# Technologies for Digitalization and Decarbonization of Individual Mobility

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## Copyright Statement

The following sections are partly comprised of content taken from the research papers embedded in this thesis. To improve the readability of the text, I omit the standard labeling of these citations.

## Abstract

The fight against climate change requires rapid global action to decarbonize both industry and society. Among the largest emitters of climate-damaging greenhouse gases, changes in individual road mobility are necessary to substantially reduce emissions. Several promising measures can be promptly implemented to reduce emissions from individual mobility. Three of the most important are the electrification of individual road mobility with electric vehicles, the integration of electric vehicles as an essential part of the electricity system, and new concepts of mobility to reduce car ownership. However, the decarbonization potential in individual measures can be leveraged only through the efficient use of digital technologies and comprehensively designed information systems. Consequently, a great need exists for research at the intersection of information systems, including digital technologies and sustainable mobility. The information systems community must help address the global challenge of decarbonizing individual mobility. This work includes seven research papers addressing the decarbonization and digitalization of transportation and energy to enable sustainable individual mobility. Therefore, this thesis first addresses the management of electric vehicle charging to accelerate the expansion of charging options. Second, it addresses the integration of electric vehicles into the electricity system, including in combination with renewable energy sources and the provision of flexibility enabled by digital technologies. Third, it describes the need for innovation in shared mobility solutions, such as carsharing, to reduce car ownership. This thesis positions itself at the intersection of green information systems and information systems for innovative mobility business models. It bridges research into sustainable energy systems and the development of new business models and services in the mobility sector.

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# 1 Introduction

## 1.1 Motivation

Climate change is advancing, posing a threat to the environment and to humanity (Mora et al., 2018). The latest Assessment Report from the Intergovernmental Panel on Climate Change (IPCC) underlines the urgent need for action: Global anthropogenic greenhouse gas (GHG) emissions have been higher in the past decade than at any time in human history (Intergovernmental Panel on Climate Change, 2014). GHG emissions have continued to increase, reaching approximately 60 Gt $CO_2$ equivalent in 2019 (Intergovernmental Panel on Climate Change, 2014). The increase in emissions has also been sustained across all sectors. In general, rates of $CO_2$ emissions have accelerated rate since 1850. For example, over 60% of global $CO_2$ emissions from 1850 to the present are attributable to the period between 1970 and today (Intergovernmental Panel on Climate Change, 2014). The further intensification of global warming will not only destroy nature, but also make weather events more extreme (P. Jain et al., 2022). In the long run, the lives and livelihoods of humankind are in jeopardy (Cook et al., 2016; WMO, 2021). To avert the greatest damage, it is important to limit global warming to 1.5 °C. However, over the past decade $CO_2$ emissions have already exhausted the remaining carbon budget to limit warming to 1.5 °C (Intergovernmental Panel on Climate Change, 2014). In the fight against climate change, rapid and global action is required to decarbonize industry and society, in line with the agreed-upon targets of the 2015 Paris Climate Agreement (Rogelj et al., 2016). In Paris, countries signed up to initiate measures to limit warming to 2 °C, preferably to 1.5 °C.

To rapidly advance decarbonization, entire energy systems must be transformed into low-carbon ones. Essentially, the decarbonization of energy systems is based on three measures: using less energy, increasing energy efficiency, and displacing fossil fuels with renewable energy (Dincer & Rosen, 1999). While individuals can do much to save energy (Stern et al., 2016) and while companies work continuously on more efficient products, expanding renewable energy requires massive political effort. The shift from fossil fuels to renewable energy sources (RES) is often referred to as the “energy transition.” In particular, the expansion of wind energy and solar photovoltaic (PV) RES offers great potential to decarbonise power generation and the electricity sector (M. Li et al., 2022). With the rapid expansion of these RES, $CO_2$-intensive forms of generation such as coal-fired power plants can be shut down, and the electricity sector, effectively decarbonized. The expansion of RES, however, also faces certain challenges (Brouwer et al., 2016).

Due to weather-induced fluctuations in renewable generation, RES have a volatile generation output (Fridgen, Körner, et al., 2021; Verzijlbergh et al., 2017). This volatility can lead to gaps in supply if, for example, the sun does not shine or the wind does not blow for an extended duration (Tong et al., 2021). On the other hand, volatility also particularly challenges the stability of the power grid. The power grid must remain always balanced (i.e. as much power must be fed into the grid as is consumed). As the share of fluctuating generation from RES increases, the challenge for grid operators also grows (Kondziella & Bruckner, 2016). Simultaneously, many countries (including Germany) plan to phase out predictable generation such as coal-fired and nuclear power plants. To cope with the increased volatility of the energy supply, flexibility in the electricity system is growing in importance (Halbrügge et al., 2021). This flexibility can be achieved in renewable energy generation (e.g. biomass), electricity demand, or complementary technologies such as energy storage (Degefa et al., 2021). With sufficient flexibility in the electricity system and with complementary technologies, the expansion of RES can greatly help to decarbonize energy systems (Heydarian-Forushani et al., 2017).

A decarbonized electricity supply helps not only to reduce emissions in the electricity sector but also to decarbonize other sectors, effecting transportation, building design, industrial activity, and how entire cities function (Fridgen et al., 2020). Through sector coupling and the use of electricity from RES, fossil fuels can be sustainably replaced, which is crucial to decarbonizing these sectors (Bernath et al., 2021). As such, these sectors increasingly interact with each other, and ultimately they must be considered together in the context of the energy transition. In the industrial sector, RES can be used to supply energy-intensive processes with renewable electricity (Wesseling et al., 2017). Green hydrogen produced by renewable electricity is also promising (Glenk & Reichelstein, 2022), as it can replace grey hydrogen produced from fossil fuels or substitute fossil fuels themselves (e.g. natural gas). In the building sector, the electricity from RES can help directly to reduce emissions and to decarbonize. Heat pumps, for example, allow for the electrification of building and hot water heating directly from RES (Bernath et al., 2019). In some countries, such as Norway, much of the heat supply is already electrified and based on RES (Seljom et al., 2011). Beyond decarbonizing, a shift from fossil fuels to RES supports countries' efforts to reduce their dependencies on global resources (F. Khan, 2022). The use of electricity from RES is particularly interesting in the transport sector. For example, electricity from RES can drive decarbonization for applications such as road transport. The electricity from RES can either be used directly — for example to power electric vehicles (EVs) — or used to produce carbon-neutral alternative fuels (Emonts et al., 2019).

The transport sector is among the greatest emitters of GHGs (Hasan et al., 2019). It is responsible for about 15% of global GHG emissions and around 25% of GHG emissions in Europe (McBain & Teter, 2022). To limit global warming to the negotiated levels, the transport sector must drastically reduce emissions. Addressing transport sector emissions is critical to reducing GHG emissions in many countries, as the sector is the largest energy consumer in 40% of the world's countries (Intergovernmental Panel on Climate Change, 2014). COVID−19-related interdiction measures have curbed transportation emissions. Global $CO_2$ emissions from the transport sector are estimated to have decreased by 11.6% in 2020, as compared to 2019 (Crippa et al., 2021; Minx et al., 2021). The transport sector includes such industries as aviation, shipping, rail, and road transport. Among these industries, road transport produces the most emissions by far, accounting for nearly 70% (Minx et al., 2021); in this category, individual transport makes up a large share. To reduce these emissions, diverse measures must be implemented. In addition to the further technical development of means of transport, reducing emissions also requires a mobility turnaround in which citizens actively change their own means of transport use (Fenton, 2017; Klecha & Gianni, 2018). The various emissions-reduction strategies in transportation divide into three categories based on the avoid, shift, and improve approach (Bongardt et al., 2014). Avoidance strategies seek to reduce emissions by avoiding transportation. For example, business travel can be minimised through digital collaboration and the use of home offices (Russo et al., 2021). Shift strategies aim to shift traffic to lower-emission transportation options, including public transportation and carsharing (CS) (R. Zhang & Zhang, 2021). Improvement strategies do not attempt to change the basic choice of transportation mode, but rather the efficiency of the trip. These strategies consider, for example, the use of EVs as an alternative to internal combustion engines.

Several measures can be implemented promptly and offer the potential to successfully transform transportation and reduce emissions (Taptich et al., 2016). Three of the most important measures are the electrification of individual road transport through the use of electric mobility, the integration of EVs as a key component of the electricity system, and the reduction of vehicle ownership.

EVs are widely seen as a critical means by which to decarbonize individual transport, and the share is increasing in all countries (Needell et al., 2016; Van Mierlo, 2018). EVs have much lower lifetime emissions than do internal combustion engine vehicles (ICEVs) (Shafique et al., 2022). The spread of EVs requires the rapid expansion of a closely-knit charging infrastructure (Funke, Plötz, et al., 2019). Historically, the expansion of charging infrastructure, especially in the public sector, has often stalled due to uncertainty about the profitability of investments in this technology. Smart charging, careful site selection, and the implementation of appropriate political support measures can be important building blocks for the urgently needed expansion, among numerous other measures.

Through the electrification of the transportation sector, EVs automatically become part of the electricity system. This integration also leads to new challenges for the electricity system. EVs increase demand for electricity, illustrating the importance of the rapid expansion of RES (Moon et al., 2018). EVs are also an increasingly large consumer of electricity, with a fluctuating demand profile that must be considered in stabilizing the power grid. On the other hand, EVs can offer new opportunities. Through adapted charging times or bidirectional charging, they can provide the flexibility urgently needed for the fluctuating energy feed-in of renewables (Gunkel et al., 2020). The combination of EVs and RES also allows new business models or private homeowners to become largely self-sufficient.

Not only does reducing the number of vehicles save resources and raw materials, but it also increases the overall energy efficiency of the remaining vehicles (Amatuni et al., 2020). Vehicle ownership can be variously reduced. In addition to the expansion and greater promotion of public transport, sharing concepts (e.g. CS) promise to reduce the number of privately owned vehicles for individual mobility (Liao et al., 2020). These services must lower entry barriers for as many users as possible and make services attractive enough to encourage them to switch from private vehicles to sharing options (Research Paper 7; Baumgarte et al. 2022). To adapt these sharing services accordingly, an understanding of potential users and their needs is necessary.

The implementation of emissions-mitigation approaches requires the end-to-end digitalization of the transport sector, as well as the entire energy system (Strüker et al., 2021). In light of the decarbonization, the increasing number of assets (e.g. EVs) in the energy system makes it important to cope with their integration (Wolf & Korzynietz, 2019). The rising number also creates more and more data, calling for suitable data management concepts that include data spaces but also analysis tools (e.g. new machine learning approaches) for successful integration. The decarbonization potential of individual measures will be leveraged only through the effective use of digital technologies and comprehensively designed information systems (ISs) (Lehnhoff et al., 2021; Maroufkhani et al., 2022). These technologies include not only approaches such as artificial intelligence (AI) to build precise prediction models, but also technologies such as blockchain and self-sovereign identities (SSI) that provide necessary data security. Companies must also continue to expand their efforts in terms of end-to-end digitalization for successful decarbonization. One example is the creation of high-resolution digital $CO_2$ proofs-of-origin and proofs-of-use for emissions within the production of EVs and their components, across supply chains (Strüker et al., 2022). Only companies fully transparent about emissions with their various stakeholders can steer their corporate processes towards meaningful decarbonization. Digital technologies and ISs can also help to process and analyze large volumes of data (e.g. data usage for mobility services) and support operators in improving their services. Therefore, such technologies are key to successfully implementing business models for individual mobility.

