIB charging management to prevent high state-of-charge (SOC) levels over time and assesses TES real-time conditions to adjust HP operation accordingly. A case study examines system performance over a representative day, achieving 81.6 % self-sufficiency and 79.8 % self-consumption rates.

1 Introduction

The entire building sector in Germany accounts for 35 % of total energy consumption. Of this, 37 % is accounted by non-residential buildings such as offices, schools, supermarkets and churches [1]. A closer look at the total final energy demand of non-residential buildings shows that space heating alone accounts for around 72 %, followed by lighting at 18 % and 5 % for air conditioning. This highlights the need to modernise the thermal and electrical energy systems of non-residential buildings and the building sector in general.

One promising approach to solving this issue is the concept of sector coupling. This refers to the coupling of different energy sectors (heat, transport and industrial/services) with the help of electricity from renewable energy sources [2]. In non-residential buildings, sector coupling focuses on the conversion of renewable electricity into heat and cold [3]. This can be achieved on a decentralised level near the customer's location through the utilisation of HPs. They are one of the most promising technologies for this application, as they can be powered by renewable electricity, have a high thermodynamic efficiency, and are suitable of both heating and cooling buildings [4], [5]. Due to their technical advantages and the introduction of federal funding for efficient buildings since 2016, there has been a steadily increasing market growth for HP systems [6]. For the year 2022, this meant that in every fourth heating system replacement in Germany, a HP was installed. It is expected that this market growth will further scale with the enactment of the Building Energy Act in January. The German government anticipates that new heating systems will cover 65 % of the heat demand from renewable sources [7]. In order to address the aspect of sustainably generated electrical energy within the concept of sector coupling, the HP is often integrated with a PV system to form a PV-HP system. The PV system is responsible for the supply of renewable PV energy. If the PV-HP system is complemented by thermal and electrical energy storage and is controlled by an EMS, a system is created that not only reduces emissions through the utilisation of renewable energies but also increases self-sufficiency and maximises self consumption [8]. By integrating energy storage technologies for both forms of energy, maximum flexibility for demand-side management can be achieved. To store thermal energy for heating and cooling purposes, latent heat TES can be utilised. Their advantage over sensible heat TES lies in their ability to compactly store thermal energy across a stable temperature range with minimal losses over time [9]. In the electricity sector, the LIB stands as the most prevalent form of energy storage system (ESS), primarily due to its rapid response capabilities, high efficiency, and the declining market prices [10].

1.1 Literature review

Motivated by this objective, a PV-HP sector coupling system with thermal and electrical energy storages is being investigated at Karlsruhe Institute of Technology (KIT). These systems have also attracted considerable research interest in the literature. Numerous studies focus on controlling and economically and sustainably evaluating PV-HP systems [8], [11], [12], [13], [14]. These systems vary in configuration, some integrating thermal and electrical energy storage, while others do not. Pinamonti et al. [11] present a rule-based control for a PV-HP system encompassing heating and cooling operations. Excess PV power is stored in water tanks and building thermal capacity. The results demonstrate enhanced self-consumption and autonomy rates through the rule-based EMS, particularly through the utilisation of building thermal capacity. Perrella et al. [12] investigate the impact of an EMS on the performance of a PV-HP system with electrical and thermal storage across two climatic zones. They demonstrate that overheating the domestic hot water (DHW) tank increases self-consumption and reduces grid feed-in demand. The adaptation of the EMS to regional climate conditions proved crucial. Battaglia et al. [8] simulated a PV-HP system with a DHW tank and electrical storage, controlled by an EMS. They have shown that grid consumption can be reduced by controlling the components with an EMS. According to the authors, this is due to the adjustment of the HP operating hours to the time window of the PV surplus power and the overheating of the DHW storage tank. The study by Baraskar et al. [13] examined a 12-month heating operation of a PV-HP system with a LIB in a single-family home. The HP is controlled by discrete SG-Ready signals, while a rule-based EMS controls the overall operation. The results indicate a reduction in household energy consumption by the PV-HP system with LIB. However, intelligent control may lead to a decrease in HP efficiency due to higher supply temperatures. Niederhäuser et al. [14] investigated a PV-HP system with a hot/cold water tank for heating and cooling operations in real-world usage. They utilised an EMS that allocates all generated PV energy for the HP. The study demonstrated an enhancement of the seasonal performance factor (SPF) of the HP due to the PV system.

The literature review reveals investigations into PV-HP systems with both electrical and thermal storage managed by an EMS. Previous studies primarily concentrate on DHW tanks or the thermal capacity of the building for storing thermal energy. In this study, however, the system diverges by employing latent heat TES for both heating and cooling operations, enabling precise thermal energy storage via the HP.

