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# *Smart and cross-sectoral energy supply for sustainable mobility*

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Vorgelegt von

**Matthias Kaiser**

aus Mauerstetten

Dekan/in: Prof. Dr. Claas Christian Germelmann

Erstberichterstatter: Prof. Dr. Jens Strüker

Zweitberichterstatter: Prof. Dr. Björn Häckel

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## Copyright Statement

The following sections partly comprise content taken from the research articles included in this thesis. To improve the readability of the text, I omit the standard labelling of these citations.

# Abstract

Climate change remains an urgent global issue, demanding immediate and effective action, particularly within the transportation sector. Despite international agreements like the Paris Agreement and European strategies such as the European Green Deal, decarbonizing road transportation poses significant challenges for policymakers, mobility providers, and infrastructure operators. These stakeholders are confronted with decisions that are inherently fraught with uncertainty. Travellers' individual attitudes and information needs challenge mobility providers and traveller information systems for intermodal mobility services. Costs associated with infrastructure development, combined with the rapid technological evolution, impose significant difficulties on operators and investors for sustainable energy supply infrastructure. This cumulative thesis is anchored in the Information Systems discipline, focusing on smart sustainable mobility. Comprising five research papers, the thesis provides methodological tools and digital solution approaches for the decision support of policymakers, mobility service providers and energy supply infrastructure operators and investors. First it analyses individual information needs for seamless intermodal mobility, with the goal of improving traveller information systems and supporting decision-making processes in urban environments. By examining key information requirements for creating seamless intermodal mobility solutions, the research aims to bridge the gap between the complexity of intermodal travel and the need for clear, accessible information. The work also tackles the economic and operational challenges of sustainable fast charging infrastructure by introducing a Revenue Management approach to maximise revenue and a smart charging optimization model considering customer discounts as flexibility incentive to minimize operating electricity costs. Expanding the scope to include green hydrogen supply infrastructure, the thesis develops a microgrid model to examine the synergies between fast charging infrastructure and locally produced green hydrogen. This provides strategic design and operational insights to ensure a cross-sectoral and profitable, low-emission energy supply for sustainable mobility. Additionally, the thesis offers policy recommendations to promote investment in fast charging infrastructure, supported by a case study in Germany. The overarching goal of this thesis is to enhance both theoretical and practical aspects of smart sustainable mobility. It provides a conceptual framework for identifying information needs in intermodal mobility and supports decision-making processes for investments in sustainable energy infrastructure. By addressing these challenges, the research contributes to the broader goal of decarbonizing road transportation, aligning with the ambitious targets of international and European climate agreements.

Keywords: transportation, hydrogen, electric vehicle, smart sustainability, smart charging

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# I Introduction

## I.1 Motivation

Climate change, an ever-growing concern, continues to impact humanity on an unprecedented scale. Despite ongoing debates and a lack of effective policies from the recent United Nations (UN) climate conference, the urgency of climate action has never been clearer. This year has witnessed record-breaking climate disasters, underscoring the immediacy of this global crisis. The Climate Council's documentation (Climate Council, 2024) paints a stark picture: Rio Grande in Brazil experienced its heaviest rainfalls, leading to historic floods. Similarly, both the United Arab Emirates and Kenya experienced extreme rainfall and flooding, with Kenya facing deadly events just a year after its worst drought. Europe, too, hasn't been spared, with Germany experiencing floods that transformed urban streets into rivers, a phenomenon that, while statistically rare, has become alarmingly frequent in recent years. On the other side of the spectrum, the wildfire season has started warningly early in Canada, following its longest and most destructive fire season ever. These shifting wildfire patterns, exacerbated by climate change, have rendered wildfires, particularly in Australia, more dangerously and likely (Climate Council, 2019). Similarly, the hurricane season is likely to extend due to the significant increase in the temperature of the Atlantic Ocean in 2024, which led to a Category 5 hurricane early in June (Poynting *et al.*, 2024). Additionally, 2024 has already set new heat records (World Meteorological Organization, 2024), surpassing those of 2023, marking the hottest day ever recorded in May.

To mitigate climate change and counteract the origin of such natural disasters, the Paris Agreement set ambitious goals, with 196 countries pledging to reduce global greenhouse gas (GHG) emissions and limit temperature rise well below 2°C (United Nations, 2015). As part of this global effort, the European Union introduced the 'Green Deal,' a comprehensive strategy aimed at achieving net-zero emissions by 2050 (EU Commission, 2019). The Green Deal encompasses various policy initiatives to decarbonise the energy sector, retrofit buildings to reduce energy demand, support green industry, and promote sustainable transportation (Fetting, 2020). A concrete initiative within the Green Deal is the "Fit for 55" package, which aims to reduce GHG emissions across Europe by 55% by 2030 compared to 1990 levels (EU Commission, 2021). This regulatory framework focuses on adjusting EU regulations to meet climate targets, particularly in the energy and transportation sectors. Despite significant emissions reductions in various sectors since 1990, the transportation sector has seen a 21% increase in emissions by 2022, with post-pandemic trends indicating further rises (European Environment Agency (EEA), 2024).

Given the persistence of high emissions and lack of decarbonisation trend in the transportation sector, the "Fit for 55" package introduces several legislative proposals. These include, for example, the Alternative Fuels Infrastructure Regulation, the directive to standardise CO2 calculation, the Renewable Energy Directive III, the Energy Performance of Buildings Directive supporting electric mobility in the residential area, and the Trans-European Transport Network-Regulation to enhance EU transport infrastructure (European Council, 2024). Reducing travel activities and transportation in general to cut emissions is neither expected nor recommended due to economic and social concerns, as evidenced by the decline in transportation activities during the COVID-19 pandemic. Hence, the "Fit for 55" package targets three primary strategies: stringent emission standards for vehicles, incentives for multimodal mobility and transport behaviour, and crucially, investments in infrastructure to support sustainable energy supply for electrified or hydrogen-powered vehicles (EU Commission, 2021). Within these regulatory frameworks, the EU aims to economically incentivize investments in electric vehicle charging infrastructure, hydrogen production sites, and supply infrastructure, while also offering subsidies (European Commission, 2020). However, operating public fast charging infrastructure (FCI) is still unprofitable due to low utilisation (Madina, Zamora and Zabala, 2016; Baumgarte, Kaiser and Keller, 2021) and infrastructure investments in green hydrogen production lack due to high capital expenditures and high cost for green electricity to produce green hydrogen (Browne, O'Mahony and Caulfield, 2012; Gustafsson *et al.*, 2021). Scaling up investments and ensuring profitable operations require smart integrated energy systems, that can use cross-sectoral synergies and make use of digital solutions to reduce operating cost and increase revenue. Smart integrated energy systems can optimize energy distribution and consumption, thereby enhancing efficiency. Additionally, these systems enable real-time monitoring and management of energy resources, which can lead to significant cost reductions and improved reliability. By leveraging cross-sectoral synergies, smart energy systems can further enhance economic viability. These synergistic interactions not only reduce operational costs but also create new revenue streams through more efficient use of resources. These systems are inherently complex, necessitating comprehensive techno-economic analyses to support investors' decision-making. Therefore, there is a pressing need for advanced analytical tools to model the intricate landscape of integrated energy systems in the transportation sector.

This dissertation aims to address this gap by developing robust techno-economic analysis frameworks and tools, thereby facilitating intermodal mobility and informed investments in sustainable transport infrastructure. Through these efforts, this thesis supports the transition towards a greener, more resilient transportation sector, aligned with the ambitious goals of the Paris Agreement and the European Green Deal.

## I.2 Research aim

As the climate crisis intensifies, the urgency for effective and sustainable transportation solutions becomes ever more critical. Given the increasing importance of digitalisation to drive decarbonisation of transportation, the Information Systems (IS) research stream on smart sustainable mobility aims to support the EU's legislative activities in advancing sustainable mobility. The integral role of IS is to facilitate the transition towards smart sustainable mobility, by leveraging data and technology to balance user needs, business goals, and environmental impacts (Ketter, Schroer and Valogianni, 2023). The literature foresees future sustainable mobility systems as connected (Batty *et al.*, 2012; Qi and Shen, 2018), autonomous (Mahmassani, 2016), shared (Eckhardt *et al.*, 2019), and electric (Sperling, 2018), perfectly aligning with the EU's regulatory activities encapsulated in the “Fit for 55” package. Thereby, IS research can provide the necessary methods helping to handle geospatial data and distributed time series data from connected vehicles, mobile devices or smart infrastructure to provide real-time information transparency (Ketter, Schroer and Valogianni, 2023). This enables, for example, the potential to allocate energy or infrastructure resources more efficiently or to influence users’ behaviour providing specific information, price incentives or other nudges.

In the context of connected and multimodal mobility, the first part of this thesis deals with the role of information in intermodal travel chains of individuals. As scholars like Batterbury (2003), Chen and He (2014) and Liotta et al. (2023) have argued, the surge in private car usage is incompatible with the goals of social welfare, sustainable urbanisation and economic development. This incompatibility is primarily due to the health hazards posed by emissions and accidents, as well as the significant space consumption associated with private vehicles. In response, there is a growing interest in intermodal mobility, which combines the strengths of various transportation modes to offer environmentally friendly and health-conscious travel options (Dacko and Spalteholz, 2014; Gebhardt *et al.*, 2016; Oostendorp and Gebhardt, 2018). However, as of 2023, intermodal mobility still represents a minority of trips, highlighting the need for a substantial shift in urban mobility behaviours. To promote intermodal mobility and stimulate a sustainable long-term change, understanding individual attitudes towards intermodal trips is crucial (McNally, 2007; De Vos *et al.*, 2016; Reck, Martin and Axhausen, 2022). Following De Vos et al. (2022), factors such as travel time, costs, and the increasing flexibility offered by new transportation systems and Mobility-as-a-Service (MaaS) concepts complicate mode choice decisions (Feneri, Rasouli and Timmermans, 2022). Therefore, travellers require comprehensive information and transparency to make decisions towards intermodal trips more attractive (Jochem, Lisson and Khanna, 2021).

Covered by Research Paper #1, this thesis addresses these challenges by analysing individual information needs for seamless intermodal mobility. By examining the key information requirements for creating seamless intermodal mobility solutions, the results of the first research objective can help to enhance travellers' information systems. Supporting the mode choice decision-making processes, these traveller information systems create incentivizes to use intermodal mobility ecosystems especially in urban environments. This aims to bridge the gap between the complexity of intermodal travel and the need for clear, accessible information.

Equally important to intermodal mobility is the ramp-up of infrastructure for a sustainable energy supply of vehicles. The "Fit for 55" package mandates a cross-European network of charging and hydrogen refuelling stations, requiring substantial investments in FCI and hydrogen supply projects (EU Commission, 2021; Vilkas, 2022). Yet, these investments are fraught with challenges due to cost intensive infrastructure, high electricity prices, and unprofitable operations at low battery electric vehicle (BEV) and fuel cell electric vehicle (FCEV) penetration rates (Siskos *et al.*, 2018; Apostolou and Xydis, 2019; Low, Haszeldine and Mouli-Castillo, 2023). Policymakers have recognised the urgent need for action and have already launched initial initiatives and strategies (BMWI, 2020; EU Commission, 2022). For example, national hydrogen strategies attempt to comply with the legislative proposal by providing investment incentives (Velazquez Abad and Dodds, 2020). However, several challenges hinder further expansion of such infrastructure projects for decarbonised road transportation. First, practitioners face cost-intensive operation (Browne, O'Mahony and Caulfield, 2012; Biresselioglu, Demirbag Kaplan and Yilmaz, 2018). Second, there is no distribution network to transfer hydrogen across long distances available in the EU yet (Astiaso Garcia, 2017). Third, to realise the long-term vision of carbon neutrality, the electricity for charging BEVs and producing hydrogen via electrolysis needs to be generated from Renewable Energy Sources (RES) (Gustafsson *et al.*, 2021). This makes demand-side management and smart resource allocation essential. Additionally, the intelligent design and operation of integrated energy supply hubs, for example in form of microgrids, accompanied by appropriate policy support measures, are necessary to enable a RES-based and profitable energy supply operation for road transportation.

Thus, this thesis further focuses on the support of political and practical decision-makers who can influence the expansion and operation of integrated energy hubs for profitable and sustainable energy supply for road transportation. Thereby, Research Paper #2 and #3 delve into smart charging and dynamic pricing as strategies to allocate electricity and power efficiently and to enhance profitability. By exploring the synergies between FCI and locally produced hydrogen for refuelling heavy-duty FCEVs, Research Paper #4 aims to design integrated hydrogen refuelling and fast charging hubs and to create profitable operating strategies. Finally, Research Paper #5 examines how policy support measures impact the profitability of differently located, designed and frequented FCI.