## 1.2 Research Aim

Effectively slowing climate change and reducing carbon emissions in transportation systems requires massive effort, and research into IS must play its part (Lehnhoff et al., 2021). The area of Green IS is promising in address sustainability challenges (Gholami et al., 2016). In particular, the electrification of transport and the use of EVs can reduce emissions in individual mobility. The ramp-up of EVs requires the development of charging infrastructure, especially fast-charging infrastructure along highways. Operators of such charging infrastructure often struggle to operate profitably. As a result, investment in much-needed expansion is stagnating. Schroeder & Traber (2012) examine the economics of fast-charging infrastructure. However, due to rapid market growth and technological innovation, the framework conditions for economic operation are continuously changing. The first goal of this thesis is therefore to analyze the economics of EV charging in different scenarios and to identify opportunities for improvement. It builds on and extends previous research on the economics of charging (Madina et al., 2016).

There are several ways to improve the profitability of charging infrastructure. This thesis investigates these means for their effectiveness in increasing profitability for operators. One means is to improve investment conditions for operators through targeted policy support (Research Paper 1). Because the expansion of public charging infrastructure is of great interest to society, this work aims to provide insights for policymakers on how to develop effective support measures to expand charging infrastructure. Another measure is smart charging, which helps to make charging both sustainable and economically attractive by controlling charging processes (Flath et al., 2012). Smart charging builds on strategies to optimize the charging schedule according to different objectives. These objectives may be to reduce costs (e.g. through grid fees) or to optimize pricing so that operators increase revenues (Delmonte et al. 2020; Research Paper 2; Research Paper 3). Developing smart charging strategies requires decision support systems based on digital technologies such as machine learning and AI. Therefore, this work investigates the effectiveness of specific technologies for smart charging.

In addition to promoting the expansion of charging infrastructure, realising EVs' full decarbonization potential requires that they be comprehensively integrated into the electricity system. Interestingly, EVs can be combined with RES to balance the volatility of this means of power generation and consumption, creating new business opportunities (Research Paper 4). Therefore, this work explores the combination of solar PV and EV charging in this innovative business and the energy sharing-model tenant electricity, particularly. It also analyzes the viability of different business models for energy storage (Research Paper 5). Energy storage can be a complementary component in the design of public charging stations (Haupt et al., 2020), but also in smaller residential applications. In any case, storages help smooth supply and demand curves and are therefore essential to integrate EVs and RESs into the electricity system.

Electricity systems that are increasingly based on RES require flexibility, which in theory can be provided by EVs (Gunkel et al., 2020). In practice, however, this is not yet the case, as there remain barriers (e.g., insufficient digitalization) to offering flexibility with EVs (Gonzalez Venegas et al., 2021). This thesis proposes an approach to improving trust in distributed flexibility markets and enabling EVs to provide flexibility. The lack of digitalization within EV integration also necessarily reduces charging options. Charging infrastructure operators enforce roaming fees upon competitors' customers, immensely increasing the cost of public charging (Research Paper 6). Distributed-ledger technologies (DLT) such as blockchain are interesting, as outlined on the following pages.

However, the decarbonization of the transportation sector requires not only alternative forms of driving technology, but also reduced vehicle ownership. Innovative mobility services such as CS can make a major contribution here (Chen and Kockelman 2016; Research Paper 7). The acceptance of innovative mobility services depends on their attractiveness for potential users. To develop such services that meet users' mobility needs, operators must understand their users and gain insights into their usage behavior. This thesis illuminates mobility services by analyzing the usage behavior of CS users with machine learning techniques.

Overall, there is a great need for research at the intersection of ISs, encompassing both digital technologies and environmental challenges. The ISs community must help address the global challenge of transformation energy systems to be sustainable. Indeed, Gholami et al. (2016) call for IS research to develop solutions to environmental problems. There are several research directions within IS research that have set out to contribute to sustainable energy systems. Watson et al. (2010) have initiated a broader discussion, proposing the idea of energy informatics within IS research. Recently the research stream around Green IS has become a significant driver of sustainability aspects in IS research (Vom Brocke et al., 2013). In the context of sustainable mobility systems, IS research can explore new mobility services enabled by digital technologies or improve existing processes by developing decision support systems (Brendel & Mandrella, 2016). Thus, IS research can leverage their capabilities and create long-term progress towards sustainable mobility (Schröder et al., 2014). To fully exploit the potential of IS for decarbonized mobility, it must contribute to the optimization and ultimately the further adoption of sustainable mobility services (Brendel & Mandrella, 2016; Hildebrandt et al., 2015). This thesis positions itself at the intersection of Green IS and IS for innovative mobility business models. It bridges the gap between research in the field of sustainable energy systems and the development of new business models and services in the mobility sector supported by digital technologies.

It further aims to provide insights on rapid decarbonization measures for individual mobility and the effectiveness of digital technologies to advance them. This thesis contributes to Green IS research and towards accelerating sustainability, as called for by Kossahl et al. (2012) in their taxonomy. Specifically, it addresses the sub-domains of the automotive and energy industries, combining RES, EVs, and mobility solutions. The findings of the thesis are based on evaluation of real-world data obtained and analyzed using both data-driven quantitative and qualitative approaches. The evaluation with real-world data contributes meaningfully to the push for Green IS research to transcend theory, as emphasized by Vom Brocke et al. (2013). It presents avenues for Green IS research, shedding light on its importance and contribution for sustainable mobility. In this way, the thesis also supports emissions reduction and combating climate change by promoting sustainable mobility solutions. It provides researchers and practitioners insight into the effectiveness of these technologies for improving existing and creating new business models for individual mobility. It also addresses policymakers, urging that they make much-needed regulatory changes to remove barriers to the adoption of sustainable forms of transport and, importantly, other digital technologies that can more effectively decarbonize individual mobility.

## 1.3 Structure of the Thesis and Overview of Embedded Research Papers

This cumulative thesis consists of seven research papers addressing the ongoing digitalization and decarbonization of individual mobility. Each of the seven research papers addresses a specific sub-area of sustainable mobility, and all contribute to the research aim of transforming mobility systems towards sustainability. Figure 1 depicts the structure of this thesis and the embedding of the research papers.

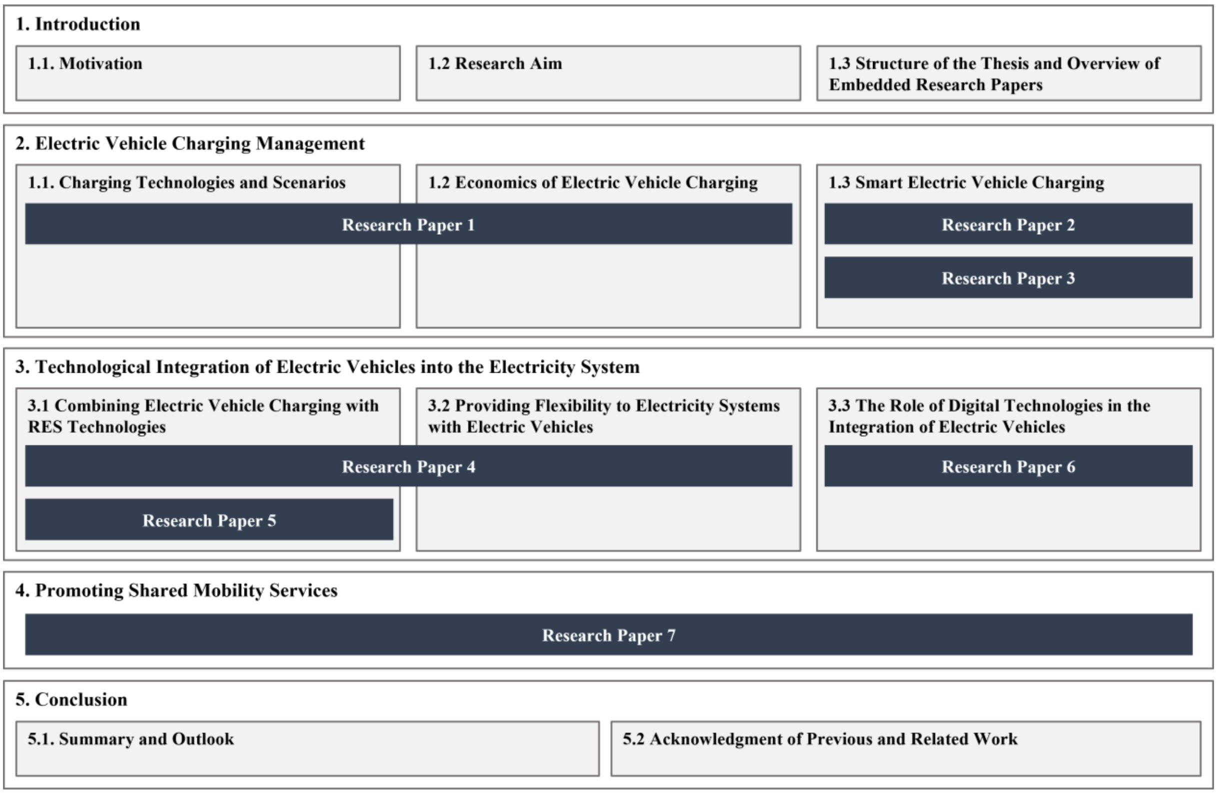


**Figure 1:** Structure of the doctoral thesis

The Introduction (Section 1) motivates the urgency of decarbonizing energy systems, the transportation sector in particular. It also outlines the need for research within this area to improve existing mobility options and to create new, sustainable mobility services.

Section 2 addresses a central issue of electrified transportation, namely the management of charging infrastructure for EVs. The challenges of charging management vary depending on the scenario. Therefore, this section first addresses the different charging scenarios and the basic types of charging infrastructure technologies (Section 2.1). Section 2.2 then elaborates on the economics of EV charging, outlines the major challenges of charging management, and explains why additional measures are necessary to improve the conditions for investments in charging infrastructure. In this context, various policy support measures are discussed regarding their effectiveness. In Section 2.3 deals with the optimization of EV charging events through smart charging.

Section 3 concerns the technological integration of EVs into the electricity system. EVs enable new opportunities for electricity systems. On the one hand, in combination with energy technologies, they can help to integrate larger shares of intermittent RES and considerably reduce emissions by coupling the electricity and transportation sector (Section 3.1). On the other hand, EVs can provide flexibility and are critical to stabilizing the electricity grid (Section 3.2). However, before they can provide real value, they must overcome different barriers that can be tackled with the use of digital technologies such as blockchain or SSI (Section 3.3).

Section 4 elaborates on the importance of new and innovative mobility solutions to reduce car ownership. In this context, CS is widely seen as a promising solution to reduce emissions within transportation systems. This section describes different CS models and provides starting points to improve the attractiveness of shared mobility services and increase their adoption.

Finally, Section 5 concludes by summarizes the contributions of the work, discussing its limitations, and outlining avenues for future research. It also acknowledges previous and related work. The references appear in Section 6. The appendix of the thesis in Section 7 contains detailed information on the embedded research papers, including the corresponding (extended) abstracts. The supplementary material contains the full texts of all seven research papers (not for publication).

# 2 Electric Vehicle Charging Management

Electrifying individual mobility on the road is a promising means of reducing $CO_2$ emissions in the transportation sector (Needell et al., 2016; Yuan et al., 2021). In this context, the electrification of mobility means switching from ICEVs to powertrains based on electric energy (O'Neill-Carrillo et al., 2021). Some in the public domain have argued that EVs are also harmful to the environment, since some of the electricity used is generated from fossil fuels. Nevertheless, studies show that EVs clearly emit the fewest emissions of all drive types (X. He et al., 2019; Shafique et al., 2022). The several forms of EVs include battery EVs (BEVs) and plug-in hybrid EVs (PHEVs), with the latter being powered partly by fossil fuels and only partly by electricity. The term "EVs" therefore often refers to BEVs, as they are powered entirely by electric energy (Ghosh, 2020). As this thesis focuses on BEVs, it assumes BEVs when referring to "EVs."