1.2 Structure

The paper's structure continues as follows: chapter 2 outlines the system setup, while chapter 3 details the energy management framework, presenting the EMS sequence, an optimised charging protocol and evaluation method for the TES. Chapter 4 presents and discusses real operation results. Finally, chapter 5 concludes the paper and offers future perspectives.

2 System Configuration and Components

At KIT, a PV-HP system with energy storages was designed and installed to provide thermal and electrical full coverage for an office building. The system was retrofitted into the building as a modernisation measure. Fig. 1 depicts the layout of the implemented system, illustrating all components, both sectors, and their interplay. Subsequently, the components will be described in detail according to their affiliation with either the thermal or electrical sector.

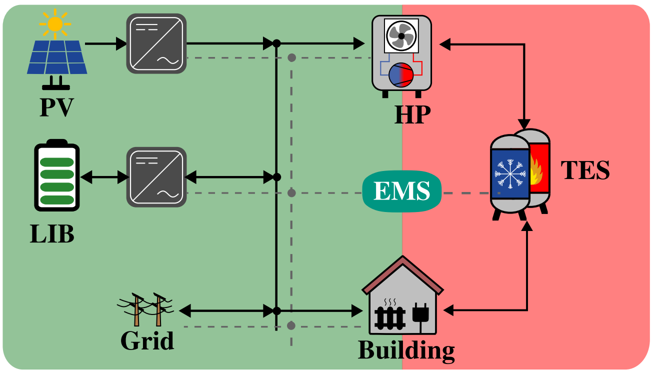

Fig. 1 System layout with solid connection lines depicting the physical connection and dotted lines depicting the communication between the components

2.1 Electrical Components

The electrical components within the system include a PV system for electricity generation, a LIB for electrical energy storage, the building load and the HP compressor.

2.1.1 Photovoltaic Energy Source: The PV system considered in this study is an existing installation from 2018, mounted on the roof of the examined office building. A total DC power of $7.2\,\mathrm{kWP}$ is installed and is directly connected to the AC grid. As the PV system is not sufficient to power the application, the system has been hypothetically scaled by a factor of 2. Consequently, the PV power profile follows the trend depicted in Fig. 4. The graph was captured on a clear sky day in spring. Noticeably absent is the peak, which is truncated by the shading of panels of the system.

2.1.2 Lithium-Ion Battery: For the storage of excess electrical energy, a LIB with a capacity of $10.2\,\mathrm{kWh}$ and an output power of $10\,\mathrm{kWP}$ is used within the office building. Similar to the PV system, the LIB is grid-connected to the AC side of the building's network.

2.1.3 Electrical Load: As this system is a modernisation of the building, the building load could not be measured. Therefore, the electrical load in this study is characterised using the standard load profile G1: Commercial, operating from 08:00 to 18:00, provided by the German Association of Energy and Water Industries (BDEW) [15]. It has been adjusted to reflect the specific conditions of the system, such as building-specific energy characteristics and usage patterns. To normalise the profile, energy characteristics measured in units per square meter were employed. Only areas conditioned by the HP system were considered, encompassing electrical loads like lighting, office equipment, and auxiliary devices such as those found in a kitchenette. For the office building under study at KIT, with a floor area of $130\,\mathrm{m}^2$, the annual energy consumption per square meter is calculated as $27\,\mathrm{kWh/m}^2$ [16]. The usage profile, indicating employee working hours, was factored into generating a weekly profile. Notably, the office building is occupied by employees on a 5-day workweek, resulting in nearly no load consumption over weekends. Incorporating this behaviour into the weekly load profile, the profile consists solely of weekdays and Sundays. Consequently, a transitional season load profile for a one-week period is generated, as illustrated in Fig. 2. As depicted, the primary load occurs mainly between 08:00 and 18:00 local time. Examining a typical workday, a decrease in power is observed during the lunch break. Here, there is a drop relative to the daily peak load of approximately $1.4\,\mathrm{kW}$. In contrast, on a Saturday or Sunday, the maximum load is only $0.08\,\mathrm{kW}$. Based on this profile, the building consumes a load of $3.64\,\mathrm{kWh}$ on a workday and $0.5\,\mathrm{kWh}$ on weekends.

