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Empowering sustainable hotels: a guest-centric optimization for vehicle-to-building integration

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Abstract

In light of global warming, hotels account for one of the highest energy demands within the building sector, offering great decarbonization potential. As electrification increases, so does the demand for electric vehicles (EVs) charging stations at hotels and the proportion of Vehicle-to-Building-capable EVs. Therefore, the study explores the potential of guest-centric energy management. To accomplish this, we develop an optimization model for an energy management system that focuses on either cost-efficiency or carbon dioxide equivalents (CO2)-efficiency, grounded in a real-world case study. Through scenario analyses considering seasons as well as different guest mobility behaviors, this study discusses the expenses associated with CO2 savings using digital solutions. It emphasizes the currently perceived conflict between cost reduction and decarbonization goals to achieve a sustainable design of information systems. Thereby, this study highlights the critical importance of individual mobility behavior in enabling sustainable energy management for hotels.

Keywords: Energy management system, Hotel energy use, Guest mobility behavior, Mobility patterns, Vehicle-to-building, Sustainable tourism, Sustainable hospitality

Introduction

To mitigate climate change and halt global warming, it is essential to decrease emissions in the tourism sector, which is responsible for 8% of global emissions, with transportation account for half of these emissions, closely followed by buildings (Lenzen et al. 2018; Merli et al. 2019). While at least a foreseeable reduction in emissions can be expected in the transport sector with the electrification of vehicles, the building sector is still stagnating. Compared to other commercial buildings, hotels demonstrate one of the highest energy demands, offering great decarbonization potential (Chung and Park 2015; Dibene-Arriola et al. 2021). Thereby, 85% of the energy demand is covered by purchasing energy, causing up to 90% of the associated emissions, depending on the composition of the electricity mix (Huang et al. 2015). The travel patterns and mobility of hotel guests, especially their reliance on fossil-based transportation for arrival and departure, substantially elevate the carbon footprint associated with their stay. Given the hotel owner's responsibility for Scope 3 emissions under the Greenhouse Gas Protocol (Hoekstra and Wiedmann 2014), hoteliers should consider guest mobility as a crucial factor in their sustainability strategies. Additionally, with the ongoing electrification of the transport sector, hotel guests increasingly demand onsite charging as a substitute for convenient home charging. During vacations, hotel guests anticipate seamless mobility, enabling them to enjoy the flexibility to engage in a variety of activities. Thus, the charging demand further burdens hotel energy demand, i.e., emissions (Funke et al. 2019). This is especially true for hotels in rural areas where the surrounding infrastructure is less developed regarding charging stations. Besides emissions, the already high costs for purchased energy will continue to rise with increasing CO_2 prices demanding a solution to maintain energy costs within acceptable bounds (European Commission 2020). Reducing hotel emissions while supporting the electrification of transport is, therefore, an environmental, economic, and social need to enable sustainable growth, control energy costs, and compete for customers.

Against the background, the literature points out that Renewable Energy Sources (RESs), digitization of energy management, and the use of energy flexibility with the help of digital technologies may accelerate the change toward sustainable hospitality (Pina et al. 2012; Heffron et al. 2020; Wilson and Styring 2017; Rej et al. 2022; Leinauer et al. 2022). For this purpose, an Energy Management System (EMS) may enable hotel owners to increase energy efficiency and flexibility, while using more RESs, saving energy, and avoiding emissions (IPCC 2022; Fiorini and Aiello 2022; Alfaverh et al. 2023; Lee et al. 2023). Current EMSs typically optimize for cost by minimizing expenses from grid purchases and onsite RES generation, based on fixed electricity prices. Consequently, the emission factor of the consumed electricity mix is often disregarded due to fixed-price contracts.

Contrarily, literature on Energy Informatics suggests that CO_2-based energy management differs from cost-based management by optimizing load allocation according to the emission factor of purchased electricity instead of its price (Fiorini and Aiello 2018). Future CO_2-based EMSs could reduce emissions by maximizing the use of owned RESs and minimizing purchases from high-emission sources, considering the RES share in the electricity mix at the time of purchase. Despite the significant decarbonization potential of CO_2-based EMSs, their impact on low-emission hotel operations remains unexplored.

Further, integrating Electric Vehicles (EVs) into a building's EMS provides additional energy storage capacity and flexibility to interact with the electricity market and increase RES utilization (Liu et al. 2013). In designing an EMS for hotels, it is crucial to incorporate the interests of all stakeholders, including hotel guests, owners, and energy suppliers, to ensure their acceptance and utilization of the Information System (IS). Consequently, to increase energy efficiency and reduce emissions, this approach falls within the domain of Green IS and Energy Informatics (Watson et al. 2010). Current research on reducing emissions in hotels with an EMS, particularly through integrating a Vehicle-to-Building (V2B) approach, is still scarce. The literature regarding EMSs lacks, to a large extent, the consideration of hotels, as the focus lies primarily on residential, industrial, and office buildings (Mariano-Hernández et al. 2021). However, the study of hotels presents a fascinating area of inquiry, particularly due to the significant array of energy-consuming devices and fluctuating occupancy rates. Given the transient nature of hotel guests, an EMS and its associated control mechanisms must be user-friendly, intuitive, and fully digitalized. This necessity arises because the frequent turnover of guests precludes the possibility of a learning curve or adaptation period. Additionally, the studies that consider hotels and model individual appliances concentrate on cost reduction than emission reduction (Mavrotas et al. 2003; de Souza Dutra et al. 2019). Turning to the literature on V2B, we also see a strong emphasis on cost reduction rather than emission reduction in residential and office buildings, and a general lack of specific buildings such as hotels (Pearre and Ribberink 2019). When designing V2B strategies, it is imperative to consider EV drivers' behavior for coordinated (dis-)charging and energy consumption at times with low emissions, as it directly affects the available battery capacity of EVs during the day. However, real-world data integrated into the V2B studies consist mainly of commuter driving behavior (Barone et al. 2019; Mao et al. 2018) and fleet vehicle availability (Barone et al. 2020). Vacation mobility behavior differs significantly from daily commuting, as it involves a more flexible schedule and a wider range of activities (Bursa et al. 2022). Concluding, little is known about the potential of a V2B approach in the EMS of a hotel, including the behavior of its guests. Therefore, we aim to examine the research question:

What are the environmental and economic potentials of integrating a Vehicle-to-Building concept in a hotel energy management system, taking into account the mobility behavior of hotel guests?

To examine this question, we develop a hotel-specific EMS, including a V2B approach in the form of a quantitative optimization model that aims to reduce either emissions or costs. For evaluation, we implement our model using real-world data from a hotel in Germany, Central Europe. The EMS considers the complex energy demand of a hotel with individual modeling of various appliances in areas such as wellness, kitchens, and guest rooms. Additionally, we include the mobility behavior of hotel guests, i.e., the EV's availability, as it differs drastically from everyday mobility behavior and has a major impact on the emission reduction potential. Within the scope of this study, we focus on developing and analyzing an electricity-based EMS for a hotel, encompassing the hotel's electricity demand, V2B capable EVs, onsite electricity generation and storage, and the grid connection. We exclude non-electricity energy carriers such as oil or gas as they do not contribute to energy flexibility. Further, concentrating on the hotel's EMS, EV charging events outside the hotel and mechanisms beyond the grid connection (e.g. electricity or balancing market) are beyond the scope of this work. This paper is structured as follows: The Section "Background and related research" provides an overview of current research and related work to V2B in an EMS and movement patterns of hotel guests. In the "Methodology" Section, we explain the methodology used to build our optimization model. The Section "Real-world case study and parametrization" presents our real-world case study and model parametrization, followed by scenario analyses in the "Scenario analyses" Section. The paper concludes in the "Conclusion, discussion and outlook" Section with a summary of our main findings and their broader implications, as well as future research options in the field of emission-based energy management and user acceptance of V2B concepts.