The overarching goal of this work is to enhance both the theoretical smart sustainable mobility research and practical impact. In the field of intermodal mobility, it provides the first step for a concept that assists in the identification of information needs for different intermodal mobility chains, depending on the phase and the combination of modes. It thus attempts to address the problem posed by Beutel et al. (2016) by identifying relevant information for mobility trips, especially to reduce the amount of information displayed on mobile devices. Further, this work supports practitioners in decision-making processes for investments in energy supply infrastructure for transportation. Modelling the energy supply operation via microgrids helps to design infrastructure efficiently and operate it profitably. Microgrid models has the advantage of simulating integrated energy systems that in practice enable local energy generation, reduce transmission losses, and enhance energy security and resilience. Therefore, this thesis delves into several microgrid models, each targeting a different approach to maximise profitability. These approaches include revenue maximisation, smart charging considering flexibility incentives, and optimized design and operation strategies for cross-sectoral charging and hydrogen refuelling stations. Hence, this thesis includes the first research approach to apply Revenue Management (RM) by expanding revenue-oriented dynamic pricing to a complete management system for demand management and resource allocation for large fast charging parks (LFCP). The RM model paves the way for further improving the profitability of LFCP operations through maximising revenue. Complementary to the RM approach, incorporating incentivised flexibility within smart charging to optimise resource allocation further maximises profitability. Following Melville (2010), this contributes to a part of the bigger research question of how information and communication technology can help to enable a more economical use of energy and charging infrastructure resources in an increasingly electrified transport system. Another microgrid model depicts a grid-connected hybrid hydrogen refuelling and electric vehicle charging environment to investigate the cross-sectoral potential to decarbonise road transportation. Thereby, this thesis sheds light on the benefits of using the correlation of volatile Day-Ahead electricity prices and the electricity's emission intensity for operation strategies, that are both economically and ecologically advantageous. In addition, this thesis leads to several findings recording the implication of regulatory and policy measures on the profitability of energy supply infrastructure operation and investment attractiveness. In detail, it provides guidance for policymakers on FCI development by demonstrating the impact of several support measures, pointing out regulatory obstacles and formulating political recommendations for action.

## I.3 Embedding of the research paper and structure of the thesis

This cumulative dissertation comprises five research papers that collectively contribute to the IS research field of smart sustainable mobility and address major challenges to decarbonise road transportation by focusing on digital solutions for decision support helping infrastructure and mobility providers to push sustainable mobility. Figure 1 presents an overview of the research articles and their embedding within the IS research based on the framework for smart sustainable mobility from Ketter, Schroer and Valogianni (2023).

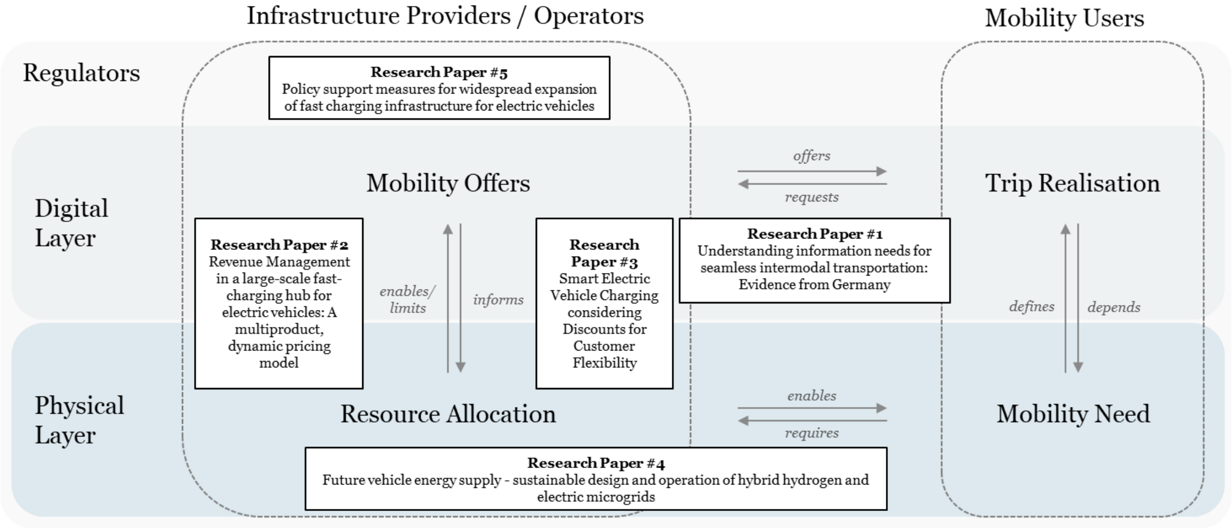


Figure 1: Overview and embedding of the research papers within the thesis

Emphasising the urgency of decarbonising the transportation sector, Section I outlines the research aim of this thesis and situates its research papers within the broader context of IS research.

Section II delves into the central theme of the thesis, encompassing various research papers that explore diverse methods and analytical techniques to aid mobility and infrastructure providers and operators in facilitating sustainable mobility. This section contributes to the decision-making processes of mobility providers in crafting appropriate mobility offerings and infrastructure investors in making informed investment and design choices. Additionally, it aids energy supply infrastructure operators in resource allocation to support mobility services and policymakers in devising effective support measures and regulatory frameworks.

Initially, Research Paper #1 addresses the challenges mobility providers face in developing user-centric services and platforms to foster sustainable intermodal mobility. Recognizing that providing individualised information throughout the intermodal journey is crucial for users' decision-making processes, this paper examines the essential information requirements across different modes and travel phases in urban settings. The findings assist mobility providers in various decision-making processes, such as designing and operating traveller information systems and formulating specific mobility offerings to facilitate seamless intermodal mobility solutions.

While Research Paper #1 focuses on decision support at the interface between mobility offerings and customer journey realisation, the Research Papers #2, #3, and #4 concentrate on decision support for infrastructure investors and providers concerning investment decisions and operational resource allocation. Research Paper #2 introduces a RM approach to optimise resource allocation for providers of LFCPs. Drawing inspiration from operations research literature and RM models used in the airline and hotel industries, this paper is among the first to adapt RM to electric vehicle charging, addressing the challenge of limited charging plugs and electrical power. To dynamically allocate power resources, smart charging technology is essential. Research Paper #3, building on smart charging literature, presents a smart charging optimisation model that take variable customer charging tariffs as determined by RM into account. In addition to considering individual prices, smart charging can enhance resource allocation efficiency when customers exhibit flexibility. Given that most public charging events are ad-hoc, flexibility is not always a given. Therefore, this paper also considers individual discounts to incentivise extended dwell times and analyses the benefits of these discounts for profit maximisation through smart charging.

Expanding the scope beyond electric vehicle charging, Research Paper #4 integrates the supply of green hydrogen for FCEVs into the sustainable energy supply framework for road transportation. This paper develops a microgrid model to examine the synergies between FCI for BEVs and locally produced green hydrogen for refuelling heavy-duty FCEVs. The findings assist infrastructure providers in making strategic design and operational decisions to ensure profitable, low emission, and seamless energy supply for sustainable mobility.

Research Paper #5 shifts the focus to policymakers, offering guidance on creating support measures to promote widespread investments in FCI. This paper analyses the impact of policy measures on the profitability of variously located and sized fast charging stations, contingent on BEV adoption rates. It then provides policy recommendations for developing effective incentive schemes. A case study for Germany selects real-world locations with varying population densities and traffic volumes, using a simulation approach to assess the profitability of FCI from an investor's perspective across three power categories. The evaluation of current and potential future policy measures demonstrates their effects on investment profitability, thereby supporting the deployment of a comprehensive fast charging network.

Section III presents a detailed summary of the main findings, highlighting associated limitations and potential future research directions. It also reviews relevant previous work accessible during the thesis's writing.

Section IV lists the references, while Section V includes the thesis appendix. The appendix offers detailed information on the five embedded papers, including their abstracts and extended abstracts. Additionally, the supplementary material contains all published research papers in its original form and the full text of all research papers, which are not intended for publication yet.

# II Digital solutions for decision support helping infrastructure and mobility providers to enable and offer smart sustainable mobility

## II.1 Understanding information needs for seamless intermodal mobility

Urban space utilisation and sustainability concerns have led cities globally to support more sustainable transportation alternatives (Atalla and Simlett, 2019). This has sparked interest in intermodal mobility, which combines the strengths of different transportation modes to reduce environmental impacts and promote healthier travel options (Dacko and Spalteholz, 2014; Gebhardt *et al.*, 2016; Oostendorp and Gebhardt, 2018). Enhancing satisfaction with each transportation mode and the overall trip experience is essential for improving attitudes towards intermodality (McNally, 2007; De Vos *et al.*, 2016; Reck, Martin and Axhausen, 2022). Accurate information provided at the right time is crucial for customer satisfaction, as it simplifies travel and aids informed mode choices (Nuzzolo *et al.*, 2014; Meng *et al.*, 2018; Jochem, Lisson and Khanna, 2021). This is especially important for MaaS platform providers, who must deliver timely information tailored to each transportation mode within an intermodal trip, a need often overlooked by common traveller information systems (Digmayer, Vogelsang and Jakobs, 2015; Chen and Chen, 2023). Existing studies primarily focus on travel satisfaction and service quality (Morris and Guerra, 2015; Isikli *et al.*, 2017; De Oña, Estévez and De Oña, 2021; De Vos, Singleton and Gärling, 2022; Sukhov, Olsson and Friman, 2022), with information mentioned as a key factor but typically in a generalised context (Gan, 2015; Ettema, Abenoza and Susilo, 2016).

Addressing this gap, Research Paper #1 aims to specify the timing and type of information needed based on the intermodal mode chain. Following a sequential mixed-method approach (Berger, Lange and Stahl, 2022), the paper first conducted a systematic literature review to understand passenger information needs for urban mobility. Using two search strings and a three-step selection process, the initial list of papers was narrowed to 51 papers, supplemented by a forward-and-backward search. The literature review results were validated through a survey of over 500 German travellers, assessing their opinions on the information required for different mode combinations and trip phases. Structured according to the mobility chain phases by Digmayer et al. (2015) and Bruntsch and Rehrl (2005), the investigation covered 14 mode combinations across five travel phases. To manage the questionnaire length, mode combinations were randomly assigned to participant groups. Participants indicated whether an information identified by the literature was necessary for each phase and mode combination.

The paper introduces the metric of Relative Importance (RI) to evaluate and compare the importance of information across trip phases and mode combinations. Findings show that important information in the disturbance phase had a significantly higher RI (e.g., alternative navigation, RI=82.9%; alternative routes, RI=81.8%) with an average RI of 71.1%, compared to a RI of 60.0%-65.3% in other travel phases. Min-max scaling was used to adjust for information identified in multiple mode chains, revealing significant phase dependencies: the amount of important information and participant agreement varied among travel phases, and the importance of information differed depending on the travel phase.

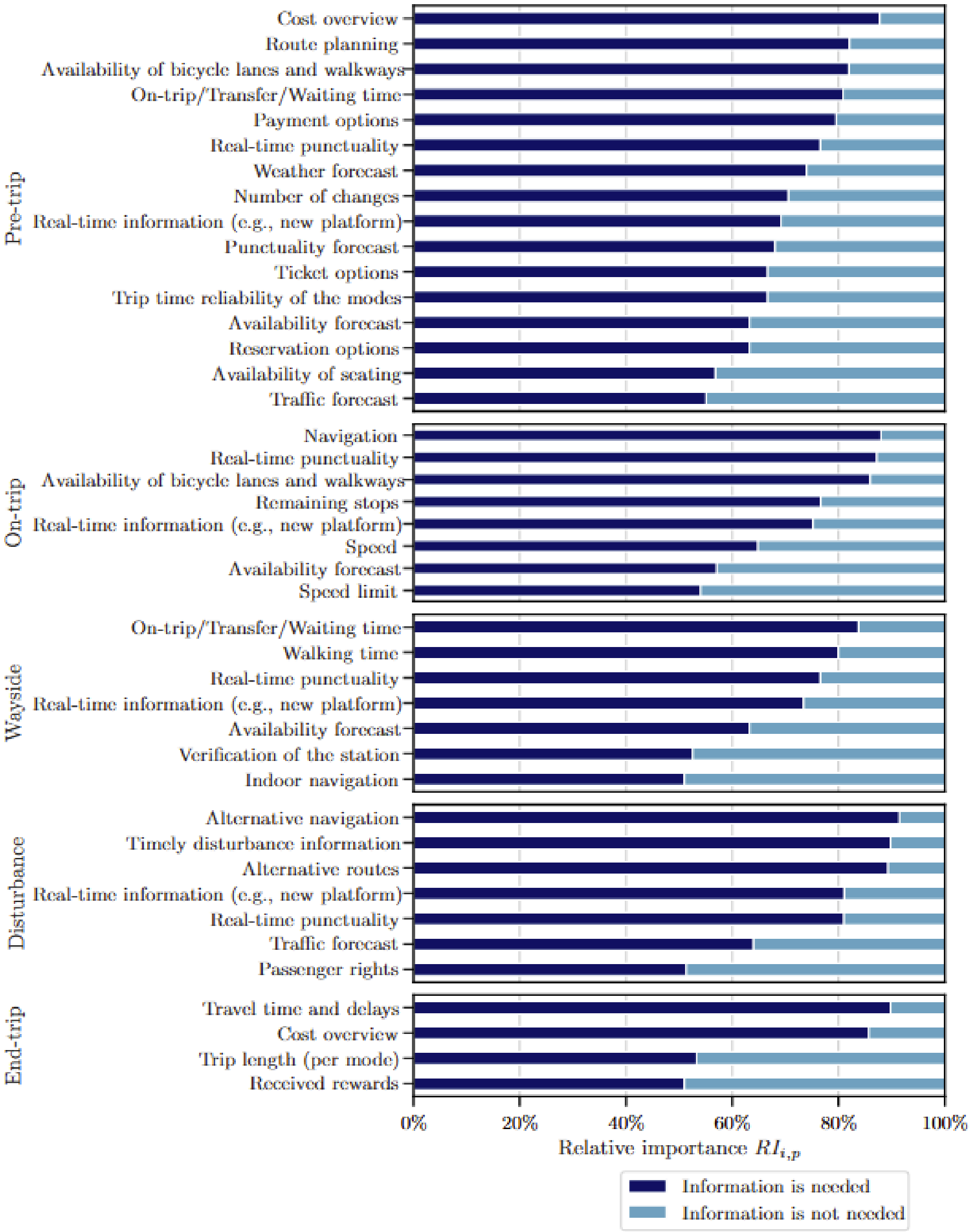


Figure 2: Important information ($RI > 0.5$) grouped by travel phase (Average RI over all mode chains is displayed)