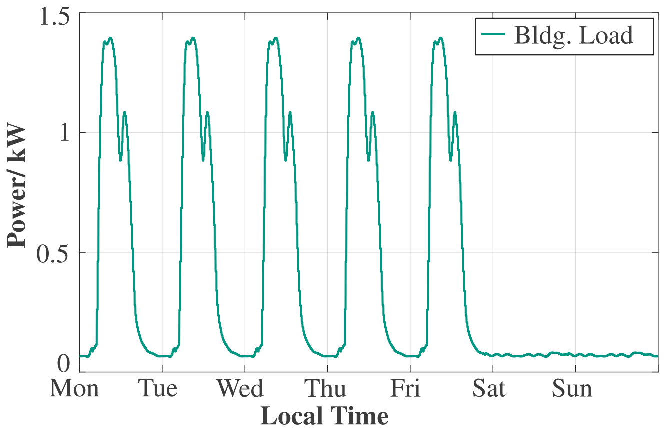

Fig. 2 One week electrical power consumption by the building, generated based on the standard load profile from BDEW [15]

2.2 Thermal Components

The thermal components within the system consists of a HP, two latent heat TES utilised for heating and cooling functions, and the building to be conditioned. The sizing of HP is based on heating and cooling load calculations, conducted using the building data of the areas requiring heating and cooling on-site.

2.2.1 Heat Pump: The deployed HP is an air/water HP with a heating capacity of $10.2\,\mathrm{kW}$. Additionally, the HP can provide cooling as well, with a cooling capacity of $10.3\,\mathrm{kW}$ in this operating mode. The compressor's power output can be dynamically controlled to adjust energy consumption. This power modulation capability facilitates seamless integration of the HP into the EMS, thus allowing for efficient operation.

2.2.2 Thermal latent heat energy storage: For the TES, two 600-liter tanks, one for heating one for cooling, filled with encapsulated PCM elements have been integrated into the PV-HP system. Water is used as the heat transfer fluid, flowing past the individual PCM elements to facilitate heat exchange. The storage tank for heating operation has a capacity of $24\,\mathrm{kWh}$, whereas the tank for cooling operation has a capacity of $19\,\mathrm{kWh}$. The PCM in the heating storage tank has a phase change temperature T_{PC} of $45\,^{\circ}\mathrm{C}$, while the temperature for the cooling storage tank is set at $10\,^{\circ}\mathrm{C}$. Both tanks are equipped with two temperature sensors each, positioned at the upper and lower ends of the tanks, to monitor temperature within the TES.

2.2.3 Thermal Load: The heating or cooling load of the office building simplistically arises from its construction, environmental conditions, and desired room temperature. Within this system, the only variable to influence the thermal load is the room temperature, which can be adjusted in two ways.

1. Through an EMS that externally controls the indoor temperature.
2. Decentralised room thermostats that allow users to adjust the indoor temperature locally.

However, in this study there is no active intervention in the thermal load of the building. Instead, the HP and TES provide the heating and cooling power required by the building's occupants on demand.

2.3 Energy Management System

For data collection, analysis, and subsequent control of individual components within the PV-HP system, an EMS based on the Open Source Framework OpenEMS is employed [17]. OpenEMS offers a modular architecture and manufacturer independence, providing high flexibility and compatibility with a wide range of devices. The EMS monitors and coordinates the energy flow of the individual components at a speed of $250\,\mathrm{ms}$.

3 Energy Management Approach

In order to achieve cross-sector operation of all thermal and electrical components, a priority-based EMS is developed in this paper. From an EMS perspective, the LIB serves as a short-term storage system capable of dynamically balancing load and generation imbalances within 250ms to improve self-sufficiency. Furthermore, the LIB should provide electrical energy for the HP and the office building during periods when PV energy is not available. The main purpose of the HP is to thermally condition the office building. In addition, the EMS should use the HP in combination with the TES to charge the TES with surplus PV power. This provides demand-side flexibility for the operation of the HP and maximises the use of the PV electricity generated. To ensure that the components can fulfil their task, the priority-based EMS determines the set points for the HP, LIB and TES to achieve an efficient and ageing-optimised operation based on their current condition and the specified priorities. Other aspects related to the thermal control for heating/cooling the building, such as operating mode and inlet temperature set point, are managed by the internal controller by the HP system. The highest priority is given to the electrical and thermal supply of the office building. Then the LIB is prioritised over the TES for charging. This sequence was selected due to the higher value attributed to electrical energy from an economic standpoint. This chapter describes the EMS approach used to optimal control the HP-PV system with all the ancillary aspects necessary for an efficient and ageing-optimised system operation.

3.1 Examination and evaluation of the TES for an EMS

As described in Chapter 2.2.3, the thermal sector operates on a demand-oriented basis. For this system, it means that whenever the set temperature deviates from the actual temperature, the room is conditioned using the TES. If the storage is not sufficiently charged, it must be replenished by the HP. From a control perspective, this entails that the state of the TES defines the state of the entire thermal sector. Consequently, the actual state of the TES needs to be monitored, evaluated, and integrated into the EMS for the optimal control of the electrical sector. This paper pursues an approach for monitoring the actual state of the TES, which divides the tank into different zones based on the measured temperatures in the upper and lower regions of the tank. This division aims to facilitate operational planning for the EMS. The zones of the heating and cooling TES are illustrated in Fig. 3. Each zone implies a distinct operating point for the HP in the EMS later on. The precise temperature thresholds for zoning are provided for both storage units in Table 1.

