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Enabling Sustainable Personal Mobility through Digitalization Aligned with Transportation Needs

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Vorgelegt von

Jessica Bollenbach

aus Augsburg

Dekan/in:	Prof. Dr. Claas Christian Germelmann
Erstberichterstatter:	Prof. Dr. Jens Strüker
Zweitberichterstatter:	Prof. Dr. Robert Keller
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“Whenever you want to achieve something, keep your eyes open, concentrate, and make sure you know exactly what it is you want. No one can hit their target with their eyes closed.”

Paul Coelho

Der Abschluss meiner Promotion bedeutet auch das Ende einer sehr prägenden und lehrreichen Zeit, weshalb ich diese Gelegenheit nutzen möchte, um Danke zu sagen.

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Abstract

Decelerating climate change and environmental depletion requires rapid decarbonization and environmental protection to achieve the ambitious goals of the Paris Agreement. Since the transportation sector is the second largest emissions-emitting sector after the energy sector, with an ongoing upward trend, a rapid transition to sustainable mobility is crucial. Within the transport sector, personal mobility accounts for two thirds of these greenhouse gas emissions due to internal combustion vehicles (ICVs) and contributes to additional environmental challenges, including local air pollutants, increased noise levels, and resource depletion. The transition towards sustainable personal mobility is an extensive and multidimensional undertaking that should consider a variety of potential avenues for decarbonization and natural environment protection. Accordingly, this transition should encompass multiple sustainable transportation strategies, including technological innovations, shifts in transportation modalities, and a reduction in travel demand. Further, new sustainable mobility solutions must cover all facets of personal mobility needs for daily commuting, long-distance travel, and recreational mobility at the destination to provide a holistic mobility system. While the primary function of personal mobility remains the physical movement of people, it is imperative to develop intelligent and user-oriented information systems (IS) to leverage the sustainable potential of alternative mobility solutions. Therefore, this cumulative thesis comprises seven research articles focusing on two strategies for transitioning to sustainable transport systems. The first series of articles delves into ISs for technological advancements, addressing the integration, operation, and management of charging infrastructure for battery electric vehicles (BEVs) along the entire range of personal mobility needs. They illuminate the coupling of the energy and mobility sectors by implementing intelligent energy management systems, which facilitate the utilization of renewable energy sources. Further, they examine revenue-optimized and customer-oriented management of large-scale fast-charging hubs. Thus, this section aims at direct measures to achieve sustainable personal mobility through transitioning from ICVs to BEVs with the support of appropriate ISs. The second strategy analyzed in this thesis is the reduction of travel demand at overcrowded tourist Points of Interest (POIs) to protect natural environments. By developing elements of an active visitor management system, these papers explore approaches to prevent potential overcrowding aiming at a POI utilization that aligns with the current infrastructure. Consequently, this section outlines indirect measures to achieve sustainable personal mobility, focusing on mitigating environmental damage by reducing crowding at touristic POIs. Overall, this thesis contributes to Green IS and energy informatics research, providing a valuable foundation for the transition to sustainable personal mobility.

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Copyright Statement

Sections of this dissertation partly comprise content taken from the research papers included in this thesis. To improve the readability of the text, I omit the standard labeling of these citations.

Declaration

I confirm that I am the author of this work and that I am fully responsible for its content. To enhance readability and ensure grammatical precision, this dissertation was reviewed using different language editing software (ChatGPT, DeepL, and Grammarly). I conducted a comprehensive review to ensure the thesis' accuracy and adherence to academic standards.

I Introduction

I.1 Motivation

Since the Industrial Revolution, global greenhouse gas (GHG) emissions have steadily increased, leading to rising temperatures and the beginning of a climate crisis (Ritchie *et al.*, 2024). In 2023, the year was observed to be the warmest on record, with temperature records being broken on numerous occasions. For the first time, a temperature increase of at least 1 °C occurred every single day compared to pre-industrial levels, with an average annual increase of 1.48 °C (ECMWF, 2024). Consequently, the impacts of global warming – such as heatwaves, heavy rainfall, and rising global mean sea levels – are already observable today (Lee *et al.*, 2023). To prevent further warming and mitigate climate change, 194 states and the entire European Union (EU) signed the Paris Agreement in 2015. This landmark agreement commits all parties to undertake regular assessments of their national contributions to GHG emissions reduction, aiming for a temperature increase limitation of at least well below 2 °C, preferably to 1.5 °C, while providing a pathway toward sustainable development (United Nations, 2015; Rogelj *et al.*, 2016). In alignment with the 'Sustainable Development Goals' (SDGs) established by the UN General Assembly in 2015 (UN General Assembly, 2015), economically powerful nations have announced individual goals and actions to fulfill the commitments of the Paris Agreement. For instance, the United States introduced the 'Inflation Reduction Act' (The White House, 2023), China pledged to achieve carbon neutrality by 2060 (Hepburn *et al.*, 2021), and the EU launched the 'Green Deal' (European Commission, 2019) and aims to lead the world in implementing ecologically necessary measures while realizing economic potential. Accordingly, under the 'European Climate Law', all 27 EU member states have committed to make the EU the first climate-neutral continent by 2050 and to reduce emissions by at least 55% by 2030 compared to 1990 levels (European Parliament, 2021). The regulations, measures, and subsidies encompass all sectors that emit GHG, including sustainable industrial production, clean energy generation, and transportation.

The European Union has made considerable progress in reducing GHG emissions since 1990, with a reduction of nearly one-third (European Commission, 2023). However, this progress is still insufficient to meet the ambitious targets within the required timeframe. A breakdown of total emissions by major economic sectors reveals that the energy sector contributes the largest share, accounting for a quarter of GHG emissions (European Commission, 2023). Despite being the largest emitting sector, the energy sector achieved the most substantial emission reductions across all sectors (Lamb *et al.*, 2022). This decarbonization of the energy sector is primarily driven by introducing renewable energy sources (RES), such as wind, solar, or hydropower, alongside the phase-out of fossil fuel power plants (Papadis and Tsatsaronis, 2020). Economically, this transformation is feasible as many new RES technologies have reached or fallen below the levelized cost of electricity of fossil fuel technologies (Timilsina, 2021). However, the transition to new energy sources and electricity generation methods leads to new challenges in the power system. Given the substantial limitations of electricity storage capacity in comparison to overall demand, it is essential to maintain a balance between electricity supply and demand. But the weather-dependent electricity generation with RES leads to high seasonal and daily fluctuations, causing problematic imbalances and a potential decline in power quality (Lund *et al.*, 2015; Sinsel, Riemke and Hoffmann, 2020). Consequently, new concepts and technologies are required to introduce flexibility on the supply and demand side to ensure balance and grid security (Michaelis *et al.*, 2024).

The literature classifies five categories of flexibility within the energy sector: supply-side flexibility, storage flexibility, transmission flexibility, demand-side flexibility, and inter-sectoral flexibility (Heffron *et al.*, 2020). Hence, integrating RES into the energy system requires adjustments not only on the electricity supply side but also entails the incorporation of new, flexible consumers. Those flexible and energy-demanding consumers can be found across industry, transport, and building (Hansen, Breyer and Lund, 2019; Körner *et al.*, 2019; Ramsebner *et al.*, 2021). The strategic integration of multiple sectors to enhance flexibility is known as Sector Coupling and facilitates system optimization to provide benefits across all sectors (Robinius *et al.*, 2017; Fridgen *et al.*, 2020). It enables adding more RES power plants into the grid, replacing conventional baseload systems through temporal and spatial energy balancing. For effective balancing, interconnected sectors must respond swiftly and accurately, requiring comprehensive digital information and communication systems that span from decentralized and centralized power plants through the electricity grid to storage and end consumers (Hansen, Breyer and Lund, 2019; Staudt, Lehnhoff and Watson, 2019). Moreover, the electrification and flexibilization of industry, transport, and building sectors contribute to their decarbonization and reduce reliance on fossil fuels.

Following the energy sector, transportation is the second-largest source of GHG emissions. Unlike the energy sector, transportation has seen an increase in GHG emissions, rising by 24% since 1990 (Lamb *et al.*, 2022; Statistisches Bundesamt, 2024). A closer examination of the transport sector reveals that passenger cars and motorcycles, i.e., personal mobility, account for 60% of the total GHG emissions in transport (Statistisches Bundesamt, 2024). The reliance on internal combustion vehicles (ICVs) not only exacerbates GHG emissions but also contributes to additional environmental challenges, including local air pollutants, increased noise levels, and resource depletion (Nykvist and Whitmarsh, 2008; Zhao *et al.*, 2020). The high dependence on cars is attributable to automobile manufacturers' typically strong economic influence, the infrastructure designed for automobiles, and the cultural status accorded to vehicles (Mattioli *et al.*, 2020). Consequently, the policy also supports preserving personal mobility through private vehicles (Mattioli *et al.*, 2020). In light of the pressing necessity for a sustainable transformation, solutions for urban areas, such as smart sustainable cities, are evolving (Meyer, 1981; Silva, Khan and Han, 2018). These solutions include an alternative to car ownership, which is achieved through providing shared services such as (car-)sharing or public transportation (Shaheen and Cohen, 2013, 2021; Felix Baumgarte *et al.*, 2021; Baumgarte, Keller, *et al.*, 2022). However, in rural areas, the economic viability of shared services is typically limited. Further, the lack of infrastructure and the distances involved hinder the utilization of micro-mobility solutions such as e-bikes and e-scooters (Flipo, Ortar and Sallustio, 2023). Therefore, private cars remain the most important means of transportation for people with a wide range of mobility demands and who live outside urban areas (Prillwitz and Barr, 2011). This personal travel encompasses daily activities such as commuting to work, shopping, local leisure activities, visiting friends and family, and the less frequently occurring long-distance trips and recreational travel at the touristic destination (Prillwitz and Barr, 2011). While frequent car use in daily life often extends to long-distance trips and recreational mobility (Prillwitz and Barr, 2011), it is striking that even strong positive attitudes towards sustainability have a limited impact on altering travel behavior (Böhler *et al.*, 2006). This underscores the pressing need to develop sustainable alternatives to ICVs.

One solution for achieving sustainable personal mobility is the utilization of Battery Electric Vehicles (BEVs). While they may have higher GHG emissions during production, the electric drive train can significantly reduce overall emissions during operation (Onat *et al.*, 2019). However, the impact of BEVs largely depends on the electricity mix used for charging. In countries that still rely heavily on fossil fuels, the environmental benefits of BEVs are not significantly better than those of ICVs (Onn *et al.*, 2017; Wolfram and Wiedmann, 2017; Trudewind, Schreiber and Haumann, 2014). Conversely, BEVs substantially improve emissions reductions in regions with high RES utilization (Hawkins *et al.*, 2013; Messagie *et al.*, 2014; Onat *et al.*, 2019). Thus, the electrification of the transport sector presents an opportunity to couple the mobility and energy sectors, facilitating the decarbonization of individual mobility as the use of RES for energy generation increases (Lamb *et al.*, 2022).

For the ramp-up of electromobility, simultaneous and continuous development of charging infrastructure is crucial (Funke *et al.*, 2019). Therefore, the EU has set the goal of installing at least 3 million public charging points by 2030 (European Comission, 2020), which is a challenging target given the current number of nearly 700’000 public charging points in 2024 (European Comission, 2024). Charging infrastructure can be divided into three levels: Level 1 refers to slow AC charging at a standard outlet; Level 2 corresponds to AC charging up to 22 kW with a wallbox; and Level 3 is the DC fast-charging infrastructure with charging capacities up to 350 kW (Lee *et al.*, 2020). Private or public charging in residential areas at Level 1 or Level 2 is the most important location, followed by charging at work due to the long dwell times (Hardman *et al.*, 2018). While Level 3 fast-charging infrastructure represents the least utilized infrastructure type, the availability is still crucial as it enables longer travel distances and acts as a safety net for unforeseen circumstances (Neaimeh *et al.*, 2017; Hardman *et al.*, 2018). Thus, the structured development of charging infrastructure requires not only an adequate number of charging stations but also a strategically thoughtful and user-oriented setup of the charging types (Kchaou-Boujelben, 2021). Additionally, user behavior, service preferences, and cost expectations vary depending on the charging level and location (Schmidt, Staudt and Weinhardt, 2020). Therefore, a customized approach for designing, operating, and managing charging infrastructure is essential. Beyond the charging availability for BEVs, the charging infrastructure serves as a crucial link between the energy and mobility sectors. Intelligent energy management systems, called smart charging, can enhance the utilization of RES by optimizing the charging schedule and power allocation (Daina, Sivakumar and Polak, 2017; Sachan, Deb and Singh, 2020). These sector-coupling smart charging approaches aim to achieve multiple objectives, including cost reduction (Seddig, Jochem and Fichtner, 2019; Yan, Zhang and Kezunovic, 2019; F. Baumgarte *et al.*, 2021), grid stabilization (Singh, Jagota and Singh, 2018) and customer satisfaction (Fridgen *et al.*, 2021; Bollenbach *et al.*, 2024). Additionally, BEVs' batteries can serve as mobile electricity storage, enabling spatiotemporal load shifting. However, to enable cross-sector automated and coordinated interaction, it is necessary to expand the hardware of BEVs and charging infrastructure and design and develop overarching Green Information Systems (IS) (Watson, Boudreau and Chen, 2010). Then, the electrification of mobility does not solely represent an additional burden on local grids and electricity demand but can also support the challenging management of volatile RES by providing additional electricity storage and demand-side flexibility (Dedrick *et al.*, 2023).

However, the mere reduction of GHG emissions in personal transportation is insufficient to achieve overarching sustainable mobility. Travelers often view vacations as a break from their usual eco-friendly behaviors, acting unsustainable as they perceive such travel as a minor fraction of their annual mobility needs (Barr *et al.*, 2010). However, when aggregated across all travelers, this disparity between sustainable values and actual behavior becomes a significant issue for tourist sites (Juvan and Dolnicar, 2014). Notably, the total increase in travel poses challenges for freely accessible and natural tourist Points of Interest (POIs). Often, single popular destinations face the problem of overcrowding and overtourism, leading to strained infrastructure and natural degradation (McKinsey&Company, 2017). The lack of adequate infrastructure results in visitors utilizing unpaved roads, parking their vehicles in protected areas without authorization, and creating new trails that contribute to the deterioration of the natural environment. Therefore, to protect rare natural phenomena, an active visitor management system is crucial to mitigate overcrowding, i.e., reduce mobility, while maintaining visitor's freedom of choice.

