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***Optimizing Electric Vehicle Charging Infrastructure:
Enhancing Efficiency, Utilizing Alternative Energy
Sources, and Addressing Transaction Costs***

Doctoral Thesis

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In Prague, 2023

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Abstract

This dissertation investigates and provides comprehensive insights into three key areas of electric vehicle charging infrastructure optimization, the integration of recuperated braking energy from trains into electric vehicle charging stations, and the influence of transaction costs on the implementation and operation of electric vehicle charging infrastructure. The study aims to address the following research questions: (1) How can electric vehicle charging points be optimized for efficient use while maintaining cost-effectiveness? (2) How can the incorporation of recuperated braking energy from trains into electric vehicle charging stations impact their energy consumption and operating costs? (3) How do transaction costs affect the implementation and operation of electric vehicle charging stations, and how can they be reduced?

To optimize electric vehicle charging points, the research reveals several effective strategies. Firstly, leveraging existing parking lots equipped with low-power chargers during off-peak hours, when they are underutilized, proves to be a viable approach. By reserving parking spaces in these lots, electric vehicle owners without private garages or chargers can access charging facilities, maximizing the potential of existing substations. Power dividing between individual charging stations and deferred charging functions are proposed to balance the load on local substations and mitigate peak demand. Integration of battery storage is explored as a solution to enhance stability and support both the local substation and the broader power grid. Additionally, the research highlights the importance of installing a sufficient number of AC (Alternating Current) chargers in urban and suburban areas, rather than focusing solely on the higher charging power of DC (Direct Current) chargers, based on real-world data analysis. Quantity over higher power output is emphasized when expanding charging facilities in public parking lots.

The incorporation of recuperated braking energy from trains into electric vehicle charging stations is investigated as a means to improve energy efficiency and reduce the strain on the distribution grid. By capturing and utilising reclaimed brake energy and using it to charge electric vehicles, it helps to minimise energy waste and reduce the load on the electricity grid. Storage of excess recuperated braking energy in battery or capacitor energy storage systems and implementing charging power management functions at individual stations are identified as effective strategies. The study also

reveals that companies responsible for powering train lines have an economic opportunity to sell recuperated braking energy for electric vehicle charging at a significantly higher value compared to selling it back to the grid. This presents a potential revenue boost for the company while potentially offering electric vehicle owners lower per kWh prices.

Transaction costs are recognized as crucial factors influencing the successful implementation of electric vehicle charging stations, and more generally sustainable mobility. Contrary to common assumptions, the research finds that transaction costs tend to increase over time due to changes in programme administration, internal programme conditions, and information loss. To mitigate the impact of transaction costs, the dissertation proposes various strategies. Streamlining programme administration processes, improving information management systems, fostering collaboration and knowledge sharing among stakeholders, and implementing standardized procedures for infrastructure development are identified as effective approaches.

The findings of this dissertation provide valuable insights and practical solutions for optimizing electric vehicle charging infrastructure, incorporating recuperated braking energy, and reducing transaction costs. The research contributes to the development of efficient and sustainable electric vehicle charging systems, facilitating the transition to cleaner transportation and supporting global efforts in mitigating climate change.

Keywords: electric vehicle, charging infrastructure, recuperated braking energy, transaction costs, cost-effectiveness, low-power chargers, shared parking, reserving parking spaces

Abstract

Tato disertační práce zkoumá a poskytuje ucelený pohled na tři klíčové oblasti optimalizace infrastruktury pro nabíjení elektrických vozidel, integraci rekuperované brzdové energie z vlaků do nabíjecích stanic elektrických vozidel a vlivu transakčních nákladů na implementaci a provoz infrastruktury pro nabíjení elektrických vozidel. Studie se zaměřuje na řešení následujících výzkumných otázek: (1) Jak lze optimalizovat dobíjecí místa pro elektromobily, aby byla efektivně využívána a zároveň si zachovala nákladovou efektivitu? (2) Jak může využití rekuperované brzdové energie z vlaků do nabíjecích stanic pro elektromobily ovlivnit jejich spotřebu a provozní náklady? (3) Jak transakční náklady ovlivňují realizaci a provoz dobíjecích stanic pro elektromobily a jak je lze snížit?

Výzkum odhalil několik účinných strategií sloužících k optimalizaci nabíjecích míst pro elektromobily. Zaprvé se ukazuje, že efektivním přístupem je využití stávajících parkovišť vybavených nabíječkami s nízkým výkonem v době mimo špičku, kdy nejsou dostatečně využívána. Rezervací parkovacích míst na těchto parkovištích mohou majitelé elektromobilů bez soukromých garáží nebo nabíječek získat přístup k nabíjecím stanicím, čímž se maximalizuje potenciál jejich využití. K vyrovnaní zatížení místních rozvodů a zmírnění poptávky ve špičce se navrhuje rozdělení výkonu mezi jednotlivé nabíjecí stanice a funkce odloženého nabíjení. Integrace bateriového úložiště je zkoumána jako možné řešení pro zvýšení stability a podporu jak místní rozvodny, tak i širší energetické sítě.

Kromě toho výzkum na základě analýzy reálných dat zdůrazňuje důležitost instalace dostatečného počtu střídavých nabíjecích stanic v městských a příměstských oblastech namísto zaměření se pouze na vyšší nabíjecí výkon stejnosměrných nabíjecích stanic. Při výstavbě nabíjecích stanic na veřejných parkovištích je důležitější zohlednit jejich počet než jejich nabíjecí výkon. Prostředkem ke zlepšení energetické účinnosti a snížení zatížení distribuční sítě se zkoumá využití rekuperované brzdové energie z vlaků v nabíjecích stanicích pro elektromobily. Zachycení zpětně získané brzdové energie a její využití k nabíjení elektrických vozidel pomáhá minimalizovat plýtvání energií a snižuje zatížení elektrické sítě.

Za účinné strategie lze považovat ukládání přebytečné rekuperované brzdové energie do bateriových nebo kondenzátorových systémů a zavádění funkcí řízení

nabíjecího výkonu v jednotlivých nabíjecích stanicích. Studie také ukazuje, že společnosti odpovědné za napájení vlakových tratí mají ekonomicky výhodnou příležitost prodávat rekuperovanou brzdou energii pro nabíjení elektromobilů za výrazně vyšší cenu ve srovnání s jejím zpětným odprodejem do sítě. To pro ně představuje potenciální zvýšení příjmů a zároveň nabízí majitelům elektromobilů nižší cenu za kWh.

Transakční náklady jsou považovány za klíčové faktory ovlivňující úspěšné zavádění dobíjecích stanic pro elektromobily a obecně udržitelnou mobilitu. Na rozdíl od běžných předpokladů výzkum zjistil, že transakční náklady mají tendenci se v průběhu času zvyšovat v důsledku změn v administraci programu, vnitřních podmínek programu a ztráty informací. Pro zmírnění dopadu transakčních nákladů disertační práce navrhuje různé strategie. Mezi účinné přístupy patří zefektivnění procesů správy programů, zlepšení systémů správy informací, podpora spolupráce a sdílení znalostí mezi zúčastněnými stranami a zavedení standardizovaných postupů pro rozvoj infrastruktury.

Výsledky této disertační práce poskytují cenné poznatky a praktická řešení pro optimalizaci infrastruktury pro nabíjení elektromobilů, začlenění rekuperované brzdové energie a snížení transakčních nákladů. Výzkum přispívá k vývoji účinných a udržitelných systémů nabíjení elektromobilů, usnadňuje přechod na čistou mobilitu a podporuje celosvětové úsilí o zmírnění změny klimatu.

Klíčová slova: elektromobil, nabíjecí infrastruktura, rekuperace brzdové energie, transakční náklady, nákladová efektivita, nabíjecí stanice s nízkým výkonem, sdílené parkování, rezervace parkovacích míst

Contents

1. Introduction.....	1
1.1 Motivation	4
1.2 Identifying and Understanding the Primary Challenges	5
1.3 Research Questions.....	9
1.4 Research Objectives.....	10
1.5 Methodological Approach Across the Three Articles	11
1.6 Structure of the rest of the thesis.....	13
2. State of the Art.....	15
2.1 Charging Infrastructure.....	19
2.2 Availability and Price of Electricity.....	21
2.3 Government Policies and Incentives.....	22
2.4 Advancement of Battery Technology.....	24
2.5 Willingness of Consumers to Embrace EVs.....	25
3. Achieved Results	27
3.1 Optimization of Electric Vehicle Charging Points Based on the Efficient Use of Chargers and Providing Private Charging Spaces.....	27
3.2 Simulation of Electric Vehicle Charging Points Based on Efficient Use of Chargers and Using Recuperated Braking Energy from Trains.....	28
3.3 Why Transaction Costs Do Not Decrease Over Time? A Case Study of Energy Efficiency Programmes in Czechia	29
4. Optimization of Electric Vehicle Charging Points Based on Efficient Use of Chargers and Providing Private Charging Spaces	31
4.1 Abstract.....	32
4.2 Introduction.....	32
4.3 State of the Art.....	35
4.4 Model of EV Charging in Shared Parking Places	40
4.4.1 User Description.....	41
4.4.2 Blocking Issues	42
4.5 Charging Scheme	43
4.5.1 Model Input Parameters	44

4.5.2	Dimensioning the Transformer Station Power.....	44
4.5.3	Charging Power Sharing Method.....	45
4.6	<i>Economics of System Dimensioning</i>	47
4.7	<i>Case Study</i>	49
4.7.1	Parking Place Input Data Analysis.....	49
4.7.2	Users Input Data Analysis.....	53
4.7.3	Technical Aspects of System Dimensioning.....	55
4.7.4	Economic Analysis of System Dimensioning.....	59
4.8	<i>Results</i>	62
4.8.1	LCOE of Charging Tariff Rate.....	62
4.8.2	Setting of Minimum Blocking Tariff Rate.....	65
4.9	<i>Discussion</i>	66
4.10	<i>Conclusions</i>	68
5.	Simulation of Electric Vehicle Charging Points Based on the Efficient Use of Chargers and Using Recuperated Braking Energy from Trains	72
5.1	<i>Abstract</i>	73
5.2	<i>Introduction</i>	73
5.3	<i>State of the art</i>	75
5.4	<i>Model of EV charging site using RBE</i>	79
5.4.1	Scheme of EV charging site with variable charging power function.....	80
5.4.2	Model input parameters.....	81
5.4.3	Variable charging power function.....	82
5.4.4	Description of users.....	83
5.4.5	Blocking issues.....	84
5.5	<i>Economic aspects of proposed model</i>	85
5.6	<i>Case study</i>	86
5.6.1	Car park description	86
5.6.2	Analysis of input users' data	91
5.6.3	Technical aspects of system dimensioning	94
5.6.4	Economic analysis of case study.....	94
5.7	<i>Results</i>	97
5.7.1	Results of economic part.....	100
5.8	<i>Discussion</i>	102
5.9	<i>Fuel transformation vs energy mix change</i>	105

5.10	<i>Conclusion</i>	107
6.	Why Transaction Costs Do Not Decrease Over Time? A Case Study of Energy Efficiency Programmes in Czechia	112
6.1	<i>Abstract</i>	113
6.2	<i>Introduction</i>	113
6.3	<i>Methodology</i>	115
6.3.1	Theoretical framework	115
6.3.2	Operational programmes	116
6.3.3	Model of transaction costs.....	119
6.4	<i>Results</i>	123
6.4.1	Costs of time.....	125
6.4.2	Costs of external services	126
6.4.3	Overall transaction costs	128
6.5	<i>Discussion</i>	130
6.6	<i>Conclusions and policy implications</i>	134
7.	Recommendation for Further Research	137
7.1	<i>Charging Infrastructure Enhancement</i>	137
7.2	<i>Smart Charging, Grid Integration, and Reservation Systems</i>	137
7.3	<i>Fast Charging and Battery Advancements</i>	138
7.4	<i>Standardization and Interoperability</i>	138
7.5	<i>Renewable Energy Integration for Sustainable EV Charging</i>	138
7.6	<i>Cybersecurity and Privacy in Connected EVs and Charging Infrastructure</i>	139
7.7	<i>Economics and Business Models for Sustainable EV Charging</i>	139
7.8	<i>User Behaviour and Adoption</i>	139
8.	Conclusion	141
	References	145
	Publications of the Author Relevant to the Thesis	163
	Other Publications of the Author	163
	Participation in Projects	165
	Internships and Training Schools	166

List of Figures

Figure 1 Car park model equipped with low-power chargers.	43
Figure 2 Nonresident charging diagram.	46
Figure 3 Resident charging diagram.....	47
Figure 4 Occupancy on weekdays ([153], calculated by authors).....	50
Figure 5 Thursday arrivals/departures ([153], calculated by authors).....	50
Figure 6 ŠKO-ENERGO charging stations ([154], calculated by authors).....	52
Figure 7 Cumulative distribution function of charging requirements [kWh] ([154], calculated by authors).....	52
Figure 8 Probability density function of daily distance driven by car [155].	54
Figure 9 Cumulative distribution function of the resident's EV full charge.	55
Figure 10 Modelled occupancy in the case of using one transformer.	57
Figure 11 The success of recharging nonresidents in case of using one transformer.....	58
Figure 12 Modelled occupancy in case of using two transformers.	58
Figure 13 Success of recharging nonresidents in the case of using two transformers.	59
Figure 14 Share of coverage of annualized costs of additional TS.	63
Figure 15 Car park model equipped with single-phase chargers and variable charging power function.	80
Figure 16 Similarity of parking occupancy data between weekdays and weekends	87
Figure 17 Similarity of parking occupancy data among years	87
Figure 18 Pražská energetika (PRE) charging stations ([196], calculated by authors)	89
Figure 19 Parking time at PRE charging stations ([196], calculated by authors)	89

Figure 20 Cumulative distribution function of charging requirements [kWh] ([196], calculated by authors).....	90
Figure 21 Probability density function of daily distance driven by car [198]....	92
Figure 22 Average electricity consumption in the car park during weekdays ...	97
Figure 23 Proportion of RBE and EDG in car park electricity consumption during weekday operation	99
Figure 24 Emissions correlated with each kWh charge to EVs at the car park	100
Figure 25 Tesla emissions [gCO ₂ /km] [203]	106
Figure 26 Supply and acceptance rate of the submitted projects in OP EIC in 2007–2013 and 2014 – 2020 [232], [233].....	118
Figure 27 Average eligible costs per 1 GJ of energy savings of the submitted projects in OP EIC in 2007–2013 and 2014 – 2020 [238], [239]....	118
Figure 28 Distribution of eligible costs (EC) in the sample and their natural logarithms.....	123
Figure 29 Distribution of relative transaction costs (TC _{rel}) in the sample and their natural logarithms.	124
Figure 30 Structure of the supported energy efficiency and RES measures. ...	124
Figure 31 Time spent with the administration of the project in hours (per size of the project in eligible costs).	125
Figure 32 Percentage of applicants outsourcing the services connected with project administration (Operational Programme Environment).	126
Figure 33 Percentage of applicants outsourcing the services connected with project administration (Operational Programme Enterprise and Innovation for Competitiveness).	127
Figure 34 Distribution of costs for external services in 2011 and 2019 depending on the size of the project (eligible costs).....	128
Figure 35 Share of transaction costs on eligible costs (%).	129

List of Tables

Table 1 Investment costs.	60
Table 2 Annual electricity bill [157], [158].	61
Table 3 Fixed operating costs.	61
Table 4 Dependence of residential LCOE on discount rate and on share of inclusion of fixed costs in residential price in case two TS are installed.	64
Table 5 Dependence of nonresidential LCOE on discount rate and on share of inclusion of fixed costs in residential price in case two TS are installed. .	64
Table 6 Nonresident blocking tariff rate in EUR/night.	65
Table 7 Resident blocking tariff rate in EUR/day.	65
Table 8 Investment costs.	95
Table 9 Annual electricity bill [199], [200].	96
Table 10 Fixed operating costs.	96
Table 11 Resident prices in cents.	101
Table 12 Nonresident prices in cents.	102
Table 13 Factors influencing transaction costs related to time [216].	116
Table 14 Number of applicants and total allocated budget of OP E and OP EIC in the programming period 2007 – 2013 and 2014 – 2020 [231]–[236].	117
Table 15 Population and sample of the questionnaire survey – number of projects.	120
Table 16 Count and size of the projects.	120
Table 17 Costs of time per project – median [EUR].	126
Table 18 Costs of external services per project – median [EUR].	127
Table 19 Transaction costs per project – median [EUR].	128
Table 20 Results of two-sample t-test for lnTCr.	129
Table 21 Relative change of transaction costs in time (2019 compared to 2011).	130

Abbreviations

BEV	Battery Electric Vehicles
CAPEX	Capital Expenditures
CDF	Cumulative Distribution Function
DSM	Demand Side Management
EV	Electric Vehicle
EDG	Electricity Distribution Grid
EG	Electricity Grid
ESS	Energy Storage System
EU	European Union
EU ETS	European Union Emissions Trading System
GHG	Greenhouse Gas
HVAC	Heating, Ventilation, and Air-Conditioning
HV	High Voltage
ICCPD	In-Cable Control and Protection Device
IMS	Information Management System
IEVCO	Integrated Electric Vehicle Charging Optimization
ICE	Internal Combustion Engine
LCOE	Levelized Costs of Electricity
LV	Low Voltage
MIP	Mixed Integer Programming
NEDC	New European Driving Cycle
NIE	New Institutional Economics
NCFC	Non-Covered Fixed Costs
OPEX	Operating Expenditures
OP EIC	Operational Programme Enterprise and Innovation (for Competitiveness)
OP E	Operational Programme Environment
P + R	Park and ride car park
P2P	Peer-to-Peer
PV	Photovoltaic Power Plant

PHEV	Plug-in Hybrid Electric Vehicles
POI	Point of Interest
PRE	Pražská energetika, a. s.
PDF	Probability Density Function
RBE	Recuperated Braking Energy
RES	Renewable Energy Sources
RCD	Residual Current Device
NACE	Statistical classification of economic activities in the European Union
TS	Transformer Station
VAT	Value Added Tax
V2G	Vehicle-to-Grid
V2H	Vehicle-to-Home
ZEV	Zero-Emission Vehicle

1. Introduction

The European Union (EU) has set ambitious targets for reducing its carbon footprint, including a goal to reduce greenhouse gas (GHG) emissions by at least 40% by 2030, compared to 1990 levels [1]–[3]. One key area of focus for achieving this goal is the transportation sector, which accounts for around 20% of EU GHG emissions [4]. In particular, the EU is focusing on the conversion of its fleet of vehicles towards electric vehicles (EVs) as a means of reducing emissions from the transportation sector [1]. The benefits of electro-mobility are clear. EVs produce zero emissions from the tailpipe and thus significantly reduce the number of harmful pollutants and GHGs released into the atmosphere [5]–[11]. Additionally, EVs are quieter than traditional internal combustion engine vehicles, which can improve local air quality [5]–[11] and reduce noise pollution [7], [12], [13]. Furthermore, the use of EVs can help to reduce dependence on fossil fuels and increase the use of renewable energy sources (RESs) [5], [14]–[16], thus contributing to the EU's goal of achieving a more sustainable energy mix [1], [2], [17]–[19].