Background and related research

Mitigating climate change and achieving the Sustainable Development Goals requires cross-disciplinary solutions and cooperation between science, business, and politics (Fuldauer et al. 2022; Soergel et al. 2021). With this goal, Green IS and Energy Informatics research strive to provide applicable theory and improve practice by combining research across multiple fields to reduce emissions and increase energy efficiency (Park et al. 2023; Seidel et al. 2017; vom Brocke et al. 2013; Watson et al. 2010). This field has generated numerous digital innovations for the energy transition, such as decentralized energy services (Idries et al. 2022), energy efficiency analyses (Watson et al. 2010), and enhancing energy flexibility through electric vehicles (Holly et al. 2020). A notable emphasis has been on increasing flexibility in energy systems with high renewable energy penetration (Sidqi et al. 2020; Bhundar et al. 2023). Thereby, a critical area of focus is energy system transformation by integrating more RES. However, as supply volatility increases, the need for sector coupling arises to balance supply and demand (Körner et al. 2022). With this, IS plays a crucial role in developing response measures by combining smart grid technologies with information and communication technologies to enable direct and automated consumer interaction (Feuerriegel et al. 2012; Granath et al. 2023).

Great potential resides in the sector coupling of the energy system with EVs by utilizing mobile batteries via intelligent charging processes. While EV charging without any active charging process management represents a mere load on the system, various IS approaches exist to realize intelligent charging processes enabling flexibility potential. Intelligent charging process management, including e.g. short-term consumer flexibility with plug-in EVs (Fridgen et al. 2016), a development of demand response measures for an EV fleet for car-sharing (Eisel et al. 2015), or an integration of EVs in an EMS for flexible industrial processes (Bayer and Pruckner 2023; Bayer et al. 2023), enables grid-friendly or optimization-objective-aligned charging. Future-oriented, a V2B approach, e.g. for a simple household EMS (Brandt et al. 2013), offers substantial flexibility and maximizes the RESs utilization by making additional battery capacity available through EV discharging. However, the IS literature still lacks a more comprehensive perspective on V2B integration regarding other building types, particularly considering EV mobility behavior.

Vehicle-to-building in an energy management system

Integrating EVs into a building's EMS offers significant cost and emission reductions by providing additional energy storage capacity and flexibility, thereby enhancing the utilization of RESs (Zhou et al. 2019). Similar to unidirectional charging processes, demand-side management of plugged-in EVs - which entails shifting the timing or load for various consumer - proves particularly effective in optimizing energy use (Palensky and Dietrich 2011). Moreover, intelligent scheduling of charging processes can reduce peak loads, thereby minimizing the impact on the grid (Ouammi 2021; Gough et al. 2017). Additionally, V2B-capable EVs further enhance this flexibility by storing and discharging surplus energy, thus balancing the energy supply (Després et al. 2017). Hence, this approach enables onsite generated energy, such as from a solar PV system, and energy from the grid with a high proportion of RESs, to be stored in EV batteries and later used within the building, resulting in lower energy-related emissions (Borge-Diez et al. 2021; Wang et al. 2016; Nguyen and Song 2012).

V2B addresses the integration of up to 30 EVs into the EMS of commercial buildings, as opposed to Vehicle-to-Home and Vehicle-to-Grid, which focus on residential buildings and grid integration, respectively (Liu et al. 2013; Pearre and Ribberink 2019). Although the concept of V2B considers all types of commercial buildings, most existing research papers concentrate on office buildings (Ouammi 2021; Zhou et al. 2019; Gough et al. 2017; Nguyen and Song 2012). Here, EVs are typically parked for long periods, allowing for greater flexibility, and the EV drivers show known commuter behavior (Kung et al. 2014; Niu et al. 2024). The few existing studies on V2B in hotels do not cover individual appliance loads and merely focus on cost reduction (Gamallo et al. 2013; Kuang et al. 2017). But with the still established fixed energy tariffs for small and medium consumers, a cost-based approach lacks the incentives to use energy during periods of high share of RES in the electricity mix. Thus, the positive correlation of electricity prices to emissions will not be exploited, resulting in the unrealized potential for emissions reduction (Förster et al. 2023). When developing a V2B concept, it is important to stress that this is not exclusively a technical solution. Instead, the availability of EVs directly depends on the behavior of the EV driver, including factors such as activity planning or the reliability of plugging in the EV. However, the only literature on the integration of V2B in hotels does not consider use-case specific driving behavior or EV availability: Kuang et al. (2017) apply a typical daily driving behavior instead of accounting for vacation-specific behavior, and Gamallo et al. (2013) solely analyze an EV fleet belonging to the hotel.

Movement patterns of hotel guests

Research on mobility behavior during vacation is still scarce (Bursa et al. 2022; Dickinson and Dickinson 2006; Gronau 2017; Schmöcker 2021). However, exemplary studies about mobility behavior exist for city vacations (Bieland et al. 2017; Le-Klähn et al. 2015), and in the Austrian Alps (Bursa et al. 2022). Generally, tourists' mobility behavior during vacations varies from their regular routines at home (Zamparini and Vergori 2021). Bieland et al. (2017) emphasize that the means of transport used to get to the vacation destination significantly influence mobility at the vacation destination. Regarding the choice of transport mode, the Austrian National Tourist Office (2022) reports that 78% of inbound vacation trips to Austria are made by private car. Factors such as the distance to be traveled and associated costs influence the decision (Lau and McKercher 2006). According to Bursa et al. (2022), private cars offer the greatest flexibility regarding attraction selection, route choice, and time utilization at the destination. Larsen et al. (2007) also emphasize the flexibility private cars provide, especially for travelers engaging in extensive social activities. Bursa et al.'s (2022) data collection reflects this preference, with almost 80% of travelers using private cars for trips to the Alpine region. Further, they suggest that private vehicles are likely to remain the primary mode of transportation, and in this context, EVs could help reduce air pollution and noise from traffic (Bursa et al. 2022).

Focusing on tourist travel patterns, the entire trip consists of the journey from home to the destination, staying at the destination with various activities, and the return journey home, as proposed by Bursa et al. (2022) and based on the theory of activity-based modeling. To develop a hotel's EMS, we focus on the tourist movement patterns during the stay at the destination that vary due to environmental factors, mobility offers, characteristics of the trip, and personal factors. With regard to environmental factors, Bursa et al. (2022) point out the weather's and the season's influence on mobility behavior. Thus, mountain regions show apparent seasonal disparities because summer activities are often associated with more complex activity chains and long journeys, in contrast to winter's more uniform and ski resort-oriented travel patterns. Concerning mobility offers, various studies highlight that the public transport offer at the vacation destination as well as the hotel offers, e.g., in the form of rental bicycles (Bieland et al. 2017; Bursa et al. 2022) and so-called bundle offers (Bieland et al. 2017), can influence mobility behavior (Le-Klähn et al. 2015; Zamparini and Vergori 2021). Furthermore, the characteristics of the trip in terms of the length (Bursa et al. 2022), as well as first-time or repeat visits (Lau and McKercher 2006) can influence the guests' behavior. Also personal factors play a role in local mobility behavior: These include which target group the guest belongs to (Bieland et al. 2017; Bursa et al. 2022), which travel partner is traveling with them (Le-Klähn et al. 2015) the presence of children (Bursa et al. 2022), and the traveler's fitness level (Bursa et al. 2022; Le-Klähn et al. 2015).

Since we develop a hotel's EMS, including V2B-capable EVs, the specific mobility behavior of hotel guests determines their EV availability. Mckercher and Lau (2008) examine movement patterns and characterize 11 groups out of 78 patterns using factors such as territoriality, number of journeys per day, or number of stops per journey. The following groups are particularly relevant for our case, as they directly influence the availability and usage patterns of EVs within a hotel's EMS. These include the groups *Single Distant Stop* and *Multiple Distant Stops*, which are characterized by a distance of more than 500 meters to one or multiple points of interest(s). *Multiple Trips* is characterized by several activities in one day, with the guest returning to the accommodation in between. There is also the *Inter-Destination Travel* group, which includes a day trip to a neighboring destination. In addition to these groups, they identify local explorations within a 500 meters radius and combinations of the above patterns.