The wider adoption of EVs would require improvements to battery technology or the construction of a more comprehensive charging infrastructure than is currently available (Gnann et al., 2018). Expansion requires new charging infrastructure in a variety of situations, including private options for charging (e.g. at home or work) (Chakraborty et al., 2019). In particular, public charging stations, such as along highways, are necessary to reduce range anxiety and to enable longer trips. The impact of range anxiety can be significant, discouraging many potential customers from switching to EVs (Neubauer & Wood, 2014). However, the murky economics of operating public charging infrastructure also prevents its rapid expansion (Madina et al., 2016). This expansion requires suitable management of charging infrastructure by operators.

In this regard, Section 2.1 describes the different types of charging infrastructure and charging scenarios, as well as the current status of public charging infrastructure and its development. Section 2.2 then explains the economics of EV charging, especially from the operators' perspective, and it discusses support measures policy makers can provide, while Section 2.3 presents the concept of smart charging as another measure for operators.

## 2.1 Charging Technologies and Scenarios

For as many drivers as possible to make the switch to EVs, charging infrastructure must be widely available (Kumar et al., 2021; Metais et al., 2022). In mostly rural areas, the installation of a single public charging station has already initiated the adoption of EVs, as by a study in Norway (Schulz & Rode, 2022). EVs tend to have a shorter range than ICEVs, even though range has increased (Hao et al., 2020). In addition, the charging process takes more time than refuelling conventional ICEVs, so charging stations are also occupied for longer periods of time. Therefore, switching to an EV also requires some behavioral change and some planning ahead for where to charge. In overview, enough charging points are needed to meet the growing demand for charging options (Fotouhi et al., 2019).

Various charging scenarios apply when drivers need to charge their EVs or expect the opportunity to do so (Powell et al., 2022). Typically, private and public charging stations provide different opportunities for charging (Csiszár et al., 2019). Private charging stations provide the opportunity for charging at home or at work, while public charging stations provide opportunities during stops on longer trips or during other activities, such as shopping (Lee et al., 2020). Overall, the home is the most common charging location, with up to 80% of EV charging occurring there (Franke & Krems, 2013). Of course, the share of home charging is significantly lower when consumers lack access to home charging (Lee et al., 2020). To date, many early adopters also have their own homes with the ability to charge their EV there (Björnsson & Karlsson, 2017). If the share of EVs is to increase, people who live in an apartment, for example, will also need access to charging infrastructure.

In addition to home charging, workplace charging is increasing significantly, as more and more companies allow their employees to charge for free or at low prices (S. Li et al., 2020). Because it provides employees access to low-cost charging, this form of charging may become dominant when combined with on-site renewable electricity generation. However, certain barriers to workplace charging remain, such as proper contract design (Fetene et al., 2016). A study in the United States found that even a few years ago, 30% of EV drivers charged only at work on most days (Idaho National Laboratory, 2015). Workplace charging can also help drive EV adoption through peer-to-peer communication (LaMonaca & Ryan, 2022). In addition, however, public charging stations are especially important for ramping up electric mobility, as they allow for longer trips and provide charging opportunities outside of daily commutes (Q. Zhang et al., 2018). Public charging stations can be located in many places: along highways, in cities, or even in rural areas. There are often also semi-public charging stations, for example at excursion destinations (e.g. museums, swimming pools, and hotels) or in shopping centre parking lots (Morrissey et al., 2016). These stations are technologically accessible to everyone, but the owners of the charging infrastructure often restrict its use to their customers and guests.

**Table 1:** Characteristics of charging types. Source: (Lutsey, 2017)

| Charging level | Type | Typical charging power | Common charging scenarios |
|---|---|---|---|
| Level 1 | AC | 1.2–1.8 kW | Home charging |
| Level 2 | AC | 3.6–22 kW | Home charging, workplace charging, public charging (within cities or destinations) |
| Fast charging | DC | ≥50 kW | Public charging (along highways) |

Depending on the charging scenario, different charging infrastructure technologies are suitable. Charging technology can be based on either alternating current (AC) or direct current (DC) components. While AC is used mainly for slower charging (at home, at work) where EVs have longer standing times, DC is often used for fast charging, for example along highways (LaMonaca & Ryan, 2022). AC chargers often have limited charging power (e.g. 11 or 22 kW). These are often called wall boxes. DC chargers can provide more than 50 kW of charging power (Lee et al., 2020). Basically, there is no universally accepted definition of the term “fast charging.” Until now, a power of more than 50 kW was often referred to as fast charging. Therefore, DC chargers are often equated with fast chargers. Today’s fast charging stations, however, are capable of delivering over 350 kW. Therefore, the term “high-power charging” (HPC) is often applied to chargers with at least 100 kW. These chargers enable very short charging processes and fast onward travel. Fast chargers with 50 kW are often used in urban areas where idle times are somewhat longer (LaMonaca & Ryan, 2022). The different types of charging infrastructure technology and the typical areas of application in the various charging scenarios are shown in Table 1.

In the absence of widely available public charging stations, home charging is a practical and cost-effective solution, especially for early adopters of EVs (Vassileva & Campillo, 2017). The growing prevalence of home charging does not reduce the importance of public charging infrastructure, especially for potential EV drivers to accept the technology. Thus, the value of public charging infrastructure is significantly greater than its share of charging currently suggests (LaMonaca & Ryan, 2022).

Although the expansion of public charging infrastructure has progressed in recent years, many places still lack public charging points. In particular, fast charging stations are still rare. For example, although Germany has set itself the goal of installing more than one million public charging stations by 2030 (Bundesregierung, 2022), so far only about 58,000 public charging points are available, and only 7000 of them are fast-charging stations. Figure 2 shows the recent development of public charging infrastructure in Germany.

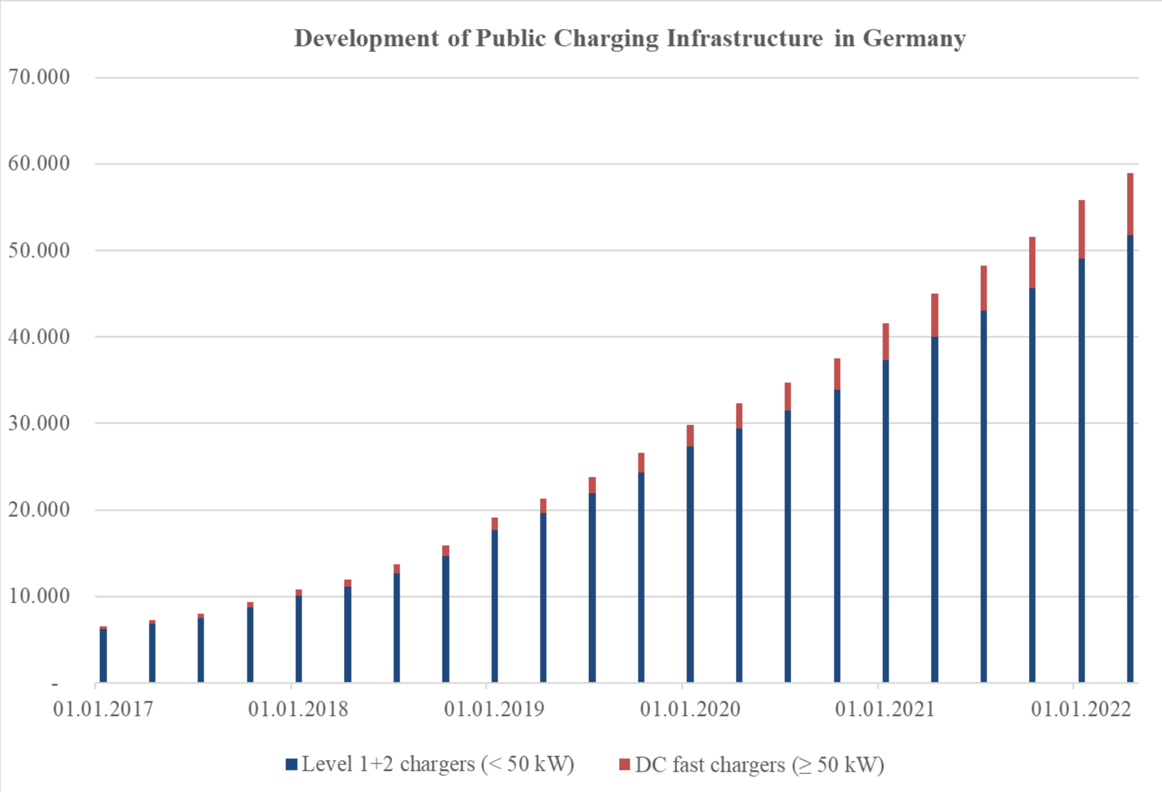


**Figure 2:** Development of Public Charging Infrastructure in Germany. Source: (Bundesregierung, 2022)

Public charging stations are of great value and can significantly increase utility for many drivers to EV drivers (Greene et al., 2020; Neubauer & Wood, 2014). Among public charging points, fast charging points are considered particularly important (Globisch et al., 2019). Analysis of customer behavior shows that fast charging is considered key by consumers (Illmann & Kluge, 2020). With many public charging stations, DC fast chargers more effectively increase EV sales and reduce emissions than do Level 2 chargers. In this sense, one DC fast charging station has a greater effect than ten Level 2 charging stations (Levinson & West, 2018). Fast chargers allow EVs to be used for trips beyond the range of a single charge, ones that would be cumbersome with slow charging. Fast chargers could make EVs more attractive to future users by helping overcome range anxiety (Neaimeh et al., 2017). Fast chargers are also important for the development of new mobility business models such as CS, based on EVs (Bekli et al., 2021). Section 4 elaborates on mobility business models such as CS and environmental impact.

## 2.2 Economics of Electric Vehicle Charging

Profitably operating fast charging infrastructure is currently difficult (Madina et al., 2016; Satterfield & Nigro, 2020). Borlaug et al. (2020) conclude that the average cost of charging an EV in the United States is $0.15/kWh using a levelized costs approach that also includes initial investment in the valuation of a single kilowatt-hour. However, this represents only an average of all charging types, and the costs for public fast charging stations tend to be significantly higher: Not only is the required investment high for the charging technology in DC fast chargers (Funke, Plötz, et al., 2019), but also the scaling effects are limited, even with the construction of several charging points. The cost of charging EVs varies widely depending on location, usage, charging behavior, and actual equipment costs (Borlaug et al., 2020). In addition to capital investment for hardware and installation, the cost components of charging infrastructure include operating costs, maintenance, and energy procurement, including electricity costs, taxes, and fees (Burnham et al., 2017; Schroeder & Traber, 2012). Previous work has shown that operating fast-charging infrastructure is unprofitable, at least with current EV shares (ICCT, 2018; Kley et al., 2011; Schroeder & Traber, 2012). Operators of public charging infrastructure and major fast-charging infrastructure are generally industrial energy consumers. For these industrial consumers, electricity costs also include a demand charge (Ansarin et al., 2020), whereby charging station operators pay a rate determined by the highest measured peak load within a given time interval. Therefore, a single charging event can already cause very high demand charges for the entire billing period. Demand charges can account for an extremely high proportion of electricity costs and make fast charging unprofitable (Flores et al., 2016). In the context of fast charging, demand charges can even account for up to 90% of total costs (McKinsey, 2018). Demand charges are also particularly difficult for charging stations in less-frequented locations, as they are relatively high when utilization is low. This is a major barrier to deployment in more rural areas. To make operations profitable, high charging fees are required to cover the high costs of investment and operation, which discourages people from using public charging stations (Ji & Huang, 2018). Serradilla et al. (2017) find that charging rates would need to be three times higher to enable the necessary investment in fast charging infrastructure.

Despite the unclear profitability, public fast-charging stations are imperative further to increase EV shares and must be promoted. Public charging stations are key to driving EV adoption (Pardo-Bosch et al., 2021). There are several ways to improve the economics of operating fast charging infrastructure. Among them is public financing by public utilities, subsidized by taxpayers or energy customers. This approach would often see consumers cross-subsidize wealthy early adopters as electric mobility ramps up (Plötz et al., 2014). Another option is to raise charging prices for customers. However, this option would probably also hamper the acceptance of EVs.