However, for the widespread adoption of EV's to take place, a dense network of charging stations is needed [6], [7], [10], [20]–[28]. Ledna et al. emphasize the significance of charging infrastructure for EV adoption, quantifying its economic value using the ADOPT model and recognizing its role in supporting EV sales [6]. Kester et al.'s qualitative review highlights the consensus on the importance of a robust charging network, addressing EV driver concerns and promoting adoption through their analysis of Nordic region experts' interviews [7]. Similarly, Falchetta and Noussan emphasize the importance of extensive charging infrastructure in alleviating range anxiety, promoting EV adoption rates, and fostering sustainable transportation. The correlation between charging availability and the uptake of EVs is highlighted, emphasizing the need for a robust charging network to support widespread adoption [10]. These collective insights underscore the critical role of a well-developed charging infrastructure in facilitating the transition to electric mobility. The EU has recognized this and takes steps to support the development of such a network. For example, the EU has set a target of at least 3 million publicly accessible charging points by 2030 [29], with a minimum of one fast-charging point per 10 vehicles on the road by 2025 [30].

However, the widespread adoption of EVs in urban areas is crucial for reducing emissions from the transportation sector [31] and for achieving a more sustainable energy mix [17], [18], [31], [32]. However, for this to happen, a dense network of charging stations must be in place to ensure that drivers have easy access to charging points and can rely on them not only for long journeys but especially for their daily journeys in and around city centres [6], [7], [22]–[27]. In particular, the deployment of alternating current (AC) charging stations in urban areas is necessary, as they are the most commonly used type of charging station and are suitable for overnight charging at home and at work [10], [11], [26], [27].

The right dimensioning of the number and power of charging stations is also crucial, as it depends on the different locations of the city [27], [33]–[36] such as business, residential and recreational areas [10], [11], [26], [27], [36], [37]. For example, in business areas, the higher demand for fast-charging stations to meet the needs of EV drivers has been emphasized and confirmed by both Pana et al. [11] and Mastoi, et al. [27]. The importance of strategically locating public charging stations in business areas to cater to the time constraints and quick recharging requirements of EV owners is highlighted by these studies.

Similarly, in recreational areas such as parks and museums, as well as in city peripheries equipped with P + R car parks with good connections to local public transport, there may be a higher demand for AC charging stations [10], [11], [26], [27], [36].

There are several reasons for the aim to create an optimal charging infrastructure for EVs. One of the main goals is to build charging stations where the demand is highest, in order to ensure that they are utilized to their full potential and that the investment in the infrastructure is worthwhile [6], [7], [22]–[26]. This is particularly important in terms of financial return or at least avoiding unnecessary spending [23], [36], [38].

To achieve this, better predictions of demand in specific locations, as well as accurate assessments of time of day and seasonal variations, are crucial. Different models and machine learning algorithms are often used to arrive at the appropriate ratio of charging stations and their output, depending on the location of the planned development. These models aim not only to efficiently design the location and network of charging stations, but also to consider the economic aspects when implementing the [6], [22], [23],

[26], [27], [31], [34]–[42] an example, Xinwei et al. [23] proposed the Integrated Electric Vehicle Charging Optimization (IEVCO) model, which incorporates travel and dwelling patterns to estimate optimal charging infrastructure placement, resulting in reduced costs and emissions. In their study, LaMonaca et. al [26] contribute to the prediction of EV charging demand in specific locations through a review of the market for EV charging infrastructure. The analysis encompasses existing charging types, the roles played by different actors, and the significance of establishing clear roles to ensure efficient infrastructure development. The article also delves into various business models and the ownership of charging point host sites, offering valuable insights for precise prediction of charging demand. Zhou, et al. [34] proposed a model that predicts EV charging demand in specific locations by considering existing charging stations, uncertainties in charging decisions, and travel demands. This model considers existing charging stations, uncertainties in charging decisions, and travel demands. By utilizing a stated preference survey and a Latent Class model, the applied approach enables a more accurate determination of the necessary battery range compared to simplified charging rules. The model considers factors such as recharge time, proximity to the nearest station, cost, remaining battery energy, and maximum recharge capacity per stop. A data-driven approach is proposed by Yi et al. [37], which combines trip origin-destination information, social features, and a modified geographical PageRank model to predict EV charging demand in specific locations. The method utilizes a directed graph representation and validates the model using real-world charging data. The obtained results are employed to optimize the spatial layout of public charging stations, addressing the spatial mismatch between demand and existing infrastructure. These models contribute significantly to enhancing the understanding and prediction of EV charging demand in specific locations.

Additionally, data analysis plays a crucial role in identifying patterns of EV usage and charging behaviour in different areas. By analysing data on the number of EVs, the distance traveled, and the duration of charging, it is possible to arrive at a better understanding of the charging needs in a given area. This information can then be used more efficiently to allocate resources, such as money, people, and materials.

The EU is also taking steps to change its energy mix towards renewables, which will help to ensure that the energy used to power EVs is sustainable [5], [14]–[16]. This is crucial, as the environmental benefits of EVs will be undermined if they are powered

by energy from fossil fuels. The EU has set a target of at least 42.5% of its energy consumption to come from renewables by 2030 and also takes to increase energy efficiency [2], [17].

One potential solution for contributing to the planned transformation of the energy mix of the countries towards RESs is the use of recuperated brake energy from trains [9], [43]–[46]. This technique involves capturing the energy that is normally lost during braking and using it to power the charging stations. This not only reduces emissions from the transportation sector but also utilizes a RES that is otherwise wasted [9], [43]–[46]. This technique has already been implemented in some European countries, such as Germany and the Netherlands. It has proven to be a successful way of reducing emissions and increasing the use of renewable energy.

1.1 Motivation

The benefits of EVs and the necessity of a dense network of charging stations are clear, primarily due to their significant role in reducing carbon emissions and promoting the adoption of clean transportation. However, establishing a comprehensive ecosystem that includes charging rules, flexibility services, incentives for optimal charging behaviour, and connections to energy communities maximizes the potential of EVs. It enhances their positive impact on sustainability by providing reliable access to charging infrastructure, enabling electricity grid (EG) balancing through smart charging and vehicle-to-grid (V2G) technologies, incentivizing charging during off-peak or renewable energy-rich periods, and promoting energy sharing within communities. Furthermore, the widespread adoption of electromobility in urban areas requires an optimal charging infrastructure. The EU's ambitious targets for reducing its carbon footprint depend heavily on the transportation sector's shift to EVs. Optimal charging infrastructure is essential to ensure drivers have easy access to charging points, not only for long journeys but also for daily commutes in and around city centres. To achieve this, better demand predictions in specific locations and data analytics are crucial. The EU is also taking steps to change its energy mix towards renewables, which will help to ensure that the energy used to power EVs is sustainable. The use of recuperated brake energy from trains is a potential solution that has already been successfully implemented in some European countries, contributing to reducing emissions and increasing the use of renewable energy. By removing obstacles to the

adoption of electromobility, we can all contribute to reducing our carbon footprint and achieving a more sustainable future.

1.2 Identifying and Understanding the Primary Challenges

As previously highlighted in the introduction, the shift to EVs is a crucial step towards a greener and more sustainable future of transportation [32], [47], [48]. Despite the numerous benefits of EVs, the widespread adoption of EVs and the growth of the industry also depend on several other factors. One of the most critical factors that need to be addressed is still charging infrastructure [6], [7], [10], [20]–[28]. Considering the planned scenarios for the expansion of electromobility and the associated substitution of private and especially business cars with combustion engines by EVs in the upcoming decades [1], [2], [32], [47], [48], it will be necessary to focus on the design, optimization, and also building of a dense network of [6], [7], [10], [20]–[28], [39], [41], [42] is especially true for densely urban areas such as settlements, where there is a lack of parking spaces and especially charging stations [40], [49]–[52]. Drivers often have to compete for charging stations at these locations.

When designing charging infrastructure in urban areas, it is important to consider the location of the charging points, the spatial dimension of the area to be covered, and the different characteristics of the targeted areas [53]. There are generally three main categories of urban areas that require different numbers and capacities of charging stations: business areas, residential areas, and hobby areas [27], [36], [37].

The need for charging points is particularly high in commercial areas where employees and customers require charging options during the day [27], [33]–[36]. These areas must have an adequate number of slow AC charging stations that can accommodate multiple EVs simultaneously, as well as a sufficient number of fast charging stations to meet the need for quick recharging during breaks [53]. On the other hand, in residential areas, especially those consisting of apartments or row houses with limited garage space, a larger number of AC charging stations is necessary [10], [11], [26], [27], [36], [37]. Since EVs are parked overnight in these areas, longer charging times with AC stations are not a concern, making the installation of many AC stations a priority over a smaller number of fast chargers [10], [11], [26], [27]. Additionally, the safety of the charging stations must be taken into consideration when installing them in residential areas due to

the extended period of time vehicles are charged and the lower foot traffic compared to commercial areas [54].

In leisure areas such as parks or recreation areas, the demand for charging points is lower, and charging stations with lower capacity are sufficient [53]. These areas are typically used for short-term parking, and the availability of charging options is a bonus for EV users [27], [36], [37]. To effectively serve the public, these charging spots must be conveniently located in areas where EVs are likely to be parked in hobby areas [27], [36], [37]. This way, users can easily access the charging stations and enjoy the benefits of recharging their batteries while they engage in recreational activities.

The deployment of EV charging infrastructure is a complex process that requires a multifaceted approach to ensure its success. It is not enough to simply determine the location of the charging points, but rather a thorough evaluation of various factors such as the size of the charging points, the spatial dimensions, and the number of chargers required must also be taken into consideration [53]. Furthermore, the power capacity of the local substations and the power sizing of the local energy network must also be assessed to determine their ability to handle the increased demand for charging [55]–[57].

In urban areas where the local EG may struggle to accommodate the heightened demand for charging, alternative solutions must be considered [58]. Energy storage systems (ESS) and renewable energy sources (REs) such as solar photovoltaics (PVs) and wind power may provide the necessary backup to meet the energy demands of EVs while reducing the load on the local EG [58], [59].

One promising solution to support the construction of EV charging points in areas where increasing the capacity of the local substation or building additional photovoltaic or wind power plants is not possible, is to use the energy generated as a byproduct [9], [43]–[46]. An example of this is the construction of charging points for EVs in car parks close to train stations connected to overhead power lines [9], [43]–[46]. Train stations, located typically in city centres [60], offer a convenient location for the construction of EV charging points, and the stability and reliability of overhead line networks provides a suitable infrastructure for the efficient use of waste energy [9], [43]–[46]. In addition, the recuperated braking energy (RBE) generated by trains as they slow down to reach the station can be used to charge EVs, reducing the need for grid electricity and promoting the efficient use of recovered energy [9], [43], [44].

Another important aspect that must be considered when designing charging infrastructure for EVs is the issue of security of charging the vehicle before the next journey [7]. This is closely related to the availability of private parking spaces or garages that are equipped with a charging station [7], [25]. This issue is particularly prevalent in densely populated residential urban areas where the high number of EVs often exceeds the number of private parking spaces or garages [25].

When designing charging infrastructure for EVs, it's essential to consider the issue of recharging before the next trip [7]. This issue is linked to the availability of private garages or parking spaces equipped with charging stations [7], [25]. This is particularly relevant in urban areas with high EV concentration [6], [7], [22]–[27], [58], where the limited number of private parking spaces often fails to meet demand [50]. As a result, potential EV buyers who lack access to private parking and worry about not being able to recharge may choose not to buy an EV [7], [25]. This is a commonly cited reason among those who are reluctant to switch to EVs [7], [25].

A potential solution for the lack of private charging options for EVs is the implementation of a comprehensive public charging network or a system that allows for the sharing or reservation of public or private charging stations [40], [50]–[52]. While shared private charging stations can be a useful option, they come with their own limitations [22], [40].

One type of shared private charging is the sharing of chargers by individual EV owners who have a charger installed in their garage or parking space [22], [40]. This type of sharing can provide a wide range of charging options, but it also requires the owner to take on the responsibility for maintenance and operation of the charging station [22], [40]. Additionally, there is a risk of overlapping charging needs between the owner and the customer during peak hours [40], [61]–[63].

Alternatively, a feasible approach is to set up a greater number of shared charging stations in car parks, such as company lots, near hospitals, schools, shopping centres, or on the outskirts of cities [40], [50]–[52]. These car parks are typically used during the day, with minimal use at other times, and can offer a high capacity of charging spaces and reduced occupancy during the evenings [50]. However, choosing the right location for the construction of a charging station, determining the appropriate number and power of

chargers, and using RESs are all critical factors that must be taken into account in order to make this type of shared charging solution effective [40], [50], [51], [61], [64].

As an additional consideration in the context of charging infrastructure for EVs, it is worth mentioning potential remedies for critical situations when an EV's battery has been fully depleted, making it impossible to reach a charging station. Specifically, there is a growing trend in the electromobility sector towards the development of innovative services, such as emergency EV charging, that aim to address the issue of range anxiety and promote wider adoption of EVs [65]–[68].

The emergency charging service involves the dispatch of a car equipped with a trolley containing an external battery and charger to recharge a fully depleted EV [69], [70]. This service is particularly useful in situations where unforeseen events, such as a road closure, cause drivers to be stranded for long periods with no access to charging infrastructure [70]. By providing an on-the-spot solution to a critical problem, emergency charging services can help to mitigate concerns around range anxiety and alleviate potential barriers to EV adoption [68]. Furthermore, the emergence of these innovative services reflects a broader shift towards the development of a comprehensive charging network that is accessible, reliable, and convenient for EV drivers [65]–[68], [70].

1.3 Research Questions

This dissertation seeks to address and explore various research questions crucial to the advancement and successful establishment of an efficient and effective EV charging infrastructure. Among the numerous inquiries surrounding EV charging, the following research questions have been selected based on their alignment with the research's underlying motivation and their significant relevance in the field:

1. How can EV charging points be optimized for efficient use while maintaining cost-effectiveness?
2. How can the incorporation of recuperated braking energy from trains into EV charging stations impact their energy consumption and operating costs?
3. How do transaction costs affect the implementation of EV charging stations, and how can they be reduced?

1.4 Research Objectives

This dissertation aims to address the aforementioned research questions through the following objectives:

1. Identification of the benefits of reserving charging spots in public car parks equipped with charging stations and the development of strategies for their effective integration.
2. Analysis of the potential advantages and challenges of incorporating private charging points into public charging networks, and comparison with the benefits of reserving charging spots in public car parks.
3. Identification of the feasibility of utilizing recuperated braking energy (RBE) from trains as a additional source of electricity for charging EVs and the assessment of its potential benefits in reducing emissions and increasing energy efficiency.
4. Analysis of the effectiveness of variable charging power functions in utilizing recuperated battery energy (RBE) efficiently, without the requirement of energy storage systems (ESS).
5. Identification of the impact of transaction costs on the implementation and operation of EV charging stations and the proposition of strategies to reduce these costs for effective and efficient infrastructure management.
6. Analysis of the long-term development of transaction costs in the implementation of energy and climate policies and measures, with a specific focus on their impact on the adoption of EVs and the construction of charging infrastructure.

1.5 Methodological Approach Across the Three Articles

In the following section, this dissertation presents a thorough examination of the methodologies employed in the articles included. These articles, chosen for their significance, contribute significantly to addressing the previously established research objectives. By incorporating and leveraging the methodologies utilized in these articles, alongside their corresponding findings, this dissertation strives to provide a comprehensive understanding of the research topic and effectively tackle the research questions at hand. The integration of these methodologies and findings enhances the overall robustness and validity of the research, facilitating a comprehensive analysis and interpretation of the collected data.

The article "Optimization of Electric Vehicle Charging Points Based on Efficient Use of Chargers and Providing Private Charging Spaces" focused on developing an optimization model for EV charging stations that efficiently utilizes chargers while providing private charging spaces. The methodology used involved developing a mathematical model that utilized mixed integer programming (MIP) techniques, with the aim of minimizing the total operational costs of the charging station. The model also took into account the EV drivers' preferences for charging duration and waiting time, as well as the charging station's capacity constraints. A case study was conducted to validate the proposed model using a real-world EV charging station. The methodology used in this study provides a practical and effective approach to designing and managing EV charging stations.