Analogous to the phase dependency, each mode combination within an intermodal mobility chain necessitates distinct information types. The analysis of the results strongly indicates that mode chains involving public transportation require the most information, whereas modes where individuals actively move themselves, such as biking or walking, demand the least amount of information. Focusing on specific information pieces, the RI varied significantly across different observations. For example, 'travel cost' was crucial (RI=88.09%) when combining active sharing modes with walking, but unimportant for biking combined with walking (RI=6.02%). Information such as 'ticket options,' 'number of changes,' 'remaining stops,' 'availability of seating,' and 'passenger rights' were important only for public transportation modes. Meanwhile, 'weather forecast' and 'availability of bike lanes/walkways' were important for active modes. To generalise, the mean difference between the highest and lowest RI per information piece across different mode chains was 35.52%. Statistical tests like Chi-square, p-value, and Cramer's V confirmed that the significance of information depends on the mode chain. Given the independent relationship between information needs and the mode chain or travel phase, the questionnaire results illustrate that the interaction between mode chains, travel phases, and information needs results in different relations. Notably, a difference of over 70% in RI was observed in some cases, indicating that information needs must be considered in the context of both the mode chain and the current travel phase. This concept is visualized in Figure 3.

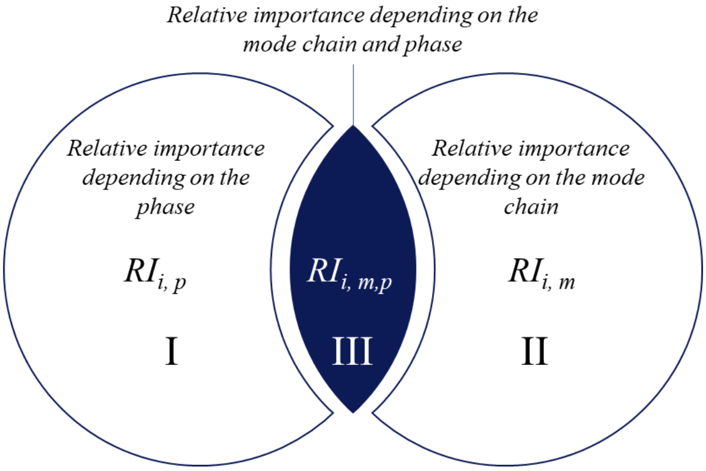


Figure 3: The interaction between information, mode chains, and travel phases.

By providing initial insights into the relationships between travel phases and mode combinations within intermodal mobility chains, this paper has laid the foundation for the concept of mode chain- and phase-sensitive information. This concept enhances the understanding of passengers' information needs across different mode chains and phases of their intermodal trips.

Interestingly, despite the sustainability benefits of intermodal mobility, information about environmental impact is deemed unimportant throughout a traveller's journey. This could be due to two reasons. First, the questionnaire specifically asked whether the information was necessary, leading respondents to view environmental information as optional but not essential. Second, the integration of environmental information into the decision-making process is closely related to research on digital nudging (Weinmann, Schneider and Brocke, 2016). Individuals may place higher value on feedback and thus consider environmental information more important in the final travel phase (i.e., 'end-trip'). This aligns with findings by Henkel et al. (2019) and Cappa et al. (2020). However, more research is needed on the provision of environmental information in transportation.

The paper theoretically contributes to research by offering initial insights into the relationships between information, mode chains, and travel phases. Therefore, it builds on the work of Lois et al. (2018), Hickman et al. (2015), Lucietti et al. (2016), and Digmayer et al. (2015). The findings can spark new discussions about the interactions between information, modes, and travel phases or any combination thereof.

Practically, the presented concept has the potential to enhance customer satisfaction by enabling mobility service providers to deliver relevant information in a timely manner. By tailoring information provision to the specific requirements of diverse intermodal mode chains, the concept can help formulate more effective strategies, ultimately enhancing passengers' overall travel satisfaction. This, in turn, could lead to reduced congestion and air pollution by encouraging more users to switch from private vehicles to intermodal mobility chains consisting of sustainable mobility modes.

## II.2 Applying Revenue Management for more efficient resource allocation in large fast charging parks for electric vehicles

To facilitate sustainable mobility, the investment and operation of energy supply infrastructure, such as public charging stations, must be a profitable business case. To improve profitability and mitigate risks associated with investments in FCI, operators can reduce operational costs or explore strategies to increase revenue. Cost-reduction strategies, such as optimal power allocation through smart charging or technical solutions like the integration of photovoltaic panels or energy storages, are already being widely discussed (Huber *et al.*, 2019; Muratori *et al.*, 2019; Seddig, Jochem and Fichtner, 2019; Yan, Zhang and Kezunovic, 2019; Sachan, Deb and Singh, 2020). In contrast, revenue maximisation for FCI operations has received less attention. Few articles shed light on dynamic pricing approaches; however, they do not consider the characteristics of LFCP locations, such as the ability to serve several customers simultaneously with high charging power (Guo *et al.*, 2016; Luo, Huang and Gupta, 2018; Baumgarte, Kaiser and Keller, 2021). To face this challenge, the application of the RM theory seems a promising approach to enhance LFCPs' revenue. Research Paper #2 examines the applicability of RM to electric vehicle charging and develops a quantitative dynamic pricing model to evaluate the quantitative impact.

To analyse whether RM is a valuable approach for revenue maximisation in LFCPs, Research Paper #2 first presents the theoretical characteristics of demand and optimisation models and the necessary prerequisites for applying RM, matching these with the characteristics of LFCPs. By combining the prerequisites and characteristics of RM with the business case, constraints, and customer behaviour of LFCPs, Table 1 presents the theoretical framework that demonstrates the transfer of RM to a dynamic pricing approach that can be implemented in LFCPs.

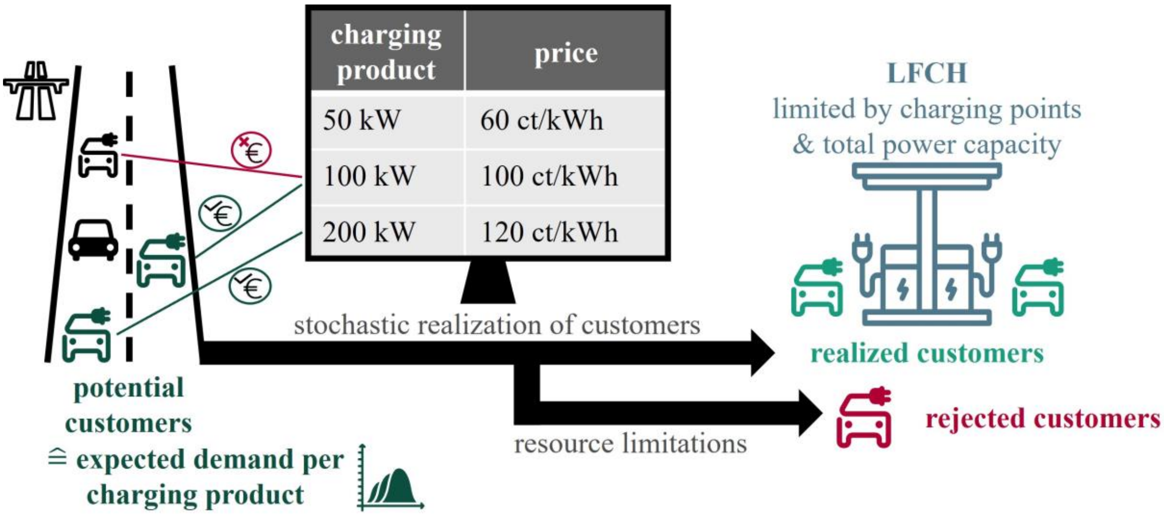
Table 1: Framework for applying Revenue Management and dynamic prices in a large fast charging park

| | **RM Element** | **Specification for the LFCP** |
|---|---|---|
| **Basic Requirements** (Kimms and Klein, 2005a) | Integration of an external factor | The external factor in a LFCP 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 LFCP 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 LFCP 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.<br>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 a LFCP 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 | A LFCP 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 behaviour and the dominating one-time customers who do not pass the LFCP regularly, it can be assumed that customers make myopic decisions based on the current price. |
| | Infinite population | Given that electricity is a consumable good it can be considered as an infinite population. |

| | | |
|---|---|---|
| | (Talluri and Van Ryzin, 2004) | |
| | Aggregate demand functions (Talluri and Van Ryzin, 2004) | The profitability of a LFCP is determined by the collective behaviour of the population of charging BEVs. Consequently, aggregate demand functions represent the population's behaviour rather than the individual assessment of BEV drivers. |
| **Dynamic Pricing Model** | No replenishment (Elmaghraby and Keskinocak, 2003a) | Since the LFCP 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 LFCP, a complete restoration of capacities occurs. |
| | Flexible resources (Bitran and Caldentey, 2003a) | 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 a LFCP, 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 LFCP utiliszation varies, and the resource capacities adapt. |
| | Multiple products (Bitran and Caldentey, 2003b) | To serve BEVs with different maximum charging power and to utilise the heterogeneous willingness to pay (WTP), multiple products should be considered in the dynamic pricing model, which are optimised simultaneously. |
| | Continuous or discrete prices (Bitran and Caldentey, 2003b) | LFCP operators 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 LFCP operator. |

Based on the framework, the paper further illustrates the development of a quantitative model in the form of a dynamic pricing optimisation model, which is used in a simulated case study for evaluation and validation. Part of the dynamic pricing model is a linear demand function that determines the price-dependent expected demand for a specific charging product (power level) and customer type (vehicle characteristic) based on several basic assumptions regarding the customer’s charging behaviour. Figure 4 illustrates the customer realisation principle. When no capacity restrictions (charging point and power availability) exist, all potential customers become realised customers. However, when at least one of the two required resources is restricted, the surplus customers are rejected. The optimisation model is a mixed integer linear programming model that includes the price optimisation of multiple products.

To incorporate the stochastic realisation of customers and the actual utilisation of resources in the charging park, we split the day into multiple periods and use 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.



| charging product | price |
|---|---|
| 50 kW | 60 ct/kWh |
| 100 kW | 100 ct/kWh |
| 200 kW | 120 ct/kWh |

Figure 4: Demand and customer realisation principle in large fast charging parks

The case study for an exemplary LFCP examines the utilisation of park resources and the revenue enhancements achievable through a dynamic pricing model under various scenarios. A sensitivity analysis explores the impact of different numbers of charging points, varying total power capacities, and an increasing share of BEVs. During low-demand periods, neither charging points nor power capacity acts as a limiting factor, resulting in equal resource utilisation at both optimised and fixed prices. In contrast, during high-demand periods, charging point utilisation is typically lower under optimised prices, regardless of which resource is scarce. This phenomenon arises because dynamic pricing prioritises higher power charging products – those that yield greater revenue – while driving the prices of lower-power options to their maximum. As a result, dynamic pricing increases the likelihood of BEV drivers finding free charging points when immediate charging is required, even in scenarios where charging points are limited. Similarly, the chances of having available power capacity for immediate charging processes rise, even during peak demand. This dynamic pricing behaviour can be clarified by observing the pricing per product and period. When charging points are the constrained resource, prices of low-revenue charging products are primarily adjusted. Consequently, these products quickly reach their maximum price, leading to decreased demand from this customer segment. This suggests that lower power demand products serve a role in demand management, occupying charging points while generating less revenue. Conversely, when total power capacity is the limiting factor, low-revenue products seldom reach their maximum price, given their minimal impact on power utilisation. High-revenue products remain favoured, exhibiting a substantial interquartile range, necessitating rapid price adjustments based on customer realisations.

Figure 5 illustrates the relative revenue improvement achieved through price optimisation. The application of Student’s t-Test reveals a significant daily revenue increase, with a confidence interval of 0.001 for all relative revenue improvements, as evident in Figure 5.

The RM approach demonstrates the greatest relative revenue improvements at charging parks with fewer charging points but relatively high total power capacities. Additionally, the relative revenue enhancement tends to flatten as the share of BEVs increases. This is due to a growing number of potential customers willing to pay for high charging power. Once the park's limited resources are fully utilised, attracting more customers does not further enhance revenue, resulting in a plateau of the relative revenue improvement curve.