The transition towards sustainable personal mobility is an extensive and multidimensional undertaking that should consider a variety of potential avenues for decarbonization and natural environment protection. Moreover, the transition should challenge existing thinking patterns and encompass travel demands beyond the daily commute, including long-distance travel and recreational mobility at the destination (Prillwitz and Barr, 2011). Alongside technological advancements and new mobility services, the development of digital IS is imperative to enable automated energy monitoring, control, management, and user integration (Strüker *et al.*, 2021). Incorporating behavior and personal preferences into the design of future sustainable mobility is essential for the acceptance of new solutions. Thus, the development of a multitude of interconnected, coordinated, and sustainable mobility options is pivotal in addressing the personal mobility needs of all individuals.

I.2 Research Aim

Sustainable transport systems are defined as those that "contribute to social and economic welfare, without damaging the environment or depleting environmental resources" (Nykvist and Whitmarsh, 2008). The creation and establishment of such systems involve a broad array of novel products and services, which are digitally interconnected across various sectors. As such, this dissertation aligns itself with the research domain of Green IS – a field that extends beyond the creation of sustainable Information and Communication Technologies (ICT) to include individuals, processes, and software in the conceptualization of ISs (Watson, Boudreau and Chen, 2010). Thereby, ICTs embedded in ISs leverage sustainable transport systems to become “intelligent” or “smart”, consequently promoting the efficient and sustainable use of scarce resources (Kranz *et al.*, 2015). Specifically, the subfield Energy Informatics in Green IS focuses on information engineering within energy networks aiming at the development of sustainable services and prototypes (Watson, Boudreau and Chen, 2010; vom Brocke *et al.*, 2013; Goebel *et al.*, 2014; Staudt, Lehnhoff and Watson, 2019). Regardless of the chosen mode of transportation, its primary function remains the physical movement of people from one place to another (Stocker *et al.*, 2021). However, IS can provide auxiliary services that enable the creation of additional digital business models or the dissemination of innovative IT-driven services (Piccinini *et al.*, 2015; Graf-Drasch *et al.*, 2023). For example, digital accessibility and convenience are critical success factors for dispersing new sustainable mobility or management services (Hildebrandt *et al.*, 2015). IS can also boost the usage of BEVs by enhancing their attractiveness. Particularly in the context of charging infrastructure, IS can simplify route planning, including charging stops, initiating reservations, and facilitating effortless payments (Brendel and Mandrella, 2016). Moreover, energy informatics enhances both economic and environmental efficiency by leveraging the flexibility of BEVs to cut costs and increase the utilization of RES (Sachan, Deb and Singh, 2020; Baumgarte, Eiser, *et al.*, 2022). Therefore, with digitalization and automation, Green IS enables the development of new products and services that drive the transition towards a sustainable personal transport system.

Nykvist and Whitmarsh (2008) identified three main strategies for transitioning to sustainable transportation: technological advancements, changes in transportation modes, and a reduction in travel demand. These strategies are interdependent and work synergistically to address not just emission reduction, but also other issues such as congestion, noise pollution, traffic collisions, and resource depletion (Nykvist and Whitmarsh, 2008). Thereby, new sustainable mobility solutions must cover all facets of personal mobility, including daily commuting and occasional travel needs. Consequently, a 3x3 matrix emerges, comprising the three transition strategies and the personal mobility requirements for daily commuting, long-distance travel, and recreational mobility at the destination (Prillwitz and Barr, 2011). Given its broad coverage of the transformation towards sustainable personal mobility, this research domain has extensive scope. Thus, to ensure a degree of specificity and academic rigor in this dissertation, I will focus on the technological innovation of BEVs, including charging infrastructure, and the reduction of travel demand at touristic POIs, by examining individual relevant aspects in these areas as illustrated in Figure 1.

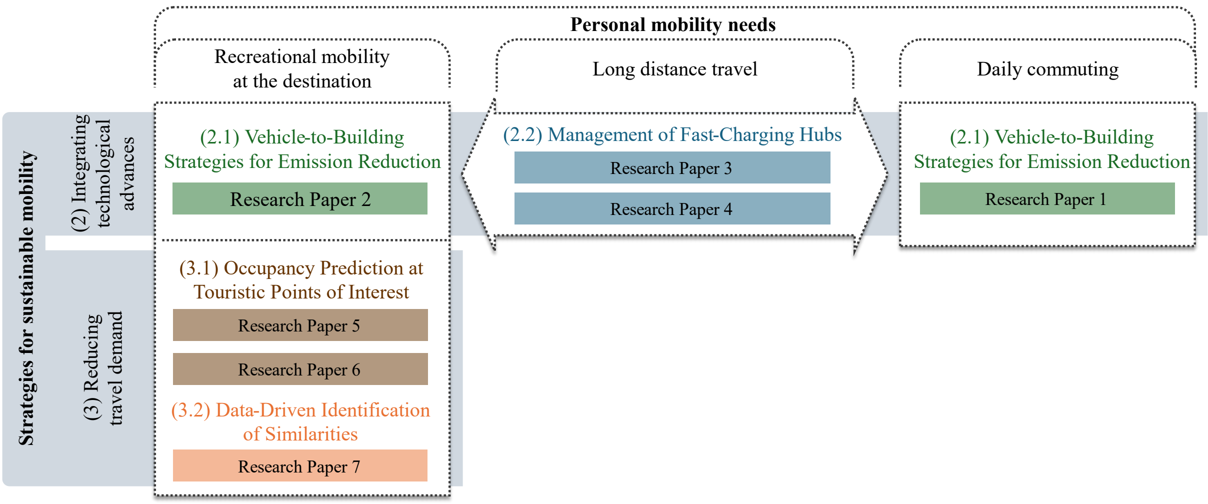

Figure 1. Research papers within the matrix of transition strategies to sustainable personal mobility

Given that cars are one of the most important modes of transportation (Prillwitz and Barr, 2011), the first area of research emphasizes the potential for emission reduction through technological advancement. The emission reduction is achieved by coupling the sectors energy and mobility, utilizing the charging infrastructure for BEVs (Robinius *et al.*, 2017; Fridgen *et al.*, 2020). As purchasing a mobility solution like a car is a significant investment, it must fulfill multiple travel demands. BEVs, as an alternative to ICVs, therefore require charging infrastructure that can meet the daily charging needs (e.g., at frequently visited locations with long dwell times, such as work or home), extend the range for long journeys (e.g., on highways and country roads), and enable trips at travel destinations (e.g., at the hotel) (Hardman *et al.*, 2018). The requirements for a charging infrastructure vary considerably based on location, BEVs' dwell time, and the expectations and behavior of BEV drivers (Funke *et al.*, 2019; Schmidt, Staudt and Weinhardt, 2020). Consequently, different ISs are required to manage the charging infrastructure and processes under the prevailing circumstances.

When BEVs are parked and plugged in for extended periods (e.g., at work, home, or hotels), an intelligent charging system can flexibly shift the charging processes to minimize associated emissions (Sachan, Deb and Singh, 2020). Bidirectional BEVs, which have both charging and discharging capabilities, can further serve as mobile energy storage, enabling the temporal and spatial shifting of stored low-emission electricity (Buonomano, 2020). Given that shifting from ICVs to BEVs already necessitates behavioral changes, additional complex and cross-sectoral energy management systems (EMS) could earn acceptance if they are built around existing behavioral patterns. Therefore, to design EMSs, including bidirectional charging for the workplace, home, or hotel, it is essential to analyze and understand how existing behavioral patterns impact the emission reduction potential and how (de-)charging processes can be integrated into a building's electricity needs (research paper 1 and 2).

In contrast, along highways and country roads, there is a growing need for large-scale fast-charging hubs (LFCHs) capable of simultaneously serving numerous BEVs. These LFCHs are characterized by high charging power, short BEV dwell times, and often limited resources due to substantial investment and operational costs (Funke *et al.*, 2019). From the operator's perspective, efficient resource use is vital for maximizing revenue. It is, therefore, beneficial to explore the applicability of revenue management (RM) theory using dynamic pricing to establish successful business models for LFCHs (research paper 3). However, even when managing the LFCH via dynamic pricing, the stochastic arrival of customers can sometimes lead to reaching the total power capacity limit. Hence, developing an additional EMS that enhances customer satisfaction by smartly distributing the available power is crucial for maintaining and increasing the acceptance of BEVs (research paper 4).

More than reducing GHG emissions is required to fully target the broader ambition of sustainable personal transport. Overloaded infrastructures resulting in congestion, extended search times for a parking spot, and illegal parking pose a challenge, particularly at freely accessible and natural tourist POIs (Paidi *et al.*, 2022). These POIs, so-called Hot Spots, often attract visitors from a wide radius, leading to overcrowding and straining of the inadequate infrastructure at the natural POI. Thus, an actual reduction in travel demand is required to solve the problem of natural depletion caused by overcrowding. Hard, restrictive visitor management measures, such as bans, provide only a solution if the visitors are already on site. They also may result in tourist dissatisfaction. Therefore, preventive, soft measures with close monitoring and active visitor management are necessary, specifically for open-spaced natural POIs (Schmücker *et al.*, 2022). Combined with digital technologies, these soft measures, such as recommendation systems, often provide untapped potential to effectively prevent overcrowding before it even occurs (Spenceley *et al.*, 2015; Veiga *et al.*, 2018). Hence, to enable an automated and fully digitalized active visitor management system, research in occupancy prediction with low time granularity of open-spaced and freely accessible POIs is required to predict potentially overcrowded times (research papers 5 and 6). To reduce travel at the overcrowded POI, similar, less busy alternatives, so-called Cold Spots, should be suggested to potential visitors so they can choose a less crowded POI or route. This necessitates the development of a method for determining route similarities, including several POIs, based on their descriptive features while minimizing the regular interference of experts for better scalability (research paper 7).

The overarching aim of this thesis is, first, to explore the coupling of the energy and mobility sector with the integration of charging infrastructure for BEVs along the entire range of mobility needs. Second, this thesis dives into reducing travel demand at natural-based POIs to protect natural environments and enable the development of an active visitor management system for potentially overcrowded POIs. From a methodological point of view, this thesis contributes to academic research by applying multiple methods, including optimization models, data analysis, Machine Learning (ML) prediction, and Shapley Additive exPlanation (SHAP) values. Thereby, the research builds upon multiple academic theories and concepts, such as the bankruptcy problem within game theory (Thomson, 2019), Expectation-Disconfirmation Theory (EDT) (Oliver, 1980; Tse and Wilton, 1988), and Revenue Management (Talluri and van Ryzin, 2004).

I.3 Structure of the Thesis

This thesis is cumulative and comprises seven research papers, as detailed in Table 1. The matrix presented in Section I.2, Figure 1 builds the basis of the structure, combining the strategies for transitioning to sustainable mobility and personal mobility needs. My research is centered on technological advances and travel demand reduction, whereby each research paper answers a specific research question. All papers are closely interconnected and align with the overarching objective of sustainable personal mobility. The remainder of this thesis is structured as follows: Section II addresses the technological advancement of charging infrastructure for BEVs, which serve as replacements for ICVs. Thereby, I shed light on how Vehicle-to-Building (V2B) approaches at the workplace (research paper 1) and hotels (research paper 2) can contribute to reducing associated emissions under consideration of individual mobility patterns. Further, I examine the operation of LFCHs with regard to the application of RM for enhancing profitability (research paper 3) and the integration of an EMS for improving customer satisfaction (research paper 4). Section III deals with the reduction of travel demand at natural tourist POIs to prevent overcrowding via an active visitor management system. The focus lies on predicting occupancy (research papers 5 and 6) and the automated identification of similar POIs to enable recommendation (research paper 7). Section IV concludes by summarizing the insights of this thesis and outlining recommendations for future research. Section V includes the references, and Section 0 is the appendix, providing detailed information on all seven embedded research papers.

Structure of the thesis		**Research paper**	**Research paper title**
2. Integrating electric vehicles in the course of technological advances	**2.1 Vehicle-to-Building strategies for emission reduction**	Research paper 1	The impact of user behavior and grid-associated emissions on the emission reduction potential of electric vehicle-based spatiotemporal residential load shifting
		Research paper 2	Empowering Sustainable Hotels: A Guest-Centric Optimization for Vehicle-to-Building Integration
	2.2 Management of large-scale fast-charging hubs	Research paper 3	Revenue Management in a Large-Scale Fast Charging Hub for Electric Vehicles: A Multiproduct, Dynamic Pricing Model
		Research paper 4	Customer Satisfaction at Large Charging Parks: Expectation-Disconfirmation Theory for Fast Charging
3. Reducing travel demand via active visitor management	**3.1 Occupancy prediction at touristic points of interest**	Research paper 5	Using Machine Learning to Predict POI Occupancy to Reduce Overcrowding
		Research paper 6	Enabling Active Visitor Management: Local, Short-Term Occupancy Prediction at a Touristic Point of Interest
	3.2 Data-driven identification of similarities	Research paper 7	The Road Not Taken - Representing Expert Knowledge for Route Similarities in Sustainable Tourism Using Machine Learning

Table 1. Structure of the thesis and overview of the research papers

II Integrating Electric Vehicles in the Course of Technological Advances

The ramp-up of electromobility depends largely on the simultaneous expansion of the charging infrastructure. Beyond the necessary hardware expansion, the design and implementation of intelligent ISs for controlling and managing the charging infrastructure represents a pivotal aspect of this evolution. Therefore, a multi-perspective approach is essential, considering BEV drivers, operators, and the energy sector. BEV drivers require a suitable charging infrastructure that aligns with their daily and occasional mobility needs, offering accessible and convenient solutions that seamlessly integrate into existing mobility patterns (Funke *et al.*, 2019). However, this requirement contrasts with the time-bound availability of RES, which are urgently needed to ensure the use of low-emission electricity to enable the sustainability of BEVs (Onat *et al.*, 2019).