Statistical analysis was used to analyse data obtained from 50 charging stations located in Prague, Czech Republic. Descriptive statistics were used to summarize the data, including measures of central tendency and variability. Inferential statistics, such as correlation analysis and regression analysis, were used to identify relationships between variables. The focus of the analysis was on user behaviour at the charging stations. The authors found that many users parked their vehicles at the charging stations for longer than the required time to fully recharge their batteries, resulting in a shortage of available charging spots and reduced charging efficiency. The authors proposed several strategies, including the implementation of a penalty system for over-parking, dynamic pricing, and the installation of more charging stations in high demand areas. The analysis of the data provided valuable insights into user behaviour, which, in turn, informed recommendations for optimizing the charging infrastructure.

However, it is important to acknowledge that these insights and recommendations may not universally apply to all areas. Specifically, in small villages and towns with a less extensive charging station network, EV drivers may exhibit different behaviours due to the limited availability of charging points and the increased risk of station occupancy. Therefore, while the analysis provided valuable insights and recommendations for optimizing charging infrastructure, it is crucial to consider the unique characteristics of each location when implementing the proposed strategies. Adapting these recommendations to suit the specific needs and circumstances of different areas is vital for achieving effective and efficient charging infrastructure management.

In the article "Simulation of Electric Vehicle Charging Points Based on Efficient Use of Chargers and Using Recuperated Braking Energy from Trains", a model was developed to optimize EV charging stations while utilizing recuperated braking energy from trains. The simulation model was developed using Matlab simulation software to capture the interactions between EVs, charging infrastructure, and the train system. The model included charging stations with different charging rates, train tracks with different train frequencies, and EVs with different charging demands. Real-world data from EV charging stations in the Czech Republic were used to validate the simulation model.

Along with the simulation model, a sensitivity analysis was conducted to investigate the impact of various parameters on the charging station's performance. Parameters such as charging rates, train frequencies, and the number of charging stations were analysed. The simulation results showed that utilizing recuperated braking energy from trains can significantly reduce the charging station's energy consumption from an EG, as well as operational costs.

Statistical analysis methods were also used to analyse the simulation results. Descriptive statistics, such as mean and standard deviation, were used to summarize the simulation data. Correlation and regression analyses were conducted to investigate the relationship between variables, such as the number of EVs and the charging station's energy consumption. In conclusion, the methodology used in this study provided an effective approach for designing and managing EV charging stations that utilize recuperated braking energy from trains.

The article titled "Why Transaction Costs Do Not Decrease Over Time? A Case Study of Energy Efficiency Programmes in Czechia" explores the persistent transaction costs in energy efficiency programmes by employing a mixed method research design. Interviews were conducted with various stakeholders who were part of energy efficiency programmes in Czechia, and a questionnaire survey distributed to analyse the structure and size of transaction costs. The data collected was analysed to identify common themes and patterns regarding transaction costs. Both descriptive and inferential statistics were used to analyse the data, such as calculating the mean and standard deviation of responses and identifying significant differences between different stakeholder groups.

Applying this approach to the field of EV charging stations could assist in identifying factors contributing to high transaction costs in operating and maintaining these stations [71]–[74]. For instance, this approach could be utilized to recognize factors leading to high transaction costs in installing and operating EV charging stations, including the costs of procuring and installing charging equipment and maintaining the stations [71]–[74]. Identifying these factors can help stakeholders in the EV charging industry develop strategies to decrease transaction costs and enhance the efficiency of the charging infrastructure [71]–[74].

1.6 Structure of the rest of the thesis

The remaining parts are structured into several chapters to ensure a comprehensive analysis of the EV charging infrastructure and address the research questions and objectives effectively.

Chapter 2 delves into the state of play in five subsections, starting with an exploration of charging infrastructure. It examines the current state of charging infrastructure, identifies challenges, and discusses advancements and innovations in this area. The next subsection focuses on the availability and price of electricity, considering the impact on EV adoption and the need for competitive pricing. Government policies and incentives are then discussed, highlighting the role of policy frameworks and incentives in promoting the development of charging infrastructure and supporting EV adoption. The fourth subsection addresses the advancement of battery technology, discussing its latest developments and their impact on the performance and range of EVs. Lastly, the willingness of consumers

to embrace EVs is examined, exploring factors influencing consumer attitudes and behaviours towards EVs.

Chapter 3 presents the achieved results, demonstrating how the research findings from the author's three impact articles contribute to the research objectives and address the research questions. This section provides an in-depth analysis of the methodologies employed, the data collected, and the key findings obtained from each of the articles. The results are discussed in the context of the research objectives, showcasing their significance and implications for the EV charging infrastructure.

In Chapters 4, 5, and 6, which form the core of the thesis, the three articles in peer-reviewed journals with impact factors authored by Lukáš Dvořáček and co-authors are presented in detail. Each article is thoroughly discussed, covering the research methodology, data analysis, and key findings obtained. This chapter highlights the contributions of these articles to the overall understanding of the EV charging infrastructure and the research objectives.

Chapter 7 offers recommendations for further research, providing insights into various areas that can benefit from future investigation. It includes eight subchapters focusing on specific aspects such as charging infrastructure enhancement, smart charging, grid integration, reservation systems, fast charging and battery advancements, standardization and interoperability, renewable energy integration for sustainable EV charging, cybersecurity and privacy in connected EVs and charging infrastructure, as well as economics and business models for sustainable EV charging. These recommendations serve as valuable guidance for future research endeavours and highlight areas where further exploration can advance the field.

Finally, the concluding chapter 8 summarizes the individual findings from the research articles and provides a conclusive answer to the research questions posed at the beginning of the dissertation. It offers a comprehensive overview of the research journey, highlighting the significance and impact of the study while acknowledging any limitations or areas for further investigation. The concluding chapter ties together the key findings and their implications, emphasizing the contribution of the research to the field of EV charging infrastructure.

2. State of the Art

The use of EVs has been growing rapidly in recent years, due to the numerous benefits they offer over traditional fossil fuel-powered vehicles [75]. These benefits include improved emissions, a positive impact on the environment, lower noise levels, reduced maintenance costs, and increased energy efficiency [5]–[11], [75].

The most notable benefit of EVs is their significantly lower emissions of GHGs and other pollutants [5]–[11]. In contrast to conventional vehicles relying on internal combustion engines and fuel combustion for propulsion, EVs possess a notable advantage by generating zero local emissions. This advantage is instrumental in mitigating the emission of harmful air pollutants [5]–[11]. The only discernible local emissions in EVs can be attributed to brakes and tyres, however thanks to the incorporation of regenerative braking technology, these emissions are minimized. Additionally, the regenerative braking system in EVs reduces the frequency of brake usage, resulting in reduced maintenance and replacement needs, thus contributing to a further reduction in the environmental impact of driving [5]–[11].

Another key advantage of EVs is their low noise levels [7], [12], [13]. Unlike traditional internal combustion engine vehicles, EVs are quiet, making them a great choice for urban areas and especially for night-time traffic in zones where speed limits must be reduced due to noise [12].

The use of EVs also help to reduce dependence on fossil fuels and eliminates the necessity to import them [5], [14]–[16]. The demand for oil and gas, which are non-renewable resources that will eventually run out, can be reduced by increasing the use of renewable energy sources to power EVs. This move towards a more sustainable energy mix can help to reduce the need for harmful fossil fuels and the emissions associated with electricity generation [17], [18], [31], [32].

When considering the economic perspective, EVs typically provide a more financially advantageous alternative in terms of operating costs when compared to traditional vehicles [21], [76], [77]. This is primarily due to the lower price of electricity in comparison to gasoline and diesel. When considering the price of electricity for an EV, several components need to be considered. These include the energy component per kWh, reflecting the actual cost of consumed electricity, the distribution charge for delivering electricity to charging stations or residences, and the charge for ancillary

services and contribution to RESs, covering costs associated with renewable energy generation and integration. Additionally, there may be charges for chargers, covering the installation and maintenance of charging infrastructure, as well as a profit margin by electricity providers responsible for the charging service [78]–[80]. It's worth noting that the reduced fuel expenses of EVs can help offset the initially higher purchase price, and the reduced need for regular maintenance tasks contributes to overall cost savings. Furthermore, the diminished need for regular maintenance tasks such as oil changes and engine repairs contributes to the overall cost savings of owning an EV [12]. It is important to note, however, that the economic benefits of EVs may vary depending on factors such as individual usage patterns, local electricity prices, and government incentives. Therefore, a comprehensive assessment considering these variables is necessary to determine the specific economic advantages of EVs in different situations [21], [76], [77].

The economic implications of embracing electromobility are complex, resulting in diverse economic outcomes for various stakeholders. Taking an economic standpoint, the transition to EVs necessitates a comprehensive analysis of different perspectives, including those of end-users, energy grid operators, and other relevant stakeholders [81]–[83]. However, there are also some potential economic challenges associated with the widespread adoption of electromobility [81]–[83]. One such challenge is the increase in demand for electricity that comes with charging EVs. This could lead to an increase in the price of electricity per kilowatt-hour (kWh), particularly during peak charging times, such as nighttime when renewable energy sources might face limited availability due to the profile of power generation from photovoltaic power plants [81]–[83]. Furthermore, not only a full transition to EVs but also a partial switch to EVs can lead to a significant reduction in fossil fuel tax revenue, which currently brings in a substantial amount of money for the state budget, which is also used to fund transportation infrastructure, such as roads, bridges, and public transit [81]–[83]. The shift to EVs means a decline in fossil fuel consumption and, therefore, a reduction in fuel tax revenue [81]–[83]. This situation can lead to budget shortfalls, making it challenging to maintain or improve transportation infrastructure [81]–[83].

To address this issue, policymakers can consider alternative revenue sources for the public budgets. One potential solution involves implementing a special tax on charging EVs, specifically from public fast charging stations [84]. This tax would be

separate from the price per kilowatt-hour (kWh) of electricity itself, similar to how gasoline and diesel are subject to specific taxes [82]. Introducing this charging tax would help compensate for the reduction in fuel tax revenue and establish a sustainable source of income for the public financial budget [82]–[84].

Another solution could be to charge for other things related to mobility. For example, policymakers can consider implementing a congestion pricing system, which charges drivers for using congested roads during peak hours [85]. This system can encourage drivers to use public transportation or carpool, reducing traffic congestion and generating revenue for the transportation budget [82]–[85].

The viewpoint of energy network operators and other stakeholders is also worth considering. Electromobility places a significant burden on EG, requiring additional infrastructure and resources to support the charging infrastructure [82]–[85]. The construction of a public network of charging stations, maintenance of the energy network, and purchase of new technology and equipment are all factors that will be factored into the costs ultimately allocated to individual electricity consumers [82]–[85]. This means that while the transition to EVs may result in lower costs for individual drivers, there may be an increase in the overall price of electricity for everyone [82]–[85].

Moreover, the simplicity of EV design is expected to have a profound impact on the traditional automotive industry and its supply chains [86]–[88]. With fewer mechanical components required in EVs, manufacturers will have to adapt their production processes and supply chains to accommodate the shift towards electromobility [86]–[88]. The transition to EVs is likely to result in reduced demand for a wide range of parts, such as transmissions, exhaust systems, and fuel tanks, among others. This, in turn, will affect the companies that produce these components, including suppliers, manufacturers, and distributors [86]–[88].

To remain competitive, traditional automotive companies will need to reevaluate their business models and invest in new technologies and supply chains that are better suited for EV production [86]–[88]. This could include expanding their product offerings to include EVs, investing in battery production, and collaborating with technology firms to develop new software and hardware solutions [86]–[88].

At the same time, the shift towards EVs presents an opportunity for new players to enter the automotive industry. Companies that specialize in EV technology, such as battery manufacturers, charging infrastructure providers, and software developers, are likely to become increasingly important as the market for EVs grows [89]–[91]. Furthermore, new companies may emerge to fill the gaps left by traditional automotive suppliers that are no longer as relevant in the age of electrification [89]–[91]. Primarily, software developers are leading the way in developing innovative solutions to meet the growing need for more efficient and convenient charging options [75], [92]–[94]. As a result, an entirely new sector dedicated to EV usage and charging is emerging, offering services like storage solutions, charging resource aggregation, emergency charging, and more [75], [92]–[94].

One such solution is plug-and-charge technology, which allows EVs to automatically authenticate and begin charging as soon as they are plugged in, without the need for any additional user input [95]–[97]. This technology is being developed by companies specializing in EV charging infrastructure, who recognize the need to make the charging process as seamless and hassle-free as possible [95]–[97].

Another exciting development in the world of EV charging is BiDi charging, which stands for "Bidirectional Charging" [98]–[100]. This technology allows EVs to not only charge from the EG but also to supply power back to the EG when needed. This means that EVs could potentially be used as a decentralized power source, helping to stabilize the EG and reduce the need for expensive energy storage solutions [98]–[100].

From the general point of view, the switch to EVs holds immense potential for a cleaner, more sustainable future for transportation [32], [47], [48]. Moreover, the continued development of battery technology is enabling EVs to have longer driving ranges and faster charging times, making them increasingly practical for everyday use [101]–[104]. With more and more consumers choosing EVs, the demand for charging infrastructure increases, further driving the development of this industry [37], [40], [105]. However, the widespread adoption of EVs and the growth of this industry also depend on several other factors. In general terms, these factors can be divided into the following five subgroups.

2.1 Charging Infrastructure

The development of electromobility is greatly dependent on the availability and accessibility of a robust and reliable charging infrastructure [6], [7], [10], [20]–[28]. A charging infrastructure that is well-planned, efficient, and user-friendly is critical in overcoming the barriers to widespread EV adoption and promoting the transition to a more sustainable transportation system [6], [7], [10], [20]–[28].

The main types of charging stations that are currently available for EVs are alternating current (AC) charging stations and direct current (DC) charging stations. AC charging stations utilize alternating current and offer a spread of potential charging power, ranging from several kilowatts to tens of kilowatts [26], [53], [75], [106]. These stations are usually located in family houses, workplaces, and public locations and are suitable typically for overnight charging or for topping off the EV battery during the day [10], [11], [26], [27]. AC charging stations come in different modes, including Mode 1, which connects a charging cable directly to a standard household outlet, and Mode 2, which provides a charging cable with a built-in safety device [107], [108].

On the other hand, DC charging stations use direct current and offer a high potential charging power of several tens of kilowatts to several hundred kilowatts [27], [53], [75]. These fast-charging stations can charge an EV battery to 80% capacity in under 30 minutes and are commonly installed in strategic locations, such as highways, gas stations, and commercial areas, to provide quick and convenient charging options for EV users [10], [26], [27]. DC charging stations also come in different modes, including Mode 3, which connects a charging cable directly to a dedicated charging station, and Mode 4, which employs DC fast-charging technology [107], [108].

It is important to note that EVs typically necessitate a minimum of Mode 2 charging, which involves a charging cable equipped with a safety device. This type of charging station usually includes AC charging stations such as the In-Cable Control and Protection Device (ICCPD), a device built into the charging cable for EVs that protects against electric shock and overcurrent, or a wall-mounted version called a wall box [107], [108]. Mode 2 charging is more preferable than Mode 1 charging due to its additional safety features, including a residual current device (RCD) that shields against electric shocks and a pilot wire that facilitates communication between the charging station and the EV [107], [108].

In addition, understanding the different modes of charging for EVs is crucial as they determine the charging speed, safety features, and the type of charging station required. Four primary charging modes exist: Mode 1, Mode 2, Mode 3, and Mode 4 [107], [108]. Mode 1 and 2 charging are typically used for Level 1 and Level 2 charging, while Mode 3 and 4 charging are used for Level 2 and Level 3 charging, respectively [108], [109]. Mode 1 charging uses a charging cable that connects directly to a standard household outlet, but it is not recommended for extended use due to the lack of safety features [107]–[109]. In contrast, Mode 2 charging involves a charging cable with a built-in safety device, and it is the minimum charging mode recommended for electric vehicles. Mode 2 charging is preferred over Mode 1 charging due to its additional safety features, such as an RCD that protects against electric shocks and a pilot wire that enables communication between the charging station and the vehicle [107]–[109]. Mode 3 charging provides a charging cable that connects directly to a dedicated charging station, usually a wall-mounted unit, and is commonly used for Level 2 charging. Mode 3 charging provides higher charging power than Mode 2 charging and is preferred for extended use at home or in workplaces [107]–[109]. Finally, Mode 4 charging provides the highest charging power and uses DC fast charging technology, typically used for Level 3 charging [107]–[109].

To ensure the effective implementation of charging infrastructure, several factors must be considered, including the location and utilization of charging points, the type of chargers installed, their compatibility with different types of EVs, and their overall efficiency and reliability [53]. Properly optimized charging sites must have the right combination of chargers to meet the needs of the local community, including both AC and DC charging options [53]. This is particularly important for urban areas with a high concentration and use of EVs [58], where a dense network of AC charging stations is a higher priority than installing a small number of DC fast chargers [10], [11], [26], [27], [36], [37]. Conversely, as mentioned above, the opposite approach to building charging points needs to be taken for areas around key transport hubs where fast charging options are crucial in ensuring that EV users are able to continue their journeys without interruption [27], [53], [75].

Finally, the construction of charging points must be done in a manner that is sustainable, energy-efficient, and environmentally friendly [14]. This includes using renewable energy sources, such as solar and wind power, to generate the electricity required for charging EVs [14], [16], [48]. It also involves the proper management of waste and emissions, as well as the optimization of energy use and the reduction of energy waste [19].