Fully Charged (Full): When both the upper and lower temperature sensors exceed the phase change temperature of the PCM T_{PC} or the upper sensor (heating)/lower sensor (cooling) exceeds the full temperature T_{Full}, the TES is considered fully charged. In this state the TES can no longer be charged by the HP.

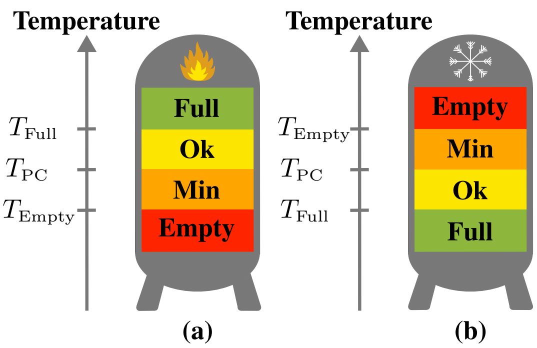

Fig. 3 Integration of TES into EMS, the four zones for (a) heating TES and (b) cooling TES based on full, empty, and phase change temperatures.

Adequately Loaded (OK): If the temperature in the TES remains within a defined range between T_{Full} and the phase change temperature T_{PC}, the TES is considered to be sufficiently charged. In this state, the building can be supplied from the TES tank. However, it is also possible to continue injecting thermal energy into the TES via the HP.

Minimum Charged (Min): When the temperature in the upper region (heating) of the tank falls below the phase change temperature T_{PC}. Vice versa for cooling. The TES is only minimally charged. In this state, the building can still be supplied from the TES tank for a limited period of time, but reliable supply over a longer period of time is no longer guaranteed. Therefore, the HP must operate in partial load mode to recharge the TES until the "OK" state is reached.

Discharged (Empty): If the temperature throughout the entire TES falls below (heating) or exceeds (cooling) the T_{Empty} temperature, the TES is considered completely discharged. In this scenario, the TES needs to be recharged as quickly as possible to ensure a demand-driven supply to the office building.

Table 1 Temperature thresholds for the TES, in cooling or heating operation, determining the state of the TES.

Temperature Levels	TES Heating	TES Cooling
Full T_{Full}	53 °C	5 °C
Phase change T_{PC}	45 °C	10 °C
Empty T_{Empty}	40 °C	12 °C

3.2 Optimised Charging Control of the LIB

The EMS includes an algorithm designed to actively mitigate premature battery ageing caused by high SOC. Accelerated ageing occurs when the LIB is charged to a high SOC too early, leaving it fully charged and unused for a significant part of the day [18]. To minimise this effect, the system uses two forecasts - a PV generation forecast and a load forecast - to determine the point at which the LIB needs to be fully charged. Based on this timing, the system then determines when and at what rate the LIB should be charged to achieve $\mathrm{SOC}_{\mathrm{max}}$ at the point of intersection. The basic principle and the implementation approach described below are inspired by Palaniswamy et al. [19] and have been extended in this work to include the inverter and battery efficiency.

1. Forecasting PV and load power: The algorithm has to retrieve the load and PV forecasts for the current day. The load forecast uses a perfect forecast of the load profile from chapter 2.1.3, with hourly resolution for a one day period. The PV forecast uses online numerical weather prediction (NWP) data. It is derived from the forecast presented in the study of Starosta et al. [20], which includes power forecasts one-day ahead with hourly resolution. The power values are calculated every six hours based on numerical online weather forecast data specific to the location of the PV system. A full description of the forecasting methodology can be found in [20]. Fig. 4 illustrates the PV forecast utilised. The prediction does not exactly match the measured data. The reasons for this are explained in Chapter 2.1.1.

2. Calculation of the cross over hour: To determine the necessary time for full charging of the LIB, a comparison is made between predicted load and PV power. Starting from midnight and moving hourly backward to the current time, each value is assessed to identify when production surpasses consumption for the first time. At this juncture, the LIB must attain $\mathrm{SOC}_{\mathrm{max}}$, as surplus power will no longer be available thereafter. Forecast uncertainties are factored into the calculation by advancing the crossover point by one hour.