One promising approach is to develop smart charging management strategies. Demand-side management strategies effectively reduce capital and operating costs (Woo et al., 2021). Such strategies can either help reduce the costs of extremely high demand charges due to peak loads or increase revenue for the sale of charging energy. Section 2.3 details both approaches. In addition, the combination of charging infrastructure and renewable energy can also be mutually beneficial and improve the economics of operation (Muratori et al., 2019). Such a combination can include both energy generation (e.g. with solar energy) and energy storage. Section 3.1 summarises the combination of EV charging and RES in this regard. Finally, policy measures are also a valid option, and they are necessary to speed the deployment of fast charging infrastructure.

There is a need for policy support for the expansion of public fast-charging infrastructure in the early stages of electric mobility to accelerate adoption (Li 2016; Research Paper 1). Many countries have already initiated a whole range of support measures. For example Finland offers a 30% subsidy for the installation of charging infrastructure, while Denmark provides an electricity tax exemption for operators of charging stations (IEA, 2022). In general, current support measures include cash subsidies for installation, tax credits, or exemptions from energy taxes.

The various policy support measures can generally be categorized into three types of measures: regulatory, soft, or financial (Bemelmans-Videc et al., 2011). Regulatory measures, such as legislation or standardization measures, help to lower barriers to market entry for new operators. Soft measures can include, for example, free advice in the planning process and help reducing the risk of hidden regulatory overhead and unexpected costs. Financial measures directly improve project economics (Research Paper 1). Many financial measures (e.g. cash subsidies) can benefit only projects that would be built anyway, however. This focus leads to the construction of charging infrastructure on busy highways, but not to new installations in rural areas (Research Paper 1). Many regulators try to counteract this limitation with special funding conditions. For instance, to evenly expand their charging infrastructure, German regulators divided their country into discrete areas and distributed subsidies evenly among them (BMVI, 2020). However, many subsidies remained unused, and only actors in the most interesting and busy locations took advantage of them.

Since a main obstacle to profitably operating charging infrastructure is soaring demand charges, policymakers could also consider lowering these charges. Another option would be to shorten demand charge billing periods. There would still be individual spikes in demand that result in high demand charges on that day, but not exorbitant demand charges for the entire year. Table 2 describes various policy support measures (selection) and how they affect the expansion of charging infrastructure. Overall, there is a high need for research into the expansion of charging infrastructure and its influence on EV adoption, considering jurisdiction-specific conditions (Funke, Sprei, et al., 2019). Further research efforts should evaluate the full range of policies but also investigate psychological factors of customer behavior. Policy support measures should be tailored to the status of charging infrastructure development, depending on the country. In addition, a push is needed to develop new business models for charging infrastructure (Q. Zhang et al., 2018). One possibility is to cross-subsidize the charging price by marketing advertising space at the charging station.

**Table 2:** Policy support measures for charging infrastructure. Source: (Research Paper 1)

| Policy support measure | Type | Effect |
|---|---|---|
| Cash subsidy | Financial | Reduces the amount of money needed for the initial investment. |
| Tax credit | Financial | Lowers the owed taxes of the party responsible for the charging infrastructure project. |
| Electricity tax exemption | Financial | Exempts operators from electricity tax that is paid per kWh sold. |
| Demand charge reduction | Financial | Reduces the rate of the demand charge paid for the highest peak load within the billing period. |
| Change of demand charge billing | Financial | Shortens the billing period for demand charges and thus reduces the long-term negative effects of individual load peaks. |
| Laws | Regulatory | Provides the appropriate regulatory framework and ensures prioritization of charging infrastructure projects. |
| Standardization | Regulatory | Allows for more efficient scaling and higher customer potential of charging stations. |
| Market entrance regulations | Regulatory | Regulates entry into the market, making it easier for smaller utilities to participate. |
| Consultation in the deployment | Soft | Helps operators during planning and deployment and reduces the risk of hidden and unexpected costs in the construction process. |

## 2.3 Smart Electric Vehicle Charging

Often referred to as “smart charging,” controlled charging is a potent approach to improving the economics of charging infrastructure (Fridgen et al., 2014; Williams et al., 2012), centred on optimizing EV charging schedules. Controlled charging is performed using information about charging profiles by applying predictive models and various data inputs. In doing so, smart charging can pursue various optimization goals, including reducing costs for charging customers (Ensslen et al., 2018; Martinenas et al., 2014) or charging infrastructure operators (Clairand et al., 2018), stabilizing the power grid (Delmonte et al., 2020), or integrating renewable energy (Fachrizal et al., 2020; Ma et al., 2013).

The implementation of smart charging requires flexibility on the part of charging customers (Develder et al., 2016). This flexibility can include temporal flexibility or product flexibility (Daina et al., 2017). Temporal flexibility takes advantage of longer idle times to optimize EV charging times (Jin et al., 2013). Product flexibility means flexibility in charging speed, power, or location. Most approaches focus on temporal flexibility. This flexibility can be used by smart charging to optimize the charging schedule. Average connection times far exceed the time needed to charge EVs (Speidel & Bräunl, 2014; Wolbertus et al., 2018). The resulting flexibility around when the EV can be charged can be exploited through smart charging. However, this flexibility is not usually a given prerequisite but must be created by incentivizing charging customers (Baumgarte et al. 2022).

Smart charging offers multiple benefits for charging infrastructure operators. Various studies have shown that smart charging is the most promising approach for fast charging and can significantly reduce peak loads on the power grid (Mangipinto et al., 2022; Sachan et al., 2020). Khaksari et al. (2021) demonstrate the impact of smart charging in reducing infrastructure costs. Smart charging can reduce the contribution to peak loads in the electricity system by approximately 37% (Kara et al., 2015). It can also reduce curtailment of renewable energy and increase the stability of the distribution system (Park et al., 2022). It is particularly important for very large charging parks with many charging points (Research Paper 2). If charging is uncontrolled, simultaneously charging multiple EVs can produce even larger load peaks and, thus, very high demand charges, as compared to individual charging points.

In addition to financial incentives, cost savings and renewable energy integration are considered the most important factors encouraging EV drivers to participate in smart charging

(Huber et al., 2019). Smart charging, which aims to improve profitability for operators and thereby increase investment, can seek either to reduce costs or to increase revenue (Research Paper 3). Most approaches seek to reduce costs by shifting charging operations. This strategy helps to decrease both demand charges and energy costs with the cheaper energy of RES. In contrast, some approaches seek to increase operator revenues through pricing strategies while maintaining high throughput (Mrkos et al., 2018; Song et al., 2021). Various methodological approaches are available to implement smart charging, such as simple rules, smart technologies, or dynamic pricing (Jia & Long, 2020). (Hildermeier et al., 2019) argues that cost-based pricing and intelligent technologies are the most effective strategies for expanding charging infrastructure to seize the environmental and economic opportunities associated with EVs.

Intelligent technologies are at the heart of smart charging. They use big data sets, predictive models, additional input on charging preferences via user apps, and other information to provide operators decision support for charging station management (Fridgen, Thimmel, et al., 2021). These technologies can include mathematical models, simulations, or machine learning or AI approaches. Recently, much attention has been given to the use of supervised and unsupervised machine learning and deep neural networks for the analysis and prediction of charging behavior (Shahriar et al., 2020). These AI or machine learning approaches can use various sub-technologies and algorithms, including clustering or reinforcement learning. Reinforcement learning, in particular, seems promising, especially for real-world application (Baumgarte, Dombetzki, et al., 2021). A rapidly growing body of research is addressing EV charging challenges using reinforcement learning (Abdullah et al., 2021). As the size of charging parks increases, the complexity of controlling EV charging also increases (Research Paper 2). More simultaneous charging operations with heterogeneous charging customers significantly increases computational costs. This is where deep reinforcement learning (DRL) can be of interest. The approach combines classical reinforcement learning with neural networks and can thus efficiently process much more information and more diverse information (Liu et al., 2020). DRL has also proven it can be an effective approach for EV charging (H. Li et al., 2020).

Although the deployment of intelligent technologies for smart charging can have multiple goals, the obvious goal of operators deploying such technologies is to reduce their operating costs, often because of high demand charges (Abdullah et al., 2021). DRL can also increase PV self-consumption and raise the EV's state of charge at departure (Dorokhova et al., 2021; S. Li et al., 2022). The use of intelligent technologies such as DRL can significantly reduce the cost of demand charges, increase utilization, and thus sustainably improve the profitability of charging infrastructure operations (Shin et al. 2020; Research Paper 2).

Another approach to managing charging is to optimize charging pricing (Kong et al., 2015; Kuran et al., 2015). This approach aims to optimize the operator's revenue by anticipating the demand for charging and exploiting individual users' willingness to pay. Such approaches are already familiar from standard gas stations, where the price of gasoline fluctuates over the course of the day. Pricing optimization can therefore steer potential charging customers before they even arrive at the charging park, as they look for favorable charging windows of time. Such pricing approaches can also represents incentives to leave the EV at the charging station for shorter or longer periods (Motoaki & Shirk, 2017). Fast charging stations are often occupied for longer than 30 minutes. A flat fee incentivizes longer stays at the charging station. With appropriate incentives, consumers can be incentivized to stay for shorter periods and reduce occupancy (Motoaki & Shirk, 2017).

Yang et al. (2021) present demand-based pricing schemes for fast charging stations for this purpose to increase revenue and reduce waiting time for customers. Operators may also consider changing their business model even further and adopting revenue management techniques from other industries. Revenue management can help operators of large EV charging stations increase revenue and profits (Research Paper 3). In this context, revenue management aims to maximize revenue by selling the right product at the right time to the right customer at the right price (Tekin & Erol, 2017). Revenue management has been used primarily in industries such as aviation or the hotel industry (Kimes & Thompson, 2004; Klein et al., 2019). Charging stations can be seen as service products similar to airline seats. Research Paper 3 presents a dynamic pricing model and shows that it can increase operators' revenues and balance and distribute the demand for charging throughout the day. This approach is supported by Kim et al. (2017) who find that the use of dynamic pricing can effectively maximize charging station operators' profits by exploiting the opportunism of the time-varying arrival of charging vehicles.

# 3 Technological Integration of Electric Vehicles into the Electricity System

EVs are an effective way to decarbonize individual mobility (Shafique et al., 2022). As they are powered by electricity, they instantly become an integral part of the electricity system as well. EVs influence the electricity system because they increase energy demand and affect grid stability (Moon et al., 2018). To be truly sustainable, it is necessary for EVs to be charged with renewable energy, deepening the demand for RES. However, EVs can also help to integrate a larger share of renewables, for example through smart charging (Taibi et al., 2018). The combination of EVs and RES also enables new business models and largely self-sufficient residential units for individual homes but also smart and sustainable districts (Parag & Sovacool, 2016). The growing share of RES and the associated volatility also increase the need for flexibility in the electricity system (Halbrügge et al., 2021). Increasingly, this flexibility is coming from distributed energy resources (DER) and based on renewable energy (Ajanovic et al., 2020). Here, EVs can also be a building block for much-needed flexibility. However, before EVs can benefit both transportation and the electricity system, they must overcome certain barriers. This is where digital technologies such as SSI and blockchain can help to overcome these barriers, even to create new opportunities for EVs in the electricity system.

Addressing the technological integration of EVs in the electricity system, Section 3.1 regards the combination of EVs and RES technologies, the exploration of new business models, and the integration of a higher share of RES. With respect to flexibility needs, Section 3.2 describes current developments in the flexibility market and the potential of EVs to provide the required flexibility. Section 3.3 addresses two barriers to the integration of EVs into the flexibility market and open access to all charging stations through the use of digital technologies such as blockchain and SSI.