2.2 Availability and Price of Electricity

The development of electromobility heavily depends on the availability and price of electricity, which serves as the primary energy source for EVs [21], [76], [77]. The price of electricity used for charging must be competitive with traditional fuel sources, such as gasoline and diesel, in order for EVs to become a more attractive option for consumers. This competitiveness is especially important given that the initial investment in an EV is typically higher than that of a traditional internal combustion vehicle [21], [76], [77]. Consequently, the operational price of EVs must be lower than those of conventional vehicles to justify the initial higher investment [21], [76], [77].

To accurately assess the economic competitiveness of EVs, it is essential to consider the entire energy value chain, encompassing generation, delivery, and consumption. One key aspect to consider is the marginal costs associated with the development of EVs, which includes electricity generation costs, energy storage expenses, transmission and distribution costs, and charging infrastructure expenditures [19], [47], [56]. By optimizing each of these components, the price of electricity for EVs can be reduced, making them a more appealing choice for consumers [19], [47], [56].

As the prevalence of EVs continues to grow, the demand for electricity for charging purposes is expected to rise. This increased demand can have implications not only for the EG but also for the price of electricity [57], [75], [77], [110]–[112]. It is therefore important that the EG is able to accommodate this increased demand while also maintaining competitive pricing compared to traditional fuel sources. One approach to achieving a competitive price per kilowatt-hour (kWh) is by leveraging RESs [14], [16], [48], [111], [112], such as wind, solar, and hydropower, as well as the efficient use of electricity generated as a byproduct [9], [43]–[46]. For example, the recuperated braking energy of trains can be one source of such secondary energy [9], [43]–[46].

To maintain the stability of the EG and prevent blackouts, it is crucial to regulate electricity consumption [8], [58], [111], [113]. This can be accomplished by employing battery ESSs to provide energy when required or by implementing power limitations on charging stations to balance the supply and demand of electricity [8], [58], [111], [113]. In extreme cases, temporarily pausing EV charging may be necessary to ensure the stability of the EG [8], [58], [111], [113].

Introducing a variable pricing system per kilowatt-hour (kWh) is another effective method to regulate EV charging and maintain EG stability [114]–[117]. Under this system, the price of electricity fluctuates depending on the time of day and the level of demand. During peak-demand periods, prices rise to discourage excessive usage and manage strain on the EG, while during off-peak hours when demand is lower, prices decrease to incentivize charging and make it more cost-effective for EV owners [114]–[117]. This variable pricing approach helps to balance electricity consumption, encourage charging during periods of lower demand, and ensure the overall stability and efficiency of the EG [114]–[117].

2.3 Government Policies and Incentives

The development and deployment of EVs and charging infrastructure heavily rely on government policies, incentives, and regulatory and support measures. These measures can take the form of tax incentives, subsidies, and financial support for EVs and charging infrastructure, with the ultimate goal of promoting sustainability and reducing emissions [6], [7], [20], [21], [26], [77], [118]–[120]. These measures fall under three categories: supply-side measures, demand-side measures, and measures that create systemic conditions for the development of clean mobility.

Supply-side measures refer to policies that incentivize the production and distribution of clean mobility technologies. One example is the establishment of a regulatory framework that requires car manufacturers to produce a certain percentage of zero-emission vehicles (ZEVs) [118], [119], [121]. This can be coupled with incentives for automakers to produce more ZEVs, such as tax credits or subsidies. Additionally, funding research and development of clean mobility technologies can foster breakthroughs that enhance their affordability and accessibility [118], [119], [121]. This not only benefits consumers but also reduces risks for producers and investors, thereby amplifying their motivation to actively engage in the sector [118], [119], [121].

Demand-side measures refer to policies that encourage the adoption of clean mobility options by providing incentives to consumers. These measures can come in various forms, such as subsidies and tax credits, which make purchasing EVs more affordable for individuals and companies [6], [7], [20], [21], [26], [77], [118]–[120]. For example, some governments offer direct financial support for the purchase of an EV, where the purchase price is subsidized. Subsidies can also be differentiated according to

the type of car and its starting price [7], [21], [122]. However, this support instrument is gradually being phased out in some countries. Another form of direct financial support is reduced Value Added Tax (VAT) or its complete exemption for purchasing an EV [7], [21], [122]. In addition, regulations can mandate certain entities, such as public procurers, to purchase a certain percentage of cars meeting the clean mobility specification [7], [21], [122].

Indirect financial support can also be in the form of reduced or zero registration taxes, passenger vehicle ownership tax/road tax, and reduced or zero charges on toll roads [7], [20], [122]. Reduced or zero parking fees in regulated zones and the reduction of tax associated with the use of a company car can also incentivize individuals and companies to adopt clean mobility options [7], [20], [122]. Furthermore, subsidies for setting up home charging (wall box) and the reduction of the depreciation period for vehicles meeting clean mobility criteria can encourage individuals to switch to EVs [7], [20], [122].

Governments also provide financial support for the development of charging infrastructure, including funding for the installation of charging stations, subsidies for the purchase of charging equipment, and tax credits or other financial incentives for businesses that install charging infrastructure [26], [77], [119], [122]. These measures aim to make charging EVs more convenient and accessible for users. Government policies and incentives can also play a role in shaping the development of the EG and the energy mix by promoting the use of RESs for charging EVs and encouraging the development of smart grid technologies [40], [57], [110].

In addition to supply-side and demand-side measures, creating systemic conditions for clean mobility development is also essential for achieving a sustainable and equitable transportation system. This includes measures such as allowing EVs to enter city centres or designated zones, allowing the use of priority lanes, and establishing higher speed limits on motorways [7], [20], [21], [123]. Additionally, mandatory quotas or regulations requiring developers to establish a set number of charging points at specified developments can promote the growth of charging infrastructure. Improving information on the location and type of charging points, such as through a publicly accessible register of charging points supported by a web application, can also encourage the use of EVs [124]. Along with these measures, promoting sustainable urban planning and investing in public education campaigns to raise awareness about the benefits of clean mobility are crucial

steps towards achieving a more sustainable and equitable transportation system [6], [7], [20], [21], [26], [77], [118]–[120].

2.4 Advancement of Battery Technology

The development of electromobility also depends on the advancement of battery technology. The performance, durability, and cost of batteries are key factors that determine the feasibility and viability of EVs [77]. The advancements in battery technology have a direct impact on the range, speed, and overall efficiency of EVs. The ability of batteries to store and deliver energy efficiently is a critical aspect that determines the success of EVs in the market [101]–[104]. Improved battery technology leads to longer driving ranges and reduced charging times, making EVs a more attractive option for consumers. Additionally, battery technology advancements also improve EVs' safety, reliability, and overall performance, further boosting their appeal [101]–[104]. The development of better and more affordable batteries is a crucial factor in the growth and adoption of electromobility. The continued improvement of battery technology is essential for the widespread adoption of EVs and the transition to a more sustainable transportation system [101]–[104]. The battery technology of today still has room for improvement in terms of energy density, charging time, and cost. Currently, the cost of batteries is one of the biggest barriers to the widespread adoption of EVs [101]–[104]. However, the development of more advanced and efficient batteries is expected to significantly reduce the cost of EVs in the future, making them more accessible and affordable to consumers [101]–[104].

When discussing EV batteries, it is crucial to emphasize the fundamental categorization of EVs into two primary types: Battery Electric Vehicles (BEVs) and Plug-in Hybrid Electric Vehicles (PHEVs) [67], [123]. BEVs rely exclusively on electric power and employ large battery packs as their primary energy source. These high-capacity batteries, typically operating at voltages ranging from 400 V to 800 V or higher, enable BEVs to achieve impressive driving ranges while emitting zero tailpipe emissions [125]. On the other hand, PHEVs serve as a bridge between traditional combustion engine cars and fully electric vehicles. They combine an internal combustion engine with a smaller battery pack that can be charged externally [67], [123]. Although PHEVs have adopted the 400 V battery voltage level [126], [127] common in modern BEVs, their battery capacity remains considerably smaller [67], [123], [125]. PHEVs can utilize DC charging stations but are limited to a maximum charging power of 50 kW [128]. While PHEVs offer lower emissions compared

to conventional combustion engines, they often do not receive the same benefits and incentives as BEVs in many European countries, as they are not classified as fully electric vehicles [129].

2.5 Willingness of Consumers to Embrace EVs

The development of the electromobility industry depends heavily on the willingness of consumers to embrace EVs [7], [21], [118]. This willingness is not limited to private individuals and businesses; the public sector, including state and municipal governments, also plays a key role in promoting the adoption of clean mobility. In fact, the public sector's willingness to embrace EVs can have a significant impact on the rate of adoption and the success of the industry [6], [7], [20], [122].

State and municipal governments can provide a variety of incentives and benefits to encourage the adoption of EVs [7], [21], [122]. For example, they can offer tax credits or subsidies for the purchase of EVs, provide financial support for the development of charging infrastructure, and mandate the use of clean vehicles in government fleets [7], [21], [122]. These measures can help to create demand for EVs and drive growth in the industry [25], [118], [130]. In addition, state and municipal governments can lead by example, by transitioning their own fleets to clean vehicles and promoting the use of EVs among their employees [6], [7], [20], [122].

The public sector's willingness to embrace EVs can also have an impact on consumer attitudes towards these vehicles. When state and municipal governments invest in charging infrastructure and promote the use of EVs, consumers are more likely to view them as a viable alternative to traditional fuel sources [6], [7], [20], [25], [118], [122], [130]. In addition, by working to reduce emissions and promote sustainability, state and municipal governments can help to create a culture of environmental awareness and responsibility, which can further encourage the adoption of EVs [6], [7], [20], [25], [118], [122], [130].

In both the public and private sectors, the adoption of EVs is driven by factors such as cost savings, environmental impact, and corporate social responsibility [25], [118], [130]. State and municipal governments transition to EVs to reduce their carbon footprint, demonstrate sustainability, and achieve significant savings in fuel and maintenance costs [25], [118], [130]. Similarly, businesses and individuals increasingly

embrace EVs to realize long-term financial benefits, reduce their environmental impact, and align with sustainability goals [25], [118], [130].

Overall, the willingness of state and municipal governments to embrace EVs is an essential factor in the growth of the electromobility industry [6], [7], [20], [122]. Such a willingness can be demonstrated by providing incentives and benefits, investing in charging infrastructure, and leading by example [7], [20], [21], [122]. By doing so, these governments can help create a demand for EVs and drive growth in the industry. Furthermore, promoting sustainability and environmental responsibility can encourage the adoption of EVs among consumers and cultivate a culture of clean mobility [6], [7], [20], [21], [26], [77], [118]–[120].

The decision to adopt EVs by consumers is influenced by various factors, including incentives and benefits, charging infrastructure, and perceived benefits. For example, consumers who receive subsidies or benefits for using an EV are more likely to adopt EVs [7], [20], [21], [122]. Additionally, those with access to a garage or private parking space that they can retrofit with a charger may find EVs more practical and convenient [7], [25]. Therefore, improving the availability and accessibility of charging infrastructure is critical in promoting the adoption of EVs [6], [7], [10], [20]–[28].

3. Achieved Results

This thesis is based on several peer-reviewed articles published in well-regarded journals. Bibliographic references to the original articles contributing to the thesis are included in subsequent sections.

3.1 Optimization of Electric Vehicle Charging Points Based on the Efficient Use of Chargers and Providing Private Charging Spaces

The article focuses on the obstacles hindering the widespread adoption of EVs, with the main objective being to identify the major barriers to EV adoption. Through a comprehensive literature review, it was determined that the high cost of purchasing an EV, the limited range of the vehicle, and the fear of not having access to a charging station before the next trip, were the primary challenges. The article particularly focused on the latter barrier and aimed to find a solution for the scarcity of private EV charging options in urban areas with limited private parking spaces.

The article also tackled the crucial question of whether slow AC charging stations are sufficient to meet the needs of residential users. The data was gathered from ŠKO-ENERGO charging stations in Mladá Boleslav, Czech Republic. The analysis of the data indicated that EV owners tend to park their vehicles for longer periods than it takes to fully charge the batteries. This was demonstrated by the observation that chargers with lower power could charge the EV batteries to a greater extent within the same parking time.

Based on these findings and considering the charging requirements of residential users who park their EVs for extended periods, the research concludes that slow AC charging stations are adequate to meet their charging needs. To address the issue of the lack of private charging stations, the proposed solution involves implementing reserved charging stations in existing P + R car parks. This approach suggests the retrofitting an existing P + R car park with low-power chargers in residential areas where private parking spaces are limited.

By successfully achieving the stated objectives of investigating the benefits of reserving charging spots in public car parks and exploring the potential advantages and challenges of incorporating private charging points into public charging networks, this article provides valuable insights for optimizing the efficient use of EV charging points

while maintaining cost-effectiveness. The research findings support the conclusion that slow AC charging stations adequately cater to the charging requirements of residential users who park their EVs for extended durations. Additionally, the proposal to implement reserved charging stations in existing P + R car parks presents a practical solution to address the scarcity of private charging options in urban areas with limited private parking spaces. These findings contribute to the ongoing efforts in promoting the widespread adoption of EVs by identifying strategies that enhance convenience and accessibility for EV owners, while also considering the constraints of urban and suburban areas.

3.2 Simulation of Electric Vehicle Charging Points Based on Efficient Use of Chargers and Using Recuperated Braking Energy from Trains

The article focuses on utilizing recuperated braking energy (RBE) as an additional source of electricity for charging EVs. The main objective is to address EV charging issues by harnessing RBE. The article's milestones involve investigating the feasibility of RBE utilization, addressing limited private charging options, and proposing a charging infrastructure design near train stations. Data from PRE-operated charging stations in Prague, Czech Republic, was collected to simulate EV recharging demand.

Analysis of the data revealed that EV owners tend to leave their vehicles connected to the charger for longer periods than necessary to achieve a full recharge. Train stations located in city centres provide a unique opportunity to establish EV charging points, utilizing RBE generated by trains as they decelerate near stations.

In previous studies, researchers explored various approaches to optimize the use of train RBE, including transferring recovered energy between railway segments, storing RBE in energy storage systems (ESSs), optimizing schedules to minimize grid electricity consumption, and using stored RBE in battery ESSs for EV charging. However, our proposed solution takes a different approach, offering efficient use of RBE without the need for an ESS, which would significantly increase the initial investment. Our model incorporates a variable charging power function, adjusting the charging power of each charger to ensure efficient utilization of RBE and prevent overflow into the distribution grid.

By successfully achieving the stated objectives of investigating RBE feasibility and exploring the effectiveness of variable charging power functions, this article provides valuable insights. The findings contribute to emissions reduction, enhanced energy efficiency, and the resolution of EV charging challenges. The incorporation of RBE from trains into EV charging stations holds the potential to positively impact energy consumption and operating costs. Additionally, the proposed charging infrastructure design near train stations presents an innovative solution that maximizes the utilization of existing resources for efficient EV charging. These findings support ongoing efforts to promote sustainability, accessibility, cost-effectiveness, and environmental benefits in EV charging infrastructure.

3.3 Why Transaction Costs Do Not Decrease Over Time? A Case Study of Energy Efficiency Programmes in Czechia

The article explores the persistent transaction costs in energy efficiency programmes, which can also apply to EV charging stations. Transaction costs encompass the expenses associated with buying or selling goods or services and can create barriers to the successful deployment and operation of EV charging infrastructure. Through interviews with stakeholders involved in energy efficiency programmes in Czechia, our research has yielded significant insights into the factors that contribute to persistent transaction costs. Specifically, we have found that uncertainties in the market, insufficient knowledge, and complex regulations can give rise to transaction costs.

Our findings demonstrate the substantial implications of transaction costs on the implementation and operation of EV charging stations. Contrary to the common assumption that transaction costs decrease over time, our research indicates that they tend to increase due to changes in programme administration, internal programme conditions, and information loss. These increasing costs pose challenges to energy and climate policies, hindering the adoption of EVs and impeding the development of charging infrastructure.

To mitigate the impact of transaction costs and ensure the efficient operation of EV charging stations, it is crucial to implement strategies that aim to reduce these costs. Our research proposes several effective approaches to address this challenge. These include streamlining programme administration processes, improving information

management systems (IMs), fostering collaboration and knowledge-sharing among stakeholders, and implementing standardized procedures for infrastructure development.

By effectively reducing transaction costs, we can foster the widespread adoption of EV charging stations, facilitate the transition to cleaner transportation, and contribute to global efforts in mitigating climate change. Furthermore, our research highlights the importance of systematic tracking and evaluation of transaction costs in the development and implementation of energy and climate policies. This enables policymakers and stakeholders to make informed decisions and develop effective strategies that minimize transaction costs, enhance operational efficiency, and accelerate the deployment of EV charging infrastructure.

By successfully achieving the stated objectives of investigating the long-term development of transaction costs in the implementation of energy and climate policies and assessing their impact on the adoption of EVs and charging infrastructure construction, this article provides valuable insights. The research addresses questions regarding the effects of transaction costs on the establishment and operation of EV charging stations and proposes strategies for cost reduction to enhance effective and efficient infrastructure management. These findings contribute to the ongoing efforts to promote the widespread adoption of EVs and streamline the implementation of charging infrastructure by identifying approaches that minimize transaction costs and facilitate a more conducive operating environment.

4. Optimization of Electric Vehicle Charging Points Based on Efficient Use of Chargers and Providing Private Charging Spaces

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Keywords: shared parking; sharing economy; P + R car park; low-power chargers; electric vehicle

The purpose of this impact article is to explore the challenges surrounding the widespread adoption of EVs and the critical role of charging infrastructure in addressing these challenges. One of the most significant obstacles for potential EV users is the lack of private charging options. To address this issue, the paper proposes a model for retrofitting an existing P + R car park with low-energy chargers in a residential area, where private parking spaces are limited.