Therefore, the subsequent sections delve into the development of multiple ISs to enable user-centric expansion of charging infrastructure while enhancing RES utilization and operability. Section II.1 is dedicated to developing and analyzing two emission-reducing EMSs, including bidirectional charging infrastructure at the workplace (research paper 1) and for a hotel (research paper 2), which integrate existing commuting and recreational mobility patterns, respectively. Turning to the fast-charging infrastructure with short dwell times, emission reduction potential diminishes while other aspects gain relevance. Thus, Section II.2 concentrates on the management of LFCHs to increase revenue via dynamic pricing (research paper 3) and to improve customer satisfaction (research paper 4) in resource-constrained situations.

II.1 Vehicle-to-Building Strategies for Emission Reduction

The coupling of the energy and transportation sectors, enabled by intelligent charging processes, not only plays a pivotal role in the decarbonization of mobility. It also contributes substantially to decarbonizing other sectors, including residential buildings, through sophisticated EMSs. The utilization of RES in the residential sector can be essential to increase the overall RES share and reduce residential GHG emissions, as this sector accounts for around 28% of total German electricity demand in 2023 (BDEW, 2023). Although the share of renewables in the electricity mix is steadily increasing in the EU and Germany (European Environment Agency, 2024; Umweltbundesamt, 2024), residential emissions have stagnated in recent years. As emission minima associated with the electricity mix and residential consumption peaks decouple over time, residential emissions remain difficult to reduce. The residential demand of residents who leave home for work (referred to as commuters) typically peaks twice: during morning and especially during evening hours (Fischer, Härtl and Wille-Haussmann, 2015). At the same time, the emissions minima associated with the region-specific electricity mix occur at divergent times. For regions with grid conditions similar to Germany, for example, emissions in summer are typically lowest during midday, primarily due to high PV output. In winter, emissions might also reach their daily low at midnight when production from wind turbines is high and electricity demand is low. Thus, RES are especially challenging to integrate into established residential demand profiles. With the growing share of RES in the electricity mix, the decoupling of electricity demand and production will aggravate further. Additionally, the ramp-up of BEVs further increases the need for solutions, as current BEV charging patterns contribute primarily to residential evening and nighttime demand, thus, amplifying the decoupling of residential electricity demand and RES production (Mu *et al.*, 2014; Muratori, 2018). Charging at the workplace is one essential means to address this issue and to link BEV charging with RES on-peak hours, which can heavily reduce charging-associated GHG emissions (Tulpule *et al.*, 2013; Buresh, Apperley and Booysen, 2020). Additionally, the bidirectional charging technology, which allows BEVs to charge and discharge their battery, enables additional flexibility (Thompson and Perez, 2020). The combination of workplace charging and V2B opens up opportunities to extend the ecological benefits of workplace charging to the residential sector. If BEVs charge at midday during RES output on-peak hours while at work, they can act as mobile energy storage and transfer energy with a high share of renewable energy to households by driving home. Through the V2B approach, i.e., bidirectional charging or discharging of the BEV's battery, BEVs can at least partially cover household demand during the night, which would otherwise have to be completely covered by electricity from the grid. This way, BEVs could reduce the decoupling between residential electricity demand and RES production by enabling virtual spatiotemporal residential load shifting. Literature refers to this combination of workplace charging with BEVs as mobile energy storage and residential discharging as Building to Vehicle to Building ($V2B^2$) (Barone *et al.*, 2019). However, the GHG emission reduction potential of $V2B^2$ heavily depends on timing electricity demand and, thus, both region-specific electricity mixes and individual behavioral patterns. So far, $V2B^2$ literature mostly neglects the influence of different user profiles and relies on exemplary simulation and synthetic profiles. Recently, Niu et al. (2024) started to address this gap by considering numerous profiles to present a margin for $V2B^2$ system costs. However, they still lack insights on why and how much their results change based on individual user behavior and the available electricity mix.

In research paper 1, we seek to analyze why and by how much the emission reduction potential of spatiotemporal load shifting within $V2B^2$ varies for a country-specific electricity mix with established individual user behavior. To analyze our question, we pick up the case of Germany and consider a stratified subsample of over 26,000 German driving and over 150 residential electricity demand profiles obtained from empirical and real-world data. Further, we utilize the 2023 electricity mix of the German electricity grid. We enhance this data by calculating the upstream and directly with electricity production associated GHG emissions, measured in Carbon Dioxide (CO_2) equivalents, at each 15-minute time step. We simulate a wide variety of different driving and residential electricity demand behavior combinations to obtain the CO_2-equivalent emissions associated with V2B² operation. We further benchmark the model against a typical at-home charging-only scenario to obtain operational CO_2-equivalent emission savings. Afterward, we select causal features to investigate the emission delta and train an Extreme Gradient Boosting (XGBoost) machine learning model. This enables us to examine in detail why and by how much the interaction between the available electricity mix and individual user characteristics changes the V2B² potential using SHAP values. Figure 2 illustrates an overview of the required datasets and modeling phases.

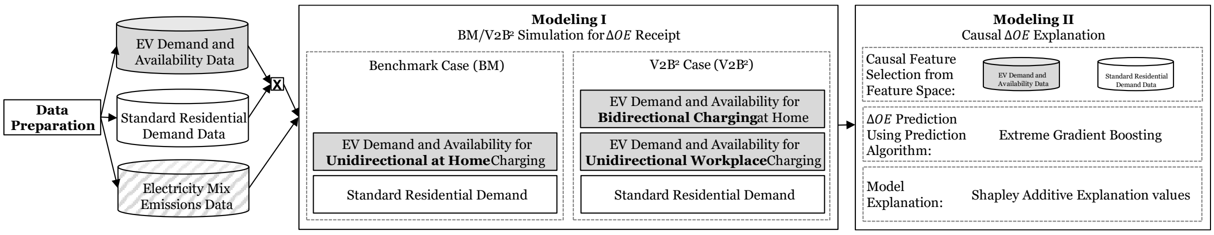

Figure 2. Illustration of datasets and modelling phases for the V2B² analyzes

Our results reveal that the operation of a V2B² concept in Germany, which draws electricity exclusively from the grid, exhibits a strong seasonal dependency on its emission reduction potential. For January, we observe an on-average negative potential of -0.2% from operating V2B². This emission increase was primarily due to greater daytime emissions compared to nighttime emissions that the German electricity mix had in January 2023. During wind-heavy months with low PV output, conventional power plants had to compensate for the high daytime electricity demand, consequently heightening the emissions. Conversely, during the night, the high output from wind turbines decreased electricity mix emissions. This results in yearly repeating months like January 2023, where average emissions are lowest at night. The pattern observed in this paper is characteristic of regions in central Europe, such as Germany. In July, there is a substantial positive shift in the average emission reduction potential of more than 23%. This shift arises from the German electricity mix in July 2023, where daytime emissions were temporarily reduced to almost half that of nighttime emissions. This is why the subsequent examination of behavior as an influencing factor will be limited to July. In the summer months, our findings align with the promising V2B² potentials identified in existing literature (e.g., Barone *et al.*, 2019, 2020; Buonomano, 2020). This correlation may be attributed to the similarities between German summers and the summer months in Italy, which are frequently referenced in these papers.

Depending on individual behavior, the user-specific potential varies considerably from the average emission reduction potential. In detail, we determine for Germany that the primary factors shaping the potential for $V2B^2$ emission reduction in July are individual charging times and the transition of charging procedures to the workplace. We find the time of arrival at home and, thus, typically, the start of BEV charging to be particularly decisive for the individual $V2B^2$ emission reduction potential. If commuters who return home late shift their charging process to the workplace within $V2B^2$, they profit by up to 10% above average. On top of that, our results indicate that especially commuters with long driving distances profit above average from implementing $V2B^2$, especially if they arrive home later. In detail, we find that commuters who drive at least 110 km a day and arrive home after 08:00 p.m. exceed the average potential by more than 10%. In addition, the concept seems particularly suitable for users who can cover a high share of their daily residential demand with the BEV. We find that this tends to be the case for commuters who arrive home before 06:00 p.m.. Since the coverage of residential demand depends on BEV availability and the basic course of demand rather than on absolute consumption, these findings are well transferable to future conditions.

In summary, our results of research paper 1 reveal that $V2B^2$ for emission reduction through spatiotemporal residential load shifting exhibits both a strong seasonal dependence under central Europe weather conditions and a strong dependence on individual user behavior. Therefore, to ensure the most efficient implementation of $V2B^2$, our results vote for a target group-specific incentivization strategy. As the literature primarily recommends monetary incentives (Kacperski and Kutzner, 2020), implementing time-dependent private electricity tariffs seems particularly promising. Especially in summer, tariff makers could encourage a shift to daytime charging by making late and night-time charging more expensive (Chakraborty *et al.*, 2019). In winter, they might encourage later charging times at night, when emissions are at their lowest, to achieve the most efficient ecological contribution to our target of a net-zero energy future.

The transition to BEVs not only offers emission reduction potential for residential electricity demand through $V2B^2$, but also provides potential for other buildings. Compared to other commercial buildings, hotels demonstrate one of the highest energy demands, offering great decarbonization potential (Chung *et al.*, 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, Wang and Wang, 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, 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, 2019). Hence, the development of an EMS to enhance RES utilization, digitize energy management, and enable the utilization of energy flexibilities with the help of digital technologies may accelerate the change toward sustainable hospitality and decrease energy costs (e.g., Heffron *et al.*, 2020; Leinauer *et al.*, 2022). Integrating BEVs into a building's EMS provides additional electricity storage capacity and flexibility to interact with the electricity market and increase RES utilization (Liu *et al.*, 2013). Similar to the $V2B^2$ EMS at the workplace, it is crucial to incorporate the interests of all stakeholders of the hotel, including hotel guests, owners, and energy suppliers, to ensure their acceptance and utilization of the IS. The literature regarding EMS 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). Additionally, the studies that consider hotels and model individual appliances concentrate on cost reduction than emission reduction (Mavrotas *et al.*, 2003; Souza Dutra, Anjos and Le Digabel, 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). As demonstrated in research paper 1, it is imperative to consider BEV drivers' behavior for coordinated (dis-)charging and energy consumption at times with low emissions, as it directly affects the available battery capacity of BEVs during the day. However, real-world data integrated into the V2B studies consist mainly of commuter driving behavior (research paper 1, Mao, Zhang and Zhou, 2018; Barone *et al.*, 2019) and fleet vehicle availability (Barone *et al.*, 2020). Recreational mobility behavior at the destination differs significantly from daily commuting, as it involves a more flexible schedule and a wider range of activities (Bursa, Mailer and Axhausen, 2022).

Therefore, in research paper 2, we analyze the environmental and economic potentials of integrating a V2B concept in a hotel EMS, taking into account the recreational mobility behavior of hotel guests. We develop a hotel-specific EMS, including the 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 Central Europe. The EMS considers the complex energy demand of a hotel by individual modeling various appliances in areas such as wellness, kitchens, and guest rooms. Additionally, we include the mobility behavior of hotel guests, i.e., the BEV's availability, as it differs drastically from everyday mobility behavior and has a major impact on the emission reduction potential.

To develop the optimization model of a hotel's EMS, we categorize the components of the EMS into four distinct areas, also illustrated in Figure 3.

1. **Hotel Electricity Demand** encompasses both controllable and non-controllable appliances. Controllable appliances, such as Heating, Ventilation, and 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** encompasses V2B capable BEVs and a stationary electricity storage system. Both systems can store electricity, either from the grid or locally generated via PV, and supply it back to the hotel.
3. **Electricity Generation** 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** includes both static and variable pricing structures for electricity purchased from the grid, as well as the associated emissions. The grid connection is a backup to meet the hotel's energy demands when renewable generation and storage are insufficient.

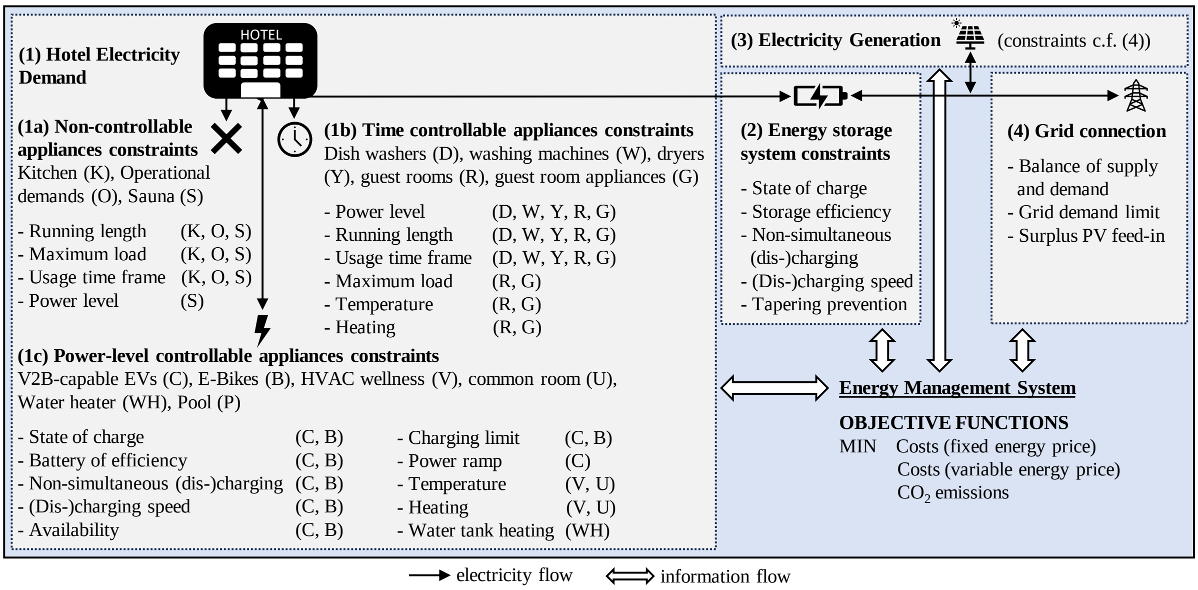

Figure 3. Overview of the optimization model of a hotel's EMS

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, 2014). The study employs Mixed-Integer Linear Programming optimization to assess three distinct objective functions (OF), contrasting two variants of a cost-based EMS (fixed and variable retail price) against a CO_2-based EMS.