## 3.1 Combining Electric Vehicle Charging with RES Technologies

An increasing share of RES are required to charge the increasing number of EVs sustainably. Conversely, EVs can also help integrate a greater share of renewables, for example through smart charging. A study with EV early adopters from Germany shows that contributing to grid stability and integrating RES are important motivating factors for the adoption of smart charging of EVs (Will & Schuller, 2016). RES and smart charging strategies are important solutions to mitigate impacts on the electricity system (Fattori et al., 2014).

A study from Portugal simulates the expected combination of EVs and RES in 2050 using a smart charging approach for EVs, and it shows that 100% renewable electricity supply is possible with certain combinations of PV and EVs. Carbon emission reduction targets can also only be met with a significant market share of EVs (Nunes et al., 2015). Therefore, the expanding charging options should consider possible combinations with RES.

A combination of charging infrastructure and RES can benefit all types of EV charging. In most cases, however, charging scenarios with longer idle times are considered, for instance in residential areas (charging at home) or at work (De Schepper et al., 2015; Tulpule et al., 2013). A study from the Netherlands demonstrates that charging EVs at work with solar energy is a sustainable approach to transportation. It offers direct use of PV electricity during the day and harnesses solar potential on building rooftops (Chandra Mouli et al., 2016). However, a combination of EV charging and RES can also benefit public charging stations. Even fast charging stations with short idle times (e.g. along highways) can be combined with RES. In such public charging stations, a greater share of locally generated electricity can significantly reduce costs. Muratori et al. (2019) show that the integration of solar PV or energy storage can minimize operating costs for fast-charging infrastructure. Guo et al. (2016) demonstrate the economic operation of a microgrid-like parking deck for EVs with on-site renewable energy generation through rooftop PV. A study of installations in parking lots of Walmart stores in the U.S. highlights the feasibility of combining EV charging stations and PV (Deshmukh & Pearce, 2021). There are several goals associated with combining EV charging stations and renewable energy. These goals may include increasing self-sufficiency, meeting regulatory obligations to increase RES, stabilizing and reducing impacts on the electric grid, reducing energy costs, or reducing demand charges. While private households often seek to increase their self-sufficiency and to reduce their overall household and mobility energy costs, avoiding costly peak loads and reducing demand charges remains the most important goal for public charging infrastructure operators.

EV charging can be combined with various technologies (e.g., solar, wind, or storage). The combination of EV charging with solar energy has already been analyzed in many studies (Bhatti et al., 2016; S. Khan et al., 2018). PV-fed charging stations are interesting investments if the right solar irradiation is available (Minh et al., 2021). Settings in residential areas with rooftop PV systems have often been investigated. A relevant case study in Ottawa shows that PV systems are effective in charging EVs and avoiding emissions (Longo et al., 2017). Access to rooftop solar makes EVs very attractive (Coffman et al., 2017). Especially at the household level, RES and solar PV in particular promise to optimize self-consumption (Facchini, 2017; Parag & Sovacool, 2016). Combining PV and EV charging stations can also significantly reduce costs (von Bonin et al., 2022). However, combining PV and EV charging at home usually requires smart charging. Household consumption profiles and charging would otherwise not match PV generation (Fretzen et al., 2021; Munkhammar et al., 2015).

Another option is to combine EV charging with energy storage. Profitable residential PV system settings often include battery storage or additional EV demand to increase self-consumption (Kaschub et al., 2016; Munkhammar et al., 2013; Sharma et al., 2020). Energy storage can provide several benefits to electricity systems, including peak shaving, self-sufficiency, and various system services to the power grid. Energy storage helps shift loads from EV charging. This shift allows energy from RES to be stored and fed into the EV later. In private homes, it helps reduce the amount of energy drawn from the grid (Gong & Ionel, 2020). In public charging stations, it helps reduce costs for operators in the absence of smart charging (Haupt et al., 2020). The startup Numbat is an example of balancing fast charging with reused energy storage. These can optimize self-consumption and achieve significant cost savings, for example through peak shaving (Numbat, 2022). Of course, multiple RES can also be combined with EV charging (e.g. PV, storage and wallbox in a residential building). Novoa and Brouwer (2018) show that combining storage, PV, and EV charging is effective. However, the investment cost for storage is quite high, and careful consideration should be given to whether it is needed in a specific setting.

A combination of RES and EV charging also enables new business models and the enhancement of existing renewable energy business models. In the residential sector, tenant electricity models (TEM) are gaining traction in Germany. TEMs could be a new business model to increase small-scale decentralized electricity generation from RES by managing household energy flows (Braeuer et al., 2022). In TEMs, the landlord invests in generation capacity, such as PV, and sells the electricity generated in the building directly to tenants (Behr & Großklos, 2017). Surplus electricity is sold and fed into the main public grid. This concept can be economically advantageous for landlords and tenants. With the integration of distributed energy sources (DERs) such as PV or battery storage into a building with multiple apartments, a TEM is conceptually no different from a microgrid, which is limited to a single building where the landlord acts as the microgrid operator (Fina et al., 2018). Figure 3 presents a conceptual implementation of a TEM. TEMs are not tied to a specific technology.

While they can use other power sources, they are typically combined with RES and especially residential PV. This business model becomes even more attractive with the advent of EVs, as residential electricity consumption also increases. EV charging can also have a load profile complementing household consumption. Research Paper 4 analyzes such complementary load profiles within TEMs in the presence of EV charging.

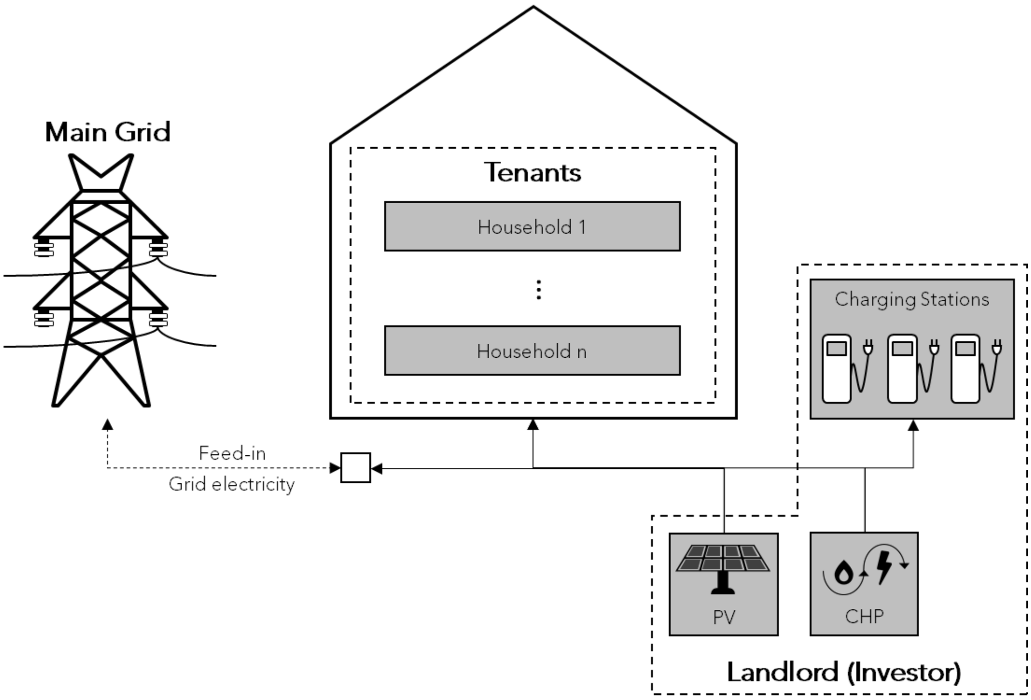


**Figure 3:** Conceptual Design of a Tenant Electricity Model. Source: (Research Paper 4)

Another interesting aspect that will receive more attention in the future is bidirectional charging. With bidirectional charging, EVs can feed into the grid or provide electricity for households. So far, this possibility has faced a number of technical challenges; few vehicles have met the prerequisites, as well as little charging infrastructure. However, this area is developing rapidly and there are new options for bidirectional charging (Hannan et al., 2022).

## 3.2 Providing Flexibility to Electricity Systems with Electric Vehicles

As the amount of intermittent RES increases, so does the load on the power grid, requiring flexibility to stabilize the grid. To cope with increasing volatility, electricity system flexibility is becoming more important (Halbrügge et al., 2021). This flexibility can come either from flexible generation plants, flexible electricity demand, or complementary technologies such as energy storage (Degefa et al., 2021; Papaefthymiou et al., 2018). With sufficient flexibility in the electricity system and complementary technologies, the deployment of RES can be significantly accelerated and can contribute to the decarbonization of energy systems (Heydarian-Forushani et al., 2017).

The move to reduce the use of fossil fuels and switch to RES is accompanied by a shift in power generation to decentralized locations (Blaabjerg et al., 2017; R. K. Jain et al., 2017). Where at one time, only a few hundred coal, gas, and nuclear power plants were sufficient to provide electricity, today energy is being generated from DERs in many more places (Ajanovic et al., 2020). The same is true of energy flexibility, which is now afforded by these DER rather than by individual generation plants. This presents certain challenges for the electricity system, but if these DERs are well managed, new opportunities for flexibility markets emerge (Eid et al., 2016).

As centralised generation plants are phased out, DERs will need to participate in and become the backbone of flexibility markets. As the energy transition continues and as an increasing amount of intermittent renewable power must be integrated, the flexibility of DERs will become critical (Schwidtal et al., 2021). DERs can thus provide benefits to flexibility markets. The flexibility of DERs to participate in flexibility markets is critical to the development of low-carbon grids (Riaz & Mancarella, 2022). For example, even a small number of DERs in the form of energy storage in multifamily buildings significantly increases available flexibility (Harder et al., 2020). The participation of DERs in flexibility markets requires aggregators that accumulate multiple DERs (Kubli & Canzi, 2021). First, individual DERs are often too small to participate, because all participants must meet a certain flexibility threshold (e.g. 0.1 MW). Second, aggregators can efficiently combine different DERs to provide more and better suited flexibility (Evangelopoulos et al., 2022). To fully utilize the flexibility available of DERs, their flexibility must be quantified and aggregated (Müller et al., 2019). Aggregating flexibility (e.g. from multiple households) smooths the available flexibility and allows for the integration of individual DERs (Harder et al., 2020).

EVs can be a DER that provides flexibility to markets by shifting the charging process, such as through smart charging (see Section 2.3). EVs can provide energy and ancillary services to the grid with smart charging (Taibi et al., 2018). They can also provide positive flexibility (feed in missing energy) from vehicle to grid (V2G) with bidirectional charging (Hannan et al., 2022). EVs open up the possibility to provide flexible services to different actors in the electricity system through smart charging and V2G technology (Gonzalez Venegas et al., 2021). In this regard, EVs could significantly impact the flexibility of the electricity system by providing flexible ramp services that ensure efficient and reliable operation of the system (Fattaheian-Dehkordi et al., 2021). Depending on current grid conditions, EVs can flexibly adapt their load or feed electricity back into the grid (Knezović et al., 2015). The flexibility provided by EVs can also be useful in providing spinning reserves and in reducing wind power curtailment (Pavić et al., 2015). The flexibility potential of EVs also applies to fast charging, in which case more charging power also creates more flexibility (Zade et al., 2020).

Despite that conceptually, EVs offer great value for providing flexibility, in practice several barriers confront the participation of EVs as DERs in flexibility markets. For example, EVs do not participate directly as DERs in the flexibility market but rely on aggregators, which act as middlemen and reduce the margin (Valarezo et al., 2021). Because of aggregators, grid operators also lack confidence in EVs as a source of flexibility because they lack information about individual DERs. Grid operators actually need data validation from individual DERs here. Furthermore, the noticeable lack of digitization in the process makes billing complicated and inaccessible. Moreover, EVs also charge at different locations and thus in different balancing groups or distribution networks. Meaningful end-to-end digitalization is necessary to allow EVs to switch between balancing groups and to participate in flexibility markets. Digital technologies can help to address these challenges. They are described in Section 3.3.