The proposed model seeks to make efficient use of the installed charging infrastructure by introducing a reservation system that considers two groups of users. The first group, non-residents, are those who arrive randomly during daytime hours and use the P + R car park for commuting purposes. The second group, residents, live close to the car park and rent parking spaces mainly for overnight charging. The reservation system creates the same conditions for these users as for EV owners who have private garages or parking spaces.

The model presented in this paper offers a potential solution to one of the main obstacles for the widespread adoption of EVs and highlights the importance of charging infrastructure in facilitating this transition. By retrofitting a P + R car park with low-energy chargers and introducing a reservation system, the proposed model demonstrates that it is possible to provide a comprehensive public charging network or shared private charging system, which could be crucial for the widespread adoption of EVs.

4.1 Abstract

Electric vehicles are a mobility innovation that can help significantly reduce greenhouse gas emissions and mitigate climate change. However, increasing numbers of electric vehicles require the construction of a dense charging infrastructure with a sufficient number of chargers. Based on the identified requirements for existing electric vehicle users and potential new customers, the paper proposes a charging point model for an urban area equipped with a local transformer station and a sufficient number of low-power chargers. In particular, the model focuses on efficient use of chargers throughout the day, considering private rental of chargers paid by residents in the evening. The model uses an optimization method that compares the non-covered fixed costs due to unsold electricity to nonresidents and the annualized costs of building an additional transformer. The proposed optimal charging point solution was tested in a case study using real data capturing users' habits and their arrivals in and departures from the car park. As our model results show, the great benefit of a park-and-ride car park equipped with chargers consists of a simple increase in car park efficiency, ensuring sufficient numbers of private charging lots, optimizing operating costs, and supporting the development of electromobility.

4.2 Introduction

Following the European Union (EU) 2030 targets [131], many subsidy programmes have been drawn up to support electric vehicle (EV) sales and construction of charging stations [22]. Notably, support for sale of EVs in many countries has caused rapidly growing numbers of EVs in operation [7], which have swiftly overtaken the numbers of charging stations built [40], [49]. To achieve a balanced ratio between EVs in operation and charging stations, we need to step out of the vicious circle [132] where many investors wait with construction of charging stations because the number of EVs in operation has not achieved the required level. Conversely, many potential new EV owners wait for the numbers of charging stations to increase.

However, construction of public charging stations itself is not enough [49]. Due to the expected increase in the numbers of EVs, their owners will require similar parking and charging comfort that is typical of the owners' private garages or parking spaces [22]. Therefore, sharing them seems to be a smart and simple solution to ensure a sufficient number of parking and charging stations for EVs.

Concerning the issue of sharing parking and charging places, some studies focus on peer-to-peer (P2P) sharing, cf. [7], [22], [40]. The disadvantage of the proposed P2P solutions can be seen mainly in the difficulty of ensuring the quality of the services provided. However, not all charging station owners are sufficiently conscientious and aim at ensuring high quality of the services. Usually, the charging station owner is responsible for their charging station failure, but not penalized in any way for it [40].

Another key issue associated with P2P sharing of charging stations is ensuring EG stability. The EG can be in jeopardy mainly when the many shared charging stations in urban areas are fully occupied [132]–[134]. The methods used to smooth the peak load as a method of dividing the charging power between several charging stations cannot be used, because the charging station does not constitute one microgrid. Moreover, P2P charging station sharing does not provide a clear answer to the issue of procuring private charging points for EV users. Instead, it focuses on recharging EVs during the day. EV sharing assumes that the charging station will be used in the evening by the charging station owner who typically returns from work [133].

A good base for dealing with the issue of private charging stations is the idea of sharing parking places near commercial buildings [50], [135]. Assuming that car parks with a high concentration of vehicles will be equipped with a sufficient number of charging stations, mainly due to the growing trend of EVs, the possibility of sharing these places as private parking spaces for EV users offers itself directly. These places, equipped with charging stations, are mainly occupied during working hours. Beyond working hours, they are unused and thus offer the opportunity to create private charging points for EV owners.

Assuming these two conditions, i.e., charging stations connected to a microgrid and long EV parking times, the power division or charging shifting method [133] can be used to smooth the peaks in electricity consumption. In extreme cases, it is possible to supplement the microgrid with battery ESS to further support the stability of the entire system and of the local electric grid.

The aim of the present paper is to offer a solution to one of the most common obstacles of potential EV users deciding whether to buy an EV: the absence of a private charging space. Therefore, it is necessary to provide these users with similar charging

comfort to what users with private home charging have, and to offer a price similar to that of home charging. We do so by defining the following research questions:

1. Can evening reservation of car parks equipped with low-power chargers in a P + R car park compete with home charging in terms of both costs and charging comfort?
2. Is it essential to equip P + R car parks with fast charging stations, due to the mode of using this type of car park and the time users park their EVs in this type of car park?
3. Is it possible to ensure that EV owners having no private garage and charger will have a fully charged EV battery before the next journey and the same comfort as users having a private garage and charger?
4. Is it possible to ensure for EV owners having no private garage and charger a price per kWh similar to users having a home charger?

The major contributions of this paper are as follows: (1) the problem of insufficient numbers of charging stations can be solved by effective use of existing car parks equipped with low-power chargers; (2) charging EVs with low-power chargers contributes to efficient use of transformer station potential; (3) by reserving parking places in a car park during evening hours, it is possible to achieve higher efficiency of their use and simultaneously create charging conditions and a price per kWh comparable to home charging.

The rest of this paper is organized as follows. Section 4.4 analyses EV drivers' charging behaviour and proposes a model of sharing parking places in a P + R car park equipped with low-power chargers. Section 4.7 presents a case study based on both the real occupancy of a P + R car park and the real charging requirements of EV users, with the objective to optimize the installed power of transformer stations and the number of chargers used simultaneously from the technical and economic point of view. Section 4.8 presents the results of technical and economic optimization of the car park model, followed by discussion in Section 4.9 and conclusions with suggestions for future research in Section 4.10.

4.3 State of the Art

There are several aspects that potential customers consider when deciding whether to purchase an EV. Firstly, the high investment costs of EVs are seen as the major barrier to EV scale-up [7], [22], [24], [133]. Furthermore, the high initial investment in EVs currently sold correlates with the users' annual income. Xu et al. [133] stratified the percentage distribution of EVs registered in California into user groups with annual incomes above and below USD 150,000. The group of registered EVs in the group of users with an annual income exceeding USD 150,000 makes up 45%. However, the percentage of registered EVs in the larger group of users with an annual income lower than USD 150,000 is only 15%.

Individual countries try to compensate for this barrier using various financial instruments. The structure and scope of the financial instrument and its implementation varies from country to country. Additionally, not all countries provide subsidies for non-business vehicles. A questionnaire conducted in the Nordic region (Iceland, Sweden, Denmark, Finland, and Norway) shows that users would prefer a tax relief to a financial subsidy when purchasing EVs [7] with the exception of Sweden, where the government has taken several reform steps since 2006 to reduce the tax burden [136], which included the abolition of the most criticized taxes on real estate and property, also including cars. Conversely, Sweden has significantly increased its fuel tax since 2014 to support CO₂ reductions and also increased the number of EVs in operation [136]. Other financial benefits that users will receive from EV, cf. [7], [22], are free parking in restricted areas, free use of motorways, and an exemption from road tax if required by a particular country.

The second important issue for potential EV users is a short range of the EVs due to the small capacity of the installed batteries. The study [40] states that the average daily distance travelled by a user living in Beijing is 50 km. Users living in California travelled less than 48 km by car during the day [133]. Respondents from the Nordic countries were also concerned about the short range of the EV, but finally, they stated that most of them were satisfied with an EV that would be able to achieve roughly 200 to 300 km per charge [7]. Only a minority of respondents would decide to purchase an EV only if the capacity of its battery allowed them to achieve a distance of at least 500 km [7].

Taking into account all currently available battery electric vehicle (BEV) models, the average installed battery capacity is 61 kWh [137], and the average energy

consumption is roughly 19 kWh/100 km [138]. The real range that EVs are able to achieve with one battery charge is approximately 314 km [139]. As can be presumed, the capacity of an installed EV battery strongly correlates with its purchase price [140]. However, EVs with a low purchase price will achieve 50 km per battery charge without difficulty. Even a two hundred-kilometre journey with a single charge is not unrealistic for them.

The third important issue for many respondents is charging EVs and the question of a dense network of charging stations [7], [22], [24], [25], [133]. The questions in the questionnaire which focused on charging efficiency, charging station locations and network density are in line with current scientific issues addressed in the literature [11], [40], [49]–[51], [135], [141]–[145]. The issue of EV charging can be principally divided into two main subcategories: home charging and public charging stations.

Home charging stations paved a new way for EV users, who are thus able to recharge their cars very comfortably. One of the most significant benefits of home charging of EVs is a lower price per kWh compared to a business fast-charging station [38], together with a higher degree of comfort and less time spent charging on public charging sites, cf. [7], [38], [40], [146]. On the other hand, the disadvantage of the home charging solution is the necessary upfront investment in the home charger set and, surely, also an investment in one's own parking place or garage, cf. [22], [40], [147].

However, not all users (especially in urban areas) have their own garage or parking place [40]. A dense network of charging stations is often a good bonus for EV users and a quick way to recharge their car during daily travel [7], but generally, EV users prefer home charging [7], [133], [148]. A private parking place or garage that provide EV users with the ability of charging an EV was very important for potential new EV users, cf. [7], [22], [40]. For instance, Zhao et al. [40] describe the ratio between the number of registered EVs and the number of private charging stations in Beijing. In 2017, a total of 124,000 EVs were registered, and 67% had their private charging stations. The remaining 33% of EVs were dependent on recharging using public charging stations. Most of the population in cities live in flats without a private garage or a private parking place [147]. These larger groups of users leave their cars in public car parks near their apartments. They do not usually have the possibility of buying a home charging set and using it to charge EVs [40]. Furthermore, in these densely populated areas, a problem arises not only with a lack of private parking places and garages but also with a lack of

free public car parks, cf. [22], [40], [49]–[52], [135]. The sharp increase in the number of cars and the expected increase in the number of EVs [149] in future means that there will be a lack of new parking places [135]. Very often, it is not possible to build new car parks in the required location at all, or it is not economically viable [150].

From a global perspective, the lack of parking places is not caused by a physical shortage of car parks, but by inefficient use of existing ones. In particular, corporate car parks, parking spaces near commercial buildings, post offices, hospitals, schools, shopping centres and banks are busy mainly during working hours, cf. [50], [51], [135]. Cai et al. [135] estimate that the percentage utilization of these parking spaces in Beijing during the day is approximately 50%. At night, the utilization decreases further to 40%.

Increasing the efficiency of use of existing car parks is therefore crucial. Several optimization methods have been used so far. Perhaps the most straightforward and now well-established method for increasing the efficiency of car parks is to reserve a particular parking place for the required time interval [150]. Friesen and Mingardo [150] focus on increasing the efficiency of car parks using a method based on revenue management and dynamic parking. This method adjusts the price of parking to the car park location, the time of day when a customer parks their vehicle, and the day of the week. Friesen and Mingardo [150] and Lei et. al. [151] came to a very similar conclusion in their studies: the dependence of users' demand for parking places depends on changing prices of parking.

Cai et al. [135] present the optimum method of sharing the same area from the perspective of car parks and users at administrative buildings. To ensure the same occupancy of individual car parks, they recommend approximately equal distances of car parks from points of interest. Better management of the occupancy of individual car parks can also be achieved by changing the price of parking. A problem may occur in residential car parks of office buildings with highly sought-after locations, where, even after the increase in the parking fees, there are still problems with lack of free parking places [135]. These car parks cannot, however, be shared with nonresidents. The authors further state that a choice of car park is negatively influenced by the parking fee, travel time, risk of no parking space, and general obstacles to parking [135].

Similarly, Huang et al. [50] agree that an effective way to solve the problem of the lack of parking spaces is not their new construction, but more efficient use of existing

ones. The main research objective was to determine the optimum number of shared parking places for the car park assumed. Assuming that the demand for parking spaces is constant and greater than the number of parking spaces provided, they conclude that the optimum number of reserved places is approximately equal to half the proportion of long-term parking users. However, it can be assumed that the number of parking places offered for sharing will depend mainly on the car park location related to the demand for the given location.

Similarly to the lack of car parks, the lack of charging stations for EVs is perceived as a significant obstacle, cf. [22], [40], [51], [52]. Sharing of existing charging stations could eliminate the vicious circle between public charging station infrastructure developers and potential EV owners [22]. From the economic point of view, the development of a dense network of public charging stations depends on increasing numbers of EVs in operation, and new EV users are often discouraged by small numbers of charging stations [22]. The incentive not only for the investor to build a dense network of charging stations is supported by the European Commission which, supports the Europe-wide electromobility initiative and Green eMotion projects with an approximate amount of EUR 41.8 million [152].

The use of existing private charging stations is inefficient, cf. [40]. EV owners usually use private charging stations in the evening and the station remains used inefficiently during the day [40]. Therefore, optimizing the use of charging stations by sharing them results in benefits not only for the charging station owners but also for other users of EVs who could then use the dense network of charging stations [3,6,18,19].

Plenter et al. [22] dealt with the development of “CrowdStrom,” representing a peer-to-peer (P2P) sharing and collaborative transportation consumption service for private charging infrastructure by using information technologies. These authors specify three main factors that an individual must ensure to provide his charging point for other EV users. The first important factor is the owner’s willingness to share their charging station with other users. The second necessary factor is to ensure free access to the charging station (which tends to be an issue, especially in private underground garages of condominiums, where only renters have primary access). The third, final factor is internet connection, important for sharing information about the station occupancy. In addition to an IT solution, the authors also asked residents about their willingness to participate in a charging station sharing project. From a total sample of 327 respondents,

45% indicated above-average interest in becoming a provider regularly offering private charging stations to the public. However, a more detailed analysis of the questionnaire data showed that only 450 shared charging points would be created in a given locality with 300,000 inhabitants. The estimate was based on the answers of respondents who had the opportunity to build a parking place and add a charging station. Additionally, with above-average interest, they had to agree with purchasing an EV and providing the charging station for other EV users.

The results of the questionnaire [22] also show that people have a better chance of sharing private charging points in suburban areas because they are more likely to have their own parking place and to equip it with a charger. Zhao et al. [40] had a similar idea of sharing private charging stations with other users. The analysis found out that the utilization rate of private charging stations in Beijing was 4.5%. By offering these private charging stations to other users, their utilization rate has increased by 0.4%. The main limitation to the study by Zhao et al. is that the charging station owners provide their charger for other EV users during the daytime, but not in the evening, when the owner occupies the charging station. We take the opposite approach. Sharing of parking places in a P + R car park, which are unused at night-time, correlates with EV users' demand for charging in the evening, when they usually return home from work.

Xu et al. [51] approach sharing of parking places and charging stations from a different angle than the two abovementioned studies. They consider sharing parking places primarily in a car park in a commercial building. The pairing of parking place owners and customers then proceeds as follows. Each parking place owner sets a minimum price of renting in the time interval when they do not use it and each customer suggests the maximum price they are willing to pay for parking. An important factor of pairing is that the parking place owner is assigned a customer who offered the same or higher price of renting the parking place. Customers' fees consist of renting a parking space and the electricity consumed. However, the customers can get a financial benefit if they opt for demand-side management (DSM). The DSM method is used to optimize the parking costs by modifying EV charging/discharging behaviour. DSM aims at encouraging consumers to use less energy during peak hours, or to shift their energy use to off-peak times such as night-time and weekends [51].

Many studies [7], [22], [40] state that owning a private parking place is often an important condition for deciding to purchase an EV. In urban areas, where there is a limited number of public parking places, the possibility of sharing offers itself directly. Car parks near commercial buildings, post offices, hospitals, schools, and shopping malls are often the best possible solution for sharing, as the studies show. Especially beyond working hours, these car parks are used with low efficiency.

The research gap to which this article responds is effective use of parking spaces near commercial buildings, shopping malls, hospitals, etc. [7], [22], [40]. These car parks will be equipped with a sufficient number of chargers due to the expected increase in EVs, resulting in a high concentration of cars in the working hours when these institutions are most busy [22]. Furthermore, these car parks are very often located near settlements. Therefore, it offers itself directly to provide these car parks equipped with a charger for EV owners living close by. Rental of these charging points then offers private charging points for EV users without a garage or home charger.

Furthermore, our article solves the problem of the absence of a private parking place equipped with a charger, which often dissuades potential customers from buying an EV [22]. This research presents a P + R car park model equipped with a sufficient number of chargers. It is assumed that P + R car parks are used mainly during the day and at least in the evening. Plenty of available charging points in the evening also correlates with EV users' demand for charging in the evening, when they usually return home from work. Thus, the proposed solution directly solves the problem of many potential EV users who do not have their own private charging points, a factor that often discourages them from buying an EV [7], [22], [40].

4.4 Model of EV Charging in Shared Parking Places

EV users come mainly from urban areas with a high proportion of apartment buildings, so they often face not only a lack of places for charging, but also places for private parking. Thus far, many charging models have focused on home and public charging, and similarly, there have already been many general ways of sharing parking places [22], [40], [50]–[52]. The proposed model combines the above approaches and models by building charging infrastructure in an existing car park and introduces the concept of sharing it. In order to increase the efficiency of use,

the model contains parking places and charging infrastructure not only for residents living around but also for those randomly arriving in the daytime.