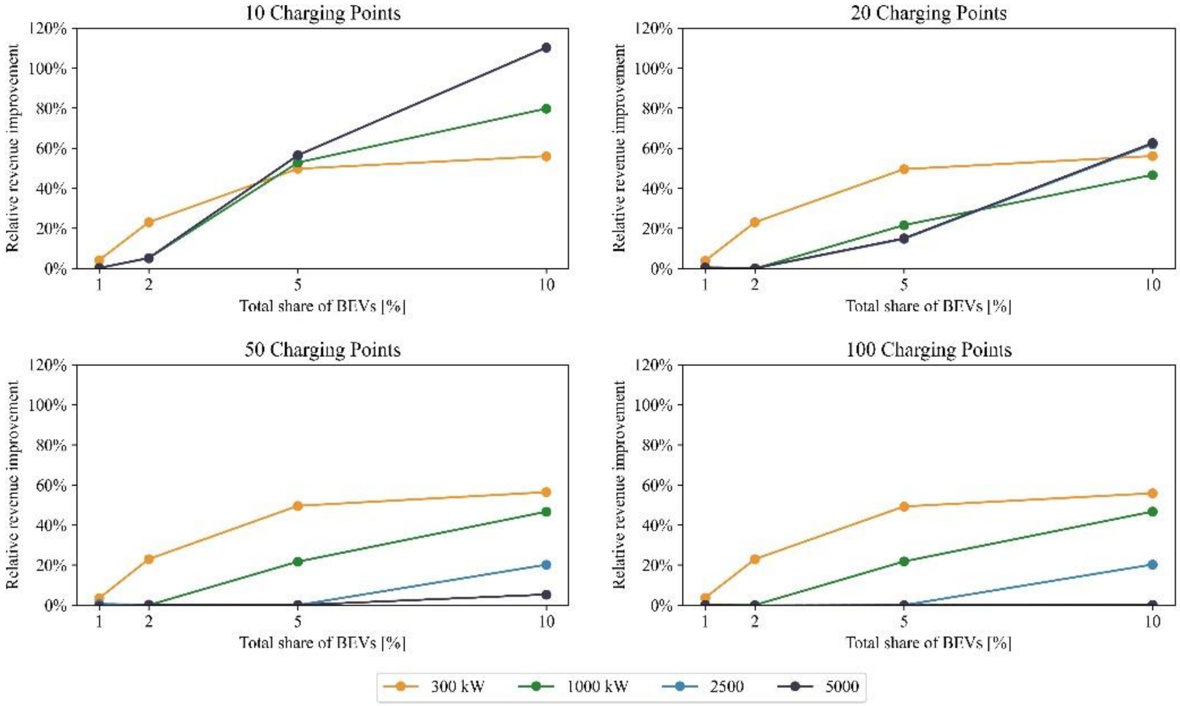


Figure 5: Relative revenue improvement of all scenarios

Overall, the results indicate that applying RM and dynamic pricing is advantageous for a LFCP, as it can enhance the operator’s revenues during periods when at least one resource – either total power capacity or the number of charging points – is scarce. The rapid adaptation of BEVs combined with insufficient charging infrastructure expansion is likely to lead to more frequent peak demand situations in LFCPs. This trend is particularly evident in countries experiencing a significant market ramp-up of BEVs without a corresponding increase in charging infrastructure (Gnann *et al.*, 2018; Funke *et al.*, 2019). Even with adequate infrastructure expansion, resources may reach full utilisation during peak demand periods, since large charging parks are typically designed for cost efficiency. Isolated peak times may not justify the additional investment needed for infrastructure expansion. Moreover, providing a one-time high total power capacity incurs high fixed operating costs due to electricity procurement price structures, resulting in caps on power capacity. Consequently, revenue and demand management become essential for delivering effective charging services. Research Paper #2 emphasises that revenue improvements are contingent upon the design of the charging park. Although the dynamic pricing model enhances a LFCP's revenue in scenarios with scarce resources, it cannot offset an unfavourable combination of resource limitations. This underscores the significance of strategic design decisions for such charging parks and their impact on profitability. Particularly, the number of charging points should be aligned with the anticipated demand. Furthermore, the limitation of total power capacity may be invisible to potential customers, leading to confusion and frustration. To address this issue, further research could explore a comprehensive management system for charging parks that takes into account factors beyond demand, revenue, and costs, including customer satisfaction.

## II.3 Smart electric vehicle charging: Benefits from discounts incentivising customer flexibility

The RM approach and the use of dynamic prices is an effective strategy for optimising customer flows, enabling charging infrastructure operators to utilise resources more efficiently and maximise revenue. However, the behaviour of individual BEV drivers, coupled with the technical characteristics of battery recharging, necessitates that LFCP operators implement complex smart charging algorithms. These algorithms aim to mitigate costly peak demand by controlling the charging processes (Flath, Ilg and Weinhardt, 2012). To effectively shift and manage charging processes within a charging park, operators require a wealth of individual customer information. Most importantly, this includes the specific technical charging behaviour of the customers' BEV, the battery's state of charge (SOC), and the customers' temporal flexibilities (Huber *et al.*, 2019). While technical data from BEVs is expected to be readily available in the near future through established communication standards between charging infrastructure and vehicles, incorporating individual behavioural aspects – such as idle times and desired target SOC – remains a significant challenge. Moreover, public charging events can be classified as ad hoc charging (Sadeghianpourhamami *et al.*, 2018). Customers with significantly shorter idle times tend to leave immediately after the charging process is completed, indicating a lack of inherent flexibility. This limitation reduces the effectiveness of smart charging strategies. To encourage customers to offer flexibility that can be harnessed through smart charging, existing literature highlights the effectiveness of monetary incentives, such as discounts (Huber *et al.*, 2019; Kacperski and Kutzner, 2020). However, these discounts represent an additional cost that directly offsets the economic benefits, namely the cost savings achieved from reducing peak demand through smart charging.

Research Paper #3 aims to determine whether the operational cost savings generated by smart electric vehicle charging overcompensates the discounts provided for customer flexibility. Initially, the paper establishes a relationship between flexibility and discounts based on existing literature and introduces a smart charging optimisation model. This model is then applied in a case study involving a LFCP to assess the research approach.

Utilising real-world data from highway traffic and charging station usage, the analysis compares various scenarios of customer flexibility, charging duration aversion, market penetration rates of BEVs, and different charging power levels. The results are benchmarked against a strategy lacking decision support for operators, who charge customers as quickly as possible, using the delta operational cash flow (ΔOCF) as an indicator.

The findings presented in Figure 6 reveal that at low BEV penetration rates, discounts for flexibility-averse customers have minimal impact, as the ΔOCF remains stable around zero. As BEV penetration increases, discounts up to 15% result in a positive ΔOCF for scenarios with lower charging power. Flexibility-seeking customers actively utilise discounts even at lower BEV penetration rates, leading to a positive ΔOCF with discount rates of 10% or even 20%, depending on the charging power level. With an increasing BEV penetration rate, the positive impact of discounts on the ΔOCF becomes significant at lower discount rates but diminishes rapidly at higher rates (c.f. Figure 7).

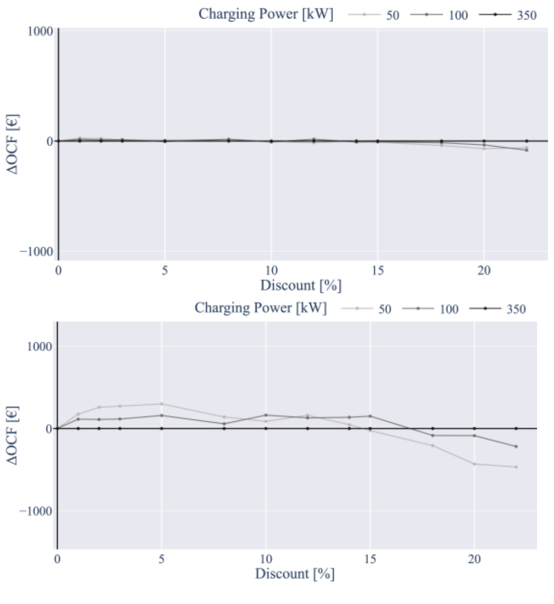


Figure 6: ΔOCF for different charging powers and BEV penetration rates of 1% (top) and 10% (bottom) for flexibility-rejecting customers

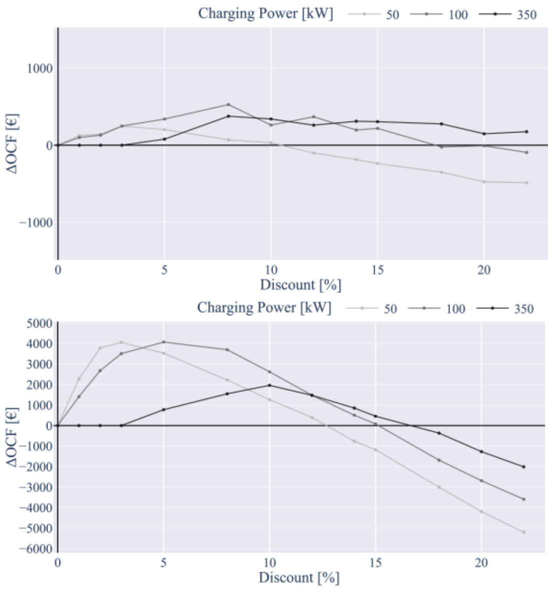


Figure 7: ΔOCF for different charging powers and BEV penetration rates of 1% (top) and 10% (bottom)for flexibility-seeking customers

These observations suggest that relatively low discounts are sufficient to generate enough flexibility for profitable smart charging, particularly as the number of customers grows in the future. However, they also indicate that with higher BEV penetration rates, the utilisation of charging infrastructure increases, which mitigates the financial impact of load peak fees relative to other costs and revenues. With rising discounts, the increased customer volume leads to high discount costs that render flexibility too expensive, thereby diminishing the value of smart charging, particularly for flexibility-seeking customers. For lower charging power levels, such as 50 kW, customers provide plenty of flexibility at lower discounts to facilitate profitable smart charging. Conversely, higher charging power levels necessitate increased discounts to maintain the value of smart charging, due to shorter charging times. Even a brief extension in charging duration can lead to a significant relative delay in service, heightening customers' sensitivity to discounts when providing flexibility.

Analysing the distribution of various simulation runs offers valuable insights into the robustness of the study's mean results. For discounts of 5% and 10%, both the expected mean ΔOCF and its variance increase as BEV shares grow, applicable to both customer preferences. In the case of flexibility-averse customers, this trend continues even for a discount of 15%. However, for flexibility-seeking customers, the situation reverses; at higher discounts, the expected mean ΔOCF decreases as BEV shares increase, while the variance continues to rise. Interestingly, the negative deviation of the variance is consistently smaller than the corresponding positive deviation across all customer preferences. The development of this deviation varies between the two customer preference scenarios as the BEV penetration rate increases. For flexibility-averse customers, the shift tends to increase, while it decreases for flexibility-seeking customers. One explanation for this phenomenon is that the likelihood of available flexibility among flexibility-averse customers rises with a larger customer base. Furthermore, the negative impact of discount costs is less pronounced for this group compared to flexibility-seeking customers. As the BEV penetration rate and discount levels rise, the ratio of absolute positive to negative deviations increases significantly across all scenarios. This suggests that discount costs become increasingly important; they can substantially enhance the benefits of smart charging when flexibility is allocable during peak demand periods. Conversely, if flexibility is not allocable during these peak times, discount costs can severely diminish the advantages of smart charging. Notably, both the highest positive and negative deviations occur at elevated penetration rates and charging power levels.

Overall, utilising discounts as incentives for flexibility in smart charging can enhance the profitability of LFCPs. However, the effectiveness of discount-based smart charging is contingent upon individual customer preferences, which must be meticulously considered when designing smart charging systems that interact with customers to leverage their unique flexibility. Given the substantial variability and unpredictability in the frequency and temporal distribution of charging events, the findings provide insights into the financial risks associated with offering BEV charging services through discount-based smart charging. At present, with low penetration rates of BEVs, the potential to mitigate costly peak loads through discount-based smart charging outweighs the risks associated with uncontrolled load peaks or excessive discounting. As BEV shares increase, however, the risk of incurring higher costs for flexibility escalates, particularly among flexibility-seeking customers. This is because discounts apply to all customers willing to offer flexibility, yet not all of that flexibility may be necessary. In this context, time-of-use pricing could serve as an additional strategy to generate flexibility while balancing the requisite discounts for charging customers. To establish optimal discounts for customer flexibility, further empirical data is essential. Notably, the reciprocal interaction between the perceived importance of discounts on charging prices and the reluctance to extend charging durations presents a compelling yet underexplored dimension that significantly influences the outcomes. To further enhance smart charging through flexibility, LFCP operators might consider providing additional services to incentivise customers to accept slower charging speeds. Examples of such services could include partnerships with restaurants or shared office spaces. Additionally, operators could implement innovative tariff structures, such as flat rate charging or fleet discounts, in conjunction with non-monetary incentives like loyalty programs or gamification approaches, to bolster utilisation and encourage the provision of flexibility. Beyond incentivised flexibility, individual user preferences warrant consideration. Although our findings indicate that the impact of varying preferences on profitability diminishes, existing literature demonstrates that differentiated treatment of customer segments can lead to increased revenues (Jonger, Piersma and Van den Poel, 2003). This differentiation could be particularly significant during anticipated peak demand periods.