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 CO_2 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, BEV availability, and hourly price or emission levels. Notably, the mobility group with a single distant stop, with the longest time spent at the hotel, discharges the most energy from the BEV's batteries to the hotel. Hence, this study provides valuable insights into the trade-off between cost-based and CO_2-based digital EMS. It demonstrates the importance of considering hotel guests' recreational mobility behavior when incentivizing and scheduling applications within their flexibility constraints.

Summarizing the first two papers that analyze and apply V2B approaches in the context of daily commuting and recreational mobility, we conclude that consistently pursuing the Paris climate goals leads to a paradigm shift prioritizing carbon reduction over mere cost savings. We, therefore, advocate focusing on emission reduction in an area traditionally dominated by cost-based strategies. Further, both presented EMSs can only be fully effective if individual mobility patterns are included in the systems' development. For successful implementation and utilization, incentives must be tailored to prevailing conditions. Therefore, it is crucial to consider both time-dependent electricity generation from RES and individual mobility patterns, which are influenced by mobility needs and personal preferences.

II.2 Management of Large-Scale Fast-Charging Hubs

Fast-charging infrastructure (i.e., level 3 charging) enables long-distance travel without excessively long charging times, and even if seldom used, it is a basic prerequisite to cover all personal mobility needs with BEVs (Funke *et al.*, 2019; Funke, Plötz and Wietschel, 2019). This type of infrastructure is specifically required along highways and country roads. The construction of LFCHs with a higher number of charging points will steadily become more relevant as fixed costs per charging station decrease with an increasing number of installed charging stations (Nicholas, 2019). Thus, LFCHs will be more economical for CPOs and, as a result, more common in the future (Haupt *et al.*, 2020). While investment in LFCHs is economical, operational profitability hinges on the location-specific utilization rates of the charging stations, which are influenced by the surrounding BEV usage and local traffic volume (Baumgarte, Kaiser and Keller, 2021). Today's BEV market share of 12 % within the EU (ACEA - European Automobile Manufacturers' Association, 2024) is still low and unevenly distributed, leading to unprofitable fast-charging infrastructure in many European areas and regions. To cover their fixed and variable electricity costs, many charging stations rely on policy support or exceptionally high charging tariffs (Madina, Zamora and Zabala, 2016; European Federation for Transport and Environment AISBL, 2020; Baumgarte, Kaiser and Keller, 2021). To improve profitability and mitigate risks associated with fast-charging infrastructure investments, operators can reduce operational costs or explore strategies to increase revenue. While cost reduction for fast-charging infrastructure is already well-researched, revenue maximization has received less attention. Thus, in research paper 3, we examine the applicability of the RM theory to LFCHs and develop an axiomatic quantitative dynamic pricing model to evaluate the quantitative impact. We conduct a simulation case study to identify the revenue improvements dependent on differently sized LFCHs through dynamic pricing compared to a fixed-price setting.

To transfer RM theory to the distinct context of LFCHs, we build a theoretical framework that demonstrates how a dynamic pricing approach can be implemented in an LFCH. Therefore, we identify the core elements of RM and map them onto the characteristics of LFCHs. This literature-based alignment is grounded in the business model, resource availability, cost structure, and customer behavior inherent to LFCHs and results in the framework presented in Table 2.

	RM Element	Specification for the LFCH
Basic Requirements (Kimms and Klein, 2005)	Integration of an external factor	The external factor in an LFCH is a customer in the form of a BEV driver who decides to charge the BEV and start a charging process.
	Stochastic, heterogenous demand	The demand trend of the LFCH depends on the location and is, for instance, influenced by the time of the week and the fluctuating, stochastic traffic volume of the adjoining roads (Xydas *et al.*, 2016; Hecht *et al.*, 2020; Baumgarte, Kaiser and Keller, 2021).
	Operational lack of flexibility	Two resources constrain the LFCH capacity: the number of charging points, and the total available power capacity, which both have an operational lack of flexibility. The number of charging points is fixed in the short term. An increase is subject to a strategic decision and requires a long-term construction project. The total power capacity is either constrained by the physical limits of the transformer that can, analogue to the charging points, only be increased by a long-term construction project. Or the total power capacity is capped to limit peak demand costs.
	Standardization of products and processes	The offered charging products of an LFCH differentiate by the charging power. The charging process is standardized and independent of the chosen product. The customer starts the charging process and ends as soon as a requested or predetermined SoC of the battery is achieved.
Demand Estimation	Myopic customers (Elmaghraby and Keskinocak, 2003)	An LFCH is often located close to highways or other highly frequented country roads, as these locations face a high demand for fast-charging, given the typical long-distance journeys (Yang, Tan and Ren, 2020). Due to this travel behavior and the dominating one-time customers who do not pass the LFCH regularly, it can be assumed that customers make myopic decisions based on the current price.
	Infinite population (Talluri and van Ryzin, 2004)	Given that electricity is a consumable good it can be considered as an infinite population.
	Aggregate demand functions (Talluri and van Ryzin, 2004)	The profitability of an LFCH is determined by the collective behavior of the population of charging BEVs. Consequently, aggregate demand functions represent the population's behavior rather than the individual assessment of BEV drivers.
Dynamic Pricing Model	No replenishment (Elmaghraby and Keskinocak, 2003)	Since the LFCH is connected to the power grid and the power supply can be regarded as continuous, customers do not consume power and charging points; they use it for a limited time. Once the customer leaves the LFCH, a complete restoration of capacities occurs.
	Flexible resources (Bitran and Caldentey, 2003)	Within the capacity limits, the two resources charging points and total power capacity allow for a flexible allocation of resources to charging products, i.e. they can offer every charging product.
	Both classes of dynamics (den Boer, 2015)	In an LFCH, two classes of dynamics exist. First, the demand changes over time, for example, due to a variable traffic load, and therefore the demand functions change (Xydas *et al.*, 2016; Hecht *et al.*, 2020). Second, the LFCH utilization varies and the resource capacities adapt.

Dynamic Pricing Model	Multiple products (Bitran and Caldentey, 2003)	To serve BEVs with different maximum charging power and to utilize the heterogeneous WTP, multiple products should be considered in the dynamic pricing model, which are optimized simultaneously.
	Continuous or discrete prices (Bitran and Caldentey, 2003)	LFCH operator are not restricted in the pricing of their products, leading to a continuous price range.
	Adjustability of prices (Talluri and van Ryzin, 2004)	The prices are highly adjustable due to the rapid dissemination of price changes, for instance, through charging apps or navigation apps. Thus, a price change does not generate additional costs for the LFCH operator.

Table 2. Framework for Applying RM with Dynamic Pricing in an LFCH

After creating the theoretical framework, we develop a dynamic pricing model in the form of a mixed integer linear programming model. The dynamic pricing model consists of two sub-models: a demand model and an optimization model. The optimization model determines the optimal price for the charging products offered at the LFCH based on the demand forecast provided by the demand model. As the demand for one charging product influences the availability of the remaining resources for other charging products, simultaneous price optimization of all charging products is necessary to integrate those dependencies into the model. Since the price optimization is deterministic, we incorporate the stochastic realization of customers, i.e., the actual utilization of resources in the LFCH, by splitting the day into multiple periods using a rolling window approach. Hence, the dynamic pricing model sets the optimal price of all charging products for one period, considering the expected demand and resource availability. Afterward, the customers realize stochastically based on the pronounced price for this period. For the following period, the optimization model incorporates the resource utilization of the actual, stochastically realized customers.

To analyze the revenue effects of the developed dynamic pricing model in an LFCH, we apply the model to a case study for various exemplary LFCHs closely connected to the highway. Our analysis indicates that using RM in the form of dynamic pricing is reasonable for an LFCH as it can increase the operator's revenues at times when at least one of the two resources for providing a charging product – the total power capacity or the number of charging points – is scarce. Thus, an optimal allocation of potential customers to available resources is required. Rapid BEV adaptation and a lack of charging infrastructure expansion will make peak demand situations in LFCHs more frequent in the near future. This is particularly evident in countries anticipating a serious market ramp-up of BEVs where the expansion of charging infrastructure is lacking (Gnann *et al.*, 2018; Funke *et al.*, 2019). Even with an adequate expansion of charging infrastructure, resources may be fully utilized during periods of peak demand because LFCHs are typically planned cost-effectively. Therefore, isolated peak times do not justify the additional investment costs. Furthermore, providing a one-time high total power capacity also induces high fixed operating costs due to the price structure of electricity procurement and is therefore often capped. Consequently, revenue and demand management become crucial in providing charging services.

Further, our results underline that the relative revenue improvements depend on the LFCH design. In the case study, the resource combination of high total power capacity and a low number of charging points exhibits the largest potential for increasing revenue. Although the dynamic pricing model improves the revenue of the LFCH in any scenario with scarce resources, it never compensates for an unfavorable combination of resources. This highlights the importance of strategic LFCH design decisions and their influence on profitability. The number of charging points should initially be chosen in accordance with the expected demand because expansion is always associated with major construction work. On the contrary, the resource limitation of the total power capacity is invisible to potential customers, who may experience irritation and frustration due to slower charging processes than expected. This invisibility highlights the necessity for an additional solution.

Limited total power capacity leads to a growing gap between prior (individual) expectations and the actual performance regarding the servicing time of charging. According to EDT, this gap negatively impacts customer satisfaction (Oliver, 1980; Tse and Wilton, 1988). Further, the demand for immediate charging at LFCHs provides no flexibility for shifting the charging processes, thus, in situations with limited total power capacity, an actual power bottleneck occurs. Allocating the limited available power among all charging BEVs at an LFCH naively, i.e., uniformly, will not systematically address customer satisfaction in charging BEVs. This uniform power allocation potentially even harms the acceptance of electric mobility. Therefore, in research paper 4, we analyze the problem at hand with a social choice theory grounded optimization model based on a utilitarian welfare function that explicitly accounts for gaps associated with unexpected long(er) servicing times at LFCHs. Further, we evaluate the applicability of the derived optimization model with a simulated case study, including different utilization scenarios to represent a current real-world case and multiple future cases.

Previous literature already identified that the gap between prior expectations and actual performance plays a central role in influencing customer satisfaction regarding fast-charging service (Halbrügge, Wederhake and Wolf, 2020). In the context of fast-charging service, customer satisfaction is generally lower if the gap is larger. In addition, the relationship between the gap and the resulting satisfaction appears to be non-linear. According to Lin et al. (2015), this non-linear correlation especially holds for negative service-expectation deviations. This implies that the longer the charging process duration deviates from a customer's expectation, the increasingly less satisfied the customer will be with the charging service. Uniform power allocation does not take into account the resulting gap between expected and actual servicing time. BEVs with lower maximum charging power tend to experience smaller gaps because they receive the (almost) expected power allocation. Conversely, BEVs with higher maximum charging power receive considerably less charging power than expected, resulting in a larger gap. Consequently, there is a spectrum of customers with small and considerably large gaps. Moreover, the interdependency with other concurrently charging BEVs in the LFCH introduces a notable degree of variability and uncertainty for BEV drivers across multiple charging events, further aggravating their dissatisfaction (Meyer, 1981).

In general, the CPO decides on the realized power allocation (among the BEVs) and might – due to the respective power bottleneck situation – allocate less power than the BEV can be charged with. By applying energy-quantity-based pricing for the charging service, reallocating the same overall amount of power at one point in time between different BEVs does not change a CPO's costs, as the demand peak remains the same. Consequently, the CPO may benefit from reallocating power to address and improve overall customer satisfaction without (negative) effects on its costs. In other words, the CPO is indifferent between a given set of feasible power allocations from a cost perspective, which directly enables a reallocation of power to increase the aggregated vehicle driver satisfaction. All allocations will be Pareto efficient in a bottleneck situation, i.e., no vehicle drivers' satisfaction can be improved without harming another driver. In this context, social choice theory builds on welfare economics and aggregates the preferences/behaviors of individuals, resulting in the concept of social welfare. The possibility to aggregate, e.g., summing up, individual satisfaction is subject to interpersonal comparability. There are different ways in which social welfare can be defined. One possibility is to sum up each satisfaction and treat each individual equally. Maximizing the social welfare of equally treated individuals (i.e., in a non-discriminatory way) refers to the utilitarian welfare function, also called the Benthamite welfare function (Bentham, 1970).

Hence, we develop an optimization model whose objective is to enhance welfare through optimized power allocation while operating at a pre-defined power bottleneck. Our optimization model is the final layer in a holistic control system for the LFCH that allocates the available power in real-time to the charging stations with plugged-in BEVs in bottleneck situations, as shown in Figure 4. Based on EDT, the gap between service expectation and actual service performance is at the core of each vehicle driver's evaluation of the servicing process. Thus, we measure satisfaction with a charging process by the gap between actual and expected servicing time for each vehicle driver d, i.e., $\Delta Time_d = Time_d^{\text{act}} - Time_d^{\text{exp}}$. Maximizing the vehicle driver's satisfaction, this gap needs to be minimized. The more the actual servicing time exceeds the expected servicing time, the increasingly less satisfied the vehicle driver tends to be. Therefore, we use an exponent to model the effect that stronger forms of aversion lead to larger gaps: $\Delta {Time_d}^q$, with $q > 1$. Finally, following the social choice theory, we aggregate individual utilities, i.e. charging customers, using a utilitarian welfare function to maximize welfare: $\max \quad W(Pow_1, \ldots, Pow_{|D|}) = -\sum_{d \in D} (\Delta Time_d + 1)^q$.