The model aims to design a technically and economically optimal solution for additional installation of 3.6 kW AC chargers and other necessary energy equipment in an existing car park. The model focuses on sharing parking places from the car park operator's perspective, trying to offer comfort and service for EV users comparable to home charging. Simultaneously, the model aims to guarantee low-power night-time charging for users' EVs, which will sufficiently compete with public fast-charging stations and achieve low-priced home charging.

4.4.1 User Description

A key issue in setting up a model of a car park equipped with chargers is to dimension and adapt its equipment to the requirements of individual groups of EV users. Generally, car park users can be divided into two main groups. The first group consists of randomly arriving EV users who commute to the site for work or other purposes. The other group comprises users (residents) who live close to the car park and rent a parking place primarily for charging. Residents are offered a level of comfort similar to that of people living in family houses and having their own garage equipped with a charger.

Our model assumes that the first group of EV users (nonresidents) use the car park primarily in the daytime. The purpose of daytime parking might be the vicinity of a shopping centre or means of public transport. Therefore, nonresident users' priority is parking rather than charging. Although the price is close to home charging, charging is not mandatory for nonresidents. Before parking, each nonresident user chooses whether they want to charge the EV. After leaving the parking place, the user pays not only an appropriate hourly parking rate but also the energy bill. Since the car park is not primarily intended as a public charging site, nonresidents are not guaranteed recharging during their whole parking time. Parking only increases the energy level in the EV; the problem of full recharging is solved by home charging or other means.

For the second group (residents), the car park model offers the possibility of renting parking places with a charger. The parking places are reserved for the residents on weekdays during the night-time. At weekends, resident parking places are also reserved for the residents throughout the day. If the residents arrive no later than at the set

evening time (T_i), they are guaranteed a sufficient number of charging hours correlated with recharging an appropriate amount of energy. However, the rules for the resident group require different settings. It is assumed that the residents want to rent a parking place mainly due to the absence of private parking and charging places.

Compared to nonresidents, residents are financially motivated to use car parks to charge their EVs. The principle of incentives we propose consists in the introduction of a minimum flat rate for residents including guaranteed charging hours, regardless of the actual use. Charging after the guaranteed hours is then calculated per kWh. The flat rate will ensure a reduction in the risk of non-covered fixed costs (NCFC) due to a blocking car with little need for charging. Another source of risk is mutual blocking of users; this is addressed in the following chapter.

4.4.2 Blocking Issues

To completely prevent charger blocking, additional installation of chargers in each parking place is assumed. The problem of sharing parking places between groups is addressed by resident membership booking for a specific day. Here, a resident does not have the option to rent a particular parking place but can book membership in a parking group. Since overlaps can occur in the case of a nonresident's or a resident's delayed departure, the calculation takes into account an overlap around the morning (X) and evening (Y) hours, when the overlaps are the most frequent. Above all, the model takes into account a capacity reserve (Q_r).

$$Q_r = Q_{pl} - Q \quad (1)$$

where Q_{pl} is the total number of parking places in a car park and Q is the number of parking places reserved for residents.

For a resident who decides not to leave, the resident daytime tariff is charged. In the case of a resident staying in the daytime, the minimum tariff rate ($R_{resident}$) is set as the product of the NCFC per unsold kWh ($L_{p_kWh_nonresident}$), the average occupancy of the charger (T_o), and the charger (P_{CH}).

$$R_{resident} = L_{p_kWh_nonresident} \cdot T_o \cdot P_{CH} \quad (2)$$

$$L_{p_kWh_nonresident} = LCOE_{nonresident} - N_{var} \quad (3)$$

where $LCOE_{nonresident}$ is the levelized costs of electricity for the nonresident group, and N_{var} is the marginal price per kWh.

For a nonresident who does not leave until the last daytime parking hour, the night-time nonresident tariff is charged. In the case of a nonresident staying overnight, the minimum tariff rate ($R_{resident}$) is set as the product of the NCFC per unsold kWh ($L_{p_kWh_resident}$), the guaranteed resident charging hours (T_g), and the power of one charger (P_{CH}).

$$R_{nonresident} = L_{p_kWh_resident} \cdot T_g \cdot P_{CH} \quad (4)$$

$$L_{p_kWh_resident} = LCOE_{resident} - N_{var} \quad (5)$$

where $LCOE_{resident}$ is the levelized costs of electricity for the resident group, and N_{var} is the marginal price per kWh.

4.5 Charging Scheme

Nowadays, building power infrastructure with a minimum charging output 50 kW DC is most common if short charging times are to be achieved. Furthermore, construction of charging infrastructure requires installation of either more local transformer stations or higher-power stations. It is also necessary to increase the capacity of the high voltage (HV) connection and increase the reserved power. The time of utilization of the installed capacity is short in this case. From the economic point of view, especially the costs associated with the increase in the reserved power from the HV power grid are not viable.

Contrarily, construction of charging infrastructure with low-power charging stations (usually up to 3.6 to 10 kW) avoids these issues. The time of utilization of the installed capacity will increase, and the smoothness of consumption ensures predictability for purchasing electricity from the trader. Installing a low-power charger in each parking place (Figure 1) then appears to be a more advantageous option for this model.

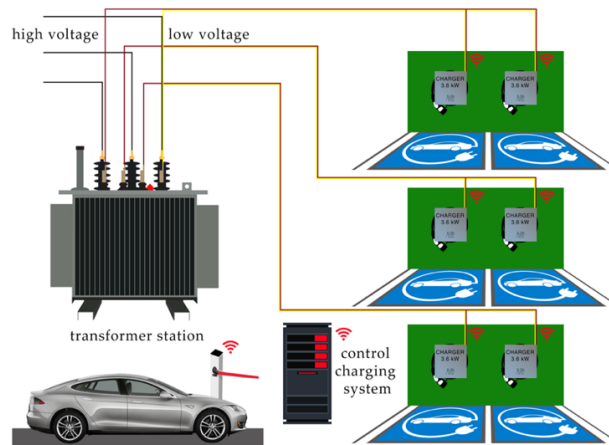


Figure 1 Car park model equipped with low-power chargers.

4.5.1 Model Input Parameters

The input parameters of the car park model equipped with low-power chargers are as follows:

- Maximum number of parking places in the car park assumed (Q_{pl});
- EV arrivals on weekdays with the highest demand for parking;
- Peak parking occupancy at the weekends (Q);
- Data describing the demand for electricity by arriving EV users;
- Maximum number of residential parking places (Q_r).

The model of charging infrastructure for an existing car park consists of a HV/LV transformer station, switch disconnectors and isolators, a circuit breaker, 16A fuses, cabling, a heat exchanger (cooler), a charging control system, and chargers.

4.5.2 Dimensioning the Transformer Station Power

The charging issue is always related to the maximum load of one or more locally installed transformers. The minimum power (P) of a transformer station is based on the total requirement for recharging the residents' EVs (E_r). Residents' recharging requirements are defined by the probability density function (PDF) of their daily mileages ($F(T_g)$). Based on the charger power of 3.6 kW AC and the given percentile of charging success (p), a minimum charging time (T_g) obtained should be guaranteed for residents. Simultaneously, information about the total energy needed for recharging (E_r) is obtained from the PDF of resident daily mileages.

To verify whether power of a group of installed transformers is sufficient, the model compares energy needed to charge the residents' EV (E_r) and the energy that the local transformers can provide in the time interval reserved for residents (E_{TR_YX}).

$$E_{TR_{YX}} \geq E_r \quad (6)$$

$$E_r = \sum_{x=1}^{Q_r} E_r(x) \quad (7)$$

$$E_{TR_{YX}} = P_{ch_{par}} \cdot (Y - X) [\text{kWh}] \quad (8)$$

$$P_{ch_{par}} = ch_{par} \cdot P_{CH} [\text{kW}] \quad (9)$$

$$ch_{par} \leq \frac{P}{P_{CH}} \quad (10)$$

where P_{ch_par} is the power consumption of the entire array of chargers used simultaneously ch_{par} . P_{CH} is the power of one charger.

The optimal number of local transformers should be the subject of economic analysis. The economic assessment also includes a comparison of NCFC due to electricity unsold to nonresidents, and annualized costs of building an additional transformer. If the NCFC exceed the annualized costs, it is advantageous to add another transformer to the transformer station.

4.5.3 Charging Power Sharing Method

An important issue in terms of charging is the distribution of the transformer station power (P) among the individual EVs. Compared to residents, nonresidents arrive in the car park randomly during the time span from (X) to (Y).

The occupancy curve strongly depends on the type of car park. Therefore, the estimate of the number of arriving nonresidents in a given period must result from long-term observation. The PDF of the length of stay (L) and the PDF of the quantity of arriving nonresidents in the given time intervals (A) are calculated from the observed data. As for the residents, we obtain information about the total energy needed to recharge their EVs (E_r) from the PDF of resident daily mileages.

The main difference in the division of the power of a local transformer station among the nonresident group is that nonresidents do not have a guaranteed energy supply (Figure 2). Therefore, the power of a local transformer station is divided among the EV being charged. The number of EVs being charged ($ch_{par}(t)$) and the number of new charging requests are monitored in the given time steps (t). The limiting factor for accepting a charging demand is the remaining unused power of the transformer stations ($P - P_{ch_par}(t) > 0$). In a situation where there are several requests for charging ($N_w(t) > 0$) and recharging of all EVs is impossible due to transformer station overload ($P_{ch_par}(t) \geq P$), the first-in, first-out (FIFO) basis is used. The charging of waiting EVs is postponed until they are guaranteed continuous charging. The EVs are then charged until either they have fully charged batteries, or their owners voluntarily interrupt charging and depart.

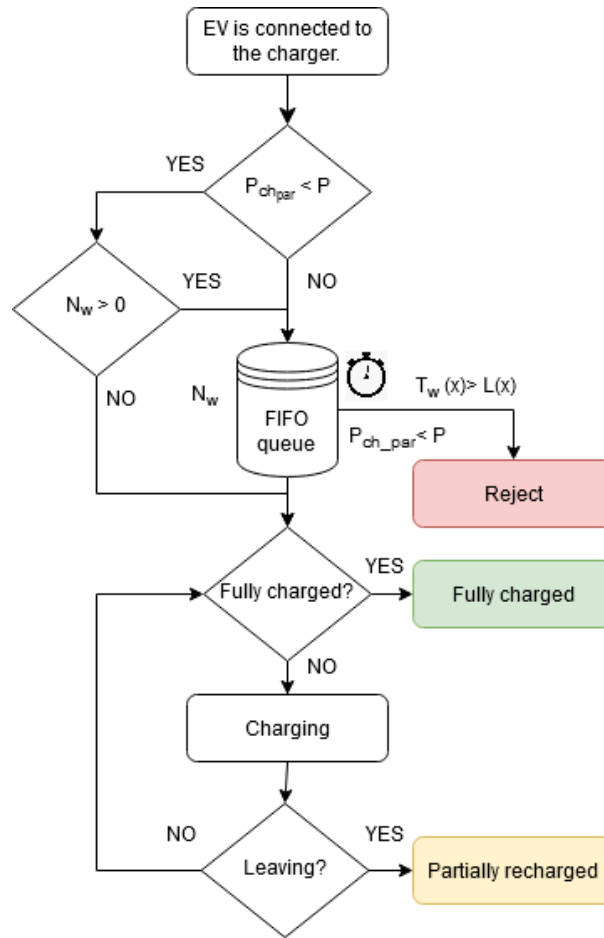


Figure 2 Nonresident charging diagram.

Contrarily, the residents have guaranteed (T_g) charging hours (Figure 3) as part of the parking rate, providing that they arrive between Y and the last morning hour (T_l). If the transformer station is not fully used and the battery of a resident's EV is not fully charged even after the guaranteed (T_g) hours, the battery is charged further. An interruption in the charging of this car will occur at the moment of the full battery capacity or on the arrival of another resident who has not exhausted the charging hours guaranteed and if the simultaneous charging of both EVs would exceed the maximum power of the transformer station.

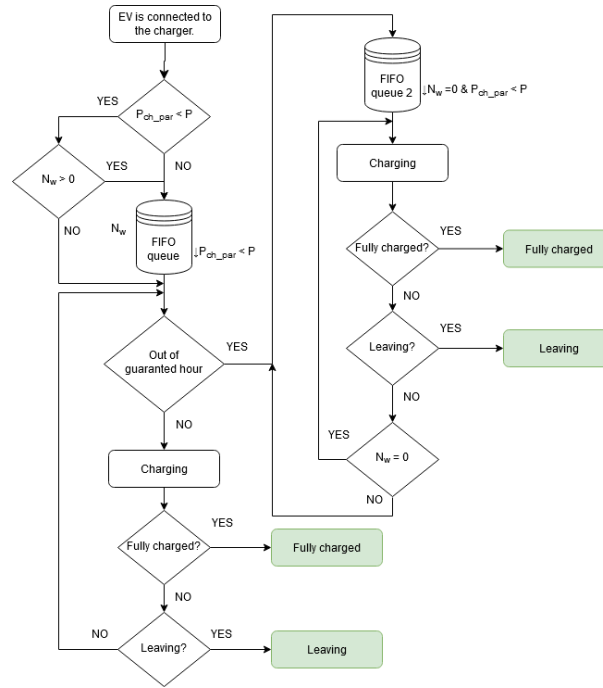


Figure 3 Resident charging diagram.

4.6 Economics of System Dimensioning

Apart from technical aspects, economic factors need to be taken into account when constructing a charging point. One of the key issues is the competitiveness of the project compared to other charging methods, such as using public fast-charging stations and home charging using a private charger. We assume that the main priority of the model is to create a sufficient number of shared parking places for residents and comfort and charging costs similar to home charging. Therefore, home charging is the main competitor for the car park with the charging infrastructure.

To assess the economic effectiveness, the model uses the levelized costs of electricity (LCOE) to recalculate individual capital expenditures (CAPEX) with different lifetimes and operating expenses (OPEX) converted to a unit price per kWh. CAPEX involve a HV/LV transformer station, switch disconnectors and isolators, circuit breaker, fuses, cabling, heat exchanger (cooler), installation material, chargers, connection fee, installation work, and charging control system. OPEX are generally divided into two items, the first one consisting of maintenance and the second one associated with electricity consumption.

Since the transformer station causes the highest losses, the empirical formula given by CSN 341610 standard is used for the estimation of annual losses in the transformer station.

$$T_L = \left[0.2 \frac{T_m}{T_0} + 0.8 \left(\frac{T_m}{T_0} \right)^2 \right] \cdot T_0 \quad (11)$$

where T_L is the annual time of full transformer losses, T_m is the utility factor, and T_0 is the annual operating time of the transformer station.

$$W_L = P_{nl} T_0 + P_{kn} \frac{S_m^2}{S_n^2} T_L \quad (12)$$

where W_L is the annual energy losses in the transformer, P_{nl} is the power transformer no-load loss, T_0 is the annual operating time of the transformer station, P_{kn} is the short-circuit transformer losses, S_m is the maximum apparent-power load of the transformer, S_n is the apparent power of the transformer station, and T_L is the time equivalent of losses at the maximum load of the transformer per year.

From a technical point of view, the power of one transformer installed in a transformer station may be sufficient for the full charging of residents' EVs, but the percentage of refused nonresidents and the associated unsold electricity can generate significant NCFC. A comparison of these NCFC with the annuity costs associated with an increase in the power of the local transformer station determines whether the increase is economically beneficial or not. The economics of system dimensioning aim at determining the levelized costs of electricity (LCOE) for both the nonresident and resident groups.

$$LCOE = \frac{\text{sum of costs over lifetime}}{\text{sum of electrical energy sold}} = \frac{N_i + \sum_{t=1}^n (M_t + N_{Et})(1+r)^{-t}}{\sum_{t=1}^n E_t(1+r)^{-t}} \quad (13)$$

where the variable N_i denotes the initial investment in the equipment; M is the annual maintenance expenditures, N_e is the electricity bill in the year t , r is the discount rate, and E denotes electricity sold in the year t [kWh].

The optimization method is based on economic cost evaluation. This method compares the NCFC due to electricity unsold to nonresidents and annualized costs of building an additional transformer. The optimization minimizes the number of refused nonresidents via installation of additional transformers. The algorithm applies a constraint that the overall costs of charging, including NCFC and annualized costs of building of another transformer, do not exceed 0.19 EUR/kWh (for both residents and nonresidents).

4.7 Case Study

The following chapter deals with an application of the model to real data. The chapter consists of four subchapters. The first and second present and analyse the real data entering the model. They are followed by technical evaluation of the case study data (third subchapter) and economic evaluation (fourth subchapter).

4.7.1 Parking Place Input Data Analysis

Data from a park and ride (P + R) car park with 650 parking places in Prague Letňany were selected for the survey [153]. The data capture the car park occupancy in five-minute intervals from the 1st quarter of 2013 to the 4th quarter of 2016. The car park occupancy data do not include data for holidays and public holidays, which would alter the occupancy information for the given days significantly. The parking data do not include any private residents.

For further processing, the car park occupancy information for individual five-minute intervals was broken down into weekdays (from Monday to Friday) and weekends (Saturday and Sunday). The average occupation level in the corresponding five-minute interval was calculated for each day based on this four-year study.

Subsequently, an extensive analysis of the data was performed in order to identify significant differences in the car park occupancy between individual weekdays (Monday to Friday), and weekdays and weekends. The analysis of weekdays shows that the user behaviour is almost identical for Monday, Tuesday, Wednesday and Thursday. On Friday, the parking places were occupied significantly less. Considering that the occupancy in the individual five-minute intervals has a normal distribution with a 64% probability, the difference in the occupancy in the time interval from 7 am to 7 pm on Monday, Tuesday, Wednesday, and Thursday is less than 3% (Figure 4).