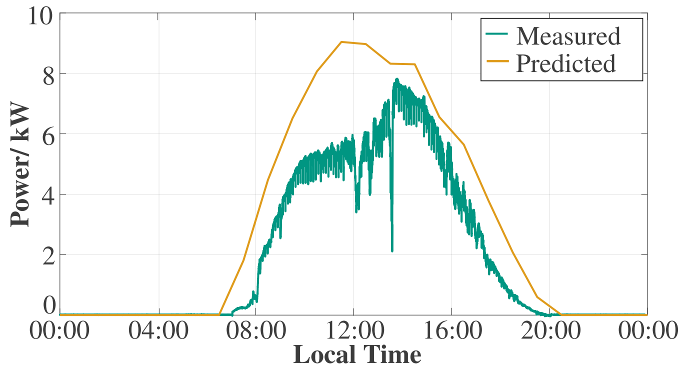

Fig. 4 PV power prediction for a sunny day compared to the measured values.

3. Hourly SOC simulation: An hourly prediction of the SOC of the LIB is calculated retroactively from the intersection point to the current time. This calculation accounts for the efficiencies of the inverter and the LIB. A predefined charging power of $P_{\mathrm{LIB}} = -3\,\mathrm{kW}$ is simulated, which can be increased up to the maximum charging power based on the predicted PV surplus. The SOC calculation will then continue for another hour based on the previously calculated SOC. This process is repeated until the calculated SOC falls below the current SOC. The point in time at which this occurs marks the beginning of LIB charging.

3.3 EMS sequence of the PV-HP system

The EMS algorithm is illustrated in Fig. 5. The control is based on the state of the TES, as explained in chapter 3.1. The system comprises four operating modes, each defining specific system control procedures. For better understanding, the following sign convention applies in this article: PV power, HP power and building load are positive. With LIB, the discharging power is positive and the charging power is negative. In addition, a positive grid power corresponds to a grid feed-in and a negative power corresponds to a grid withdrawal.

In the **Full** operating mode, the HP is deactivated. If the PV power P_{PV} exceeds the building power P_{Bldg}, surplus PV power charges the LIB. Otherwise, energy is drawn from the LIB until $\mathrm{SOC}_{\mathrm{min}}$ is attained, at which point the system switches to grid supply.

In the operating mode **Ok**, surplus PV power is initially directed towards LIB charging before the TES is charged. Excess energy is fed into the grid once the $\mathrm{SOC}_{\mathrm{max}}$ for the LIB and HP power P_{HP} are attained. In the event of insufficient PV surplus, the LIB is discharged before switching to grid supply.

In the **Min** operating mode, the HP operates at partial load with a fixed relative power set point $r_{\mathrm{P,HP}} = 50\,\%$, independent of the PV surplus. In the **Empty** mode, the HP operates at full load ($r_{\mathrm{P,HP}} = 100\,\%$). Afterwards in both modes, the surplus power is attained by comparing hp and building loads with the PV power. If surplus power exists, it is stored in the LIB. Upon reaching (SOCmax), surplus energy is directed to the grid. In the absence of surplus, energy is withdrawn from the LIB until SOCmin, at which point grid supply is engaged.

4 Results and Discussion

The system presented in chapter 2 is operated with the EMS introduced in chapter 3 for a test period of 7 days from 22.04.2024 to 27.04.2025. This chapter aims to analyse, evaluate, and illustrate the operation of the system. Additionally, it examines the approach of the TES and visualises the results