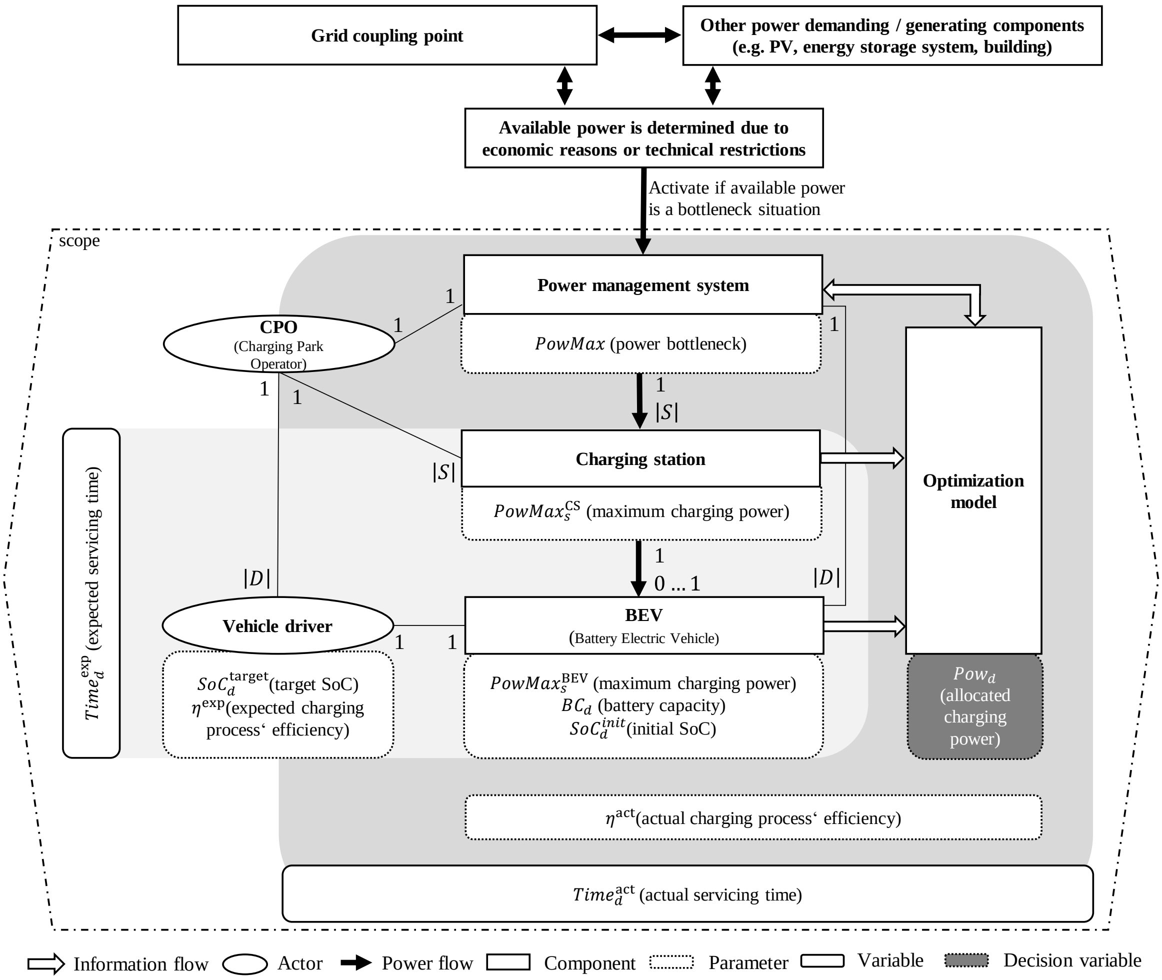

Figure 4. Model setting. The stated numbers along the different lines indicate the number of connected components or actors

For evaluation, we conduct a simulated case study that includes a scenario analysis of varying bottlenecks (i.e., total power capacity) and varying numbers of charging BEVs. Further, we evaluate five cases regarding the technological advancement of BEVs, which is characterized by an increasing battery capacity and maximum charging power, as well as an adjusted market share per BEV vehicle type. The results demonstrate that the optimized power allocation enhanced customer satisfaction compared to a uniform benchmark allocation. This is reflected not only in improving overall customer satisfaction with an increased welfare gain but also at the individual vehicle driver's level by a reduction of the average gap in minutes since extreme values could be eliminated. Improvements for individual vehicle drivers can especially be realized concerning decreasing standard deviations of servicing times, as uncertainty additionally negatively affects satisfaction. It should be emphasized that welfare gains of our model – associated with generally reduced gaps – increase with a scarcer average available power per BEV compared to the benchmark power allocation, as long as there are sufficient planning degrees of freedom. Such effects may be considered "positive" as they add the more welfare, the more critical the bottleneck. However, the absolute level of welfare generally declines the stronger, the scarcer the available power per BEV. We can, therefore, conclude that our model will generally utilize resources more "efficiently" than a uniform power allocation between all charging BEVs (i.e., our benchmark power allocation). However, similar to the dynamic pricing approach, our model may not overcompensate for poor LFCH planning, where power bottlenecks appear to be very large (Gnann *et al.*, 2018). This may be the case when such a big gap between expected and actual servicing time results in the vehicle driver not recognizing an improvement due to the optimized power allocation. Overall, we quantitatively support the initial hypothesis that allocating power uniformly across all charging stations is not optimal concerning customer satisfaction using a utilitarian welfare function.

To conclude the papers regarding LFCHs, even with optimal planning in the design phase, scarce resource capacities will occur due to irregular demand peaks. Therefore, dynamic pricing enables optimized use of resources to enhance profitability for LFCH operators and reserve resources for urgent charging demands. However, with the stochastic realization of customers, it is foreseeable that bottleneck situations of limited total power capacity will continue to occur. To enhance customer satisfaction by minimizing the gap between expected and actual servicing time, we developed an optimization model for non-linear power allocation. With technological progress and an additional increase in the number of BEVs on roads, it is important to emphasize that our dynamic pricing and customer satisfaction enhancement approach is becoming increasingly relevant as bottleneck situations will occur even faster and more frequently. Hence, intelligent layering and integration of ISs for the optimal operation and management of an LFCH can boost electromobility due to increased customer satisfaction, i.e., acceptance of electromobility, as well as the crucial expansion of charging infrastructure by securing profitability for LFCH operators.

III Reducing Travel Demand via Active Visitor Management

While reducing GHG emissions by transitioning from ICVs to BEVs is a vital step towards a more sustainable mobility system, it is not a sufficient standalone solution. As Nykvist (2008) argues, transportation systems should not only mitigate their impact on global warming but also avoid harming the natural environment. Environmental damage, particularly resulting from overloading mobility infrastructure, manifests in forms such as traffic congestion, prolonged search times for parking spots, and illegal parking (McKinsey&Company, 2017; Paidi *et al.*, 2022). The interplay between utilization and environmental damage (Monz, Pickering and Hadwen, 2013) leads to problems such as alterations in vegetation, shifts in wildlife behavior, compromised water quality, and elevated levels of noise and air pollution (Liddle, 1997; Newsome, Moore and Dowling, 2012; Wall, 2019).

The challenges particularly arise at popular touristic POIs, where destination management organizations (DMOs) have often prioritized fast economic growth, resulting in uncontrolled tourism growth and, consequently, mobility growth (Séraphin *et al.*, 2019; Butler and Dodds, 2022). Due to insufficient implementation of sustainability-oriented recreational mobility at the often environmentally vulnerable destinations, the non-scientific community came up with the term overtourism to describe the negative impacts stemming from the constant growth of tourism (Ali, 2016, 2018). Closely related to overtourism is the concept of overcrowding, which refers to the temporary accumulation of people rather than the long-term problematic development of unsustainable tourism (Butler, 2018; Oklevik *et al.*, 2019). In tourism, human crowding (i.e., limited space) and physical crowding (i.e., limited activities) are particularly relevant (Yin *et al.*, 2020) and are reflected in the associated arrival traffic. Thus, overtourism and overcrowding are concerned with the subjective perception of the situation and its measurable impacts rather than relying on an absolute measurement of carrying capacity (Wall, 2019; Dogru-Dastan, 2022). Regarding location, overcrowding primarily occurs at freely accessible tourist destinations and POIs without access restrictions. These may include open-access, often historic, city centers or open-spaced, natural POIs. By an open-spaced POI, we understand a site that does not include a clear boundary allowing people to move freely and widely. While prior tourism-based research predominantly focused on overcrowded cities like Venice or Barcelona (McKinsey&Company, 2017; Mihalic, 2020; Butler and Dodds, 2022), natural POIs are highly vulnerable to environmental damage resulting from the strain on their often underdeveloped mobility infrastructure.

To mitigate the harmful effects of overtourism and overcrowding, implementing visitor management measures is crucial for distributing tourists both temporally and spatially (Zelenka and Kacetl, 2013; McKinsey&Company, 2017). There are two approaches to implementing visitor management, referred to as "hard" and "soft" approaches (Kuo, 2002).

While "hard" visitor management is mandatory, "soft" visitor management is optional and may result in the self-regulating behavior of the tourists (Mason, 2005). Kuo (2002) separates the "hard" approach into three subcategories: (1) physical (e.g., constructions to protect nature sites, viewing platforms) (Butler and Dodds, 2022); (2) regulatory (e.g., rules and regulations to limit the number of visitors) (Bertocchi *et al.*, 2020); and (3) economic (e.g., dynamic pricing or increased entry fees to distribute visitors to less popular days) (Enseñat-Soberanis, Frausto-Martínez and Gándara-Vázquez, 2019). On the other hand, "soft" approaches appeal more to the visitor's goodwill by informing them about alternative tourist destinations or offering directional information like signs or a code of conduct (Kuo, 2002). If too many visitors are already at the POI, hard measures are no longer sufficient. Instead, preventive measures with close monitoring and active visitor management are required, specifically at open-spaced natural POIs (Schmücker *et al.*, 2022).

The following sections are, thus, devoted to the partial development of an active visitor management system to distribute visitors across multiple tourist destinations. The aim is to reduce associated mobility at the crowded destination without overloading another region. Section III.1 dives into monitoring an open-spaced and freely accessible POI aiming at the occupancy prediction of potential overcrowding events (research papers 5 and 6). Section III.2 elaborates on the identification of similar tourist destinations to enable recommendations based on similarity rather than geographical proximity to reduce overcrowding in a specific region (research paper 7).

III.1 Occupancy Prediction at Touristic Points of Interest

In active visitor management, spatiotemporal granularity is arguably the most important property of occupancy prediction of open-spaced and freely accessible POIs. Identifying potential overcrowding events via monitoring and prediction necessitates a fine-grained analysis of both the geographical location and the temporal distribution. A systematic literature review of peer-reviewed research articles (Webster and Watson, 2002) revealed that the number of approaches for fine temporal or spatial granularities is quite limited. Regarding the time dimension, monthly and seasonal granularity are the most frequently used prediction times, whereas week is less frequently used than day. This may be because the day of the week plays an important role in tourism, as weekends are usually significantly more crowded than weekdays. Similarly, we observed that the year is a less frequently investigated prediction period, possibly due to its limited expressiveness. Regarding the spatial dimension, an interesting exception occurs for closed areas (i.e., hotels and parking lots), which have been more frequently regarded than open-spaced POIs, cities, or regions. Most likely, however, this is because closed areas are much easier to analyze due to the availability of clear measurement points and (often) booking data. In addition to these separate perspectives, the combination of both dimensions is particularly interesting within the scope of active visitor management. The combination confirms that for open-spaced POIs, no research exists for an hourly prediction, and only below 1% of research includes a daily occupancy prediction.

Hence, to enable active visitor management at an open-spaced POI, we investigate in research papers 5 and 6 the predictive performance of various prediction models in predicting occupancy, especially peak occupancy. Further, we analyze what impact search query data have on the prediction performance and how the individual features influence the predicted value. To answer these research questions, we conduct a case study focusing on beach occupancy at the Bay in Lübeck, Scharbeutz, located on the Baltic Sea in northern Germany. We compare various cases in the prediction model development to pinpoint the optimal configuration to enable active visitor management. In predicting *visitor movements*, we differentiate between two variations: the visitor count prediction (which merely accounts for the entering people) and the occupancy prediction, which considers the beach occupancy. We further compare the performance of two different temporal aggregations, called *time granularity*, with 4-hour and 24-hour timesteps because a higher aggregation may result in better predictions for a longer prediction time horizon. The *spatial granularity* refers to the spatial segmentation of the POI, where we consider entrances, beach sections, and the beach. In addition, we compare three different *prediction time horizons*: four hours, one day, and three days ahead, i.e., how far in advance the visitor movements are predicted.

Our analysis reveals that XGBoost and Random Forest stand out as the most suitable prediction models for visitor movement prediction to enable active visitor management (c.f. Figure 5). Despite the slightly weaker prediction accuracy of beach occupancy compared to visitor count, beach occupancy remains a vital and required prediction for facilitating active visitor management. While visitor count merely reflects the number of ingoing individuals, it lacks information about the duration of their stay - a critical factor influenced by external variables such as season or weather. Consequently, precise identification of crowding or overcrowding times based solely on visitor count is challenging for the DMO. For instance, a similar visitor count in summer may result in overcrowding due to prolonged stays, while in winter, people often take brief walks and cause no overcrowding. In contrast, beach occupancy encompasses both the duration of stay and the precise time of crowding and overcrowding, providing a more nuanced understanding and enabling the implementation of time-specific steering measures. This underscores the significance of occupancy prediction in active visitor management, streamlining the need for multiple threshold definitions to initiate appropriate measures. Further, the beach occupancy prediction model should be applied at a larger spatial granularity, such as the entire beach. This approach ensures accuracy in occupancy calculations, even when individuals use different entrances for exiting compared to entering the beach. Additionally, our findings suggest a preference for a shorter prediction time horizon for beach occupancy, as it significantly enhances prediction quality.