Given these multifaceted insights into the intersection of environmental goals, technological advancements, and the specific mobility behaviors of hotel guests, the integration of a V2B concept into a hotel's EMS emerges as a promising solution. By harnessing the unique flexibility offered by EVs and synchronizing their usage with the energy demands and renewable energy availability of the hotel, both environmental and economic advantages can be achieved. The distinct mobility patterns of hotel guests, particularly those involving multiple stops or extended trips, create opportunities to optimize the charging and discharging cycles of EVs, thereby enhancing energy efficiency and reducing emissions. This integration not only aligns with broader energy transition and sustainability goals but also positions hotels as proactive participants in smart energy management. Consequently, the V2B concept, when adapted to the specific mobility behaviors of hotel guests, is a promising strategy for realizing the environmental and economic potential of EVs within the context of hotel EMSs.

Methodology

Within this work, we follow Meredith et al. (1989) to describe, explain, and test our developed optimization model of a hotel's EMS. We categorize the components of the EMS into the four following distinct areas, also illustrated in Fig. 1:

1. **Hotel Electricity Demand**: Hotel electricity demand encompasses both controllable and non-controllable appliances. Controllable appliances, such as Air-Conditioning (HVAC) systems, dishwashers, and laundry machines, can have their usage adjusted based on optimization algorithms within specific framework conditions. In contrast, non-controllable appliances, including lighting and elevators, operate according to fixed schedules or immediate demand.
2. **Energy Storage**: This area encompasses V2B capable EVs and a stationary Energy Storage System (ESS). The V2B capable EVs can store electricity and supply it back to the hotel, while the stationary ESS stores surplus electricity generated from RES or the grid for later use.
3. **Electricity Generation**: This area involves the generation of electricity through a PV system. The PV system harnesses solar energy to produce electricity, contributing to the hotel's renewable energy supply.
4. **Grid Connection**: This area includes both static and variable pricing structures for electricity purchased from the grid, as well as the associated emissions. The grid connection serves as a backup to meet the hotel's energy demands when renewable generation and storage are insufficient.

Based on this categorization, we construct our optimization model by accounting for each component's specific energy flows and operational constraints. This model aims to optimize the overall energy management of the hotel, balancing demand, storage, generation, and grid interaction to achieve cost efficiency or CO_2 efficiency (Gruber and Prodanovic 2017). Figure 1 illustrates the optimization model with the Objective Function (OF) and constraints of energy demand regarding areas and specified appliances (1), as well as storage (2), generation (3), and grid connection (4).

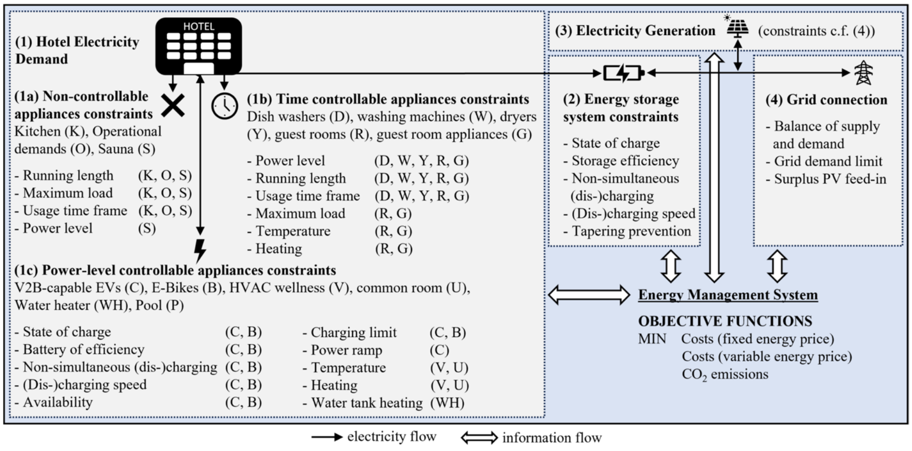

Fig. 1 Overview of the optimization model of a hotel's EMS

The study employs Mixed-Integer Linear Programming optimization to assess three distinct OFs, contrasting two variants of a cost-based EMS against a CO_2-based EMS. The underlying model remains consistent across all variants except for differences in the input parameters of the OFs:

The primary cost-minimizing OF emulates the prevalent electricity tariff structure for hotels, featuring a fixed retail price per kWh for energy purchase and feed-in. In contrast, the secondary cost-minimizing OF integrates variable retail prices while upholding a constant feed-in tariff. In their results, both economic models' OF values reflect the monetary energy expenditures encompassing all energy consumptions and generations, inclusive of EVs charging and discharging activities, over one day within a hotel energy system. The third OF, which is based on CO_2 minimization, incorporates an emission factor to mitigate associated emissions. Its OF value mirrors the emissions generated over one day across all energy consumptions and generations, including EVs' charging and discharging within a hotel energy system. All three OFs follow the same structure whereby the energy purchased is subtracted from the energy feed-in.

$$\mathbf{min}\,\text{Costs}\,\textit{or}\,\text{Emissions} = \text{Demand} - \text{PV feed in} \tag{1}$$

Depending on the chosen OF, Eqs. (2) and (3) select the corresponding values from the variables x, y, and z. Regardless of the chosen OF, the following hotel EMS constraints will remain the same. The optimization model and nomenclature are documented in Appendices I-J, while its corresponding parameterization is detailed in Appendices H-G to ensure rigor and comprehensiveness.

$$\text{Demand} = \text{Grid Demand} \times x + \text{RES consumption} \times y \tag{2}$$

$$\text{PV feed in} = \text{feed in quantity} \times z \tag{3}$$

$$x\begin{cases}\text{fixed retail price}\\ \text{variable retail price}\\ \text{emission factor grid}\end{cases} \quad y\begin{cases}\text{operational costs RES}\\ \text{operational costs RES}\\ \text{emission factor RES}\end{cases} \quad z\begin{cases}\text{feed in tariff}\\ \text{feed in tariff}\\ \text{emission factor RES}\end{cases}$$

Typically, hotels consume energy in the guest rooms, operational areas, and wellness areas (Ali et al. 2008). Especially in the guest rooms, there is a substantial variability depending on occupancy, temperature perception, and appliance utilization. In contrast, public spaces in the hotel exhibit peak demands based on the time of the day, e.g., during mealtimes when most guests actively use the hotel's infrastructure. For clarity reasons, we combine some appliances to the area of operational demand (e.g., light, elevator, energy demands from employees) and a kitchen area (e.g., electric stoves, ovens, fryers). In addition, the increasing expansion of electric mobility adds mobility devices to the energy demands, such as EVs and e-bikes. Independent of the appliance type, those can either be flexible (allowing for control over time or power level) or non-controllable. Thus, for non-controllable appliances, it is necessary to know the demand distribution over time.

Turning to the development of our optimization model, many appliances need similar constraints, such as a limit on runtime, maximum load, time constraints, or the required power per period. However, the time or power-level controllable appliances need some additional constraints specified for their utilization to enable flexible operation. Further, to not interrupt ongoing processes (i.e., washing machines or dryers), we guarantee running continuity once an appliance has been started (Hou et al. 2019). For modeling the thermal demands as HVAC for guest rooms, wellness area, and operational area, as well as water heating and the swimming pool, we follow de Souza Dutra et al. (2019); Shao et al. (2012) with constraints regarding temperature (initial temperature, changes, and limits), heating, and cooling processes which cannot occur simultaneously. However, to ensure feasibility and due to the lack of data, we apply a minor simplification by assuming a constant temperature within one area or pool, independent of varying room heights. Further, we assume that solar radiation, heat resistance, humidity, and heat from people are insignificant for the optimization model. We follow de Souza Dutra et al. (2019); Shao et al. (2012) to model the water heaters, with temperature constraints for initial temperature, changes, and preferred ranges for hot water. Hereby, the water is only heated and stored in one central water tank with negligible influence of ambient temperature or losses through the pipes. Besides the thermal demands, mobility appliances require several additional constraints due to the information density and setting possibilities to enable flexible control that integrates touristic behaviors. Hence, we want to highlight the most important constraints. The model considers the EV's availability because guests need their cars for excursions. Additionally, the battery's State of Charge (SOC) must reach a certain level before a trip, departure, or the end of the day to ensure the EV's mobility. The required constraints for all appliances and areas are illustrated in Fig. 1.