## 3.3 The Role of Digital Technologies in the Integration of Electric Vehicles

There are several barriers and challenges to integrating EVs into the electricity system. Among these barriers is the lack of digitalization in the electricity system. As described in Section 3.2, digitalization is currently lacking in flexibility markets with DERs, and so a lack of trust in distributed flexibility. Currently, DERs also rely on aggregators. In the future, such a system of DER flexibility, often called crowd balancing, could be operated in a peer-to-peer manner. There are also digitalization deficits in the public charging of EVs that result in roaming charges.

In the past, when flexibility markets were dominated by a few large power plants, grid operators could maintain close relationships with power plant operators. In flexibility markets based on DERs, aggregators play a central role, as they aggregate DERs and are responsible for communicating with grid operators. However, they aggregate large volumes of DERs, greatly increasing the number of parties involved. This proliferation in parties poses a problem for network operators because they lack transparent and verifiable information about the existence and availability of individual DERs. A trust gap then emerges. One technology that can help increase trust in flexibility markets based on DERs is SSI (Dehalwar et al., 2022). SSI is a paradigm rather than a technology in which a trusted entity issues a credential to the holder (Allen, 2016; Cameron, 2005). The holder can then present the credential to a third party, the verifier. The verifier then verifies the credentials presented by the holder. Using digital signatures, they can clearly determine their integrity and the origin of the issuance. They only accept verifiable credentials that come from trusted issuers (Mühle et al., 2018). The credential signature represents the trust relationship between the verifier and the issuer (Soltani et al., 2021). In flexibility markets, the holder is the DER itself or the owner of the DER. The verifier is the system operator. The issuer can be any trusted third party, such as regulators or companies specializing in providing trusted credentials. SSI can also benefit other applications in the electricity and transportation sector (Stockburger et al., 2021).

Another technology that can help accelerate digitization and the integration of EVs into the electricity system is blockchain. Blockchain offers several advantages for electricity and mobility applications, such as efficiency, effectiveness, and security (Research Paper 6). Blockchain can also benefit EVs that provide flexible services. One example is the Equigy platform, which is based on a blockchain implementation and has already launched several real-world projects with European grid operators and various system services in recent years (Equigy, 2022). Blockchain technology can be used to improve the operation of markets for system services with flexibility from RES. Blockchain-based registries and smart contracts can automate many control services, such as the registration, verification, and approval required for DER market participation (Alt & Wende, 2020; Mehdinejad et al., 2022). Smart contracts can also be used to automate the activation and billing of system services provided by DERs such as EVs (Esmat et al., 2021; Thomas et al., 2019). In addition, they can optimize billing processes characterized by laborious manual work (An et al., 2020; Neves et al., 2020; Tushar et al., 2021).

Blockchain can also be helpful in overcoming the current challenges due to the lack of digitalization in public charging for EVs. Normally, EV drivers need a certain network membership to be able to charge at public stations. For charging customers who have network memberships that differ from that of the charging point, operators charge a fee. This is known as e-roaming, and it makes charging unnecessarily expensive. Blockchain can help reduce the cost of e-roaming and solve the problem of limited access to charging stations by enabling the free and secure exchange of relevant data regardless of charging network membership (Hasankhani et al., 2021; T. Zhang et al., 2018; Research Paper 6). Blockchain technology can facilitate the exchange of charging data for EVs as well as transactions between charging point operators and mobility service providers (Hoess et al., 2022). Blockchain can also be used to store identity-related documents, making the identification and authentication of EV customers easy and secure (Research Paper 6). The blockchain validates and verifies the authenticity of documents. Once charging is complete, smart contracts are used to validate credentials and automatically generate invoices.

In addition to the benefits, however, the implementation of blockchain projects in practice encounters a variety of challenges. The challenges are far more specific and numerous than most of the benefits. They include organizational, technical, and regulatory challenges, although are often use-case specific. To date, few real-world projects have been able to show that they have overcome these challenges. Research Paper 6 examines the potential benefits and challenges of adopting blockchain technology in the electricity system.

# 4 Promoting Shared Mobility Services

In addition to the electrification of transportation, a meaningful reduction of emissions in the transport sector also requires a reduction in the number of owned cars (Migliore et al., 2020). Reducing car ownership can significantly impact and accelerate the transition to clean and sustainable mobility (T. D. Chen & Kockelman, 2016). Sustainable mobility is key to the social, environmental, and economic success of modern urban environments.

Inspired by the sharing economy movement, shared mobility is a lever to reduce the ownership of cars and mobility assets and to promote more sustainable and efficient use of transportation (Burghard & Scherrer, 2022; Nansubuga & Kowalkowski, 2021). As such, it shapes the decarbonization of transportation. Therefore, this section describes car sharing as the most widespread form of shared mobility and discusses the benefits and challenges of such shared mobility. It also highlights some ways and technologies to address the current challenges of shared mobility. The various forms of shared mobility include sharing cars, bikes, and e-scooters (Blazanin et al., 2022; B. Y. He et al., 2020; Shaheen et al., 2019). Within the car-based models of shared mobility, there is CS, but also models such as ride sharing, ride-hailing, or ride-pooling (Burghard & Scherrer, 2022; Kostorz et al., 2021; Machado et al., 2018).

The best-known form of shared mobility is CS. CS majorly reduces car ownership and thus presents great potential for emissions savings (Liao et al., 2020; Namazu & Dowlatabadi, 2018; Nijland & van Meerkerk, 2017). CS has already been introduced in almost all major cities around the globe. There, CS can be an essential component of future sustainable and multimodal transport systems in urban environments (Spickermann et al., 2014). Individual but sustainable forms of mobility such as CS can significantly reduce the number of private cars in already densely populated urban areas (T. D. Chen & Kockelman, 2016; Migliore et al., 2020; Riggs & Appleyard, 2021; Te & Lianghua, 2020).

There are different types of CS, involving many different business models and practicalities. CS systems are either business-to-consumer or peer-to-peer models (Münzel et al., 2018; Nansubuga & Kowalkowski, 2021; Remane et al., 2016). Business-to-consumer are commercial and most widely used models. Peer-to-peer models are often based in and limited to smaller communities, such as specific neighbourhoods (Barbour et al., 2020). Peer providers participate not only for monetary reasons, but also strive for the purposes of ecological interest, lifestyle, helping others, and sustainability (Wilhelms et al., 2017). Within business-to-consumer CS, there are several forms of CS business models. Most are either station-based CS or free-floating CS systems (Wagner et al., 2014). Within station-based CS, a distinction is made between one-way or two-way CS (Willing, Klemmer, et al., 2017). In one-way CS, users can choose at which station they drop off the vehicle. In two-way CS, users must end their trip at the station where they started. In free-floating CS, vehicles are distributed throughout the service area, and users can start and end their trips anywhere in the area (Boldrini et al., 2016). Free-floating and one-way station-based services are frequently used for short trips, while two-way station-based CS is generally used for longer trips (Alencar et al., 2021). CS systems can also be distinguished by technology type, for example EV or ICEV (Illgen & Höck, 2018). For truly sustainable mobility services, CS systems should be built on EVs, especially since most CS trips tend to be short. EVs also make CS a more attractive option for potential users (J. Kim et al., 2017).

CS offers several benefits for users of such services, but also for other citizens and for the environment. From a sustainability perspective, the most important benefit is that it can reduce car ownership. A study on CS in Seoul estimates that each shared car replaces 3.3 private cars (Ko et al., 2019). A study in Germany finds that one additional station-based car leads to a reduction of about nine private cars (Kolleck, 2021). However, the exact relationship between CS has not yet been conclusively researched. No statistically significant effect was found for the relationship between car ownership and free-floating CS (Kolleck, 2021). CS also reduces parking scarcity in densely populated areas and links suburbs to cities (E. Martin & Shaheen, 2011; Willing, Brandt, et al., 2017). It also provides cost savings and convenience for individual CS users (Shaheen et al., 2014). CS supports environmentally sustainable urban development by reducing car ownership (Giesel & Nobis, 2016; Nijland & van Meerkerk, 2017). As a result, it contributes greatly to reducing $CO_2$ emissions from mobility and in cities (T. D. Chen & Kockelman, 2016; E. W. Martin & Shaheen, 2011; Nijland & van Meerkerk, 2017). It also complements public transport to meet the mobility needs of individuals (Namazu & Dowlatabadi, 2018).

However, the adoption of CS also faces certain challenges. Its adoption requires a fundamental change in users' deeply ingrained habits of daily mobility (Kent & Dowling, 2013). A Swedish study found that CS in cities is too often just a supplement to existing private car use, rather than a substitute for it (Bocken et al., 2020). To operate CS sustainably, operators also require sustainable business models. Economic viability is a prerequisite for companies operating CS business models. Even if they have some additional support and can cross-fund their services, a sound economic operating model is also important for government-supported organizations to provide CS services. However, a viable business model for CS has yet to be found, and an increase in users does not necessarily translate into profitability (Lagadic et al., 2019). In the current research, the challenge of running CS businesses profitably is often related to understanding user behavior (Golalikhani et al., 2021; Jorge et al., 2015). One reason many operators struggle to operate their CS business model profitably is that they lack insights about their users and city-specific conditions. Supra-regional operators seem to be expanding their blueprint model to other cities, hoping that the services will be well received there. But they likely lack knowledge of the context and the specifics of local users to situationally adapt their system to those needs. Ferrero et al. (2018) also notes a significant lack of research in CS customer segmentation here. Operators in smaller urban areas, such as municipal utilities that operate both public transportation and CS, instinctively understand user needs much better, but they cannot manage extensive usage data and derive insights from it.

However, there are always examples showing that CS business models can be operated successfully. Regional operators in Germany have highlighted proximity to their customers as one of their success factors (Schreier et al., 2018). A promising opportunity is to combine knowledge about the urban environment and users with insights through analysis of usage data. Analyzing usage data can greatly help operators understand their CS customers and improve their business model according to these needs (Research Paper 7). Such adjustments may include changing fee structures, services, locations, or availability. One example is customer-centric pricing systems based on customers' driving habits (Feng et al., 2020; Perboli et al., 2018). To gain the necessary insights, technologies such as ML can help operators. ML has already proven useful in CS research (Wang et al., 2021). For example, ML modelling can help predict trip initiation and travel time (Z. Chen & Fan, 2021; Cheng et al., 2019). Data-driven models can also provide insights into predicting customer trip length, which is a good indicator of operational revenue (Baumgarte, Keller, et al., 2022). The distance travelled during a CS trip, in combination with the time of use, has a significant impact on the resulting user fee per CS trip (Golalikhani et al., 2021). Trip length also influences the decision to use a particular vehicle type (Costain et al., 2012; Jian et al., 2017).

One concept for future mobility systems, especially in urban areas, is Mobility as a Service (MaaS) (Alonso-González et al., 2020; Matowicki et al., 2022). MaaS combines various mobility services into one system (Lopez-Carreiro et al., 2021). For example, users can use CS, bike-sharing, cabs, and public transportation through a single platform or app and a single sign-up with transparent fee structures (Christensen et al., 2022). MaaS can also be designed as a mobility flat rate, where users pay a fixed monthly fee and can seamlessly use all modes of transportation. A prominent example of a mobility flat rate is the city of Augsburg, which introduced such a system in 2019 (SWA, 2022). Although the economics of such a mobility flat rate are unclear for operators, this could be an interesting starting point for the development of new mobility business models that can satisfy users and thus help to achieve the ultimate goal of ownership reduction and decarbonized mobility.