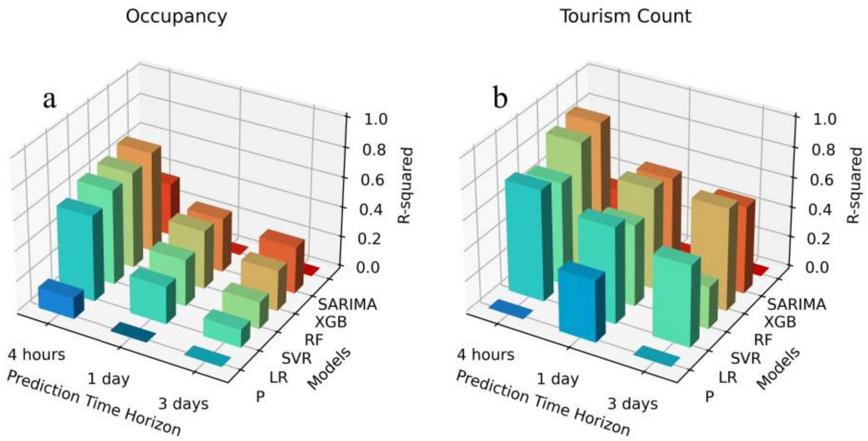

Figure 5. R^2 measures for the visitor movement, both occupancy (a) and visitor count (b), on the beach across all model types and prediction time horizons with a time granularity of 4 hours

Concerning the integration of Google Trends data, our findings align with those of Önder et al. (2019). Due to the variability between use cases, an individual assessment of the improvement potential is required for each case. The marginal impact and modest improvement observed in the prediction models upon integrating Google Trends data can be attributed to the inherent characteristics of the data itself. Factors such as holidays or weather influence search query data and, thus, overlap with the features of our visitor movement prediction models. Consequently, the shared reliance on these influencing factors diminishes the potential for substantial improvement in the prediction models. However, despite the marginal improvement, the Google Trends features are still considered important in the SHAP value analysis because they reflect a similar trend to the visitor movement. Hence, due to the overlaps and dependencies with the Google Trends data, they distort the importance of the other features. Therefore, the importance of the factors should be interpreted without Google Trends data.

To analyze the importance of features and how they influence the prediction, we utilize SHAP values. The most important features are the lagged historical values, time-related, and holiday-related features. The mixed importance of weather categories implies that tourists primarily focus on simple weather forecasts, including temperature or precipitation form, but do not consider more detailed information. Our findings show that including detailed weather features only impacts visitor movement predictions when tourists consider such information during their planning process. Here, it is essential to emphasize in enhancing prediction models that the primary objective is not the precise prediction of visitor movement but, rather, the accurate anticipation of peak periods. Already, the correct identification of peaks during, for example, holidays or breeding season allows one to decide about the right steering measures in an active visitor management system. Besides the potential improvement of the prediction models, the transferability to other public, open-spaced POIs is essential. Generally, the presented approach serves as a blueprint for measuring and predicting visitor count and occupancy of a public, open-spaced POI to identify potential demand peaks. The first step to transferring the approach to a new POI is to define the geographic boundaries of an overcrowded and monitored POI. Secondly, as with the beach entrances in Scharbeutz, sensors should be installed at natural bottlenecks, where there are optimally no or only unattractive alternative routes for people to pass by. Thirdly, data collection begins after installation, and visitor capacity updates may be accessed through DMO portals. After accumulating sufficient data over at least one season, the ML models XGBoost and Random Forest can be trained, evaluated, and deployed for ongoing occupancy monitoring and prediction. In addition to the universal implementation of occupancy prediction systems for individual use cases, models trained in similar environments, such as beaches, may be reused for comparable settings. Distinct POIs, such as mountainous regions geared towards hiking, necessitate developing new models tailored to specific features. However, determining the extent to which model reuse is feasible and identifying relevant features per case category remain areas for further investigation. The nature of the POI determines whether we can predict only visitor count or both visitor count and occupancy. Predicting occupancy is feasible for POIs resembling the beach, where visitors tend to stay and use the same exit as the entrance. However, at POIs like mountains with diverse hiking paths, visitors often choose different routes for the outward and return journey, resulting in higher error values when calculating occupancy. Despite this specific problem for occupancy prediction, visitor count still offers valuable insights with probably high prediction quality, and active visitor management remains feasible in multiple POIs to enable active visitor management. Identifying potential overcrowding events enables the development and implementation of an overarching active visitor management system that can mitigate peak times and ultimately benefit economic stakeholders, tourists, and the entire region towards sustainable growth.

III.2 Data-Driven Identification of Similarities

By predicting the tourism demand with ML algorithms, tourist destinations are able to better prepare in advance for days with peak demand. However, preparation at the destination itself is insufficient to avoid crowding and enable sustainable tourism. Therefore, overarching measures are required to distribute visitors across multiple tourist destinations and reduce the number of people at the crowded destination without overloading another region. One approach to developing sustainable IS, i.e., an active visitor management system, is a "data-based system that recommends sustainable product alternatives" (Tomkins *et al.*, 2018; Lehnhoff, Staudt and Watson, 2021; Neubig *et al.*, 2023). In this case, a visitor guidance concept serves as a solution, whereby in a predicted case of crowding (research papers 5 and 6), a recommendation system directs the tourists in advance to alternative tourist destinations, i.e., an alternative POI or route. Hereby, the recommendation system's method of identifying alternative destinations determines whether crowding can be mitigated. Most current approaches recommend tourist destinations based on geological data and distance, which does not solve the crowding problem as most tourists stay in the general area (Yin *et al.*, 2013; Wang *et al.*, 2015; Pham, Li and Cong, 2017). Furthermore, many recommendation algorithms suggest popular POI instead of less overcrowded alternatives (Yuan *et al.*, 2013; Yuan, Cong and Sun, 2014; Yao *et al.*, 2016). This only increases the number of tourists at trending tourist destinations. To solve the crowding problem, the recommendation system should be based on the similarity of the tourist destination rather than geographical proximity. With the similarity of destinations as the basis of the recommendation system, the number of suggested destinations increases. Hence, tourists can choose from more destinations, and the crowding of overloaded regions can be reduced. Further, identifying similarities should be widely automated and digitized to enable large-scale use.

While the similarity of POIs has been addressed in current research (Wang, Lu and Huang, 2019; Zhao *et al.*, 2019; Qiu, Gao and Lu, 2021), there is still a lack of literature considering the similarity of routes. In contrast to single POIs, a route can consist of several POIs and is composed of various properties. This implies that crowding occurs not only at the individual POIs but along the entire route in a larger area. Therefore, an alternative must be located outside this network of congested routes and crowded POIs. Especially for rural tourism, routes (e.g., trails, paths) are increasingly becoming more relevant for crowding analysis since recreational tourism, such as hiking, has increased significantly in recent years (Calbimonte *et al.*, 2021). Furthermore, due to their exposed location, hiking trails are usually accessed by car, and there is a limited availability of parking spaces. If crowding on hiking trails can be mitigated, the environmental impact of travel mobility can also be reduced by limiting the use of shortcuts and eliminating illegal parking. Thus, in research paper 7, we develop a method to determine the similarity of routes based on their descriptive features. Thereby, we answer the question of how accurately various distance-based similarity and ML algorithms calculate route similarities using labeled and unlabeled data. Further, we analyze the most relevant features and how they influence the similarity prediction. To answer the research questions, we propose a method to evaluate the similarity of routes by applying and comparing two distance-based similarity and five ML algorithms. This approach is then applied and tested in a case study about the similarity of hiking routes in a nature park in the South of Germany with descriptive company data provided by the online outdoor platform “Outdooractive”. In the case study, we integrate human expert knowledge by training and evaluating the models using survey results on the similarities of hiking routes conducted by nature park rangers. Furthermore, since many ML algorithms act like a “black box” (Bauer *et al.*, 2021; Pfeuffer *et al.*, 2023), we use SHAP values to shed light on the most significant descriptive features of the hiking routes and how they influence the prediction model.

All relevant hiking route data was identified based on the geographical location within the nature park and downloaded using the Outdooractive API. After cleaning, 50 one-day routes are picked randomly using random sampling to get two sample datasets for further evaluation (Singh, 2003). Both contain the same routes, but in addition to the base dataset, the extended dataset also contains the tag features (e.g., *dining*, *suitable for families*). Both datasets are standardized before calculating the similarities to ensure that all features are on the same scale and, thus, no feature with a larger scale (e.g., *length*) could have a greater impact (Lesot, Rifqi and Benhadda, 2009).

To determine the similarities between the hiking routes, we first calculate the Euclidean and Gower similarity for each route pair in the base dataset and the extended dataset on unlabeled data. Examining the correlation between prediction and rating from the expert survey reveals a positive correlation, which is supported by the Spearman rank correlation. When comparing the base dataset with the extended dataset, both similarity algorithms outperform across all metrics on the base dataset. Although the Gower similarity algorithm achieves a slightly higher R^2 and lower MSE score than the Euclidean algorithm, the Spearman rank correlation is higher for the Euclidean similarity. Thus, the distance-based similarity algorithms enable a general prediction of similarity. Comparing the results of the similarity algorithms with ML models, the ML models demonstrate superior performance, particularly when trained on the extended dataset. Already achieving higher R^2 values, there is a 4.2% increase in the R^2 score from the base to the extended dataset. Among the ML algorithms, Random Forest Regression performs the best, with SVR achieving lower R^2 and MSE scores but better results for the Spearman correlation. Despite the differences in performance among ML algorithms, the results are closely clustered.

The utilization of SHAP values allows a closer examination of the various features. Figure 6 presents a global SHAP values plot for the Random Forest Regression, the best-performing model, trained and evaluated on the extended dataset. All features with "tag" in their names exclusively belong to the extended dataset, while all other features are part of both datasets. Although calculated differently from the feature importance determined by the models, SHAP values also identify *length* as the most important feature, followed by the *duration*, *maximum elevation*, and *total ascent*. The most important additional feature from the extended dataset is *scenic*, followed by the *suitability of a route for families*. Interestingly, despite the 15 least important features being tags (five depicted, ten not depicted), models trained on the extended dataset outperform those on the base dataset. Examining the distribution of features impact, we observe that the *length* values are mostly evenly distributed, although slightly skewed to the right. The *time* feature exhibits a high concentration of values with a negative impact of approximately -0.3. In contrast, values with a positive impact do not display a similar accumulation. The *maximum altitude* contains numerous values with minimal impact and several extreme outliers that notably influence the model output. In terms of correlation, we generally expect a negative correlation between the features and the target data, given that the features represent the distance between two routes. This holds true for most features, although with some exceptions (i.e., *elevation descent* or *ridge*). Concluding, the analysis of SHAP values allows for an interpretation of how various features influence prediction performance. However, it is essential to note that SHAP values describe the model's interpretation of features and may not capture general relations, given that the Random Forest Regression model does not achieve perfect results. This becomes evident as some features influence the model in the expected way while others do the opposite.

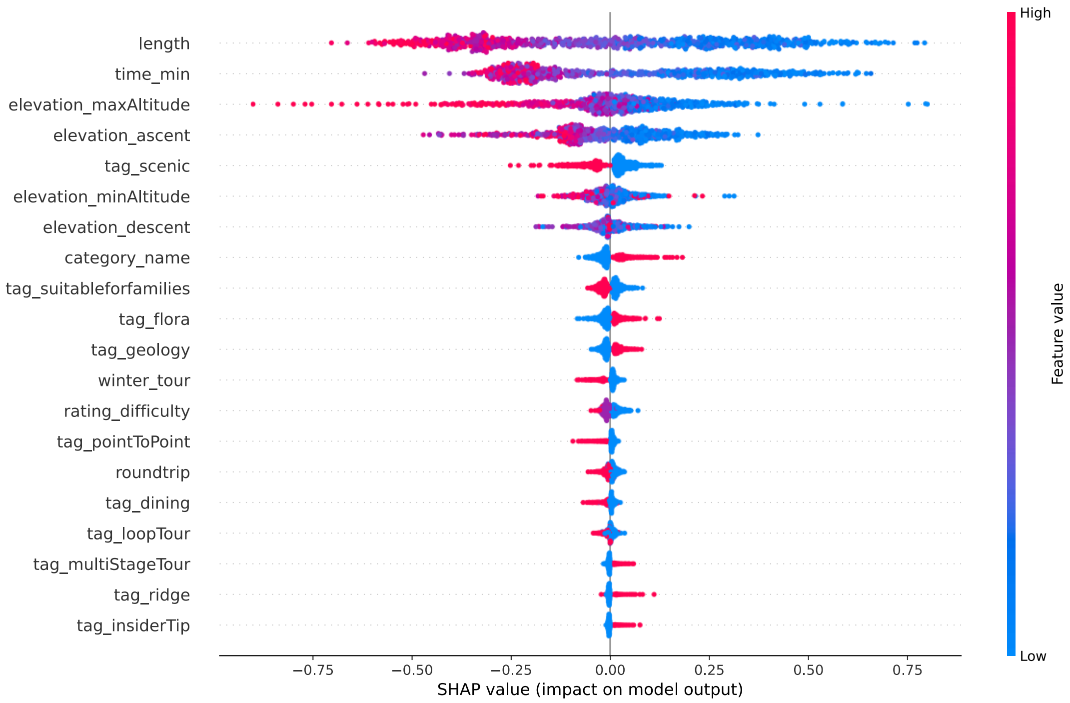

Figure 6. SHAP values of the Random Forest Regression

By analyzing and comparing various algorithms for distance-based similarity alongside ML approaches, we aim to pave the way for more sustainable recreational tourism practices and enrich the toolkit available to researchers and practitioners for recommendation systems in diverse domains. Contributing to practice, these insights enable the implementation of a recommendation system fit for the interest of users and to prevent crowding. Contrary to many other recommendation systems, this approach can suggest routes outside of a crowded region based on inherent route similarity, contributing to a more even distribution of visitors. Therefore, the number of visitors can be aligned with the existing infrastructure, reducing illegal parking and minimizing search traffic. Furthermore, designated trails remain adequate, as visitors refrain from creating additional paths to avoid crowded areas. Implementing such measures not only results in fewer people per square meter and reduced utilization but also mitigates trampling effects, leading to a decline in the deterioration of flora and fauna. Finally, lower emissions contribute to the overall protection of the natural environment and climate. Beyond environmental protection, active visitor management offers notable social benefits. Restricting the maximum number of visitors can alleviate traffic congestion, crowded public transport, and long queues. This, in turn, enhances tourism acceptance among residents, fostering increased friendliness and openness while preserving the integrity of the local culture.