The stationary ESS stores surplus energy from the PV and may source low-cost or low-emission energy from the grid. Due to similar functionality, ESS has similar constraints to V2B-capable EVs (e.g., SOC, efficiency, non-simultaneousness). The initial value corresponds to the value in the last period, allowing for a multi-period model. Additionally, batteries show a decreasing (dis-)charging performance at the lower and upper capacity limits, called tapering (Haupt et al. 2020). Thus, we include constraints for tapering prevention by continuously reducing the (dis-)charging speed as it approaches the capacity limits.

Regarding the interdependence between energy generation and grid demand, they collectively meet the total energy demands. The constraints consistently maintain the equilibrium between demand and supply, impose an upper limit on grid demand, and permit energy feed-in merely from the PV system.

Real-world case study and parametrization

In this Section, we present a detailed case study of a real-world hotel in Germany, Central Europe. We subsequently develop and explain the various optimization objectives of its EMS, along with the parameterization of the corresponding optimization model. The parametrization subsections are categorized into hotel-specific parameters and behavior-related parameters. Appendices A-H contain the exact values and associated sources.

Real-world hotel energy management system

We present a real-world case of a hotel and its EMS situated in Germany in Central Europe, a bustling tourism region with nearly 16 million overnight stays per year (Allgäu

GmbH 2021). This hotel comprises 60 guest rooms offering half-board services. It holds certification from an association dedicated to eco-friendly hospitality, ensuring a carbon footprint of less than 40 kg CO_2 per guest per night and an exclusive energy supply from RESs (Verein Bio Hotels 2021). To validate the proposed OF discussed in the "Methodology" Section, we utilize real-world data as EMS parameters, considering a day as 24 one-hour periods for optimization. Table 1 contains the literature used for the parameterization of the optimization model, structured according to the hotel's general EMS scheme (cf. Fig. 1).

Considering the published targets of various automobile manufacturers in the vehicle-to-grid sector (The Mobility House 2024), we anticipate a future scenario characterized by a significant prevalence of EVs. In this scenario, it is assumed that half of the guests will arrive with EVs capable of V2B functionality. The EVs must reach a SOC of 75% before their respective absences to ensure the guests' mobility. The charging speed (11 kW) and battery-conserving conditions are based on Haupt et al. (2020); Hou et al. (2019); Sarasketa-Zabala et al. (2016). EV charging aligns with mobility patterns as well as guest arrivals and departures, influencing vacuum cleaning schedules. E-bike trip end times are evenly distributed from 12 p.m. to 8 p.m. More information regarding the non-controllable devices is available in Appendix C, and details concerning the controllable devices can be found in Appendix D. Regarding temporal flexibility, meals, wellness,

Table 1 Optimization model components' parametrization

Area	OF or appliance	Source of parametrization
Objective	i. Fixed energy price	Biohotel Eggensberger (2021)
	ii. Variable energy price	entso-e (2022b)
	iii. CO_2 emissions	entso-e (2022a); Umweltbundesamt (2022)
(1a) Non-controllables	i. K	Hausjournal (2022b); Öko-Institut e.V. (2012)
	i. O	Beleuchtungdirekt.de (2022); Garcia et al. (2016); Tukia et al. (2016); Swiss Federal Office of Energy (2010)
	i. S	Biohotel Eggensberger (2021)
(1b) Time controllables	i. D, W, Y	Miele and Cie (2023)
	ii. R, G	Hou et al. (2019)
(1c) Power-level controllables	i. C	Haupt et al. (2020); Hou et al. (2019); Sarasketa-Zabala et al. (2016)
	ii. B	Robert Bosch GmbH (2023)
	iii. V, U	Biohotel Eggensberger (2021); DWD Climate Data Center (2021); Sas-Wright and Clark (2023)
	iv. WH, P	Deng and Burnett (2002); Lévesque et al. (2004); Viessmann Climate Solutions SE (2022)
(2) Energy storage system	i. ESS	Biohotel Eggensberger (2021); Haupt et al. (2020);
(3) Electricity Generation	i. PV generation	Riffonneau et al. (2011); Solcast (2022)
(4) Grid connection	i. Feed-in	Bundesnetzagentur (2021)

check-in, and -out times set the optimization timeframe (Biohotel Eggensberger 2021) (cf. Appendix A). A PV system with 170 kWp represents the onsite energy generation (cf. Appendix G). Additional details regarding the other model components are also available in Appendices A-H.

To evaluate the three distinct optimization objectives, we select one day within each season of the year that we considered representative of typical conditions. These selected days represent the median share of RESs within the electricity mix from 2022 in Germany. To analyze the impact of seasonal variations on emission factors and the share of RESs in the German electricity mix, we followed these steps: Firstly, we calculated the hourly emission factors of the electricity mix for each day in 2022 based on actual energy generation data per production type published by entso-e (2022a). These factors were then averaged to obtain a daily mean value, enhancing representation and comparability across different periods. For each astronomical season, we computed the days with minimum, maximum, and median share of RESs to the electricity mix in Germany. To facilitate a focused analysis, we identified a representative day for each season, resulting in: 22/05/2022 in spring, 04/07/2022 in summer, 28/11/2022 in autumn and 13/02/2022 in winter (cf. Table G18 in Appendix G). By selecting the days with a median value of RESs, we aimed to capture typical seasonal conditions and avoid extremes that could potentially skew the results. These four days illustrate the seasonal fluctuations in the electricity generation mix in Germany, particularly from PV and wind power. During the summer day, PV dominates the electricity mix with 32.29 MWh at 1 p.m. (Bundesnetzagentur 2022), reaching its peak due to long daylight hours and high solar irradiance. In contrast, PV generation sharply declines in winter and becomes minimal in autumn due to shorter days and lower sunlight intensity. Conversely, wind power, especially onshore, becomes more prominent in autumn (19.59 MWh at 4 a.m. (Bundesnetzagentur 2022)) and winter (36,73 MWh at 9 p.m. (Bundesnetzagentur 2022)), where stronger and more consistent winds compensate for the reduced solar output. This seasonal shift results in a reliance on PV during the warmer months and on wind power during the colder, windier periods, illustrating the dynamic nature of RESs throughout the year. We utilize data from the identical days for the OF input values and for calculating the PV generation.

The cost-based OF with a fixed electricity price is based on the hotel owner's electricity contract. The cost-based OF with variable prices utilizes three distinct time series of variable prices as input. These time series are derived from real-world data of the German day-ahead energy market (entso-e 2022b). Their selection corresponds to the identified characteristic days of RESs share in the electricity mix. For the CO_2-based OF with variable emission factors, we calculate the emission factors based on the proportional composition of energy sources per hour (entso-e 2022a; Umweltbundesamt 2019), derived from the same time periods as the prices in the cost-based objective. Therefore, the emission factors vary over time with the electricity mix, and due to its own generation, we assume no CO_2 emissions from the PV system. Appendix B contains the exact input values for the OFs.

The computation of PV generation uses data from Solcast (2022) and follows the methodology outlined by Riffonneau et al. (2011). This involves analyzing the global horizontal irradiance (W/m^2) at the hotel site in 15-minute intervals. We apply the relevant equation for a PV system with a rated power of 170 kWp and an area of 1000 m^2 (Biohotel Eggensberger 2021). Appendix G lists the detailed input values.