## II.4 Sustainable design and operation of hybrid hydrogen and electric energy supply for road transportation

Researchers predict a future in which BEVs will dominate short-distance individual transport, while FCEVs will serve heavy-duty long-distance transport, suggesting a complementary coexistence in decarbonised road transportation (Eberle and Von Helmolt, 2010; Morrison, Stevens and Joseck, 2018; Michalski, Poltrum and Bünger, 2019; Çabukoglu *et al.*, 2019). In response, the "Fit for 55" package mandates the establishment of a cross-European network of charging and hydrogen refuelling stations. National hydrogen strategies are being developed to align with this legislative framework, offering investment incentives (Velazquez Abad and Dodds, 2020). However, significant challenges remain, including the cost-intensive operation of hydrogen infrastructure (Browne, O'Mahony and Caulfield, 2012; Biresselioglu, Demirbag Kaplan and Yilmaz, 2018), the absence of a robust distribution network for long-distance hydrogen transfer within the EU [23], and the necessity for green hydrogen production via electrolysis from RES (Gustafsson *et al.*, 2021). These factors underscore the importance of demand-side management and energy storage solutions to mitigate the volatility associated with RES supply (Bussar *et al.*, 2015; Soares *et al.*, 2022). Microgrids – small, decentralised electricity distribution systems – emerge as a promising solution by integrating renewable generation, energy storage, and hydrogen production technologies, thereby facilitating charging and hydrogen refuelling services. A feasible approach involves a grid-connected microgrid that utilises RES for charging stations while also generating hydrogen and implementing a hybrid battery-hydrogen energy storage system (Rose and Neumann, 2020; Mansour-Saatloo *et al.*, 2021). Despite existing research, current studies often examine only isolated components of microgrid design and operational strategies, failing to address the synergistic potential of serving both BEVs and FCEVs while incorporating dual energy storage options. For instance, Haupt et al. (2020) focus on sizing battery energy storage systems (BESS) for renewable fast charging hubs, whereas other studies (Valverde, Rosa and Bordons, 2013; Alam, Kumar and Dutta, 2019) emphasise the integration of hydrogen energy storage for long-term microgrid management. Research by Baghaee et al. (2016) highlights long-term energy management using hydrogen in remote microgrids, and Yassuda Yamashita et al. (2021) explore hybrid hydrogen-battery systems to enhance supply reliability and self-sufficiency in residential and public infrastructure. The design of hydrogen refuelling stations necessitates careful consideration of demand behaviour and RES availability (Grüger *et al.*, 2018; Xu *et al.*, 2022). Alavi et al. (2017) investigate the synergies between FCEV refuelling demand and energy reconversion in residential microgrids, while Han et al. (2019, 2020) analyses the operations of islanded hybrid hydrogen-battery microgrids. Dawood et al. (2020) present a comparative analysis of scenarios employing only BESS, only hydrogen storage, and a hybrid approach, assessing their costs and GHG reduction potential. Collectively, these studies provide insights into the synergies between BEV charging and the operation of hydrogen refuelling stations, integrated with hydrogen production (Dispenza *et al.*, 2017; Xu *et al.*, 2020; Liu *et al.*, 2021, 2021; Mansour-Saatloo *et al.*, 2021). Nevertheless, decision-makers currently lack comprehensive techno-economic guidance for the design and operation of hybrid charging and hydrogen refuelling station microgrids that achieve low GHG emissions.

Research Paper #4 aims to fill existing gaps in the literature and facilitate the deployment of charging and hydrogen refuelling infrastructure for decarbonised road transportation. The study introduces a microgrid framework and a mathematical optimisation model designed to minimise total energy costs during the operation of a microgrid that provides high-performance hybrid charging and hydrogen refuelling services. Infrastructural design and operational strategies significantly influence total energy costs and decarbonisation potential. The optimisation case study examines various configurations of BESS and Hydrogen Storage Systems (HSS), alongside two operational strategies: Day-Ahead market participation and self-consumption optimisation without grid feed-in. This analysis spans three consecutive years – 2019, 2020, and 2021 – resulting in six distinct scenarios.

Findings, illustrated in Figure 8, reveal that the implementation of BESS within a hybrid charging and hydrogen refuelling station microgrid effectively reduces demand charges and overall energy costs. The BESS flattens electricity demand from the grid by storing surplus electricity generated from photovoltaic systems and charging during low electricity price periods. Without grid feed-in, the BESS optimises self-consumption, while Day-Ahead market participation allows for additional revenue through electricity trading, reducing total energy costs. In 2019, differences between operational strategies were marginal due to higher BEV charging demand, leading operators to be indifferent. However, in 2020 and 2021, electricity marketing became more attractive, making Day-Ahead market participation the preferred strategy. Additionally, total annual energy costs decrease and decarbonisation potential increases as the performance and capacity of the HSS system improve. The electrolyser (EL) is the primary electricity consumer, and higher production capacities enable increased hydrogen production during periods of abundant renewable energy or low Day-Ahead electricity prices. Enhanced storage capacity allows for continuous hydrogen production without maintaining minimum hydrogen levels. While fuel cell (FC) utilisation is low in most scenarios, there is an increase in utilisation within the self-consumption strategy in 2020, particularly with smaller HSS configurations. The surplus electricity from the photovoltaic system justifies converting excess hydrogen back into electricity to support charging during lower renewable energy availability. Outside such scenarios, FC operation is often economically unviable due to significant efficiency losses in the hydrogen generation and reconversion process (Ueckerdt *et al.*, 2021). This suggests that FC capacity must be optimally sized when integrating FC technology into hybrid charging and hydrogen refuelling stations.

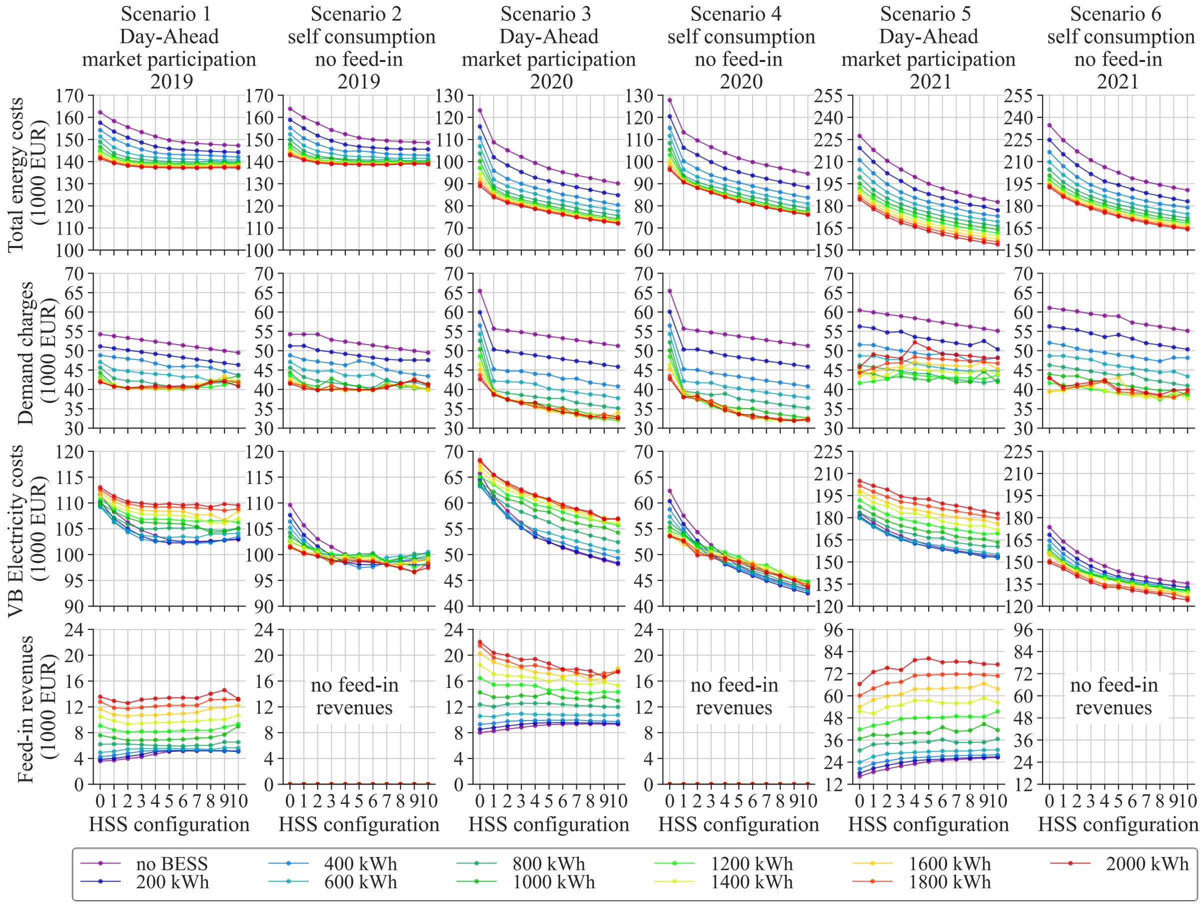


Figure 8: Economic viability analysis of the optimisation results for different BESS and HSS configurations and operational strategies

The decarbonisation (c.f. Figure 9) analysis reveals that a higher decarbonisation potential can be realised through self-consumption optimisation compared to participation in the Day-Ahead market. The main difference between the operating strategies is the higher electricity volume procurement due to the marketing potential within the Day-Ahead market participation strategy. The higher volume of electricity purchased from the grid increases the average emission factor, as grid electricity has a significantly higher average associated emission factor than on-site photovoltaic electricity.

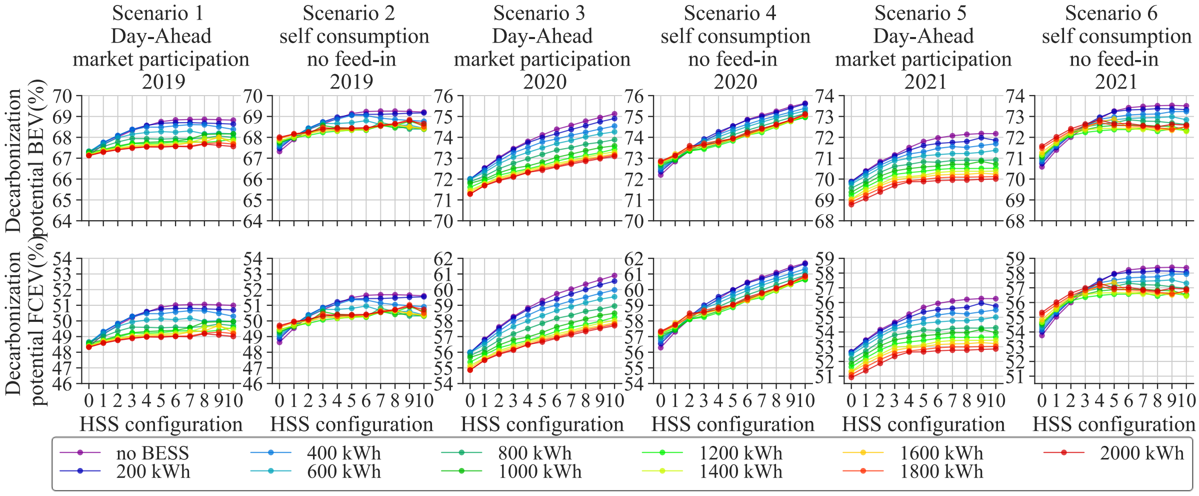


Figure 9: Illustration of the decarbonisation potential of BEVs and FCEVs in comparison to reference passenger cars and heavy-duty trucks with fossil fuel powered engines.

The results further present a misalignment between the cost-effectiveness of designing and operating microgrids for hybrid charging and hydrogen refuelling stations and the progress towards decarbonisation. This finding is unexpected, given that feed-in from RES in Germany is prioritised over fossil fuel plants under the merit order model (Sensfuß, Ragwitz and Genoese, 2008). It is anticipated that in self-consumption scenarios with high energy storage capacities, increased procurement of low-cost electricity from RES would simultaneously reduce total costs and emissions. For instance, BESS can mitigate peak loads and balance electricity demand from the grid throughout the year, while feed-in revenues are generated by capitalising on price fluctuations in the Day-Ahead market. However, electricity with higher emission factors is often procured, undermining decarbonisation efforts. A notable correlation between Day-Ahead spot prices and emission factors is observed, with a stronger correlation in 2020 compared to 2019 (see Figure 10). The price deviation increased significantly over the analysed years, nearing five times higher in 2021 than in 2019. This positive correlation indicates that achieving low-cost and low-GHG operations for hybrid charging and hydrogen refuelling microgrids could be feasible without trade-offs, particularly as rising CO2 pricing is likely to enhance this correlation in the future. Nevertheless, our findings suggest that from an economic standpoint, it is more beneficial to minimise load peaks and opt for a steady electricity inflow from the grid, rather than relying on increasing peak loads to exploit low-price procurement opportunities. Consequently, the anticipated benefits of the positive correlation between electricity prices and emission factors in the Day-Ahead market are not realised in the operation of these microgrids. This leads to a decrease in the decarbonisation potential across both scenarios without grid feed-in. Nonetheless, minor improvements at individual hybrid charging and hydrogen refuelling stations can yield substantial GHG emission reductions at scale.