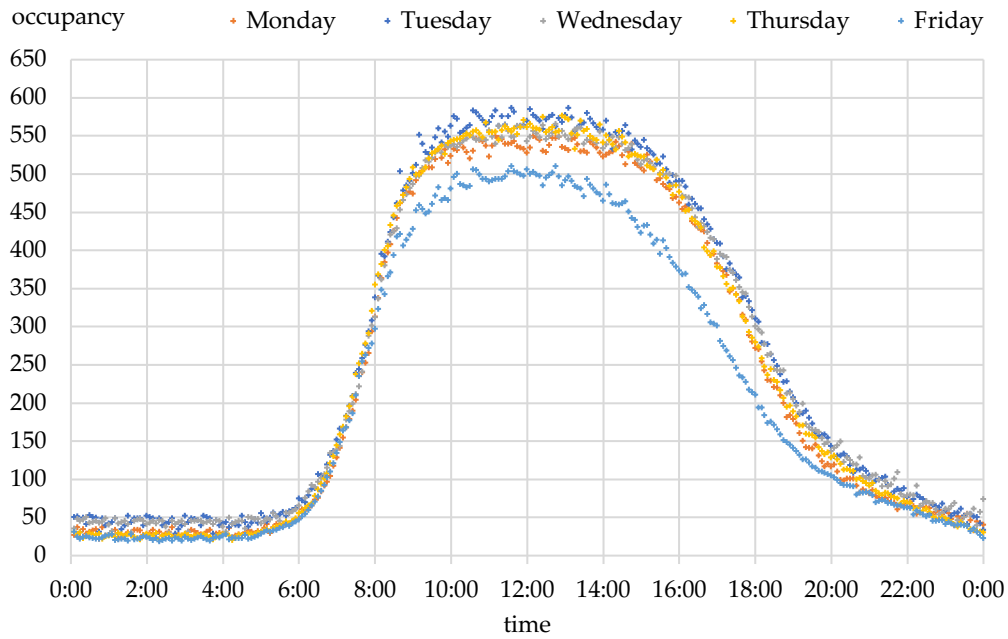


Figure 4 Occupancy on weekdays ([153], calculated by authors).

Moreover, an analysis was performed to identify changes in user behaviour depending on the quarter of the year. The analysis shows that the user behaviour remains almost unchanged throughout the year. For example, for Thursday, considering that the occupancy values in each five-minute interval have a normal distribution with a probability equal to 64%, the difference in occupancy from 7 am to 7 pm in the first, second, third and fourth quarters is less than 6% (Figure 5).

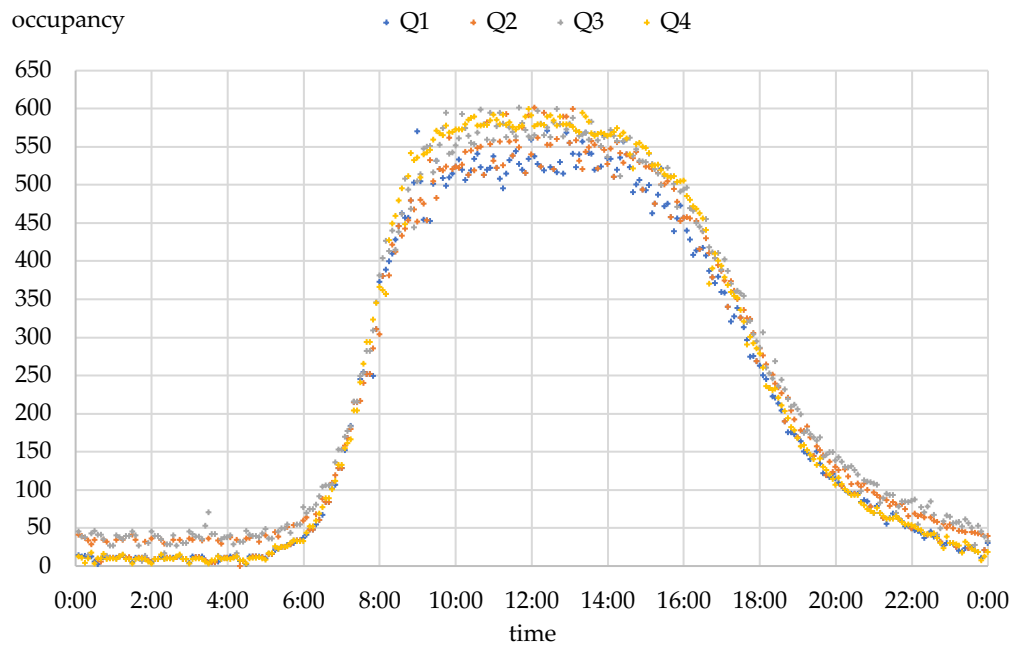


Figure 5 Thursday arrivals/departures ([153], calculated by authors).

Since the user behaviour in individual quarters and on weekdays, except Friday, was nearly the same, we selected the Thursday occupancy for further modelling. In terms of parking place occupancy, Thursday parking place occupancy has the character of the busiest weekday. Furthermore, the weekend car park occupancy analysis shows that the user behaviour on both Saturday and Sunday is the same in all the quarters. The average occupancy on these weekend days is constant, equal to 100 parking places.

The disadvantage of the provided data describing only the car park occupancy is the loss of information on arrivals and departures within the measured five-minute interval; for example, arrivals and departures of the same number of cars in the same five-minute interval show a zero change in occupancy. Therefore, the Poisson distribution using random arrivals of individual cars was used to approximate the real car park occupancy. The departure time, which correlates with the parking time for a car in a parking place, was modelled using a Gaussian distribution with a 4 h mean and a standard deviation of 1 h.

Data obtained from charging stations operated by ŠKO-ENERGO (Mladá Boleslav, Czech Republic) were used to simulate demand for recharging of EVs [154]. During the three-month testing in 2020, data on 330 charging iterations from various types of EVs were obtained. The charging data were obtained from seven charging points, each equipped with a 22 kW DC power charger. At four of these seven charging points, it was also possible to use a 50 kW DC charger [154]. A more in-depth analysis of the data provided information about the time spent in the car park and the time required for sufficient charging. The analysis shows that users left the EVs parked and connected to the charger for a longer time than required to recharge the battery. This can be demonstrated by the fact that it is possible to recharge the battery of a EV more with a lower-power charger over the same parking time. Figure 6 shows that users park for longer than is needed to recharge the battery to full capacity, thus unnecessarily blocking the possibility of recharging other EVs.

Almost 90% of the car users analysed would have done with a shorter charging time to recharge the required energy or using a 3.6 kW AC charger to achieve the same recharging level in the same amount of parking time (Figure 6).

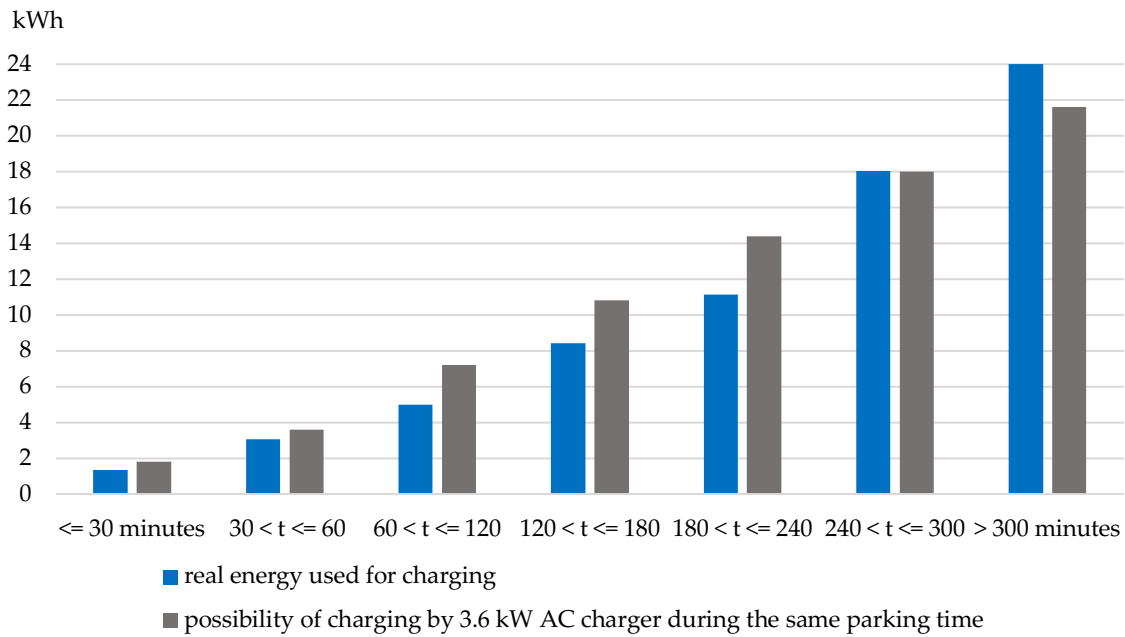


Figure 6 ŠKO-ENERGO charging stations ([154], calculated by authors).

The EV charging sample also offers a valuable outline of the demand for electricity recharging. The data obtained from 330 charging iterations were sorted based on the energy consumed and subsequently used to calculate the cumulative distribution function (CDF) (Figure 7). The most frequent group (16%) are EVs with an 11 kWh charging requirement. The charging requirements show that 90% of arriving EVs require less than 18 kWh to recharge, which corresponds to approximately 5 h of recharging with a 3.6 kWh charger (Figure 7).

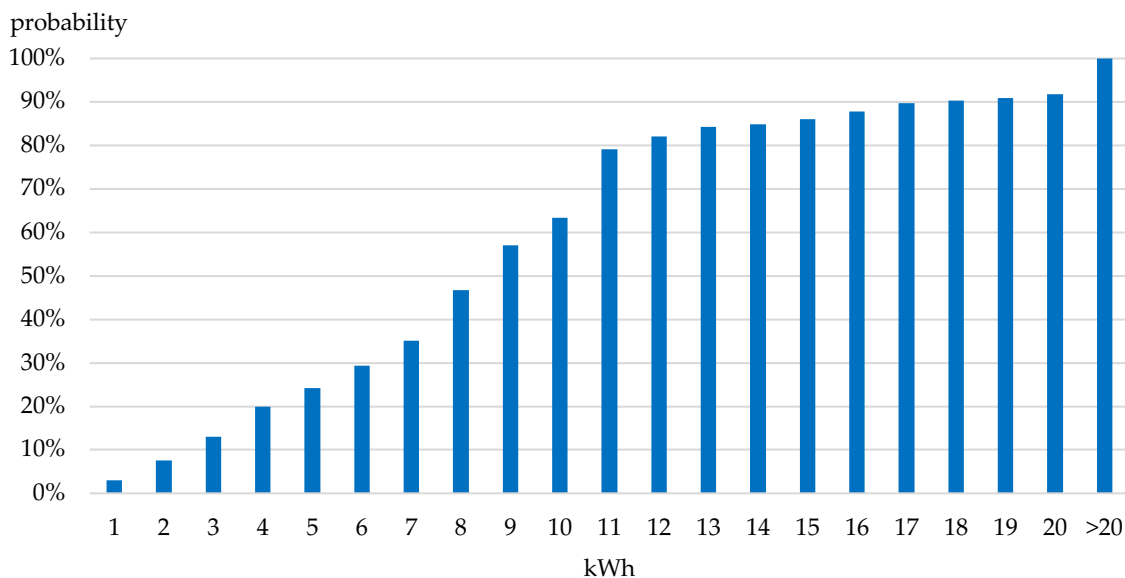


Figure 7 Cumulative distribution function of charging requirements [kWh] ([154], calculated by authors).

4.7.2 Users Input Data Analysis

The case study considers integration of charging infrastructure into an existing P + R car park with 650 parking places (Q_{pl}) in Prague Letňany. The real data analysis revealed that the average weekend occupancy of the car park (Q) is 100 parking places. Therefore, 550 parking places (Q_r) out of the total parking capacity of 650 (Q_{pl}) can be reserved for residents. A more detailed analysis of the input data describing the car park occupancy set the residents' interval from $X = 7$ am to $Y = 7$ pm. The input data vector describing the one-day car park occupancy is composed of 288 five-minute intervals. The number of predicted nonresidents who arrived in a given five-minute period ($A(t)$) is estimated using the normal distribution function. The mean value and standard deviation needed to calculate the normal distribution are achieved from the five-minute intervals, which correspond with both the day of the week and the placement of the five-minute period on a given day. (For example, the calculation concerning all the first five-minute periods obtained from each Monday.) Similarly, the time spent by a nonresident in the parking place is estimated using the normal distribution function, where the mean value equals to 4 h and the standard deviation is 1 h.

The Poisson distribution was used to predict the demand for charging nonresidents ($E_n(x)$), where λ corresponds to the mean value of the data obtained from the charging stations operated by ŠKO-ENERGO.

The requirements for charging are described as follows:

$$\hat{A}(t) \sim N(\mu_A(t), \sigma_A(t)) \quad (14)$$

$$L(x) \sim N(\mu_L, \sigma_L); \mu_L = 4 \text{ h}, \sigma_L = 1 \text{ h} \quad (15)$$

$$E_n(x) \sim \text{Poisson}(\lambda); \lambda = 8 \text{ kWh} \quad (16)$$

where \hat{A} denotes a vector with the distribution of arrivals of nonresidents in five-minute intervals during the day expressed by the average $\mu_A(t)$, and the standard deviation $\sigma_A(t)$. The variable L is the length of nonresidential stay with a normal distribution with the average μ_L and the standard deviation σ_L . The last variable denotes a recharging requirement approximation by the Poisson distribution.

The case study for the resident group models the charging demand only. The charging demand is based on the study [155] focusing on the PDF of daily distance driven by car (Figure 8). The assumed demand for charging characterizes the residents' behaviour. They primarily charge their EV once a day after returning

home, similar to most users with their own charger and a garage. The arrival curve and the time spent by the residents in the car park have not been accounted for. In the case study, we assume that a sufficient number of residents will arrive before the set time (T_l) required for a guaranteed charge.

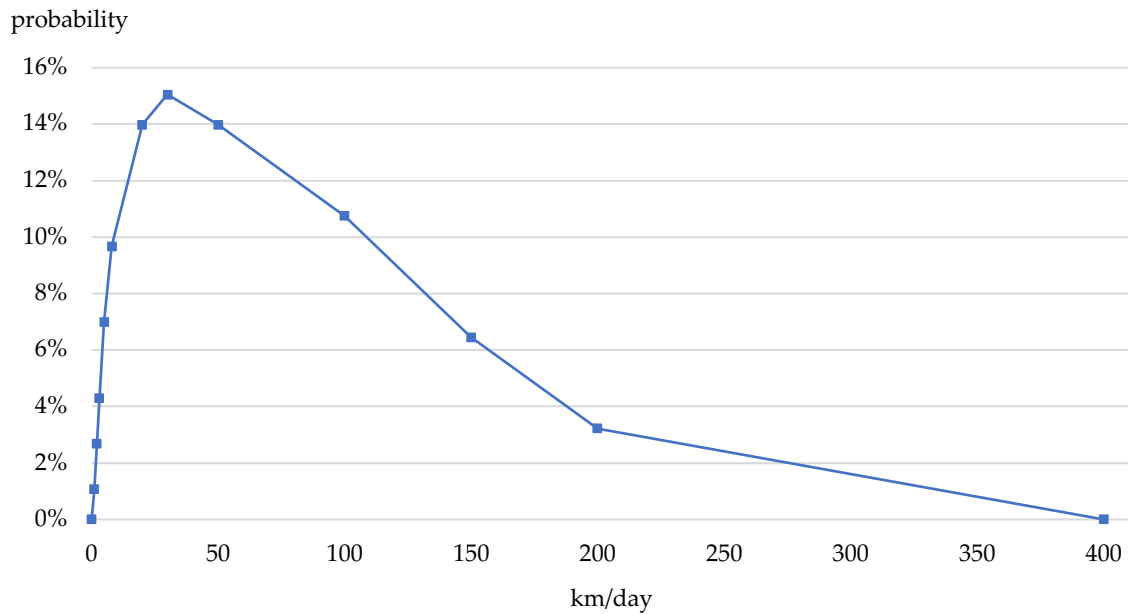


Figure 8 Probability density function of daily distance driven by car [155].