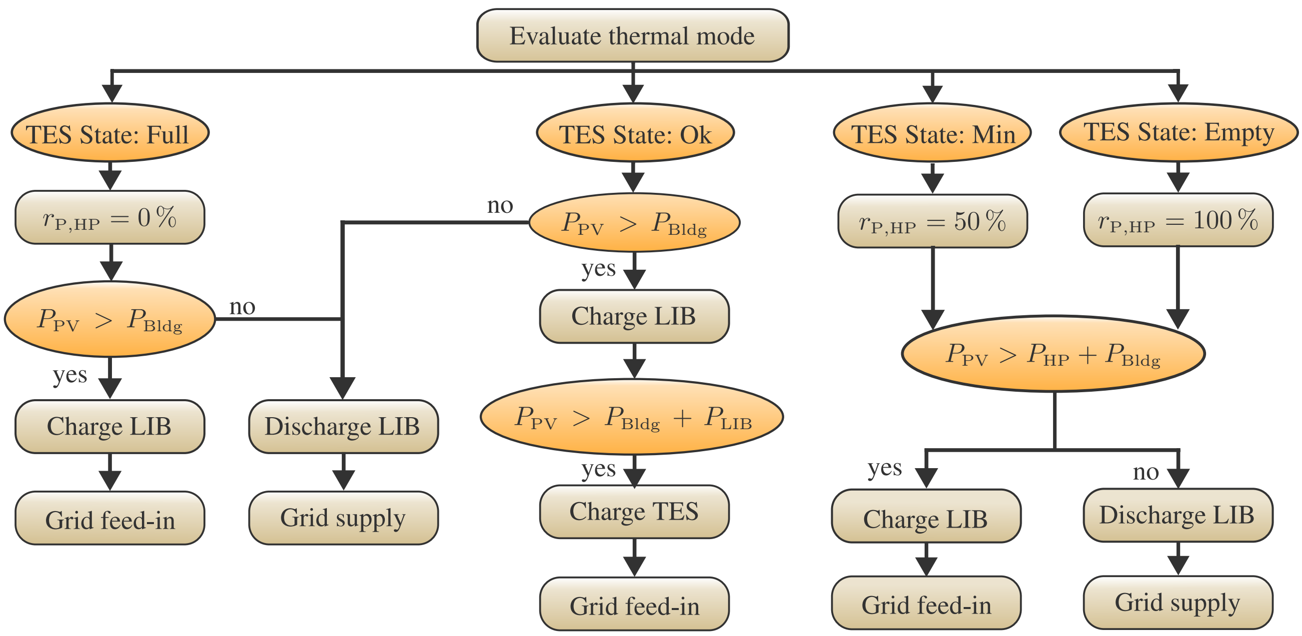

Fig. 5. Energy Management Sequence.

of the optimised charging control. To illustrate this, the operation is analysed using measurement data from an exemplary day within the test period. Firstly, it should be noted that the day shown here is a weekday when the office building only needed to be heated. Throughout this day, the minimum outside temperature was 2 °C and the maximum outside temperature reached 13 °C. Therefore, this study does not include results of the HP and TES in cooling mode. Shown is an overcast day with clouds, rain and sunshine.

An exemplary day is depicted in Fig. 6, presenting the complete operational data of the PV-HP system from April 25, 2024. Fig. 6a shows the power curves of the PV system, the building load, the HP and the LIB. Fig. 6b displays the grid power, derived from the aforementioned components. Analysis of the data in Fig. 6 reveals April 25, 2024, as a cloudy day, during which the PV power was available between 07:15 and 20:15 o'clock. The building load follows the pattern described in Chapter 2.1.3, with significant demand during working hours. The HP operates according to the building's comfort settings from 05:00 to 19:00 o'clock. From 05:00 o'clock onwards, the building is supplied solely with thermal energy from the TES. By 05:30 o'clock, the TES is discharged, prompting the HP to operate initially at full load and subsequently at partial load to recharge the TES. Throughout the day, the HP operates at higher power during the morning hours compared to the afternoon and evening. The HP stops running at 17:50 o'clock for this day. In contrast to the PV system and the HP, the LIB operates throughout the day, typically regulating grid power to 0 kW. This behaviour is clearly evident outside the PV window.

The optimised charging management of the LIB, as described in chapter 3.2, is depicted for the considered day in Fig. 7. The plot includes the PV and load forecasts used to calculate the intersection point, as well as the measured SOC profile of the LIB resulting from the use of the optimised charge control. The target time for the $\mathrm{SOC_{max}} = 94\,\%$ for this day is 18:30 o'clock and is represented by the vertical cross over line. The LIB is mainly used to cover the base load and support the HP operation during the night and morning. This results in the LIB being fully discharged at 11:00 o'clock. At 13:30 o'clock, the optimised charge management allows the LIB to be recharged. This allows the fully discharged LIB to be fully recharged with PV surplus power up to the crossover hour, without having to rest for long periods at high SOC levels. This aligns with the data from Fig. 6.

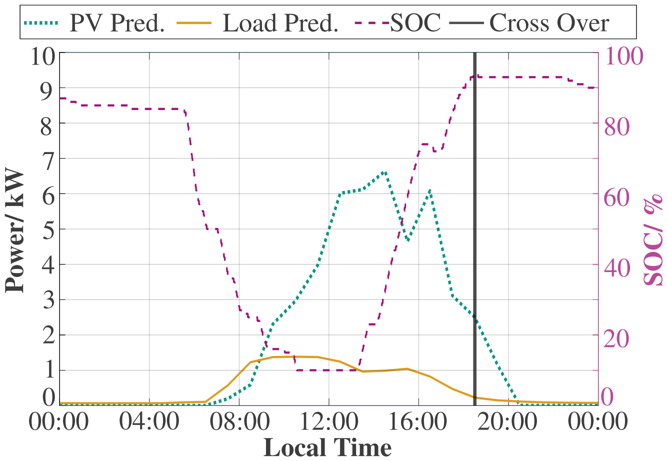

Fig. 7 SOC curve of the LIB with optimised charge management based on the intersection of load and PV forecast.