Mobility pattern's parametrization

This study explores the use of EV batteries as energy storage in a hotel setting, explicitly focusing on the V2B function and its decarbonization potential in the hospitality industry. As guests often use their vehicles for trips, we integrate various mobility patterns that consider the different availability of EVs. Based on Mckercher and Lau (2008) study on tourist movement patterns within a destination, as well as considering meal times in the hotel and its surroundings, we identify four distinct patterns applicable to the hotel context: *Single Distant Stop, Multiple Distant Stop, Multiple Trips,* and *Inter-Destination Travel*. Within the context of a capacity-maximized hotel, we stratify the mobility groups into four homogeneous groupings, each comprising five vehicles. Table 2 provides an overview of the mobility groups' absences, which adhere to the following meal schedule: breakfast from 8 to 10 a.m., salad bar from 12 p.m. to 2 p.m., and dinner from 6 to 9 p.m (Biohotel Eggensberger 2021).

We opt not to differentiate the energy consumption among the groups, as such distinctions are heavily influenced by driving habits and environmental variables such as temperature. Therefore, we assume that the SOC drops to 30% SOC during an excursion, regardless of the mobility group. We implement constraints to ensure that the EVs maintain a 75% SOC before excursions to guarantee guests sufficient range and retain a 50% SOC at the end of the day to enable sustainable charging the next day. We further assume that guests will plug in their EVs to the charging station immediately upon arrival, a practice confirmed by the hotel operator as a standard and reliable procedure. To reflect realistic charging needs, we differentiate between five car models, some of which have different battery capacities and charging rates. Given the context of the case study as a premium eco-hotel in the Allgäu region of southern Germany, our focus is on medium and compact car models (EV Database 2023), assuming that the hotel's guests prioritize comfort over smaller car types for travel. For a more authentic representation, we have opted to consider the top five EVs registered in Germany in 2021 in these vehicle classes (Kraftfahrt-Bundesamt 2022): Tesla Model 3, Volkswagen ID.3, Nissan Leaf, Kia e-Niro, and Ford Mustang Mach-E. However, with the rapid pace of technical development, we assume all vehicles are already V2B-capable. Each mobility group includes every model, as all models can complete any excursion.

Table 2 Mobility patterns in a hotel context

	Mobility group	Absence	Exemplary acitivity
A	*Check-out*	10 a.m.–12 a.m.	Breakfast before check-out
B	*Check-in*	12 a.m.–2 p.m.	Exploring the hotel's surroundings
C	*Single Distant Stop*	11 a.m.–1 p.m.	Exploring a nearby town
D	*Multiple Distant Stop*	9 a.m.–2 p.m.	Hiking in the Allgäu region and visiting points of interest
E	*Multiple Trips*	9 a.m.–12 p.m. and 3 p.m.–6 p.m.	Hiking in the morning and shopping in the afternoon
F	*Inter-Destination Travel*	10 a.m.–6 p.m.	Skiing or city-trip

Scenario analyses

After introducing our model development and the implementation of three distinct OFs: the cost-based OF with fixed prices, the cost-based OF with variable prices, and the CO_2 -based OF, each including a real-world parametrization (cf. Section "Methodology" and "Real-world case study and parametrization"), this Section presents our scenario analyses. We conduct scenario analyses by varying the dimensions of OFs (i.e. fixed and variable electricity prices and emission factors), seasons (i.e. days considered for input parameters), and mobility patterns (i.e. different availabilities). To examine our research question, we focus, in particular, on the OF with fixed prices as a benchmark and the OF designed for emission reduction in the following. In light of the policy-driven implementation of variable electricity prices for end customers in Germany (Bundesministerium für Wirtschaft und Klimaschutz 2024), our research also explores the implications of adopting a variable electricity pricing model as a future outlook.

We structure the following analysis into three subsections. The first subsection compares the OF values of the models across different seasons and contrasts CO_2 savings among the optimization models. It also explores the potential correlation between favorable day-ahead electricity prices and low emission factors as well as the usefulness of V2B functionality in general. The second subsection examines the energy use, visualizing the charging and discharging processes within the hotel context, and analyzing the V2B function in relation to the hotel's energy demands. This includes assessing how the models schedule flexible charging and discharging operations around the hotel's partially fixed consumption and comparing seasonal influences on these processes. The third subsection investigates the use of the V2B function by EVs with different mobility patterns.

Economic and ecological energy costs

We identify electricity costs and potential emissions savings by analyzing the EMS's economic and environmental OF values. Thereby, we uncover a multitude of seasonal patterns. The utilization of V2B demonstrates variability across seasons and optimization models among all mobility groups. Furthermore, the seasonal dynamics of V2B utilization within specific groups are contingent upon the emission factor. Additionally, we conclude this subsection by highlighting the general usefulness of the V2B function compared to baseline scenarios without this functionality.

Regarding energy costs, the OF with a fixed electricity price results in daily expenses ranging from EUR 754.63 to EUR 969.97, with spring emerging as the most economically advantageous season. These costs represent the optimized energy expenditures across all hotel operations managed by the EMS over a single day. In contrast, the OF with a variable electricity price introduces more pronounced fluctuations: under the OF with a variable electricity price, daily electricity costs range between EUR 294.10 and EUR 997.73, with winter proving to be the most economically favorable season. Despite variations in pricing and environmental considerations, the comprehensive findings consistently highlight autumn as the most cost-intensive season in across all models (i.e. OF with a fixed electricity price, OF with a variable electricity price, and OF with a variable emission factor), underscoring the importance of seasonal influences on hotel energy management strategies. In terms of CO_2 emissions, the OF with a variable emission factor identifies spring as the season with the lowest CO_2 emissions at 1684.10 kg, while fall exhibits the highest emissions at 2267.61 kg. For the OF with a fixed electricity price, CO_2 emissions are also lowest in spring at 1836.94 kg, but highest in fall at 2341.70 kg. Similar to the monetary costs, the OF with variable electricity prices shows more pronounced extremes, with CO_2 emissions lowest in spring at 1729.26 kg and highest in fall at 2371.34 kg.

Table 3 displaying the OF values and their conversion into CO_2 emissions or EUR indicate that lower costs during the summer season — corresponding to the currently prevailing optimization approach of cost minimization — compared to fall and winter do not consistently correspond to lower emissions — corresponding to the desirable more environmentally friendly optimization approach of CO_2 minimization. Based on these findings, it is worthwhile to examine the cost implications of implementing an emission-reducing EMS control for effective decarbonization. Therefore, we analyze emission levels and the cost-effectiveness of emission savings:

Spring emerges as the season with the most favorable CO_2 reduction-to-cost ratio when comparing the OFs, achieving a reduction of 152.84 kg CO_2 for an additional cost of EUR 8.86. In contrast, summer shows a reduction of 81.91 kg CO_2 at an extra cost of EUR 9.99, autumn achieves a reduction of 72.10 kg CO_2 with an additional cost of EUR 4.96, and winter achieves a reduction of 120.98 kg CO_2 with an additional cost of EUR 14.67. Comparatively, the OF with variable prices exhibits a total emission reduction potential of 108.59 kg over a year, positioning it closer to emission-minimizing control than the OF with fixed prices. This reduction in emissions can be attributed to a correlation between advantageous electricity prices on the day-ahead electricity market at times with an increased proportion of renewable energy sources. Winter stands out within this context as the season with the most favorable CO_2 reduction-to-cost ratio, achieving a reduction of 20.63 kg CO_2 for an additional cost of EUR 9.03. In contrast, spring shows a reduction of 45.16 kg CO_2 at an extra cost of EUR 26.64, summer achieves a reduction of 151.72 kg CO_2 with an additional cost of EUR 139.21, and autumn achieves a reduction of 103.74 kg CO_2 with an additional cost of EUR 255.09. Considering these savings are for a single day, there is significant potential for CO_2 reduction when extrapolated over an entire season.