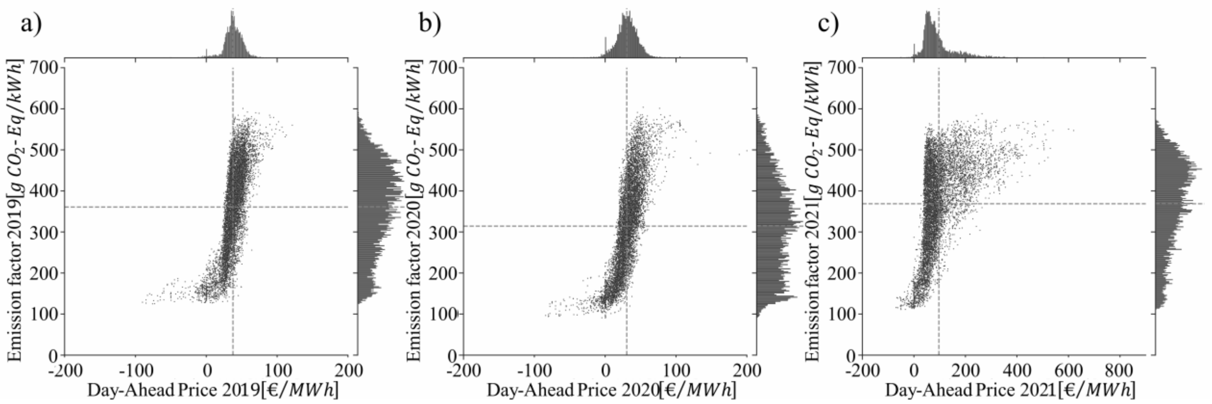


Figure 10: Illustration of the relationship between Day-Ahead prices and GHG emission factors of the years 2019 (a) and 2020 (b). Each Figure show the Day-Ahead prices on the x-axis and the emission factors on the y–axis. At the top and right of each graph, we include a histogram illustrating the distribution of prices and emissions. We include both the mean value and the standard deviation for prices and emission factors. Data: (ENTSO-E, 2022b, 2022a; Lauf, Memmler and Schneider, 2022).

In conclusion, Research Paper #4 reveals that the choice of microgrid configuration design, sizing and operational strategy strongly influences total energy costs and the decarbonisation potential of BEV charging and FCEV refuelling. While high BESS capacity can significantly reduce total energy costs, GHG emissions increase. However, the simultaneous maximisation of cost efficiency and high decarbonisation of hybrid charging and hydrogen refuelling stations is discouraged by current grid demand charge regulation. The findings of this paper lead to several implications for policy, practice, and research.

First, we identified grid demand charges as a major factor preventing the benefits of the positive correlation of Day-Ahead electricity prices and emission factors for simultaneous economic and ecological operation in our case study. While high energy storage capacities are mostly associated with decreasing GHG emissions, significantly high grid demand charges hinder simultaneous economic and ecologic operation in a Day-Ahead marketing scenario. A modification of the grid charge regulatory can enable decentralised electrolysis systems to benefit from a higher load peak during RES oversupply periods in the public grid.

Second, besides subsidising infrastructure, tax incentives during operation may accelerate deployment of charging and hydrogen refuelling microgrids at scale and promote market ramp up of BEVs and FCEVs to achieve decarbonisation in road transportation.

Third, power plants with low GHG impacts such as photovoltaic plants and wind turbines should be integrated cross-sectoral with transportation electrification.

Finally, the results reveal design and operational guidance for microgrid operators. Microgrid investors and operators should exploit the high-cost reduction potential of higher BESS capacity to improve economic viability. In addition, the operating strategy of participating in the Day-Ahead market offers an economic advantage for large corporations with access to the

Day-Ahead market. In contrast, operators of charging and hydrogen refuelling stations without access to the Day-Ahead market may adopt the operating strategy of self-consumption optimisation. This strategy may prove beneficial if the company's core activity does not involve electricity marketing or if company resources cannot be dedicated to this purpose.

This study focuses on the variable electricity market prices of the German Day-Ahead bidding zone and German regulation. Future studies could examine the impact of participation in other or multiple markets, such as intraday or ancillary services markets, on microgrid design and operation. Also, transferring our study design to other regions with different regulatory or market characteristics, analysing external effects of different shares of the electricity mix or BEV/FCEV penetration rates, or considering long-term electricity price or mobility forecasts could provide further valuable insights for researchers, practitioners, or policymakers.

## II.5 Helping policy makers to elaborate policy support measures for widespread expansion of fast charging infrastructure for electric vehicles

Based on the EU's regulatory framework "Fit for 55," member states are mandated to develop national laws and regulatory changes that will facilitate the expansion of energy supply infrastructure to effectively decarbonise road transportation. For instance, Germany plans to establish 90,000 fast charging stations by 2030 (Lucien *et al.*, 2020). To counter investment shortfalls, policymakers are providing financial support, allocating €2.5 billion for charging infrastructure expansion (BMF, 2020), typically through subsidies on purchase costs, tax rebates, and electricity tax exemptions (Hannisdahl, Malvik and Wensaas, 2013; Cansino, Sánchez-Braza and Sanz-Díaz, 2018). However, many support measures are overly generic and may not ensure an equitably distributed fast charging network. A pertinent example of poorly regulated infrastructure development is the expansion of mobile internet in Germany, which has disproportionately favoured high-demand regions, leaving rural areas disadvantaged (Hirler, 2019).

Research Paper #5 specifically examines how policy measures influence the profitability of various fast charging locations in relation to BEV adoption rates and formulates policy recommendations for effective incentive schemes. Profitability, a key driver of FCI investments, is heavily impacted by high capital and operational costs, including variable energy procurement costs, taxes, levies, grid fees, and demand charges (Schroeder and Traber, 2012; Burnham *et al.*, 2017; Levy, Riu and Zoi, 2020). Demand charges, which are based on the maximum power peak within a specified period, tend to be higher in locations with low utilisation rates (Knupfer, Noffsinger and Sahdev, 2018). While existing global subsidy programmes, such as cash subsidies or tax credits, significantly reduce high investment costs, they often fail to account for regional differences in profitability or the impact of other cost drivers like demand charges. This oversight poses a risk to the rapid adoption of BEVs and necessitates policy measures that consider local discrepancies to support a well-distributed fast charging network. To investigate how political support measures contribute to the expansion of FCI, this study employs established investment evaluation methods to assess the economic viability of fast charging locations within the German freeway network. Using an agent-based simulation approach, the study analyses local charging volume based on BEV driving and charging behaviour, comparing profitability across three distinct locations with varying traffic volumes. The net present value (NPV) is used to evaluate the impact of investment subsidies, electricity tax exemptions, demand charge reductions, and daily demand charge billing intervals, with scenarios ranging from a low BEV penetration rate of 0.3% to 2.2%.

Results indicate that neither investment subsidies nor tax exemptions significantly enhance the profitability of FCI in low-utilisation areas, failing to support widespread infrastructure expansion. However, a 50% reduction in yearly demand charges generally improves the NPV, particularly at stations with higher charging power (see Figure 11). Notably, profitability improves with increasing BEV penetration, especially in low-utilised locations. Furthermore, locations with high charging volumes see a more pronounced benefit from demand charge reductions, exemplified by a 60% greater average increase in NPV at a 350 kW station in location B compared to location C. This reduction also smooths NPV fluctuations, particularly at higher charging power stations.

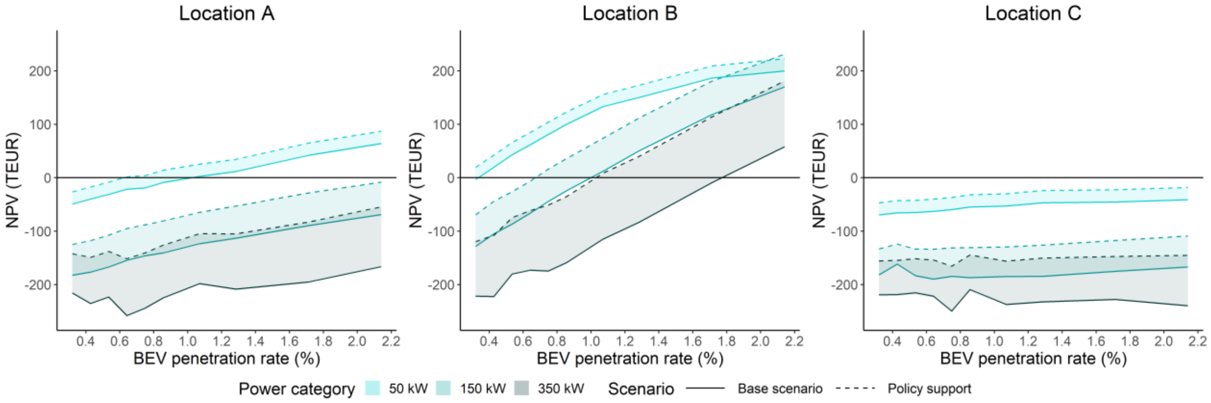


Figure 11: The impact of 50 % demand charge rate reduction among the locations A, B and C for three different charging power levels 50 kW, 150 kW and 350 kW

Another policy instrument to address high demand charges is to change annual demand charge to daily demand charge billing. Daily accounting only charges the daily peak demand at the daily demand charge rate on days on which the charging processes take place. As Figure 12 demonstrates, daily demand charges proportional to the annual rate mainly affect unprofitable stations providing higher charging power. For example, at location C, all power categories benefit, but mainly the 150 kW and 350 kW stations. In contrast, at locations A and B, the 50 kW and 150 kW stations hardly benefit or do not benefit at all. It is noticeable that across all cases, the beneficial impact of daily demand charges decreases with increasing penetration rate so that fast charging stations gain most of the profit in their early stages when utilisation is low. The benefit from funding shrinks as they become profitable due to sufficient penetration rates. For example, the 350 kW fast charging station at location A and C receive enormous support when utilisation is low, while stations providing 50 kW almost receive no support. Additionally, daily demand charges firmly smooth the volatile NPV estimations for the 350 kW stations, because high annual demand charge rates no longer penalise sporadic power peaks.

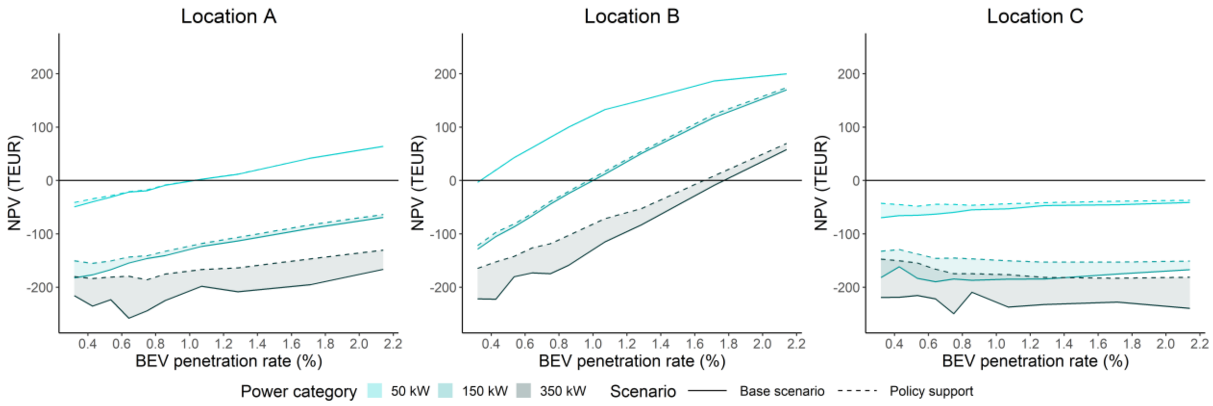


Figure 12: The impact daily demand charge billing intervals among the locations A, B and C for three different charging power levels 50 kW, 150 kW and 350 kW

Overall, the results of the case study indicate that location characteristics significantly influence profitability, playing a crucial role in the allocation decisions of investors and contributing to the uneven distribution of FCI. Policymakers must ensure that subsidies account for these location-based differences to assist areas that currently lack attractiveness for investment. However, existing subsidy mechanisms, such as Germany's nationwide tiling procedure for regional subsidy allocation (BMDV, 2022), fail to consider local profitability fluctuations. It is imperative to expand this allocation procedure to identify profit-weak locations and implement location-specific subsidy distributions. This approach is particularly vital for less densely populated countries, where the unequal distribution of FCI can have even more severe consequences. Moreover, the partial implementation of electricity tax exemptions undermines the widespread deployment of FCI by favouring locations that already present a positive business case as utilisation increases. In contrast, areas requiring subsidies do not benefit from these tax exemptions. A similar concern arises with the exemption or reduction of grid fees, which predominantly supports already profitable locations. Reducing the demand charge rate produces two contrasting effects. While stations with higher charging power benefit more and experience reduced fluctuations in profitability due to lower costs from outbound power peaks, already profitable locations gain slightly more, further disadvantaging less attractive sites. Changing the demand charge billing period from yearly to daily primarily benefits low-frequency stations with high charging power. Although this shift supports under-utilised locations, it does not aid already profitable ones, thus promoting a more evenly distributed investment landscape for FCI. However, the advantages of daily billing will diminish as the market for BEVs and FCI utilisation expands. Future research should explore the combined effects of various policy instruments on the development of widespread FCI. Policymakers may find it beneficial to evaluate the cost-efficiency of different alternatives, comparing their impacts to total funding costs and establishing relevant funding timelines. Incorporating diverse charging fees and analysing the price sensitivity of BEV drivers could enhance simulations of actual charging behaviour. Additionally, considering complementary technologies and conducting thorough risk assessments will provide a clearer understanding of FCI investment attractiveness.