# 5 Conclusion

## 5.1 Summary and Outlook

The transport sector is among the largest emitters of climate-damaging greenhouse gases. Individual road traffic is by far the greatest source of emissions. Several measures can be implemented promptly and promise great potential for a sustainable transformation of mobility and a reduction in emissions. Three of the most important measures are the electrification of individual road transport through the use of electric mobility, the integration of EVs as a key component in the electricity system, and the reduction of owned vehicles. The spread of EVs also requires the rapid expansion of charging infrastructure and sensible management of charging. Measures such as smart charging or the implementation of political support measures can be important building blocks for the urgently needed expansion. Through the electrification of transport, EVs automatically become part of the electricity system and must be integrated accordingly. This necessity also leads to new challenges for the electricity system, as EVs increase the demand for renewable energy, but it further offers opportunities, such as new sources of energy flexibility. In addition, new business models can develop from the combination of EVs and RES. However, digital technologies remain the most important driver of these developments. CS offers a promising option for individual mobility to reduce car ownership, but services need to be developed such that they are attractive and encourage users to switch from private vehicles to sharing options. The decarbonization potential of individual measures can be leveraged only through the efficient use of digital technologies and comprehensive design of the corresponding IS. Digital technologies and information services have great potential to contribute to the creation of digital and decarbonized individual mobility.

This thesis comprises seven research papers concerned with the decarbonization and digitalization of transportation and energy to enable sustainable individual mobility. Specifically, it addresses three areas of action: the shift towards EVs, the integration of EVs into the electricity system, and the reduction of car ownership through shared mobility. Therefore, this thesis first addresses the different charging types of EVs including different charging scenarios and technologies (Section 2.1). It then discusses the economics of EV charging, highlighting the main challenges, and why additional support measures are needed (Section 2.2). Optimizing EV charging through smart charging offers one possible solution (Section 2.3). For the integration of EVs into the electricity system, a combination with RES can be helpful (Section 3.1). On the other hand, EVs can provide flexibility and play an important role in stabilizing the power grid (Section 3.2). To overcome barriers to integrating EVs, digital technologies can be pivotal (Section 3.3). Reducing car ownership requires innovative mobility solutions, such as CS, but these services require innovation to increase attractiveness and adoption (Section 4).

This work contributes to Green IS research and to the transformation of the transport sector towards sustainable mobility. In many cases, the results of the papers embedded in this thesis are based on the evaluation of real-world data and thus also have practical benefits that go beyond theory. The contributions show ways forward for Green IS research and underline the importance of IS and digital technologies for sustainable mobility. In this way, the work also indirectly contributes to reducing emissions and combating climate change by promoting sustainable mobility solutions. Furthermore, it provides insights into the effectiveness of digital technologies to improve business models for individual mobility and outlines action options for policy makers and practitioners for the use of digital technologies that can more effectively decarbonize individual mobility.

Naturally, this thesis also contains limitations and does not consider all options for reducing emissions in the transport sector. In addition to the electrification of transport and the reduction of car ownership, other measures can contribute to sustainable mobility. For example, there are other options for managing EV charging. The benefits of EVs for reducing emissions are discussed, but there are also multiple challenges associated with EVs: They rely heavily on renewable energy, require many rare earth materials for battery production, and face certain issues in the recycling of these materials. Emissions in the manufacturing process and new path dependencies have not yet been considered. It also still needs a behavioral perspective on the adoption of digital technologies. Even when they are available, scalability requires organizational capabilities from companies that they often have not yet learned. Moreover, some of the research paper's assessments are based on individual cases. An analysis of the proposed actions in different locations and cases would improve the results.

The shift toward sustainable mobility requires extensive research and support from the research community. Several starting points for further research emerge from this work and the embedded research papers. EVs are only one individual road mobility technology that can reduce emissions. Research should continually examine all potential technologies and explore ways to implement them. With respect to EV charging, all efforts that promote more rapid expansion of charging infrastructure should be explored. There are certainly other measures that can be implemented by policymakers, as well as operators and individuals, to accelerate the deployment of the necessary charging facilities. Future work should continue to explore economically efficient options for combining renewable energy and EVs in multifamily buildings and lower-income areas so that the whole society can participate in clean energy and mobility. Special interest should be given to new digital technologies and IS to understand their benefits for sustainable mobility, but also the challenges organizations face in adopting them. Overall, the transformation of the transport sector requires the active participation of all stakeholders and a combination of different measures to achieve digital and decarbonized individual mobility.

## 5.2 Acknowledgment of Previous and Related Work

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

The papers by Halbrügge et al. (2020) and Haupt et al. (2020) deal with fast charging of EVs and the specific case of the large-scale fast charging park in Zusmarshausen on the A8 freeway. Thus, they form a basis for the analyses and evaluations in Research Paper 1, Research Paper 2, and Research Paper 3. In addition, Hegele et al. (2020), Baumgarte et al. (2021) and Fridgen, Thimmel, et al., (2021) (Fridgen, Thimmel, et al., 2021)already deal with smart charging and include important prior considerations for Research Paper 2. Research Paper 4 extends the work of Töppel (2019) by including EV charging in the evaluation of TEMs. It also benefits from ideas from Fridgen et al. (2018) and Schott et al. (2018). The insights from Strüker et al. (2018), Richard et al. (2019), Rieger et al. (2019), Sedlmeir et al. (2020), and Sedlmeir et al. (2021) on blockchain applications were all important inputs for Research Paper 6. Finally, by looking at sustainability aspects in urban environments, Keller et al. (2019) provided starting points for Research Paper 7.

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# 7 Appendix

## 7.1 Research Papers Included in This Thesis

Papers 1–7 are available in the supplement. Kindly note that their formatting may differ from the published papers to allow for a consistent layout. Each paper has a separate reference section, as well as a separate numbering of figures, tables, and footnotes, if applicable.

**Research Paper 1**

Baumgarte F., Kaiser M., & Keller R. (2020). Policy Support Measures of Widespread Expansion of Fast Charging Infrastructure for Electric Vehicles. In *Energy Policy*.

DOI: 10.1016/j.enpol.2021.112372

VHB Jourqual 3: B, SNIP 2020: 1.941, SJR 2020: 2.093, CiteScore 2020: 10.2 / 95 percentile

**Research Paper 2**

Baumgarte F., Dombetzki L., Kecht C., Keller R. & Wolf L. (2022). Deep Reinforcement Learning for Optimization of Large Electric Vehicle Charging Parks.

*Submitted*

**Research Paper 3**

Baumgarte F., Bollenbach J., Kaiser M., Keller R. & Weibelzahl M. (2022). Revenue Management in a large-scale fast charging hub for electric vehicles: A multiproduct, dynamic pricing model.

*Submitted*

**Research Paper 4**

Altheimer J., Baumgarte F., Keller R. & Sauerwein T. (2022). Coupling Households and Mobility: Economics of Tenant Electricity Models with Electric Vehicle Charging.

*Submitted*

**Research Paper 5**

Baumgarte, F., Glenk, G., & Rieger, A. (2020). Business Models and Profitability of Energy Storage. In *iScience.*

DOI: 10.1016/j.isci.2020.101554

VHB Jourqual 3: NA, SNIP 2020: 1.156, SJR 2020: 1.805, CiteScore 2020: 3.4 / 83 percentile

**Research Paper 6**

Roth T., Utz M., Baumgarte F., Rieger A., Sedlmeir J. & Strüker J. (2022). Blockchain Adoption in Electric Power Systems: A European Perspective.

*Submitted*

**Research Paper 7**

Baumgarte F., Brandt T., Keller R., Röhrich F. & Schmidt L. (2021). You'll Never Share Alone: Analyzing Carsharing User Group Behavior. In *Transportation Research Part D: Transport and Environment*.

DOI: 10.1016/j.trd.2021.102754

VHB Jourqual 3: B, SNIP 2020: 2.229, SJR 2020: 1.600, CiteScore 2020: 9.1 / 96 percentile

Over the course of my dissertation, I also contributed to a number of other publications, which are listed below. These works are not part of this thesis.

**Research papers**

- Hegele T., Markgraf M., Preißler C. & Baumgarte F. (2020). Intelligentes Entscheidungsunterstützungssystem für Ladevorgänge an Stromtankstellen. In *Proceedings der 15. Internationalen Tagung Wirtschaftsinformatik 2020, Potsdam*.
- Baumgarte F., Dombetzki L., Kecht C., Wolf L. & Keller R. (2021). AI-based Decision Support for Sustainable Operation of Electric Vehicle Charging Parks. In *Proceedings of the 54th Hawaii International Conference on System Sciences, Honolulu, HI.*
- Baumgarte F., Keller R., Röhrich F., Valett L. & Zinsbacher D. (2022). Revealing Influences on Carsharing Users' Trip Distance in Small Urban Areas. In *Transportation Research Part D: Transport and Environment*.
- Baumgarte F., Eiser N., Kaiser M., Langer K. & Keller R. (2022). Smart Electric Vehicle Charging considering Discounts for Customer Flexibility. Forthcoming *Proceedings of the Americas Conference on Information Systems (AMCIS) 2022, Minneapolis, Minnesota.*

**Reports and book chapters**

- Röglinger M., Baumgarte F. & Fischer D. (2021). Prozessdigitalisierung für das „New Normal“: Branchenübergreifende Studie zu Herausforderungen und Chancen der Prozessoptimierung.
- Baumgarte F., Keller R., Roth L., Strüker J. & Wolf L. (2022). Elektromobilität im Tourismus - Herausforderungen und potenzielle Lösungsansätze. In Gardini A. & Sommer G. (Eds.), *Digital Leadership im Tourismus*. Springer.

## 7.2 Declaration of Co-authorship and Individual Contribution

This doctoral thesis is cumulative and comprises seven research papers. All of them were written in collaboration with multiple co-authors. In this section, I will describe my individual contribution to each of the seven papers.

**Research Paper 1:**

I co-authored this research paper with Matthias Kaiser and Robert Keller. All authors contributed equally to this paper. I contributed to the definition of the objectives of the paper: Comparison of policy instruments regarding their contribution towards a widespread charging infrastructure. I also participated in the conceptual development of the paper's methodological approach and formal analysis. Moreover, I was responsible for validating the results of the analysis for their generalizability and transferability. I also reviewed and substantially edited the original draft of the paper.

**Research Paper 2:**

I co-authored this research paper with Luca Dombetzki, Christoph Kecht, Robert Keller, and Linda Wolf. I proposed the research question and contributed by initiating and developing the conceptional approach and evaluation case. I also reviewed related literature and wrote the manuscript. I am the lead author of this research paper.

**Research Paper 3:**

I co-authored this research paper with Jessica Bollenbach, Matthias Kaiser, Robert Keller, and Martin Weibelzahl. All authors contributed equally to this paper. I contributed by proposing the idea for the paper and its objectives: the application of revenue management to a new and innovative industry of electric vehicle charging. I also contributed to the development of the evaluation case and validated the results of the initial analysis for their generalizability and transferability. Lastly, I reviewed and substantially edited the original draft of the paper.

**Research Paper 4:**

I co-authored this research paper with Julia Altheimer, Robert Keller, and Theresa Sauerwein. I contributed significantly by supervising the research project, including conceptualization and formal analysis. I also conducted the literature review and validated the results for transferability. I created the figures for the conceptual approach. Finally, I substantially edited the original draft and wrote large parts of the paper.

**Research Paper 5:**

I co-authored this research paper with Gunther Glenk and Alexander Rieger. All authors contributed equally to this paper and jointly developed the business model framework. I was responsible for the collection and curation of data. Together with Alexander Rieger, I reviewed current literature to establish the profitability of the characterized business models. Moreover, I engaged in the formal analysis. Together with Gunther Glenk, I wrote the original draft of the paper.

**Research Paper 6:**

I co-authored this research paper with Tamara Roth, Manuel Utz, Alexander Rieger, Johannes Sedlmeir, and Jens Strüker, whereas Tamara Roth and Manuel Utz acted as lead authors. I contributed by validating the results of the analysis together with Alexander Rieger. I also provided feedback on the conceptual approach and assistance with the literature review and data collection and compiled the tables within the appendix. Lastly, I reviewed and edited the original draft of the paper.