Table 3 OF values and their conversion in different seasons

OF	Unit	Spring	Summer	Autumn	Winter
Fixed electricity price	Euros (EUR)/day	745.63	838.38	969.97	874.33
Variable electricity price	EUR/day	508.55	939.30	997.73	294.10
Variable emission factor	EUR/day	763.51	848.37	974.93	889.00
Fixed electricity price	kg CO_2/day	1836.94	2144.37	2341.70	1928.49
Variable electricity price	kg CO_2/day	1729.26	2214.18	2371.34	1828.13
Variable emission factor	kg CO_2/day	1684.10	2063.46	2267.60	1807.51
Baselines without V2B:					
Fixed electricity price	EUR/day	997.29	1081.04	1212.63	1117.00
Variable electricity price	EUR/day	649.55	1183.05	1226.91	370.67
Variable emission factor	kg CO_2/day	1711.75	2107.04	2327.59	1881.15

Finally, we evaluate the overall usefulness of the V2B functionality of EVs by calculating the OF values for each model and each season with EVs but without the V2B functionality. In addition to the aforementioned OF values, Table 3 also presents baseline scenarios for comparison. As illustrated in Table 3, the inclusion of the V2B function of EVs leads to cost savings or emissions reductions. This is evidenced by consistently higher OF values in scenarios without V2B functionality across all model variants. Specifically, the OF values of the model with a fixed electricity price but without V2B functionality are between 25.04 % to 33.78 % worse, depending on the season, when compared to the model with V2B functionality. Furthermore, the results indicate that the model with a variable electricity price but without V2B functionality performs between 22.97 % and 27.72 % worse in terms of electricity costs across seasons compared to the V2B-enabled model. In terms of emissions, the model without V2B functionality exhibits a performance degradation of 1.64 % to 4.07 %, depending on the season. Thus, incorporating the V2B functionality of EVs into the EMS proves beneficial, regardless of the optimization approach employed.

Energy management in different seasons

In this subsection, we examine two models in more detail regarding the V2B function of the EVs and their interaction with the hotel's energy demands, PV generation, and ESS. First, we consider the approach with an OF with fixed electricity prices, which represents the real world. We then compare the approach with an OF with a variable emission factor, which would be more target-oriented with regard to the acute climate crisis and the adopted emission reduction targets.

Under the OF with a fixed electricity price, the hotel's energy consumption maintains a relatively stable pattern throughout the day, as the fixed pricing structure does not encourage adjustments in charging processes. Across different seasons, the only influencing factor on the scheduling of flexible appliances and on the charging processes of EVs is the availability of PV-generated energy. The daily profiles of the different seasons illustrate that the hotel's energy demand is planned consistently at all times of the year, with the EVs being flexibly scheduled around these demands. In all seasons, the EMS exclusively utilizes the V2B function of the EVs at 1 p.m. to meet the high energy demands of the hotel at midday. Additionally, a substantial number of EVs charge at 7 or 8 a.m. throughout all seasons. Furthermore, in the afternoon or evening following excursions, the EMS efficiently manages the high charging demand: Due to the different PV generation patterns, a demand peak of 250 kWh occurs at 8 p.m. in spring, while in summer and autumn, the demand peak is at 8 a.m. In addition, the autumn profile shows a second demand peak at 4 p.m., when PV electricity is no longer available, which also leads to a winter demand peak of almost 250 kWh at 4 p.m.

The OF with variable emission factors and the fluctuating PV generation results in different energy consumption profiles. The composition of the electricity mix within the grid impacts the emission factor, with a greater presence of RESs leading to a reduction in the emission factor. As the graphical presentation in Fig. 2 of the CO_2-based OF illustrates, the largest share of PV energy is also generated during periods with particularly low emission factors. Regarding energy utilization, the system predominantly relies on the available PV energy during midday to meet the hotel's non-shiftable energy

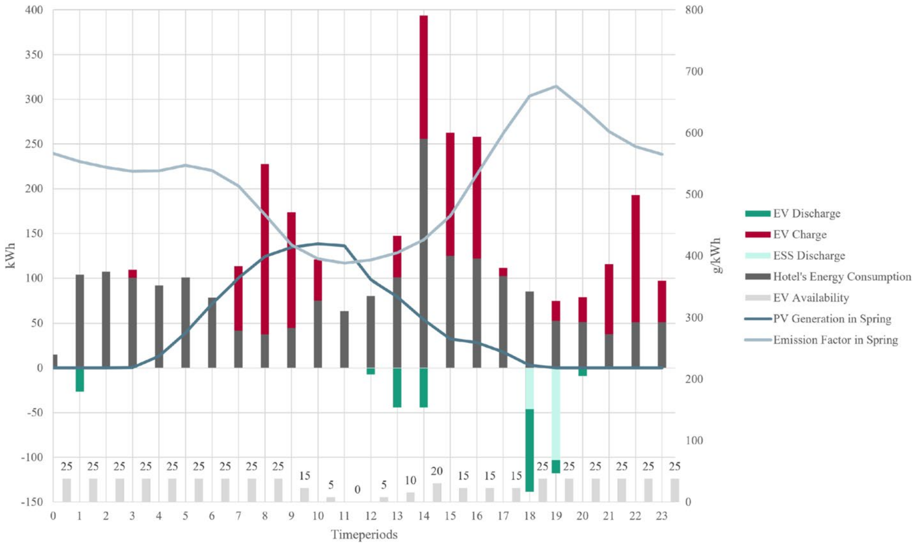

Fig. 2 Energy flows of CO_2-based optimization in spring with EV availability

demands. Additionally, the emission factors fluctuate across the seasons, ranging from 388 to 676 g/kWh in spring, 453–664 g/kWh in summer, 504–741 g/kWh in autumn, and 321–712 g/kWh in winter (cf. Table B6 in Appendix B). Consequently, the emissions attributed to the electricity mix demonstrate an almost twofold increase over the course of a day. As a result, the timing of energy consumption significantly influences the overall emission intensity. Further, guests' mobility patterns strongly impact EVs' (dis-)charging processes throughout all seasons. Due to the absence of EVs, or their limited number, during periods 11 and 12 – when PV availability is at its peak and emission factors are typically low – these periods are unsuitable for charging purposes.

During spring (cf. Fig. 2), the emission factor remains approximately at 500 g/kWh until 7 a.m., falling afterward with a minimum below 100 g/kWh around noon and reaching a peak from 6 p.m. to 7 p.m. To minimize emissions, the EMS schedules as many charging processes as possible (e.g., considering availability restrictions and battery preservation) between 7 a.m. and 4 p.m. when the emission factor falls below 500 g/kWh, and PV energy is available. In the evening, the EMS utilizes more CO_2-efficient energy from EVs via the V2B function and the ESS.

During the exemplary summer day, the EMS schedules a substantial energy demand for the hotel at 11 a.m., leveraging the very low emission factor and the comparatively high availability of PV energy. The EMS optimizes the charging schedules of EVs to coincide with periods of low emission factors and peak availability of PV energy. This synchronization is aimed at minimizing emissions, reflecting the new optimization approach towards sustainable energy utilization. To reduce emissions during peak periods at 4 a.m. and 7 p.m., the EMS utilizes the V2B function of the EVs and discharges the ESS.