IV Conclusion

IV.1 Summary and Outlook

In light of the still-growing issue of emissions from the transport sectors, making personal mobility more sustainable is of utmost importance. The transition towards sustainable mobility can be accomplished through combining complementary strategies, including technological innovation, a reduction in travel demand, and a shift towards alternative transport modes. Novel sustainable mobility solutions must encompass the full spectrum of mobility needs, ranging from daily commuting to long-distance travel and recreational mobility at the destination (c.f. Figure 1). In addition, the successful introduction of new services and products demands considering and integrating several perspectives. Enhancing acceptance requires user-oriented systems built on viable business models to ensure longevity. Simultaneously, effective resource allocation is crucial including the consideration of sector coupling to proactively manage the utilization of RES. Therefore, the integration of all requirements necessitates the implementation of overarching ISs that leverage ICTs to promote the development of sustainable, intelligent, and user-oriented personal transport systems.

This doctoral thesis comprises seven research papers collectively aimed at enabling the transformation toward sustainable personal mobility (c.f. Table 1). The thesis addresses two key aspects: introducing technological advancements along with mulitple mobility needs and reducing travel demand for recreational mobility at the destination. Section II dives into the technological advancement of BEVs, focusing on the challenges of integrating charging processes in established mobility behaviors and enhancing RES utilization via sector coupling. Specifically, in Section II.1 I develop and analyze V2B strategies for maximal RES utilization within the contexts of the workplace (paper 1) and a hotel (paper 2), taking established mobility behaviors during recreational and daily activities into account. In Section II.2 I elaborate on the application of RM in LFCHs to maximize revenue under scarce resources (paper 3) and improve customer satisfaction through optimized power allocation (paper 4). Thus, this section aims at direct measures to achieve sustainable personal mobility by supporting the shift from ICVs to BEVs with appropriate ISs to facilitate user-oriented charging infrastructure that maximizes RES utilization. Section III addresses the reduction of travel demand in recreational mobility to prevent environmental damage due to overcrowding caused by overloaded infrastructure. The overarching objective is to enable the development of an active visitor management system that employs soft steering measures to distribute visitors across a wider area, thereby avoiding overloading any specific POI. To achieve this, Section III.1 concentrates on predicting crowding events (papers 5 and 6). Building on this, Section III.2 investigates automated and digitized identification of similarities (paper 7) to enable crowding prevention through recommendations. Consequently, this section outlines indirect measures to achieve sustainable personal mobility by reducing the crowding at touristic POI and, thus, reducing arrival mobility and environmental damage.

The thesis contributes to the research field of Green IS and sustainable personal mobility by developing various optimization models, e.g., energy management, revenue optimization, and customer satisfaction enhancement. It utilizes multiple real-world data sets to analyze, combine, and develop ML models. Moreover, widely recognized theories and methods, such as RM with dynamic pricing or EDT including utilitarian welfare function are applied within a new context. From a practical point of view, the thesis offers insights into newly developed EMSs, including bidirectional charging, while considering established user behavior to enhance acceptance and raise RES utilization. It provides recommendations for revenue-optimized yet user-oriented management of LFCHs to facilitate long-distance travels with BEVs. Further, by predicting occupancy and identifying similarities, the research proposes data-driven solutions to distribute visitors more evenly across multiple POIs. Consequently, this thesis offers policymakers and practitioners new approaches and recommendations to support the transition towards sustainable personal mobility.

IV.2 Limitations and Future Research

The research field of sustainable personal mobility and mobility needs is extensive, which is why this thesis, like any scientific research, is subject to certain limitations while also offering potential avenues for further research.

Firstly, the majority of analyses were carried out using regional data sets (e.g., mobility demand or RES expansion). Similarly, the selected data for investigating influences of specific behaviors was drawn from the European region or was based on standard Western behaviors. As a result, the specificity of analysis and recommendations is confined to regions and behaviors that precisely match the referenced data. Therefore, to provide a comprehensive understanding of the research questions, further studies are necessary to assess the applicability of these findings across different regions.

Secondly, the analyses, optimizations, and ML models were all carried out with attention to user needs. However, while established behaviors and expectations were incorporated into the research, there was no explicit investigation into the acceptance of the proposed approaches. Thus, to validate whether the developed ISs attain the desired outcome, they could be deployed, and their usage could be studied experimentally in future research, either through simulation or real-world application.

Thirdly, this dissertation presents the development, implementation, and analysis of several components of ISs. Each was designed with the intention of integration into a comprehensive IS framework. For instance, the effective management of LFCHs at scarce resource availability necessitates the combination of the dynamic pricing model with the power allocation model to enhance revenue and customer satisfaction. Similarly, including occupancy predictions alongside similarity identifications is essential for active visitor management systems. This work's findings open various possibilities for future research beyond merely combining these IS components. For example, integrating local PV generation or electricity storage solutions for LFCHs could further optimize revenue, grid stability, and customer satisfaction, offering yet another potential area of exploration. In the case of active visitor management, the recommendation system should be examined in more detail to provide an overarching solution. In summary, before implementing individual parts of IS, it is essential to explore and expand upon them further in a research context and subsequently deploy them in real-world applications. This transition can be carried out cohesively, with initial real-world execution also providing an avenue for further research into practicality and acceptance.

While this thesis primarily focuses on analyzing and developing new ISs for specific applications, future research may consider a comprehensive perspective across all mobility solutions and mobility needs. This would enable the prioritization of targeted technologies, the development of policy measures, and the identification of appropriate user incentives. In conclusion, this doctoral thesis substantially contributes to advancing the understanding and implementation of sustainable personal mobility. By addressing both the technological advancement of BEV adoption and travel demand reduction via active visitor management, the research provides multiple approaches toward decarbonization and environmental protection. The findings underscore the importance of interdisciplinary collaboration and digital technology integration, driving the transition toward a more sustainable and resilient future.

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VI Appendix

VI.1 Research Articles Relevant to this Doctoral Thesis

Research Paper 1: The impact of user behavior and grid-associated emissions on the emission reduction potential of electric vehicle-based spatiotemporal residential load shifting

Bollenbach, J.; Eiser, N.; Keller, R.; Strüker, J. (2024). Impact of country-specific electricity production and individual user behavior on the ecological potential of electric vehicle-based spatiotemporal shifting of residential electricity demand. *Working paper submitted and under review in Cleaner Production.*

Research Paper 2: Empowering Sustainable Hotels: A Guest-Centric Optimization for Vehicle-to-Building Integration

Valett, L.; Bollenbach, J.; Keller, R. (2024). Empowering Sustainable Hotels: A Guest-Centric Optimization for Vehicle-to-Building Integration. In: *Energy Informatics*.
(VHB-Jourqual 3 Category: n.a.; SJR 2023: 0.568; CiteScore 2023: 5.5 / 67th Percentile)

Research Paper 3: Revenue Management in a Large-Scale Fast-Charging Hub for Electric Vehicles: A Multiproduct, Dynamic Pricing Model

Bollenbach, J.; Kaiser, M.; Baumgarte, F.; Keller, R.; Weibelzahl, M. (2024). Revenue Management in a Large-Scale Fast-Charging Hub for Electric Vehicles: A Multiproduct, Dynamic Pricing Model. *Working paper submitted and under review in Applied Energy*.

Research Paper 4: Customer Satisfaction at Large Charging Parks: Expectation-Disconfirmation Theory for Fast Charging

Bollenbach, J.; Halbrügge, S.; Wederhake, L.; Weibelzahl, M.; Wolf, L. (2024). Customer Satisfaction at Large Charging Parks: Expectation-Disconfirmation Theory for Fast Charging. In: *Applied Energy*. DOI:10.1016/j.apenergy.2024.122735.
(VHB-Jourqual 3 Category: n.a.; SJR 2023: 2.820; CiteScore 2023: 21.1 / 99th Percentile)

Research Paper 5: Using Machine Learning to Predict POI Occupancy to Reduce Overcrowding

Bollenbach, J.; Neubig, S.; Hein, A.; Keller, R.; Krcmar, H. (2022). Using Machine Learning to Predict POI Occupancy to Reduce Overcrowding. In: *INFORMATIK 2022. Lecture Notes in Informatics (LNI).* DOI:10.18420/inf2022_34.
(VHB-Jourqual 3 Category: C)

Research Paper 6: Enabling Active Visitor Management: Local, Short-Term Occupancy Prediction at a Touristic Point of Interest

Bollenbach, J.; Neubig, S.; Hein, A.; Keller, R.; Krcmar, H. (2024). Enabling Active Visitor Management: Local, Short-Term Occupancy Prediction at a Touristic Point of Interest. In: *Information Technology & Tourism*. DOI:10.1007/s40558-024-00291-2.
(VHB-Jourqal 3 Category: n.a.; SJR 2023: 1.901; CiteScore 2023: 18.1 / 96th Percentile)

Research Paper 7: The Road Not Taken – Representing Expert Knowledge for Route Similarities in Sustainable Tourism Using Machine Learning

Bollenbach, J.; Rebholz, D.; Keller, R. (2024). The Road Not Taken – Representing Expert Knowledge for Route Similarities in Sustainable Tourism Using Machine Learning. *Working paper submitted and under review in Electronic Markets.*

Beyond the research papers included in this dissertation, I also co-authored the following research paper, whitepapers, and book chapter, which are not part of the doctoral thesis:

- Bayer, D.; Bollenbach, J.; Lersch, J.; Rusche, S.; Weibelzahl, M. (2023). Smart Mobility Meets Industry: Enhancing Energy Flexibility Potentials by Combining Industrial Production & Electric Vehicle Charging. In: *AMCIS 2023 Proceedings. 13. (VHB-Jourqual 3 Category: D)*
- Jordan, P.; Scharmer, V.; Schulz, J.; Wörle, M.; Zäh, M.; Hohmann, A.; Karg F.; Roth, S.; Bollenbach, J.; Buhl, H. U.; Michaelis, A.; Parak, D.; Renner, J.; Weibelzahl, M.; Winter, C (2023). Energieflexible Modellregion Augsburg – Lessons Learned aus dem konzeptionellen Testbetrieb zum regionalen Energieflexibilitätshandel. DOI:10.14459/2023MD1687088
- Menke, F.; Bollenbach, J.; Keller, R. (2024): Why do we crowd? Causal Explanations for Visitor Management. *Working Paper*
- Buhl, H. U.; Bollenbach, J.; Breiter, K.; Weissflog, J. (2024): Schaufenster für Quartiere der Zukunft. Erfahrungen aus der Praxis. Technische Hochschule Augsburg. Institutsteil Wirtschaftsinformatik des Fraunhofer-Instituts für Angewandte Informationstechnik FIT, Augsburg/Bayreuth.
- Eisele, J.; Bollenbach, J.; Brey, S.; Schubert, J.; Sommer, G.; Keller, R. (2022). Besucherlenkung und Reduktion des motorisierten Freizeitverkehrs – das Potential datengetriebener und flexibler Busangebote. In: Leonhardt, S.; Neumann, T.; Kretz, D.; Teich, T.; Bodach, M. (Hrsg.), In: Innovation und Kooperation auf dem Weg zur All Electric Society (S. 175-193). Wiesbaden, Deutschland: Springer Fachmedien Verlag.

- Schoormann, T.; Kammler, F.; Gembarski P. C.; Hagen, S.; Brinker, J.; Bollenbach, J.; Jussen-Lengersdorf, I.; Keller, R.; Kortum-Landwehr H.; Möller, F.; Petrik, D.; Schweihoff J.; Stachon, M.; Winkelmann S. (2024): Sustainable ecosystems: Findings from the NaWerSys workshop series. In: *INFORMATIK 2022. Lecture Notes in Informatics (LNI). (VHB-Jourqual 3 Category: C)*

VI.2 Individual Contribution to the Research Papers

This is a cumulative doctoral thesis and consists of seven research papers. Since all of them were written in collaboration with multiple co-authors, I will outline my individual contribution to each of the seven papers in the following.

Research paper 1 (cf. VI.3) was written by a team of four co-authors. The paper was initially submitted to the Journal of Applied Energy and is currently being revised for a new submission. All authors contributed equally to this paper. My involvement in this research project included contributing to ideating and conceptualizing the research aim. Additionally, I supervised the overall research process, including the development of the evaluation framework and critically analyzing the results. Further, I took a central role in reviewing and editing the original draft of this paper.

Research paper 2 (cf. VI.4) was written by a team of three co-authors. The paper is accepted for publication in the Journal of Energy Informatics. The paper started as a conference paper with equal contributions from each of the three co-authors. As it evolved into a journal article, we agreed that Lynne Valett would continue in the role of lead author while I would continue to provide support as a subordinate author by reviewing and editing. In the initial submission, I was primarily responsible for compiling, researching, and writing the introduction and literature review regarding V2B in an EMS and the embedding in the IS research field. Further, I supported the conceptualization and evaluation of the analysis and wrote parts of the methodology and case study.

Research paper 3 (cf. VI.5) was written by a team of five co-authors, and all co-authors contributed equally to this paper. The paper was submitted to the Journal of Applied Energy and is currently under review. I took a key role in initiating the project. I conceptualized the research approach, implemented the simulated case study, and evaluated the results. Further, I wrote the initial draft of the entire paper. During the revision process of this paper, I was highly involved in the additionally demanded analysis and evaluation, as well as the contextualization of the results in the discussion.

Research paper 4 (VI.6) was written by a team of five co-authors, and all co-authors contributed equally to this paper. The paper was submitted and published in the Journal of Applied Energy. My main responsibilities included conceptualizing and implementing the simulated case study for the optimization model. Additionally, I evaluated the results and wrote and edited the relevant sections of the study. In the revision phase, I conducted further research in academic literature and edited a majority of the paper for improvements.

Research paper 5 (VI.7) was written by a team of five co-authors, with me as the lead author. The paper was submitted to and presented at the INFORMATIK 2022 conference and subsequently published in the Lecture Notes in Informatics. As the primary author, I was responsible for structuring the research process, designing the research approach, and implementing the case study, which involved evaluating the results. Besides one part of the literature review, I wrote and edited the entire paper and carried out the revision.