**Research Paper 7:**

I co-authored this research paper with Tobias Brandt, Robert Keller, Felix Röhrich, and Lukas Schmidt. All authors contributed equally to this paper and jointly developed the research question. I contributed to the conceptual development of the methodological approach and provided feedback in all steps of the research process. I also validated the results of the initial analysis for their generalizability and transferability. Finally, I reviewed and substantially edited the original draft of the paper.

## 7.3 Research Paper 1 — Policy Support Measures of Widespread Expansion of Fast Charging Infrastructure for Electric Vehicles

Authors: Baumgarte, Felix; Kaiser, Matthias; Keller, Robert

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.

## 7.4 Research Paper 2 — Deep Reinforcement Learning for Optimization of Large Electric Vehicle Charging Parks.

Authors: Baumgarte, Felix; Dombetzki, Luca; Kecht, Christoph; Keller, Robert; Wolf, Linda

*Submitted*

Extended Abstract: The transportation sector is one of the largest emitters of greenhouse gases and urgently needs to reduce emissions to meet climate targets (IEA, 2021). Electric vehicles (EVs) are widely regarded as one of the most important means of decarbonizing personal transportation, and the share is increasing across countries (Van Mierlo, 2018). The ramp-up of EVs requires the rapid expansion of a close-knit charging infrastructure. Especially along highways, there is a need for large EV charging parks that provide sufficient fast charging options and enable long-distance travel (Funke et al., 2019). The necessary expansion is held back as operators often struggle to operate the charging park profitably due to high costs for power peaks which is even more imminent for large charging parks with multiple simultaneous charging events. A key solution component for reducing peak loads and improving the profitability of charging parks is smart charging (Spencer et al., 2021). Smart charging strategies are often implemented in the form of mathematical optimization models (Nimalsiri et al., 2021) and machine learning algorithms (Tuchnitz et al., 2021). These strategies can be very effective but are often designed for small charging parks and do not scale well. Operators of large charging parks need tools with low computational complexity that can easily scale and provide real-time decision support. In addition, these charging strategies should maximize the use of on-site solar generation (Heinisch et al., 2021), which is available in many large charging parks. In this paper, we present a charging strategy that schedules the charging operations of multiple EVs considering peak load pricing and on-site renewable energy. For this purpose, we use the deep reinforcement learning algorithm (DRL) Proximal

Policy Optimization (PPO). We evaluate the model in a case study of the three largest charging parks in Germany with real-world data on highway traffic and day-ahead energy prices, as well as simulated solar irradiance for the charging park's own PV energy generation. The results show that DRL, and PPO in particular, is a viable solution for implementing a smart charging strategy for the profitable and sustainable operation of large EV charging parks. Peak loads are reduced, and PV energy is almost fully utilized while maintaining a high throughput, enabling more cost-effective charging. This paper extends our previous work (Baumgarte et al., 2021) by evaluating PPO-based smart charging for different charging park locations and scenarios.

**References**

Baumgarte, F., Dombetzki, L., Kecht, C., Wolf, L., & Keller, R. (2021). AI-based Decision Support for Sustainable Operation of Electric Vehicle Charging Parks. *Proceedings of the Annual Hawaii International Conference on System Sciences*, 868–877. https://doi.org/10.24251/hicss.2021.107

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Tuchnitz, F., Ebell, N., Schlund, J., & Pruckner, M. (2021). Development and Evaluation of a Smart Charging Strategy for an Electric Vehicle Fleet Based on Reinforcement Learning. *Applied Energy*, *285*, 116382. https://doi.org/10.1016/j.apenergy.2020.116382

Van Mierlo, J. (2018). The world electric vehicle journal, the open access journal for the e-mobility scene. *World Electric Vehicle Journal*, *9*(1), 1. https://doi.org/10.3390/wevj9010001

## 7.5 Research Paper 3 — Revenue Management in a large-scale fast charging hub for electric vehicles: A multiproduct, dynamic pricing model.

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

*Submitted*

Extended Abstract: The transport sector is responsible for 23 % of the greenhouse gas emissions in the EU, and significant decarbonization of this sector is essential to reach climate targets (EEA Web Team, 2021). Compared to an internal combustion engine car, battery electric vehicles (BEVs) can decrease the global warming potential by 9 % - 24 % (Hawkins et al., 2013). However, the adaption of BEVs is closely connected to the existence of sufficient and widely distributed charging infrastructure (European Court of Auditors., 2018). To enable longer driving distances and prevent queuing at charging locations, the demand for large-scale public fast charging hubs (LFCH) along highways with multiple charging points and high total power capacity increases (Greene et al., 2020). To achieve this, massive private and public investments in fast charging infrastructure is necessary, for which a profitable operation of fast charging sides is essential. However, the profitability of fast charging infrastructure operation hinges on the location-specific utilization of the charging stations (Baumgarte, Kaiser, et al., 2021). Due to unpredictable peak loads from simultaneous fast charging processes, today's small market share of BEVs and high electricity costs make investments in LFCHs a risky venture. To improve the profitability and reduce the risk of fast charging infrastructure investments, operators can attempt to reduce their investment or operational cost or look for options to increase the potential revenue. Revenue maximization for fast charging infrastructure operation could be interesting but has so far drawn less attention. In this work, we elaborate on the applicability of a RM technique for LFCHs and develop a dynamic pricing model to analyze the impact of RM in a LFCH. We contribute by developing a theoretical

framework demonstrating how a dynamic pricing approach can be implemented in a new industry. We conduct a simulation case study to identify the revenue improvements dependent on differently sized LFCH through dynamic pricing compared to a fixed price setting without using dynamic pricing. The results prove that RM is applicable in LFCHs and illustrate that the developed dynamic pricing model increases the revenue for operators. Particularly, it is useful when charging power is scarce and the number of charging points is low. Overall, applying dynamic pricing in LCFHs makes investments more attractive and contributes to the expansion of charging infrastructure.

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

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## 7.6 Research Paper 4 — Coupling households and Mobility: Economics of tenant electricity Models with electric vehicle Charging.

Authors: Altheimer, Julia; Baumgarte, Felix; Keller, Robert; Sauerwein, Theresa

*Submitted*

Extended Abstract: The transition towards renewable energy generation leads to increasing decentralization of energy systems where generation becomes more local, closely-knit to the actual point of con-sumption. Connecting local renewable energy sources and the residential sector has enormous potential as it accounts for large shares of distributed energy consumption (Parag and Sovacool, 2016). Especially on a household level, renewable energy and in particular solar photovoltaic (PV) promises optimized self-consumption (Facchini, 2017). There is a range of incentive mechanisms to promote the development of local and renewable power generation. Such incentives often include net-metering and feed-in tariffs (Del Carpio-Huayllas et al., 2012). If electricity can be generated locally for costs lower than the costs of purchasing elec-tricity from the grid, self-consumption offers the most extensive economic benefit. However, the generation and resulting self-consumption are limited to those who have access to, e.g., a rooftop to install solar PV (Jager-Waldau et al., 2018). With falling feed-in tariffs, private in-vestors seek new opportunities to find profitable investments in renewable energy at local scale. One promising alternative is tenant electricity models (TEMs), where landlords sell lo-cally generated electricity directly to tenants. TEMs extend self-consumption and can be eco-nomically beneficial for both landlords and tenants. The growing electricity demand from charging electric vehicles (EVs) at home further increases the potential of self-consumption. Here, we analyze the profitability of TEMs with EV charging from an investor perspective. We model the electricity consumption of households based on real-world data for consump-tion and charging behavior of tenants using clustering ap-

proaches. We find that TEMs are viable alternatives for distributed renewable energy sources investments that become even more interesting in the presence of EVs. However, TEMs are highly sensitive to the genera-tion, and adding EV charging turns investments unprofitable if PV is the sole generation source. The resulting model enables landlords to evaluate the profitability of tenant electricity investments based on the households' specific electricity demand and EV charging.

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Parag, Y., & Sovacool, B. K. (2016). Electricity market design for the prosumer era. *Nature Energy*, *1*(4), 16032. https://doi.org/10.1038/nenergy.2016.32

## 7.7 Research Paper 5 — Business Models and Profitability of Energy Storage.

Authors: Baumgarte, Felix; Glenk, Gunther; Rieger, Alexander

Published in: *iScience* (2021)

Abstract: Rapid growth of intermittent renewable power generation makes the identification of investment opportunities in energy storage and the establishment of their profitability indispensable. Here we first present a conceptual framework to characterize business models of energy storage and systematically differentiate in- vestment opportunities. We then use the framework to examine which storage technologies can perform the identified business models and review the recent literature regarding the profitability of individual combinations of business models and technologies. Our analysis shows that a set of commercially available technologies can serve all identified business models. We also find that certain combinations appear to have approached a tipping point toward profitability. Yet, this conclusion only holds for combinations examined most recently or stacking several business models. Many technologically feasible combinations have been neglected, indicating a need for further research to provide a detailed and conclusive understanding about the profitability of energy storage.

## 7.8 Research Paper 6 — Blockchain Adoption in Electric Power Systems: A European Perspective.

Authors: Roth, Tamara; Utz, Manuel; Baumgarte, Felix; Rieger, Alexander; Sedlmeir, Johannes; Strüker, Jens

*Submitted*

Extended Abstract: Blockchain has attracted attention across many industries and has gained a reputation as a hype technology. In a predominantly technology-driven effort, various industries have initiated projects to test the prospects and limitations of blockchain applications. Success stories from other industries have fueled similar expectations for the use of blockchain in electric power systems (Lüth et al., 2018; Mengelkamp et al., 2018). In particular, blockchain's ability to enable distributed transactions was expected to support the integration of an increasing number of distributed renewable energy sources (RES) (Andoni et al., 2019; Di Silvestre et al., 2020). The intermittency and distribution of these RES requires more flexible local concepts that could be realized with blockchain applications (Baumgarte et al., 2020). Accordingly, various research and pilot projects began to explore use cases for blockchain in electric power systems (Lin et al., 2019). Yet, many of these projects have since been abandoned or are still at a pilot stage – especially in Europe (Tushar et al., 2021). To identify the reasons for this slow progress, we reviewed the recent energy literature regarding the use of blockchain, analyzed industry reports, and interviewed experts who have conducted blockchain projects in Europe's electric power systems. Our analysis reveals eight common use cases, their expected benefits, and the challenges encountered. We find that the expected benefits are often little more than generic hopes, largely outweighed by technical, organizational, and regulatory challenges. The identified challenges are significant and numerous, especially for peer-to-peer trading and microgrid operation use cases. The fact that few projects have yet provided robust evidence for profitable use suggests there is a rocky

road ahead until blockchain can be used in Europe’s electric power systems. Moreover, many use cases appear to require more than just blockchain technology to succeed. In particular, privacy, security, and data quality requirements often call for systems in which blockchain only takes a backseat. This realization may be essential for the future use of blockchain in electric power systems – in Europe and beyond.

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## 7.9 Research Paper 7 — You'll Never Share Alone: Analyzing Carsharing User Group Behavior

Authors: Baumgarte, Felix; Brandt, Tobias; Keller, Robert; Röhrich, Felix; Schmidt, Lukas

Published in: *Transportation Research Part D: Transport and Environment* (2021)

Abstract: The rapidly developing concept of carsharing is an essential and scalable part of sustainable, multimodal mobility in urban environments. There is a clear need for carsharing operators to understand their users and how they use different transportation modes to intensify the development of carsharing and its positive impacts on the environment and urban cohabitation. We foster this understanding by analyzing usage data of carsharing in a medium-sized German city. We compare user groups based on individual characteristics and their carsharing usage behavior. We focus on a station-based two-way carsharing scheme and its relation to free-floating carsharing. Based on different clustering and segmentation approaches, we defined 20 particularly interesting user groups among the carsharing users and analyzed noticeable usage patterns. Additionally, we examined these partially overlapping user groups in the spatial dimension. With these results, we support research and operators in understanding carsharing customers and assessing users' individual behavior.