On the exemplary day in autumn, the emission factor fluctuates closely between 500 and 600 g/kWh until 10 p.m (cf. Fig. 3). Only in the last hour of the evening it peaks at 750 g/kWh, prompting the EMS to use the ESS to meet the energy demand. The PV energy primarily serves the hotel's energy demand. Notably, the EMS plans the highest

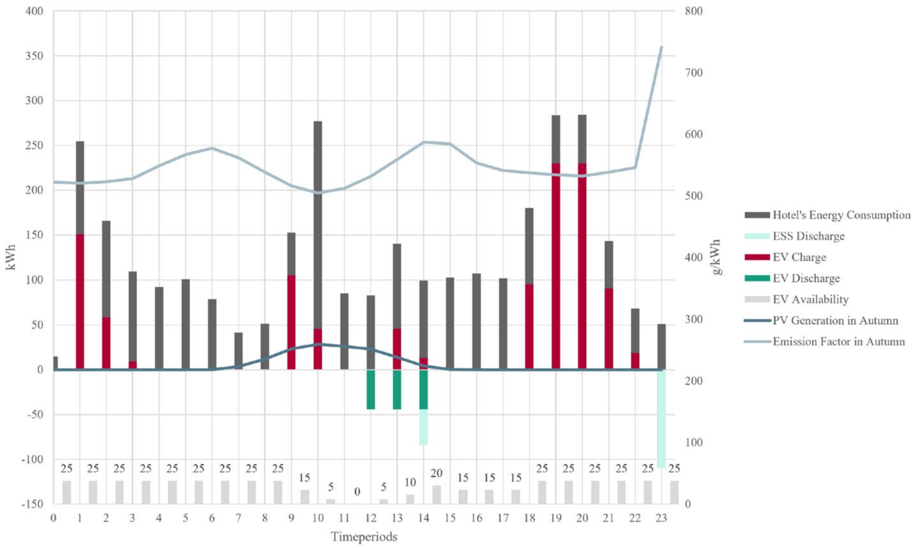

Fig. 3 Energy flows of CO_2-based optimization in autumn with EV availability

energy demand of the hotel on that day during the hour with the most PV energy and the lowest emission factor to avoid emissions (cf. at 10 a.m. in Fig. 3). The EMS utilizes the V2B function of the EVs during the midday hours from 12 to 2 p.m.

On the exemplary day in winter, we identify the hour with the lowest emission factor at 1 p.m. (190 g CO_2/kWh) across all seasons. At 55.5 GWh per hour, RESs constituted 69.9% of the electricity generation at this time (Agora Energiewende 2022). This significant contribution is primarily attributable to a midday peak in solar power production (24.83 GWh per hour) and consistently high electricity generation from onshore wind power throughout the day (17.83 GWh per hour). Consequently, this hour represents the peak energy demand on the winter day. The emission factor is highest at the beginning of the day, prompting the use of the V2B function at 1 a.m. to fulfill the fixed demands of the hotel while minimizing emissions. Between 7 a.m. and 3 p.m., when there is generated PV energy and a lower emission factor, the EMS schedules a large portion of the EV's charging demand. During the evening emission peak, the EMS utilizes the EVs and the ESS to discharge low-emission energy.

Besides the currently established fixed electricity price, energy market research discusses the transfer of dynamic pricing, as used in industry to manage peak loads and enable electricity trading, to other contexts (Dutta and Mitra 2017). Accordingly, we develop and analyze a third OF considering variable day-ahead electricity prices. Compared to the other two OFs, it reveals significant differences in the energy profile across seasons.

In spring and summer, the EMS optimizes by utilizing the lowest day-ahead prices for peak energy consumption as well as EV and ESS discharging while minimizing costs during expensive morning and evening hours. The exemplary autumn day exhibits a different profile with cost-efficient early morning hours from 0 to 5 a.m., followed by a sustained high-price plateau until approximately 8 p.m. Therefore, the EMS shifts energy demands to early and late hours, using EVs' V2B function during high-price periods. On the exemplified winter day, the price trend displays notable fluctuations, with a dip to negative pricing observed at noon. The EMS takes this opportunity to schedule most of the hotel's energy consumption and uses the available PV-generated energy. Only the guests within mobility group *E Multiple Trips* are present during this period, leading to the simultaneous charging of all available EVs.

When comparing the fixed cost-based OF with the variable cost-based OF, we confirm the correlation of low variable energy costs with low CO_2 emissions, i.e., a reduction in emissions for most seasons (except for autumn). This supports the conclusion drawn by Förster et al. (2023), suggesting that the full potential of this correlation remains underutilized. Regarding mobility patterns, the variable cost-based OF utilizes the V2B function most intensively in terms of energy quantity compared to the other OFs. The V2B function contributes to cost minimization in 23 out of 24 scenarios, and the cars collectively discharge 1724% more to the hotel compared to the fixed OF. In contrast to the CO_2-based OF, the EMS utilizes the groups most intensively in summer (groups *B, C,* and *F*) and autumn (groups *A, D,* and *E*) and less intensively in winter. This finding supports our conclusion that a hotelier should establish incentives to encourage favorable mobility behavior to maximize cost and emission reduction potential. Further, those incentives, such as adapted meal times or attractions in the hotel, should be tailored to the current season.

Energy management of mobility patterns

Since EVs availability strongly influences the (dis-)charging processes, we further examine the individual effects of the mobility patterns.

In our investigation, we note distinct strategies employed by our EMS across varying OFs. Specifically, under a fixed electricity price scenario, the EMS selectively utilizes group *C Single Distant Stop*, characterized by shorter absence times, for storage purposes, aiming to minimize costs. However, with the OF featuring a variable emission factor, the EMS adopts a broader approach, utilizing all mobility patterns for storage. Notably, the introduction of a variable CO_2-based OF highlights the emergence of our V2B functionality as a significant contributor to CO_2 reduction across 19 out of 24 scenarios. Moreover, we observe a notable increase in the collective discharge of vehicles to the hotel by 1365% under the variable CO_2-based OF compared to the fixed OF, as illustrated in Table 4.

Further, this Section details the intensity of V2B function usage for each mobility pattern: The EMS with fixed electricity prices as OF discharges the EVs in group *C* the most in autumn. In contrast, the EMS with a variable emission factor as OF actively uses all mobility patterns to achieve a CO_2 reduction and exhibits seasonal differences in the usage intensity (cf. Table 4). It uses the groups *A Check-out* and *B Check-in* most intensively in winter. In Summer, it primarily uses groups *D Multiple Distant Stops*, *E Multiple Trips* and *F Inter-Destination Travel* as storage. The utilization of the V2B function predominantly depends on the availability of vehicles, the hourly emission factor, and the electricity demand.

- **Group *A*** (*Check-out* available until 10 a.m.) is primarily utilized in the variable emission factor model, contributing to CO_2 reduction, especially in winter.

Table 4 Use of V2B function (i.e. discharge amounts in kWh) for each mobility group across seasons for the OF with variable emission factor

Mobility Group	Spring	Summer	Autumn	Winter
Group A	0.00	9.36	0.00	19.84
Group B	11.70	0.00	0.00	24.89
Group C	81.70	70.00	44.46	77.95
Group D	44.46	64.68	44.20	38.30
Group E	53.68	73.90	44.20	56.61
Group F	46.00	71.81	0.00	27.52

- **Group *B*** (*Check-in*, available from 2 p.m.) sees the most usage in winter under the variable emission factor model for CO_2 reduction.
- **Group *C*** (*Single Distant Stop*, absent from 11 a.m. to 1 p.m.) contributes to minimization in all optimization models. It is exclusively utilized in the fixed electricity price model in autumn, while under the variable emission factor model, it is most utilized in spring, contributing to CO_2 reduction.
- **Group *D*** (*Multiple Distant Stops*, absent from 9 a.m. to 2 p.m.) is most utilized in summer under the variable emission factor model, leading to CO_2 reduction.
- **Group *E*** (*Multiple Trips*, absent from 9 a.m. to 12 p.m. and from 3 p.m. to 6 p.m.) is most utilized in spring under the variable emission factor model, leading to CO_2 reduction.
- **Group *F*** (*Inter-destination travel*, absent from 10 a.m. to 6 p.m.) is most utilized in spring under the variable emission factor model, leading to CO_2 reduction.

Following the analysis of V2B function usage across different groups and OFs, our attention shifts to group *C*, known as *Single Distant Stop*, which exhibits the highest energy discharge among all groups in both OFs. Particularly notable is the exclusive use of group *C* EVs as storage in the OF with a fixed electricity price, spanning all seasons. This preference likely stems from the fact that group *C* stays in the hotel the longest, with only a brief 2-hour absence. It is plausible to infer that group *C's* availability during energy-intensive periods leads to its extensive utilization as a storage resource. Our findings suggest that longer stays correlate with more intensive V2B function usage, facilitating greater cost or CO_2 reduction.