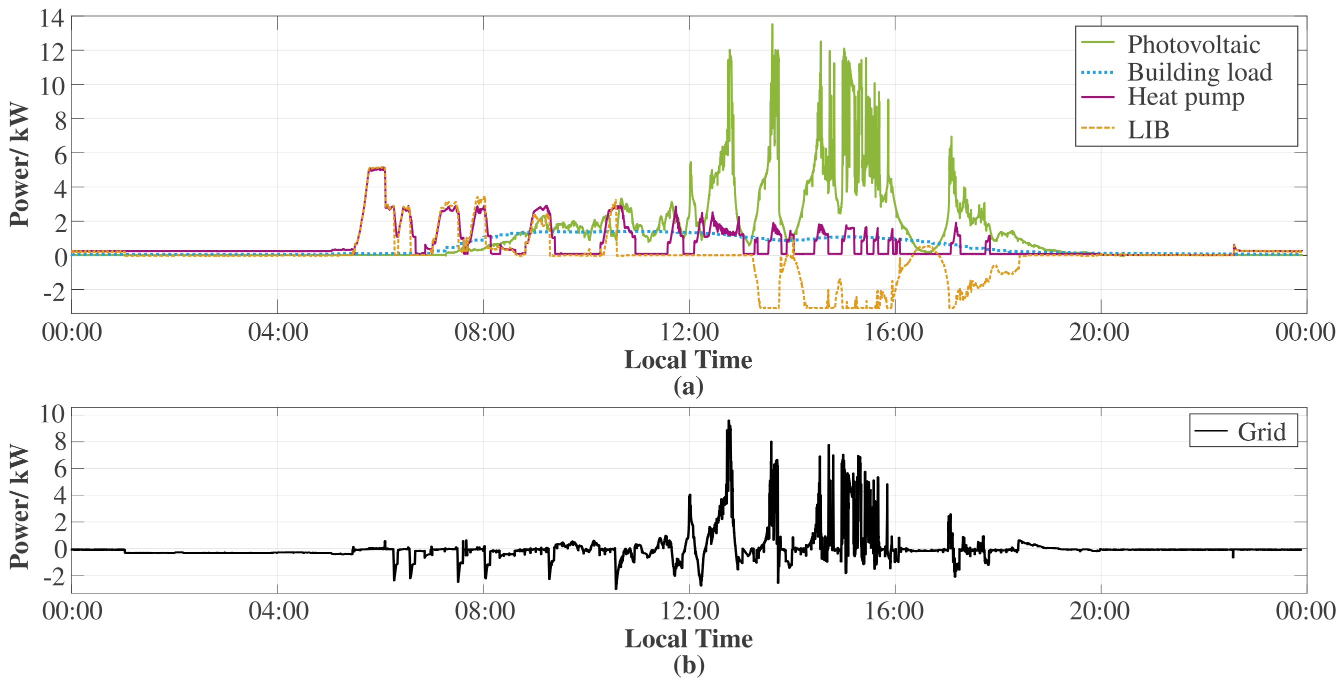

Fig. 6 Operation of the PV-HP System with EMS on a normal day with moving clouds - April 25, 2024. (a) power curve of system components; (b) power curve of the grid

To analyse the temperature profile of the TES during heating operation, the measured temperatures for the upper and lower areas of the tank are shown in Fig. 8. The zones defined in Chapter 3.1 and the time windows during which they are active are also depicted in the graph. The zones can be used to illustrate the operation of the TES in conjunction with the EMS. In general, the temperature profile shows that the TES is utilised at the start of the comfort period in the morning at 05:00 o'clock. A significant temperature drop, which puts the TES in empty state, is observed at 05:30 o'clock. This requires the storage to be recharged and the HP to be activated. This is confirmed by the power data of the HP in Fig. 6. Throughout the morning, the TES alternates between the operating states Ok and Min until it is fully charged at 13:00 o'clock. Until the end of the comfort period at 19:00 o'clock the TES state alternates between the states Full and Ok. In general, the visualised TES zones show that the TES is predominantly in the OK state and switches to the full state in the afternoon, when the PV power is at its highest.