# III Conclusion

## III.1 Summary and outlook

The transportation sector is a significant contributor to GHG emissions, necessitating a technological transition towards new energy vehicles such as BEVs and FCEVs and the promotion of intermodal mobility behaviours, particularly in urban environments. The EU's Green Deal, alongside its "Fit for 55" package, provides a comprehensive regulatory framework for member states to foster intermodal mobility and enhance the energy supply infrastructure critical for the widespread adoption of BEVs and FCEVs. However, the implementation of these initiatives on national level presents considerable challenges for policymakers, mobility providers, and infrastructure operators and investors. These stakeholders are confronted with decisions that are inherently fraught with uncertainty. For a substantial shift in urban mobility behaviours towards intermodal mobility, the traveller's individual attitude and information need challenges mobility providers and traveller information systems. A particularly pressing issue impeding the transformation of drive technology is the precarious landscape of subsidies for BEVs and FCEVs. It hampers rapid market adoption and complicates the establishment of a predictable demand for charging and hydrogen supply services. Moreover, the high costs associated with infrastructure development, combined with the rapid technological evolution of charging and electrolyser systems, impose significant difficulties on infrastructure operators and investors. They are required to make complex sizing and operating decisions to ensure that the charging and hydrogen supply infrastructure aligns optimally with application needs, thereby maximising efficiency.

In the context of smart sustainable mobility, the IS research provides methodological tools and digital solution approaches for the decision support of policymakers, mobility service providers and energy supply infrastructure operators and investors. This cumulative thesis comprises five research papers using IS methods to enhance or create decision support systems.

First, this work helps mobility service providers to offer user-oriented travel information via traveller support systems to increase seamless intermodal travel services (Section II.1). Therefore, Research Paper #1 conducted an online survey among >500 German travellers to validate relevant travel information regarding the travel phase and mode chain taken. The results led to three key learnings, which formed the foundation of the concept of travel phase- and mode chain-sensitive information need for intermodal mobility. First, the results indicated that information needs vary depending on the travel phase. Second, each information piece in the questionnaire was heterogeneously evaluated depending on the combination of nodes in an intermodal mobility trip. Lastly, the results indicated that a holistic understanding of information requirements necessitates an examination of the interplays between travel phases and mode chains. The paper developed a framework that encompasses mode chains, travel phases, and their interactions, providing a comprehensive picture of information needs in intermodal mobility trips. By tailoring information provision to the specific requirements of diverse intermodal mode chains timeously, the concept can help mobility providers to formulate more effective strategies, incentivising more users to switch from private vehicles to intermodal mobility chains consisting of sustainable mobility modes.

Second, this thesis helps operators and investors of fast charging and hydrogen supply infrastructure in strategic, operational, and design decisions (Sections II.2, II.3 and II.4). Investigating the impact of dynamic pricing on revenue maximisation, Research Paper #2 examines the applicability of RM in LFCPs and develops a quantitative dynamic pricing model for the evaluation. Complementary, Research Paper #3 studies whether the economic benefit, i.e., cost savings from reducing expensive electricity peak demand, overcompensates discounts provided to incentivise customer flexibility. Both research articles use mathematical optimisation and dynamic pricing either with the aim of maximising revenue following RM (Research Paper #2) or managing charging events to minimise electricity procurement costs (Research Paper #3). The results indicate, that both operational strategies can lead to significant improvement in profitability. But choosing the right discount rate or charging offer depends on the infrastructural design. Both strategies cannot compensate bad strategic design decisions regarding the number and characteristic of charging points and the available power capacity. Hence, modelling micro-grids to simulate operational strategies and design opportunities is necessary for the investors and operators' decision support. The individual case studies conducted in the Research Papers #2 and #3 indicate that discounts are particularly valuable when the charging station utilisation is low, and the technical available charging power is high. In contrast, applying RM is economically most favourable when utilisation is high, and the number of charging points or available charging power is scarce. For operators of fast charging equipment, an integrated view of different operation strategies is recommended. Another micro-grid model applying mathematical optimisation to provide techno-economic guidance for decision-makers in designing and operating a hybrid charging and hydrogen refuelling station is implemented by Research Paper #4. Likewise, the results demonstrate, that the choice of microgrid configuration design, sizing of hydrogen and battery storages and operational strategy strongly influences total energy costs and the decarbonisation potential of BEV charging and FCEV refuelling. Due to the paper's specific case study, high BESS capacity can significantly reduce total energy costs, while GHG emissions increase. High performance power of EL, FC as well as HSS capacity results in a reduction of the total energy costs and an improvement of the realised decarbonisation of BEVs and FCEVs, but at the same time, the total annual utilisation rate of the HSS decreases.

Further, the results identify grid demand charges as a major factor preventing the realisation of benefits through the positive correlation of Day-Ahead electricity prices and emission factors for simultaneous economic and ecological operation. Overall, this thesis demonstrates that such micro-grid models enable investors and operators to make more profound decisions.

Third, this work supports policy makers in creating effective support measures that incentivise widespread investments in FCI (Section II.5). To find out, how specific policies affect the profitability of FCI locally, Research Paper #5 analyses the impact of various policy support measures on the economics of FCI of different locations and sizes depending on BEV adoption rates. Therefore, a simulative approach for BEV driving and charging behaviour to analyse FCI's profitability is applied. In their present form, currently available policy instruments, such as subsidies on the investment of FCI, do not sufficiently contribute to a comprehensive and widespread deployment of FCI. Other popular funding options like exemption of the electricity tax, grid fees or similar levies does not have the desired effect as well. The beneficial impact increases with growing utilisation of FCI, which counteracts the goal of promoting underutilised locations. A promising approach is reducing the settlement period of demand charges. This can be realised by calculating the electricity load peak daily instead of recording the maximum load annually. Profit weak locations are explicitly supported at low penetration rates while the support decreases on its own as profitability increases.

## III.2 Limitations and future research

Like any research, this thesis has limitations and at the same time opens new avenues for future research. Specific limitations for the various research papers can be found in the articles themselves. This section presents general limitations with relevance to the entire thesis.

(1) The validity and interpretability of data-driven research methods are often constrained by the quality of the underlying data. In Research Paper #1, the reliance on self-collected data via an online questionnaire introduces an inherent bias stemming from the survey's design. Notably, the survey was conducted exclusively in Germany, and the use of an online platform resulted in a participant demographic predominantly comprising young individuals aged 20 to 40. This narrow age range limits the generalisability of the findings. For broader applicability, a larger and more diverse sample, encompassing multiple countries, is essential. Additionally, the characteristics of public transportation and mobility services can vary significantly across different nations. Therefore, any transnational interpretations arising from the study must be approached with caution and undergo thorough discussion in subsequent research. In the Research Papers #2, #3, and #4, the authors employ data-driven simulation case studies using real traffic data from a single motorway section to analyse the charging behaviour of BEV-

drivers. While the conclusions drawn from these studies may be robust, the potential impact of alternative datasets on the results remains an open question. Future research should strive to incorporate datasets from varied geographic locations and implement comprehensive sensitivity analyses, thereby enhancing the credibility and depth of the thesis findings.

(2) The mathematical optimisation models developed in the Research Papers #2, #3, and #4 operate under the assumptions of complete information and rational decision-making. These models incorporate parameters such as electricity prices, charging and hydrogen refuelling demand, and photovoltaic generation capacity. However, this reliance on idealised conditions represents a significant limitation in the transferability of the quantitative results to real-world scenarios. Given these assumptions, the economic potentials calculated within the models should be interpreted as maximum achievable outcomes, as actual conditions often exhibit deviations that lead to a reduction in the economic potential. Therefore, to enhance the robustness of future research, it is imperative to integrate stochastic elements and forecasting methods into the parameters and time series analyses. In this context, the application of data-driven artificial intelligence methods, which have demonstrated high predictive performance across various domains, may provide a valuable avenue for further investigation. Such approaches could yield more accurate and applicable results, thereby enriching the understanding of economic potentials in real-world settings.

(3) The thesis predominantly emphasises FCI across the Research Papers #2, #3, #4, and #5, positing that FCI is crucial for the widespread adoption of BEVs. This focus is justified by the significant role FCI plays in maintaining power capacities, where timely utilisation can substantially influence electricity purchase costs, grid load, and the technical feasibility of managing large electricity volumes. However, while FCI is essential, other charging use cases may also present considerable potential for the dynamic pricing and smart charging strategies discussed. Existing literature highlights the advantages of dynamic pricing for grid stability (Limmer, 2019; Valogianni *et al.*, 2020) and for profit maximisation at public parking lots (Guo *et al.*, 2016; Luo, Huang and Gupta, 2018). Consequently, future research should rigorously examine the benefits of implementing RM or discount-based smart charging approaches in these contexts. Moreover, the policy measures proposed in Research Paper #5 are exclusively tailored to fast charging scenarios. Given that operators of regular charging infrastructure encounter distinct challenges, it is imperative that future research investigates specific policy measures or incentives aimed at supporting these operators. This broader perspective will enhance the applicability and effectiveness of strategies designed to facilitate the transition to electric mobility.

Despite these limitations I am confident that the analysis, conclusions, and policy recommendations presented in this thesis present a valuable contribution for enhancing smart sustainable mobility solutions and for shaping a climate-neutral future.

### III.3 Acknowledgement of previous and related work

In all my research papers, I collaborated with colleagues at the Branch Business & Information Systems Engineering of the Fraunhofer Institute for Applied Information Technology (FIT) and the FIM Research Centre. I therefore present how my work and the embedded research papers build on previous and related work.

Dealing with the information need along different trip phases within an intermodal travel chain, Research Paper #1 were mainly inspired by Digmayer et al. (2015). This foundational work advocates for the consideration of trip phases in the design of traveller information systems, thereby establishing a critical framework for subsequent studies. In this context, the paper also engages deeply with the research on customer satisfaction in the mode choice decision-making process, a theme extensively explored by Dacko and Spalteholz (2014), de Ona (2020, 2022), de Ona et al. (2021) and De Vos et al. (2016; 2022). Collaborative efforts in Research Paper #5 are grounded in the pioneering analysis of the economics of fast charging infrastructure for electric vehicles conducted by Schroeder and Traber (2012). Their work lays the groundwork for understanding the economic implications of such infrastructures on a national scale. Furthermore, the case studies presented in Research Papers #2, #3, and #5 build upon collaborative initiatives from the ODH@SIZ project, funded by the Bavarian Ministry of Economic Affairs, Regional Development and Energy (Open District Hub e.V., 2024). Research Paper #2 uses the foundational literature on RM, drawing from the works of Kimms and Klein (2005b) and Klein et al. (2020) to open up a new application for RM. It also incorporates early studies on dynamic pricing in electric vehicle charging, notably by Kim et al. (2017) and Limmer (2019). In parallel, Research Paper #3 further develops the concept of customer-specific discounts as articulated by Halbrügge et al. (2020) and builds on the paradigm of user centric power allocation considered by Fridgen et al. (2021). Additionally, the demand model utilised to simulate charging behaviour in Research Papers #2, #3, and #4 is informed by the data-driven demand calculation framework proposed by Baumgarte et al. (2021), which leverages real traffic data for enhanced accuracy. Finally, the microgrid model development outlined in Research Paper #4 is significantly influenced by the research of Haupt et al. (2020), thereby enriching the theoretical and practical implications of our work within the broader context of energy systems and electric vehicle infrastructure.

Please note that I utilised common large language models such as ChatGPT and DeepL to enhance the language and readability of this work. However, I take full responsibility for the content of this thesis, and I reviewed and edited the material as necessary.

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# V Appendix A:

## V.1 Research papers relevant to this thesis

**Research Paper #1: Understanding information needs for seamless intermodal transportation: Evidence from Germany**

Meyer-Hollatz, T., Kaiser, M., Keller, R., Schober, M. (2024) „Understanding information needs for seamless intermodal transportation: Evidence from Germany”, *Transportation Research Part D*, 130, p. 104161, https://doi.org/10.1016/j.trd.2024.104161

(VHB-JQ3 Category: B)

**Research Paper #2: 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”, *Submitted (Applied Energy)*

(VHB-JQ3 Category: B)

**Research Paper #3: Smart Electric Vehicle Charging considering Discounts for Customer Flexibility**

Baumgarte, F., Eiser, N., Kaiser, M., Langer, K., Keller, R. (2022) „Smart Electric Vehicle Charging considering Discounts for Customer Flexibility”, *AMCIS 2022 Proceedings*, 9, https://aisel.aisnet.org/amcis2022/sig_green/sig_green/9/

(VHB-JQ3 Category: D)

**Research Paper #4: Future vehicle energy supply - sustainable design and operation of hybrid hydrogen and electric microgrids**

Förster, R., Kaiser, M., Wenninger, S. (2023) „Future vehicle energy supply - sustainable design and operation of hybrid hydrogen and electric microgrids”, Applied Energy, 334, p. 120653, https://doi.org/10.1016/j.apenergy.2023.120653

(VHB-JQ3 Category: B)

**Research Paper #5: Policy support measures for widespread expansion of fast charging infrastructure for electric vehicles**

Baumgarte, F., Kaiser, M., Keller, R. (2021) „Policy support measures for widespread expansion of fast charging infrastructure for electric vehicles”, *Energy Policy*, 156, p. 112372, https://doi.org/10.1016/j.enpol.2021.112372

(VHB-JQ3 Category: B)

Over the course of the dissertation, I also co-authored the following book chapters and research papers. These papers are not part of this doctoral thesis.