Regarding the other mobility groups, the EMS employing the variable CO_2-based OF demonstrates notably higher intensity in utilizing the V2B functionality of mobility groups *D, E,* and *F* (absences less than 10 h) compared to groups *A* and *B*, with factors ranging from 1.24 to 5.28. This comparison underscores the pivotal role of EV availability in determining V2B application efficacy.

Conclusion, discussion and outlook

Our study highlights that an EMS as a holistic IS, in conjunction with a V2B concept, has the potential to decarbonize the hospitality industry by optimizing both energy generation and consumption. We compare CO_2-based EMSs to cost-based counterparts, developing three optimization models with numerous hotel appliances. Additionally, we consider seasonal factors and the availability of EVs in terms of hotel guests' mobility patterns. We assess the impact of fixed and variable electricity prices and emission factors on scheduling hotel appliances based on real-world conditions and scenario analyses.

Our findings reveal significant differences in economic and environmental costs, seasonality, and V2B usage depending on the applied OF. Using our CO_2-based OF, our real-world case study reveals the greatest savings of 152.84 kg during spring compared to a cost-based OF with fixed prices. Notably, this CO_2 reduction incurs an additional energy cost of only EUR 8.86, emphasizing that a CO_2-minimizing EMS can be both environmentally and economically viable. The cost of these savings is lower than the market price for a ton of CO_2 on the same day. When scaled up to one ton, the expenses for these CO_2 savings add up to EUR 58.14, whereas offsetting at market prices costs EUR 84.20 per ton (Trading Economics 2022). The V2B function contributes to cost and emission reduction in the EMS in varying degrees. In the OF with fixed electricity prices, the EMS utilizes the V2B function only during midday to meet the hotel's high energy demands. Conversely, in OFs with variable electricity prices and emission factors, the EMS employs the V2B function differently across seasons, depending on the availability of PV power, EV availability, and hourly price or emission levels. Notably, the *Single Distant Stop Group C*, with the longest time spent at the hotel, discharges the most energy from the EV's batteries to the hotel. Hence, this study provides valuable insights into the trade-off between cost-based and CO_2-based digital EMS and shows the importance of considering hotel guests' mobility behavior when scheduling applications within their flexibility constraints.

In summary, a consistent pursuit of the Paris climate goals results in a paradigm shift that prioritizes CO_2 reduction over pure cost savings. We therefore advocate a new approach, called CO_2-based management, in an area traditionally dominated by cost-based strategies, especially in the hotel sector. By introducing this novel paradigm, we aim to demonstrate the potential for significant CO_2 savings in hotel operations. It is crucial to recognize that a CO_2 minimization approach does not always coincide with cost minimization strategies, indicating that existing management practices are not fully aligned with the demands of climate change mitigation. As evidenced in the findings presented in the Section "Economic and ecological energy costs", an optimization strategy incorporating variable electricity prices - which will be available to German consumers starting in 2025 (Bundesministerium für Wirtschaft und Klimaschutz 2024)—already results in lower emissions compared to the conventional fixed electricity tariff approach. However, this variable pricing strategy does not yet achieve the minimum possible emissions, as demonstrated by the comparison with the CO_2-based optimization approach. Our analysis underscores the significance of employing emerging technologies, such as EVs and ESSs, to enhance operational flexibility and reduce emissions. Notably, the storage capabilities of the ESS facilitate CO_2 reduction by enabling the storage of low-carbon electricity for use during periods of higher emissions intensity. Furthermore, the integration of V2B functionality greatly expands storage capacity, presenting significant opportunities for further emission reductions in the hotel sector.

Due to the complex processes within a holistic hotel EMS, our work is subject to the following limitations: The EMS currently accounts for common electricity demands in a hotel. However, the rising CO_2-prices and the increasingly frequent variable electricity tariffs provide economic and ecological incentives for electrification and load optimization. This may lead to the replacement of oil and gas heating systems with electric-powered heat pumps. Future research could therefore expand the EMS to include heat pumps, introducing a new source of flexible electricity demand that could enhance overall system flexibility. Nonetheless, even with full electrification, the potential for load shifting remains constrained by the hotel's significant fixed energy demands during evening hours. Consequently, another potential extension to the model could involve broadening the system boundaries to include neighboring agricultural or business entities within an energy community. Integrating such daytime energy consumers with complementary load profiles could provide further opportunities for load shifting and increase the potential for CO_2 reduction. Regarding the EMS evaluation, the parametrization is based on a case study conducted in Central Europe, which limits the extent to which its findings can be generalized. For instance, the application of the EMS with different OFs in regions with varying electricity pricing structures may yield different results. Further, the selection of a representative day for each season across all OFs presents a challenge. While choosing a day based on the electricity mix improves the expressiveness of the CO_2 minimization results, the day-ahead price— essential for cost-minimizing OF with variable prices—is influenced by additional factors. Consequently, relying solely on the electricity mix as the selection criterion may result in suboptimal choices, limiting the expressiveness of economic outcomes under variable pricing. To address this limitation, a more comprehensive evaluation that spans the entire year may be necessary to capture subtle variations and improve overall accuracy. Furthermore, the underlying data is partly synthesized from the literature, as not all required parameters could be obtained from the hotel. Additionally, we assume full hotel occupancy with half of the guests arriving in EVs. Future research could consider varying hotel occupancy rates corresponding to high and low seasons during the analysis. Moreover, we integrate these EVs into the hotel's EMS assuming a high user acceptance for the V2B function. As user acceptance has the potential to alter the composition of available vehicles in the mobility groups, future research could explore which mobility group demonstrates the highest and lowest acceptance for the V2B function. Given the V2B function's contribution to decarbonization, investigating various incentive mechanisms from a hotel perspective—such as discounted room rates linked to EV availability—holds promise. Hence, further studies could analyze the effect of different emission-saving incentives on guest behavior and, thus, actively include the preferences and resulting decisions in the EMS and the subsequent scheduling of loads. Furthermore, it would be valuable to gain insights into the demographic characteristics of individuals willing to make their EV available for V2B in hotels and examine their influence on decisions, such as target SOC or charging time windows.

In conclusion, this paper introduces a comprehensive IS framework for a hotel's EMS, integrating stakeholder interests and societal factors such as mobility patterns alongside technical considerations. Our study emphasizes the shift from traditional cost-efficiency to prioritizing CO_2 efficiency in hotel EMS operations as a pivotal, potentially cost-effective strategy for advancing digital decarbonization within the hospitality industry. Adopting the proposed approach enables hotels to minimize their CO_2 emissions in alignment with their guests' preferences and operational constraints. This proactive stance not only supports global efforts to mitigate climate change but also promotes a sustainable trajectory for the industry, ensuring a greener future for generations to come.

Abbreviations

CO_2	Carbon dioxide equivalents
EMS	Energy management system
ESS	Energy storage system
EU	European Union
EV	Electric vehicle
EUR	Euros
HVAC	Heating, ventilation, and air-conditioning
IS	Information system
OF	Objective function
PV	Photovoltaic
RES	Renewable energy source
SOC	State of charge
V2B	Vehicle-to-Building

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s42162-024-00400-9.

Supplementary material: 1. Model Parameters: General Information. 2. Model Input: Objective Function. 3. Model Parameters: Non-controllable Appliances. 4. Model Parameters: Controllable Appliances. 5. Model Parameters: Thermal Appliances. 6. Model Parameters: Storage. 7. Model Parameters: Generation. 8. Model Overview. 9. Nomenclature. 10. Mathematical Formulation.

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Author contributions
L.V.: Project administration, Conceptualization, Design, Writing-Original Draft, Writing-Review and Editing. J.B.: Conceptualization, Writing-Review and Editing. R.K.: Conceptualization, Supervision, Writing-Review and Editing. All authors read and approved the final manuscript.

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Availability of data and materials
The majority of the data generated or analysed during this study are included in this published article and its supplementary information files. The remaining datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
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Competing interests
The authors declare that they have no competing interests.

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