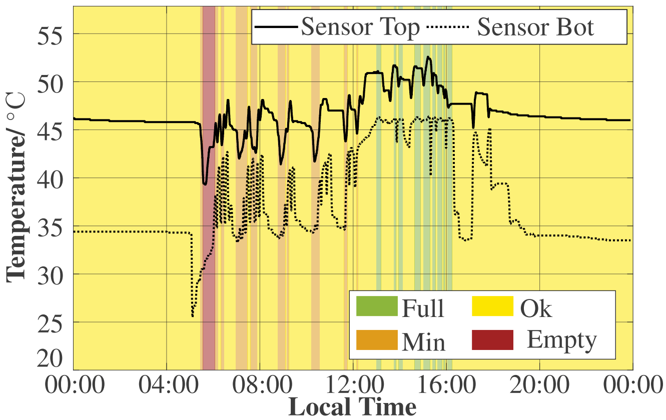

Fig. 8 Temperature curve in the upper and lower area of the heating TES with visualisation of the TES states from an EMS perspective.

Analysing the interplay between optimised charging management and EMS reveals that system components have distinct operational windows throughout the day. For instance, in the heating operation depicted here, the HP primarily operates in the early morning or forenoon to condition the space for the upcoming day. As this operational window falls outside the PV power window, the LIB is utilised to power the HP. Once the space is adequately conditioned, the TES is recharged from late morning until noon using surplus PV power. In the afternoon, with the building conditioned and the TES recharged, optimised charging management enables the LIB to be charged with the remaining PV power, ensuring it is fully charged for the night and the following day. Examining the grid power depicted in Fig. 8b, it becomes evident that the EMS does not perform optimally, particularly in regulating the HP load, especially during the morning hours. During this time, the LIB prematurely reduces its discharge power, resulting in grid power being sourced when it could have been covered by the LIB. For the depicted day, the system achieved a self-sufficiency of 81.6 %. Moreover, the self-generated PV electricity was consumed within the system with a self-consumption rate of 69.7 %. Considering solely the HP, it operated with a solar fraction of 73.4 % from sustainably generated solar power. This power originated either directly from the PV system or from the LIB. The LIB contribution to the HP amounted to 89.1 % of the total discharged energy. The portion drawn from the LIB to supply the office building constitutes 10.9 % of the total extracted energy.

5 Conclusion and outlook

This study focuses on the control of a PV-HP sector coupling system with LIB and TES in an office building application at KIT. The aim of this work is to develop an EMS that facilitates an efficient and ageing-aware cross-sector operation of the PV-HP system with latent heat TES and LIB, optimising self-sufficiency to minimise grid dependency. Firstly, the system and its components have been presented. The thermal components are a reversible, power-controlled HP and two TES, one for heating and one for cooling, as well as the thermal load. The electrical components consist of a PV system, a LIB and the electrical load. In order to optimise control of the PV-HP system, a priority-based EMS was developed in this study. The EMS acts as a supervisory control unit, controlling the component operation according to the current system state and defined priorities. The EMS includes a mechanism for optimised LIB charging control, which actively avoids high SOC levels to reduce LIB ageing. Furthermore, a method for evaluating TES data into four operating states to facilitate seamless integration of the thermal sector into the EMS is included. The operational performance of the PV-HP system was illustrated and analysed for an exemplary day to evaluate and interpret its performance. Based on the visualised data, it has been shown that the developed EMS enables a cross-sector operation of the PV-HP system with LIB and TES. It has also been proven that the optimised charge management actively avoids periods of high SOC, thus preventing accelerated ageing of the LIB. The extent to which ageing of the LIB has been avoided must be quantified in the future. The self-sufficiency of the office building is improved by storing surplus PV energy in the LIB and TES. Through the utilisation of the EMS the individual components operated at defined time windows, in particular the LIB and the TES. Notably, the TES is fully charged in the morning, while the LIB is charged in the afternoon, ensuring both storage's are charged by the end of the PV window for the next day. Furthermore, the data indicates that the LIB is primarily utilised to cover the HP load outside the PV window. Additionally, the data highlights that the EMS is not permanently able to control the LIB discharge power accordingly the HP load, as grid power is drawn despite being potentially covered by the LIB.

In this respect, the EMS needs to be further developed in order to minimise grid consumption even further and to ensure an ageing and efficiency-aware operation of the HP. It is therefore essential to accurately model the actual operation of the HP and TES. A better understanding of the sector coupling behaviour of the HP would allow for dynamic set points that are adaptable to the PV surplus. Similarly, for the TES, a deeper insight into the state of energy (SOE) would allow a more dynamic assessment beyond the limited four states used in this study. In addition, the system is still under construction. Additional temperature sensors will be retrofitted throughout the building to monitor the indoor temperature and influence the thermal load. The system will also have decoupled operation between the HP and the office building. This will allow functions such as heating the building while the HP is charging the cooling TES. All these system extensions and additional understanding of component behaviour will be integrated into the EMS of the PV-HP system in the future. As a perspective, various optimisation methods will be implemented in the EMS to achieve the overall objective of a cross-sector economic and sustainable operation of the PV-HP system.

6 Acknowledgements

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