- Dautzenberg, A., Kaiser, M., Weibelzahl, M., Weissflog, J. (2024) „Industrial multi-energy communities as grid-connected microgrids: Understanding the role of asymmetric grid-charge regulation”, Journal of Cleaner Production, 466, p. 142738, https://doi.org/10.1016/j.jclepro.2024.142738
- Kaiser, M., Stohr, A., Strüker, J., Weibelzahl, M., Weissflog, J., Ali-Will, F., Hesse, E., Trbovich, A., Tzavikas, S., Pulvermüller, B., Richard, P. (2023) „Das dezentralisierte Energiesystem im Jahr 2030“, Deutsche Energie-Agentur (Hrsg.)
- Kaiser, M., Stirnweiß, D., Wederhake, L. (2023) „Hierarchische Eignungsprüfung von externen (Open) Data Sets für unternehmensinterne Analytics- und Machine-Learning-Projekte, *HMD*, 60, p. 144-161, https://doi.org/10.1365/s40702-022-00842-3
- Kaiser, M., Buhl, H. U., Moors, M. (2024) “What to expect from local climate pact initiatives and which policy support measures effectively support reducing industrial emissions”, *Submission (Energy Policy)*

## V.2 Individual Contribution to the included research papers

This doctoral thesis is cumulative and comprises five research papers. All of them were developed in collaboration in teams and with multiple co-authors. In this section, I will provide specific information on my individual contribution to each of the five research papers.

**Research Paper #1**, titled "Understanding information needs for seamless intermodal transportation: Evidence from Germany", was co-authored by four team members. Two authors, including myself, were jointly responsible for writing the text of the originally submitted version and the revised versions of the article. Further, we both were responsible for the structured literature review, conducting the survey and the data collection. Thereby I was primarily responsible for initiating the research idea and the successful framing of the research, which is particularly evident in the motivation, the literature review and the discussion of the paper. The other two co-authors supported us in the conceptualization of the research project and provided feedback. As a team, we agreed that the first named author should assume the role of the lead author, as this author was mainly responsible for the data analysis of the survey results in the originally submitted version and further analysis within the revision processes.

**Research Paper #2**, titled "Revenue Management in a large-scale fast-charging hub for electric vehicles: A multiproduct, dynamic pricing model", was co-authored by five team members. The first two authors were jointly responsible for writing the text of the originally submitted version of the paper and contributed equally to this article. The other three authors contributed as a subordinate author, mainly in the form of feedback during the submission and review process and in their roles as scientific supervisors and mentors. In particular, I was responsible for the framing of the paper and gave the main assistance in writing and result interpretation.

**Research Paper #3**, titled "Smart Electric Vehicle Charging considering Discounts for Customer Flexibility", was co-authored by five team members. All authors contributed equally to this paper, while I was responsible for organizing the research project, in particular. I closely assisted in writing and together with two other authors I was in charge of the case study from design to the result interpretation. Finally, I presented the paper at a scientific conference.

**Research Paper #4**, titled "Future vehicle energy supply - sustainable design and operation of hybrid hydrogen and electric microgrids", was co-authored by three team members. While all authors contributed equally to this paper, together with one co-author I was responsible for the framing of the paper, in particular. Moreover, I provided feedback for the literature review, the model development and the evaluation of the simulation results. With reference to the text of the paper, I closely assisted in writing it.

**Research Paper #5**, titled “Policy support measures for widespread expansion of fast charging infrastructure for electric vehicles”, was co-authored by three team members. In particular, I contributed to the research paper by conducting the literature review, developing the simulation model that analysed the charging behaviour of BEV drivers, and by analysing and interpreting the results of our work. Moreover, I organized the research project and worked closely together with one co-author in terms of framing and elaborating the contribution of our work. Furthermore, I also wrote the major share of the text in the article. As a team we agreed that one co-author and I should assume the roles of lead authors of the research article. The other co-author contributed as a subordinate author, mainly in the form of feedback during the submission and review process and in his role as a scientific supervisor and mentor.

## V.3 Research Paper 1: Understanding information needs for seamless intermodal transportation: Evidence from Germany

**Authors:**

Tim Meyer-Hollatz, Matthias Kaiser, Robert Keller, Marcus Schober

**Published in:**

Transportation Research Part D (2024)

**Abstract:**

Cities worldwide are seeking to enhance their sustainable mobility by reducing individual motorized transportation. While intermodal mobility – combining multiple transportation modes in one journey – is a key solution, individuals encounter challenges initiating intermodal journeys owing to the proliferation of mobility services. Providing accurate information at the right time is crucial amidst this complexity. While research has examined information needs for each mobility mode independently, the relationships between modes, phases, and information needs have barely been empirically investigated. Through a sequential mixed method approach involving a literature review and a survey of >500 participants, this study identifies and validates the concept of phase- and mode chain-sensitive information needs. The findings provide initial insights, emphasizing phase relationships, mode chain relationships, and the interplays between phases and mode chains – a holistic understanding. This research can guide the design of more effective traveller information systems, aiding the shift toward sustainable urban mobility.

**Keywords:**

Intermodal mobility, Sustainable mobility, Traveler support systems

## V.4 Research Paper 2: Revenue Management in a large-scale fast-charging hub for electric vehicles: A multiproduct, dynamic pricing model

**Authors:**

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

**Submitted to**:

Applied Energy

**Keywords:**

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

**Extended Abstract:**

The substantial contribution of the transport sector to greenhouse gas emissions, accounting for 24% in the EU, necessitates significant measures towards decarbonization to achieve climate objectives (European Comission, 2023). Battery electric vehicles (BEVs) present a promising solution for emission reduction, especially when powered by renewable energy (Hawkins *et al.*, 2013; Onat *et al.*, 2019). Beyond environmental advantages, BEVs are becoming economically competitive due to lower operational costs and decreasing battery prices, potentially aligning their purchase costs with internal combustion engine vehicles (Liu *et al.*, 2021). However, the widespread adoption of BEVs is contingent upon the availability of adequate charging infrastructure, particularly large-scale public fast-charging parks (LFCPs) along highways, which are crucial for supporting extended driving ranges and reducing queuing times.

To meet the EU's target of at least 3 million public charging points by 2030, substantial investments in fast-charging infrastructure are imperative, given the current infrastructure of approximately 700,000 public charging points in 2024 (European Comission, 2024). The profitability of these charging stations relies heavily on location-specific utilisation rates, which are influenced by BEV adoption and local traffic volumes (Baumgarte, Kaiser and Keller, 2021). Despite a BEV market share of 12% in the EU, uneven distribution results in unprofitable operation in many regions. Consequently, many stations depend on policy support or high charging tariffs to cover costs (Madina, Zamora and Zabala, 2016; Baumgarte, Kaiser and Keller, 2021).

Addressing these challenges, operators can either reduce operational costs or explore strategies to enhance revenue. While cost reduction strategies for fast-charging infrastructure,

such as smart charging and integration of renewable energy sources, are well-researched (Huber *et al.*, 2019; Muratori *et al.*, 2019), revenue maximisation has received less attention. Existing literature primarily focuses on stations with limited charging points and grid stability, leaving a gap in research for LFCPs (Kong, Bayram and Devetsikiotis, 2015; Kuran *et al.*, 2015). The potential for strategic revenue maximisation through dynamic pricing, particularly for LFCPs, remains underexplored.

This paper investigates the application of Revenue Management (RM) theory to LFCPs, proposing a dynamic pricing model to optimise revenue. The model leverages the unique characteristics of fast charging parks, which include the ability to concurrently serve multiple customers with high charging power, but also present challenges such as high electricity demand peaks. By employing dynamic pricing, charging park operators can manage demand and optimise resource allocation, akin to strategies used in the hotel and airline industries. This approach could significantly enhance profitability, enabling further investment in LFCPs and supporting the broader adoption of BEVs.

Our study develops a quantitative dynamic pricing model and evaluates its impact through a simulation case study, comparing revenue improvements across different LFCP configurations under dynamic versus fixed pricing settings. The analysis reveals that dynamic pricing can increase revenues when either total power capacity or the number of charging points is scarce. These findings underscore the importance of strategic LFCP design, as dynamic pricing alone cannot rectify poor design choices regarding infrastructure capacity.

However, the model's applicability may be limited by its reliance on linear demand functions, primarily based on highway traffic data. Future research could refine demand estimation by incorporating BEV driving behaviour, such as state of charge levels and charging curves, or customer flexibility in dwell times. Additionally, integrating dynamic pricing with smart charging algorithms could further optimise resource utilisation and revenue. Expanding the model to include long-term profit maximisation and variable power capacity limits represents another avenue for exploration.

In summary, the proposed RM-based dynamic pricing model offers a promising strategy for enhancing LFCP profitability, addressing the critical need for efficient charging infrastructure development in the context of accelerating BEV adoption. This research not only contributes to the academic discourse on revenue management in the fast-charging sector but also provides practical insights for policymakers and industry stakeholders aiming to foster a sustainable and economically viable charging network.

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## V.5 Research Paper 3: Smart Electric Vehicle Charging considering Discounts for Customer Flexibility

**Authors:**

Felix Baumgarte, Niklas Eiser, Matthias Kaiser, Kilian Langer, Robert Keller

**Published in:**

Twenty-eighth Americas Conference on Information Systems, Minneapolis (2022)

**Abstract:**

The expansion of large-scale charging infrastructure is crucial to cope with growing shares of electric vehicles. However, operators often struggle with profitable operation due to volatile occupancy and high costs for peaks in charging demand. Using information and communication technology may enable smart charging and thereby profitable operation by addressing the challenge of costly peak demand but requires customer flexibility to shift and manage charging processes. Therefore, operators must offer discounts on charging prices for customers to provide flexibility, which in turn mark an additional cost. Here we provide a model to analyse whether the costs to allocate flexibility exceed cost savings through smart charging. The model is evaluated in a case study of a large-scale charging park with real-world data on highway traffic and charging station usage. The results indicate that smart charging can provide net benefits even if operators are required to offer discounts for charging flexibility.

**Keywords:**

Electric Vehicle Smart Charging, Discount-based Flexibility, Green IS, Individual Customer Preferences

## V.6 Research Paper 4: Future vehicle energy supply - sustainable design and operation of hybrid hydrogen and electric microgrids

**Authors:**

Robert Förster, Matthias Kaiser, Simon Wenninger

**Published in:**

Applied Energy (2023)

**Abstract:**

To decarbonise road transport, EU policymakers promote battery electric vehicle and fuel cell electric vehicle adaption and advocate the expansion of charging and hydrogen refuelling infrastructure in the Fit-for-55 package. However, infrastructure operators face cost-intensive operations and insufficient low greenhouse gas (GHG) hydrogen availability. Grid-connected hybrid hydrogen refuelling and electric vehicle charging microgrids with on-site hydrogen production, battery and hydrogen energy storages and renewable energy can help to solve these challenges. We investigate the influence of various microgrid design and operation strategies regarding their contribution to profitability and decarbonisation in an optimisation study. Our findings in a realworld case study within Germany indicate that the cost-effectiveness of designing and operating such microgrids does not contribute to the decarbonisation of road transportation under common operation strategies and current demand charge regulations. We advocate revising German demand charge regulations to support sustainable design and operation of future charging and hydrogen refuelling microgrids.

**Keywords:**

Microgrid, Hydrogen infrastructure, Electric vehicle charging, Hybrid energy storage systems, Decarbonization, Road transportation

## V.7 Research Paper 5: Policy support measures for widespread expansion of fast charging infrastructure for electric vehicles

**Authors:**

Felix Baumgarte, Matthias Kaiser, Robert Keller

**Published in:**

Energy Policy (2021)

**Abstract:**

Public fast charging infrastructure (FCI) is essential for the adoption of electric vehicles (EVs). To reach higher EV penetration, investments into the development of a comprehensive and widespread fast charging network are necessary. However, current investments in FCI are only profitable in specific locations resulting in a severe lack of deployments in most areas. The wish for rapid development of both, EVs and related charging opportunities, requires political support measures for FCI. This paper investigates various support measures regarding their contribution to a comprehensive expansion of FCI through profitability enhancement. We illustrate the impact of different support measures on the profitability of three different charging power categories at three different located charging sides along the German freeway. Besides the traffic volume, the profitability of FCI strongly depends on the location's surrounding charging facilities and population characteristics and decreases with increasing charging power. Currently available support measures such as investment subsidies or the exemption from the electricity tax do not contribute significantly to a widespread expansion of FCI. Changes in the demand charges have a higher potential to support nationwide investments in FCI.

**Keywords:**

Electric vehicles, Fast charging infrastructure, Profitability analysis, Policy support