Research paper 6 (VI.8) was written by a team of five co-authors, with me as the lead author. The paper is a further development of the previous paper and was submitted and published in the Journal of Information Technology & Tourism. Continuing in my role as the primary author, I conceptualized the enhancement of the research, expanded the model, and conducted and evaluated additional results. Furthermore, I broadened the embedding of the results in the research field and deepened the discussion.

Research paper 7 (VI.9) was written by a team of three authors. The paper was initially submitted to the Journal of Business Information Systems Engineering and is currently being revised for a new submission. All authors contributed equally to this paper. I contributed by supervising the research project, including conceptualization, structuring, and formalizing the analysis. Further, I provided input for the literature review. Regarding the text of the paper, I closely assisted in its development and composition.

VI.3 Research paper 1 – The impact of user behavior and grid-associated emissions on the emission reduction potential of electric vehicle-based spatiotemporal residential load shifting

Authors

Bollenbach, Jessica; Eiser, Niklas; Keller, Robert; Strüker, Jens

Status

Under Review in Cleaner Production

Extended abstract

Decelerating climate change and accelerating the transition toward a more sustainable net-zero society requires a set of different measures, including decarbonization of residential electricity demand. Although the share of renewables in the electricity mix is steadily increasing in the EU and Germany (European Environment Agency, 2024), residential emissions stagnated in recent years as RES production peak and residential consumption peak decouple over time (Umweltbundesamt, 2016). Residential demand of residents who leave home for work (referred to as commuters in this paper) typically peaks twice: during morning and especially during evening hours (Fischer, Härtl and Wille-Haussmann, 2015). At the same time, minima of emissions associated with the country-specific electricity mix occur at divergent times. For regions with grid conditions similar to Germany, for example, emissions in summer are typically lowest during midday, primarily due to high photovoltaics (PV) output. In winter, emissions might also reach their daily low at midnight when production from wind turbines is high, and electricity demand is low. Thus, RESs are especially challenging to integrate into established residential demand profiles. Therefore, households need solutions for energy storage to combine their morning and evening demand peaks with periods of high RES output. Additionally, the decarbonization of transport via electrification further increases the need for residential storage solutions, as current BEV charging patterns contribute primarily to residential evening and nighttime demand (Muratori, 2018). Charging at the workplace is one essential means to address this issue and to link BEV charging with RES on-peak hours, which can heavily reduce charging-associated GHG emissions (Buresh, Apperley and Booysen, 2020). Workplace charging offers even more opportunities by considering BEVs as a vital part of the ecosystem. Often, these concepts involve bidirectional charging, which allows BEVs not only to charge but also to discharge their battery and feed electricity back into the home, building, or grid (Thompson and Perez, 2020). More specifically, this paper adapts and investigates the operation of a V2B[2] concept where electric vehicles charge grid electricity at the workplace, act as mobile energy storage when driving home, and cover residential electricity demand through battery discharging. To maximize residential emission reduction under this strategy, timing electricity demand is the key factor. However, individual user

behavior constrains the possibility of optimization. Here, we seek to analyze why and by how much the emission reduction potential of spatiotemporal load shifting within V2B² varies for a country-specific electricity mix with established individual user behavior. Here, we contribute to the current literature by picking up the case of the German electricity mix and analyzing why and by how much the emission reduction potential changes for different German residential electricity demands and driving behaviors. In this way, we identify key parameters for countries with comparable conditions that drive the potential to guide locally targeted V2B² implementation measures. For the simulation of our at-home charging benchmark scenario and the V2B² implementation, we rely on a huge dataset of empirical and real-world behavioral data. The results indicate that the potential of a grid-dependent V2B² operation in Germany is highly seasonal. In winter, we find an average emission increase (-0,2%), while summer yields a promising average potential (23% emission reduction).

Keywords

Electric vehicle, Emission reduction, Established user behavior explanation, Mobile energy storage, Shapley additive explanations, Spatiotemporal load shifting

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Buresh, K.M., Apperley, M.D. and Booysen, M.J. (2020) 'Three shades of green: Perspectives on at-work charging of electric vehicles using photovoltaic carports', Energy for Sustainable Development, 57, pp. 132–140. Available at: https://doi.org/10.1016/j.esd.2020.05.007.

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Muratori, M. (2018) 'Impact of uncoordinated plug-in electric vehicle charging on residential power demand', Nature Energy, 3(3), pp. 193–201. Available at: https://doi.org/10.1038/s41560-017-0074-z.

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VI.4 Research paper 2 – Empowering Sustainable Hotels: A Guest-Centric Optimization for Vehicle-to-Building Integration

Authors

Valett, Lynne; Bollenbach, Jessica; Keller, Robert

Status

Energy Informatics (2024)

Extended 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 Vehicle (EV) 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 (CO_2)-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 CO_2 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

VI.5 Research paper 3 – Revenue Management in a Large-Scale Fast-Charging Hub for Electric Vehicles: A Multiproduct, Dynamic Pricing Model

Authors

Bollenbach, Jessica; Kaiser, Matthias; Baumgarte, Felix; Keller, Robert; Weibelzahl, Martin

Status

Under Review in Applied Energy

Extended abstract

Battery electric vehicles (BEVs) offer considerable potential to reduce emissions compared to internal combustion engine cars, especially when charged using renewable energy sources (Hawkins et al., 2013; Onat et al., 2019). However, the adoption of BEVs heavily relies on the availability of sufficient and widely distributed charging infrastructure (Robinson and Erickson, 2021). To enable longer driving distances and prevent queuing at charging locations, the demand is growing for LFCHs along highways, which offer multiple charging points and high total power capacity (Neubauer and Wood, 2014; Greene et al., 2020). However, the profitability of LFCHs hinges on the location-specific utilization rates of the charging stations, which are influenced by the surrounding BEV usage and local traffic volume (Baumgarte, Kaiser and Keller, 2021). Today's BEV market share of 12 % within the EU (ACEA - European Automobile Manufacturers' Association, 2024) is still low and unevenly distributed, leading to unprofitable fast-charging infrastructure in many European areas and regions. While cost reduction for fast-charging infrastructure is already well-researched, revenue maximization for fast-charging infrastructure operations has received less attention. Most of the literature about revenue maximization in the field of electric vehicle charging relates to stations with only a few charging points. It focuses on grid stability or energy distribution between several charging points, which reveals itself as closely connected to the cost minimization literature (Kong, Bayram and Devetsikiotis, 2015; Kuran et al., 2015). Few articles apply a dynamic pricing approach to maximize revenue for charging infrastructure operations. However, they do not consider the characteristics of large fast-charging locations, such as the ability to serve several customers simultaneously with high charging power (Guo et al., 2016; Luo, Huang and Gupta, 2018). Thus, we examine the applicability of the RM theory to LFCHs and develop an axiomatic quantitative dynamic pricing model to evaluate the quantitative impact. We conduct a simulation case study to identify the revenue improvements dependent on differently sized LFCHs through dynamic pricing compared to a fixed-price setting. We contribute to the literature by developing a theoretical framework demonstrating how a dynamic pricing approach can be implemented in an LFCH and evaluate the actual performance with a sensitivity analysis. The results underline that RM can be effectively applied in LFCHs and that the proposed dynamic pricing model significantly increases the revenue for LFCH operators

when resources are scarce. Particularly with scarce charging points and sufficient power capacity, the highest relative revenue improvements are realized, whereby the model cannot compensate for bad strategic LFCH design decisions. Overall, applying dynamic pricing in LCFHs can make investments more attractive and facilitate the expansion of charging infrastructure.

Keywords

Charging Hub Operation, Electric Vehicle Charging, Dynamic Pricing, Revenue Management

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VI.6 Research paper 4 – Customer Satisfaction at Large Charging Parks: Expectation-Disconfirmation Theory for Fast Charging

Authors

Bollenbach, Jessica; Kaiser, Matthias; Baumgarte, Felix; Keller, Robert; Weibelzahl, Martin

Published in

Applied Energy (2024)

Abstract

Drivers of battery electric vehicles, especially along motorways, require fast-charging services and expect maximum charging power to overcome long servicing times. However, charging park operators cannot always meet customer expectations due to economic and technical restrictions. According to the expectation-disconfirmation theory, the resulting expectation-performance gap increases the dissatisfaction of vehicle drivers regarding the servicing time in a non-linear manner. Therefore, we present an optimization model with a utilitarian welfare function grounded in social choice theory. Besides a current real-world case based on a fast-charging park in Germany, we analyze further (technical) developments of electric mobility with four future cases. Compared to a uniform power allocation, our results display a reduced absolute average gap of up to 4 min (i.e., 13.3%) between expected and actual servicing time in the real-world case, thus, improving welfare by 22.9%. With an increased average gap reduction of up to 5.2 min, our future cases show the importance of addressing the expectations of battery electric vehicle drivers. Without a smart power allocation, the gap and simultaneously the dissatisfaction of vehicle drivers regarding the servicing time can increase, and potentially more hardware upgrades may be necessary.

Keywords

Electric mobility, Smart charging, Fast charging, Utilitarian welfare, Customer satisfaction, Expectation-performance gap

VI.7 Research paper 5 – Using Machine Learning to Predict POI Occupancy to Reduce Overcrowding

Authors

Bollenbach, Jessica; Neubig, Stefan; Hein, Andreas; Keller, Robert; Krcmar, Helmut

Published in

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Abstract

Due to the rapid growth of the tourism industry, associated effects like overcrowding, overtourism, and increasing greenhouse gas emissions lead to unsustainable development. A prerequisite for avoiding those adverse effects is the prediction of occupancy. The present study elaborates on the applicability and performance of various prediction models by taking a case study of beach occupancy data in Scharbeutz, Germany. The case study compares different machine learning models once as supervised machine learning models and once as time series models with a persistence model. XGBoost and Random Forest as time series demonstrate the most accurate prediction, followed by the supervised XGBoost model. However, the short prediction span of time series models is a disadvantage for longer-term visitor management to avoid the explained unsustainable effects through steering measures, so depending on the use case, the XGBoost model is to be favoured.

Keywords

Beach Occupancy, Time series Forecast, XGBoost, Random Forest, Support Vector Regression, SARIMA, Tourism Demand

VI.8 Research paper 6 – Enabling Active Visitor Management: Local, Short-Term Occupancy Prediction at a Touristic Point of Interest

Authors

Bollenbach, Jessica; Neubig, Stefan; Hein, Andreas; Keller, Robert; Krcmar, Helmut

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Information Technology & Tourism (2024)

Abstract

After the temporary shock of the COVID-19 pandemic, the rapid recovery and resumed growth of the tourism sectors accelerates unsustainable tourism, resulting in local (over-)crowding, environmental damage, increased emissions, and diminished tourism acceptance. Addressing these challenges requires an active visitor management system at points of interest (POI), which requires local and timely POI-specific occupancy predictions to predict and mitigate crowding. Therefore, we present a new approach to measure visitor movement at an open-spaced, and freely accessible POI and evaluate the prediction performance of multiple occupancy and visitor count machine learning prediction models. We analyze multiple case combinations regarding spatial granularity, time granularity, and prediction time horizons. With an analysis of the SHAP values we determine the influence of the most important features on the prediction and extract transferable knowledge for similar regions lacking visitor movement data. The results underline that POI-specific prediction is achievable with a moderate relation for occupancy prediction and a strong relation for visitor count prediction. Across all cases, XGBoost and Random Forest outperform other models, with prediction accuracy increasing as the prediction time horizon shortens. For effective active visitor management, combining multiple models with different spatial aggregations and prediction time horizons provides the best information basis to identify appropriate steering measures. This innovative application of digital technologies facilitates information exchange between destination management organizations and tourists, promoting sustainable destination development and enhancing tourism experience.

Keywords

Visitor management, Tourism demand, Machine learning prediction, Sustainable tourism, Overcrowding

VI.9 Research paper 7 – The Road Not Taken - Representing Expert Knowledge for Route Similarities in Sustainable Tourism Using Machine Learning

Authors

Bollenbach, Jessica; Rebholz, Dominik; Keller, Robert

Status

Under Review in Electronic Markets

Extended abstract

With the rapid recovery of tourism after the COVID-19 pandemic, the benefits of economic growth and employment opportunities are returning, but so is the problem of crowding, which is a major concern for many popular tourist destinations (Palacios-Florencio et al., 2021; Tiwari and Chowdhary, 2021). Crowding causes environmental degradation, loss of natural biodiversity, and increased pollution (Wall, 2019). Furthermore, it negatively impacts the local infrastructure, tourist infrastructure, and living conditions, as well as the cultural heritage of the residents (Adie, Falk and Savioli, 2020; Drápela et al., 2021; Milano, Novelli and Cheer, 2021). While the latter primarily affects nature and local residents, crowding also deteriorates the tourist experience (Tokarchuk, Barr and Cozzio, 2022). Most efforts to mitigate the effects of crowding are often insufficient to actually prevent crowding as a cause of these effects, as many approaches focus on a single tourist destination (Butler and Dodds, 2022). However, to avoid crowding and enable sustainable tourism, preparation at the destination itself is not sufficient. Therefore, overarching measures are required to distribute visitors across multiple tourist destinations and reduce the number of people at the crowded destination without overloading another region. To facilitate sustainable tourism, an information system for visitor management, including recommendations, is required. A significant challenge in this context is the identification of similar routes for recommendations outside the congested area. Therefore, the paper proposes a method to calculate route similarities based on descriptive data to enable the redirection of visitors to alternative, less-crowded routes. Distance-based algorithms and machine learning models are used to analyze labeled and unlabeled route data. To validate this approach, a case study in a nature park is conducted by training the models on real-world hiking data provided by the outdoor platform Outdooractive. Further, labeled data of route combinations' similarities is obtained with an expert survey to evaluate the results and enhance the model's accuracy. The findings reveal that while traditional distance-based methods provide a baseline, integrating them with machine learning significantly enhances accuracy and alignment with expert assessments. The research advances sustainable tourism management by providing a data-driven approach to identifying route similarities aligning with tourist preferences.

Keywords

Visitor management, Route similarity, Machine learning, Sustainable tourism, Overcrowding

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