By dividing the daily distance driven by car and the average EV consumption by 100 km (19 kWh), we obtain information about the required energy charge. In order to charge energy, it is also necessary to take into account the compensation for electrical losses that occur during charging. A test of power consumption in EVs [156] shows that EVs consume between 10 and 25 per cent more electricity than their onboard computers show. However, it can be assumed that charging with a low-power 3.6 kW AC charger results in the losses being closer to the 10% value. By dividing the charging power of the charger and the required charge energy ($E_r(x)$), including losses during charging, we obtain information about the required charging time ($T_r(x)$) (Figure 9).

$$T_r(x) = \frac{E_r(x)}{3.6\text{kW}} \quad (17)$$

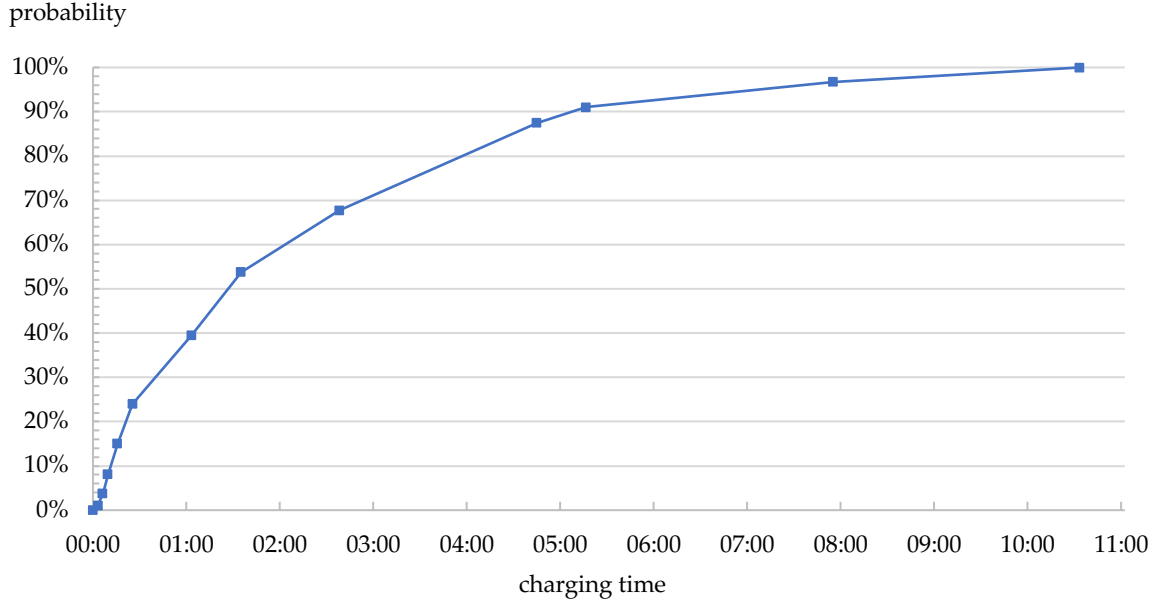


Figure 9 Cumulative distribution function of the resident's EV full charge.

Both the number of guaranteed charging hours (T_g) and the limit that residents must meet to obtain guaranteed charging hours (T_l) were determined based on the time needed to charge by 95% of the residents.

$$AF(T_g) = p ; p = 95\% \quad (18)$$

$$T_g = F^{-1}(95) \cong 6 \text{ h} \quad (19)$$

$$T_l \leq X - T_g ; X = 7 \text{ h}, T_g = 6 \text{ h} \quad (20)$$

$$T_l \leq 1:00 \text{ AM} \quad (21)$$

4.7.3 Technical Aspects of System Dimensioning

Local transformer station capacity will be first dimensioned to meet the residents' requirements, even though we assume higher utilization of the car park and the entire charging infrastructure by the nonresident group. From the existing series of transformers, it is possible to choose any combination of transformers with different power ratings to ensure the required power output. However, a transformer with an apparent power of 630 kVA is selected for installation in the case study.

The total requirement of recharging 550 resident EVs (Q_r) obtained from the PDF of the daily distance driven by car and average EV consumption corresponds to 5303 kWh (E_r). Within the 12 h reserved for residents ($Y - X$), the assumed local transformer with an apparent power of 630 kVA can supply ($E_{TR,XY}$) 7182 kWh, and thus fully meets the residents' charging requirements.

$$P_n = S_n \cdot \cos \varphi \quad (22)$$

$$P_n = 630 \cdot 0.95 = 598.5 \quad (23)$$

$$E_{TRYX} = P_n \cdot (Y - X) \text{ [kWh]} \quad (24)$$

$$E_{TRYX} = 598.5 \cdot (19 - 7) = 7,182 \text{ [kWh]} \quad (25)$$

$$E_{TRYX} \geq E_r \quad (26)$$

$$E_{TRYX} \geq Q_r \cdot P_{CH} \cdot T_g \quad (27)$$

$$3.6 \geq T_g \quad (28)$$

$$ch_{par} \leq \frac{P}{P_{CH}} \quad (29)$$

$$ch_{par} \leq \frac{598.5}{3.6} \approx 160 \quad (30)$$

Based on the assumed model parameters, each parking place is equipped with a 3.6 kW AC single-phase charger. From the load optimization point of view, the car park is divided into three parts. Each is connected to one of the three phases of the transformer. The first and second phases of the transformer are connected with 217 chargers. The third phase then provides power to 216 charging stations. Due to the maximum load of one transformer, it will never charge more than 160 EVs at the same time (ch_{par}). Even though one transformer fully satisfies the requirements for recharging 550 residents, they cannot be guaranteed the required 6 h of charging. With one transformer, it is possible to guarantee each resident 3.6 h of charging. However, 3.6 h of guaranteed charging led to a full charge for only 75% of residents (Figure 9).

Besides, the car park control system, which directs arriving users to the parking places to ensure optimal loading of the entire charging system, helps to optimize even loading of both the transformer stations and their phases.

In the following part of the case study, we will focus on the car park operation in the interval reserved for nonresidents. Their behaviour characterized by charging requirements, arrival times, and parking times is described in the last part of the case study focusing on user' characteristics.

In the case study, we will assume that all nonresidents require both parking and charging of EVs. Several restrictions are associated with the power of the local transformer station (P), determined based on residents' charging requirements. One of them is the maximum number of chargers used simultaneously (ch_{par}). This is also the reason why it is necessary to postpone some of the nonresidents' charging in very busy intervals (Figure 10).

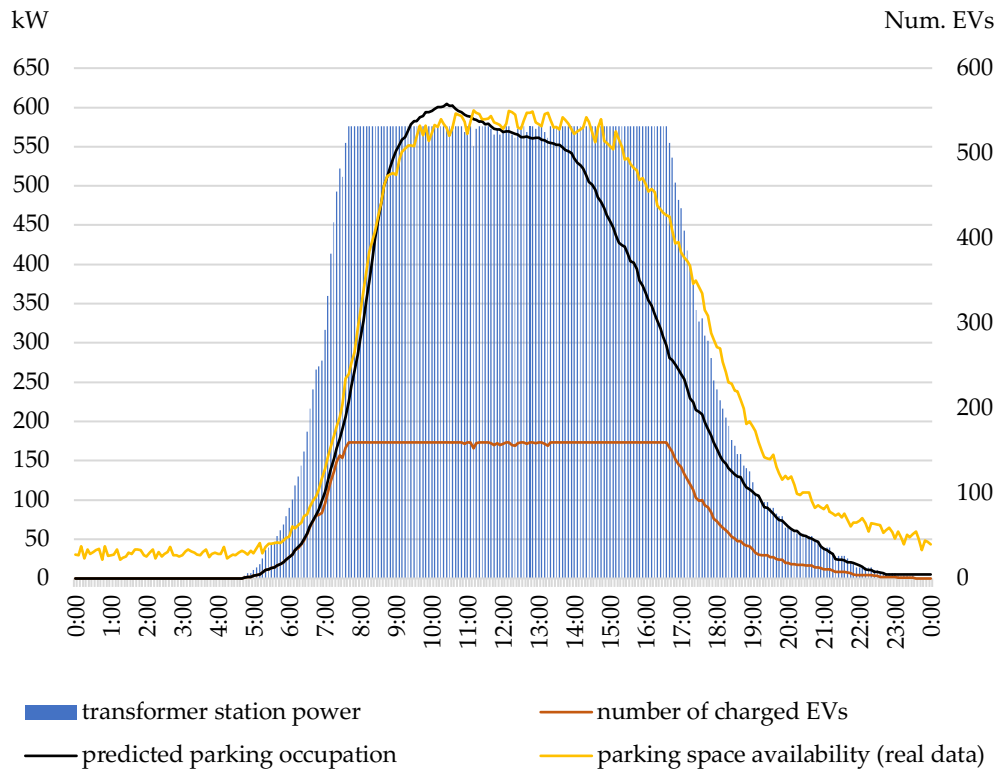


Figure 10 Modelled occupancy in the case of using one transformer.

Nonresidents who have been refused charging wait until one of the previously connected nonresident EVs is fully charged or has finished charging and leaves. The FIFO principle is used for the choice of the next EV for charging from the group of waiting nonresidents, where the longest-waiting nonresident is chosen for charging preferentially (Figure 2).

From the charging point of view, we divide nonresidents into three parts. The first part is composed of nonresidents who were able to recharge throughout the parking time (fully charged). The second part comprises nonresidents whose recharging was shortened due to a shift in the start of charging (partially charged). The third part includes nonresidents whose charging did not start due to a shift in the start of charging (refused).

In the case study, 20 simulations were performed. The number of nonresidents did not change between individual simulations, but their behaviour (charging requirements, arrival times and parking times) did. The results of the simulations showed that on average, 25% of nonresidents were refused, 15% were partially charged, and 60% were fully charged (Figure 11). The course of one of the simulations with one transformer is shown in Figure 10, presenting the load of one transformer and the occupancy of the car park compared to the measured real occupancy.

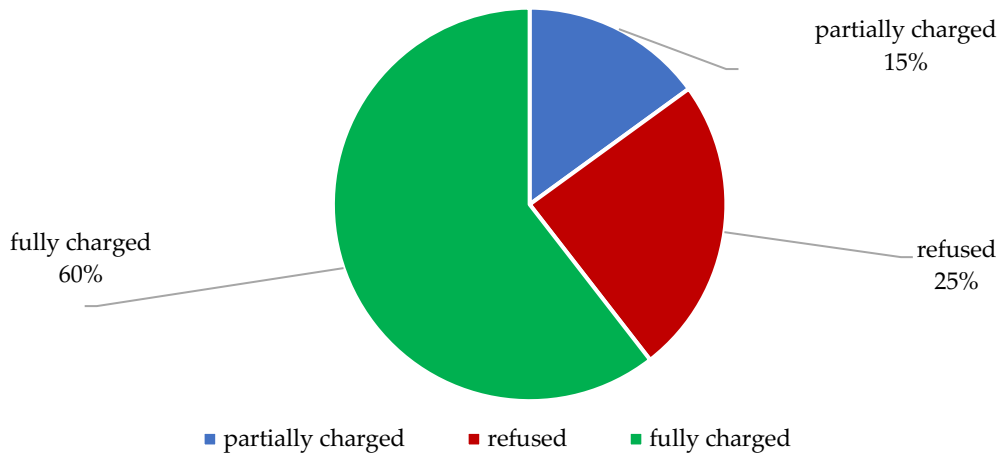


Figure 11 The success of recharging nonresidents in case of using one transformer.

Subsequently, the same set of 20 simulations was performed, but with a difference in the local transformer station power. The existing transformer was supplemented with another one with identical parameters and apparent power in these simulations. This pair of local transformers had a combined power of 1197 kW, enabling the simultaneous charging of 320 EVs. The part of nonresidents with refused charging was eliminated due to the increased local transformer station power (Figure 12).

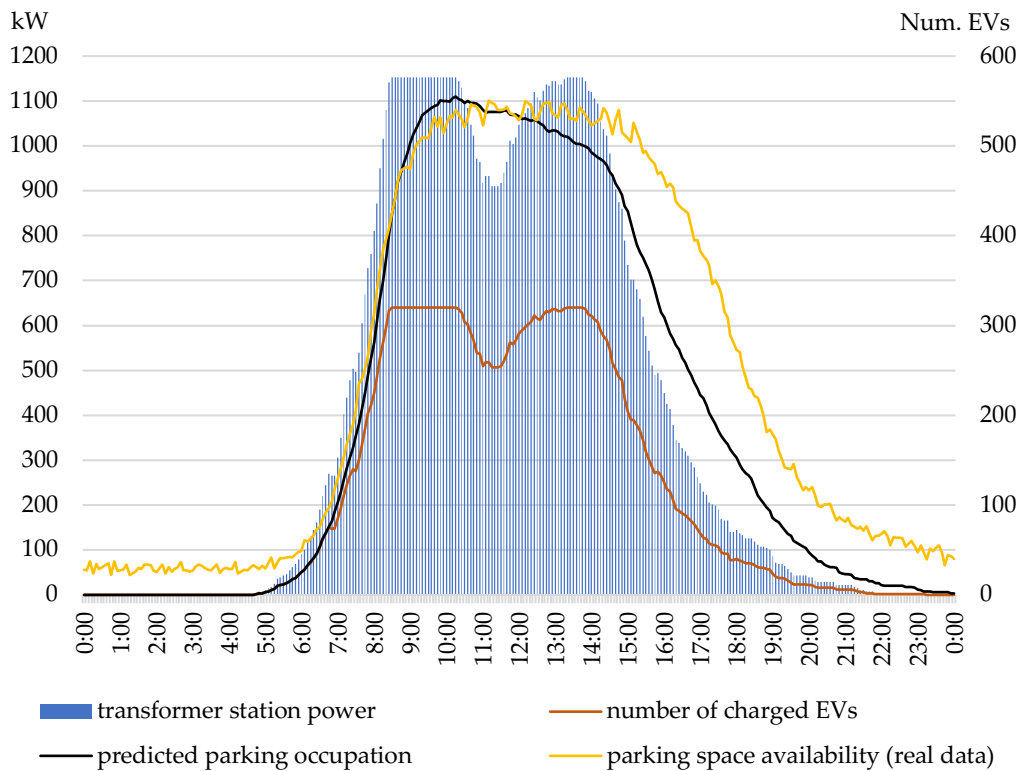


Figure 12 Modelled occupancy in case of using two transformers.

The pair of local transformers reduced the percentage of partially charged nonresidents to 4% and eliminated the part of nonresidents with refused charging (Figure 13). The course of one of the simulations with two transformers is shown in Figure 12, which presents the load of two transformers and the occupancy of the car park compared to the measured real occupancy.

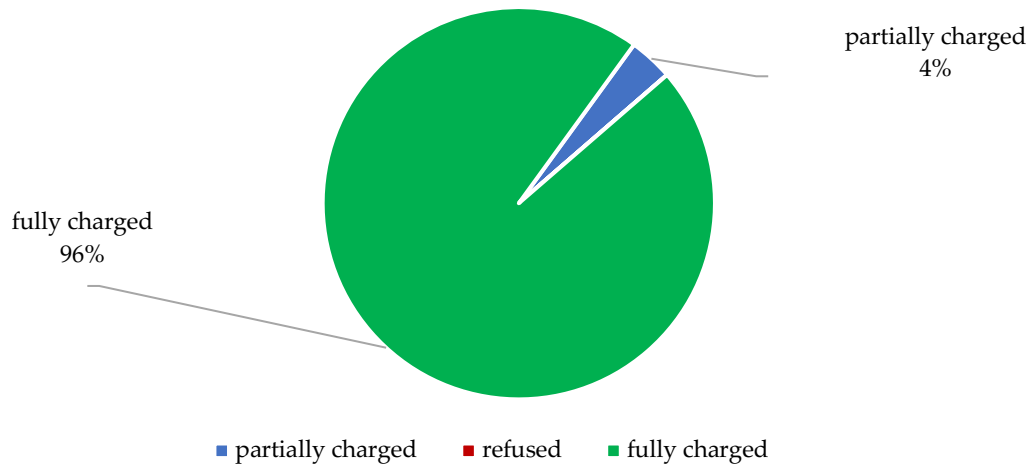


Figure 13 Success of recharging nonresidents in the case of using two transformers.

For the resident group, increasing the output of the local transformer station has the benefit of guaranteeing 6 h of charging (T_g) and a 95% success rate of full charging for residents.

4.7.4 Economic Analysis of System Dimensioning

From an economic point of view, it is essential to set the business model parameters so that the costs associated with parking and charging can be competitive with home charging. The key issue is to correctly set the ratio of the CAPEX division between nonresidents and residents. The case study presents the range of recharging costs depending on how CAPEX are distributed among users (Table 1).

The costs associated with electricity consumption (OPEX) are slightly different across countries. Since the car park is located in the Czech Republic, the price of electricity consists of a fixed and a variable part. The fixed part includes the fee for reserved power, renewable energy sources (RES) and the market operator, while the variable part, depending on electricity consumed, includes the price of energy, distribution services, system services and the electricity tax. The modelled annual electricity consumption and actual prices are shown in Table 2.

	TLT	q	Unit Price	Total Costs of 1 TS	Costs of Additional TS	Annuity for 1 TS	Annuity for Additional TS
	Year	-	EUR	EUR	EUR	EUR	EUR
TS-22kV/0.4kV	35	1	13,208	13,208	13,208	3,303	3,303
Disconnecter and isolator	35	1	566	566	566	142	142
Circuit breaker BH400	35	1	453	453	453	113	113
Fuses PM45 16A	35	3	74	221	221	55	55
Cabling [m]	50	2,150	9	19,877	0	4,969	0
Heat exchanger (cooler)	35	1	102	102	102	25	25
Pipes for cooling	35	1	302	302	302	75	75
Installation material	35	1	377	377	377	94	94
Charging control system	35	1	37,736	37,736	0	9,438	0
Charging station	10	650	755	490,566	0	137,394	0
Connection fee	35	1	6,038	6,038	6,038	1,510	1,510
Labour	35	1	45,283	45,283	45,283	11,325	11,325

Table 1 Investment costs.^a

^a Exchange rate: 1 EUR = 26.5 CZK

	Unit	Unit Costs (Incl. VAT)	Total Annual Costs	Additional TS Annuity Costs
Energy	EUR/MWh	75.34	169,944	-
Distribution services	EUR/MWh	3.37	7,604	-
Reserved power	EUR/MW/month	3,856	27,762	27,762
System services	EUR/MWh	3.52	7,943	-
RES fee	EUR/MW/month	2,633	18,961	18,961
Electricity tax	EUR/MWh	1.29	2,915	-
Market operator fee	EUR/month	0.23	0.23	-
Additional sale 2nd TS	EUR/MWh	83.52	-	54,800

Table 2 Annual electricity bill [157], [158].^b

Table 3 shows the fixed operating costs related to transformer maintenance and overhauls and the annual energy losses incurred.

	Costs Incl. VAT [EUR]	Annualized Costs [EUR]	Additional TS Annual Costs [EUR]
Annual inspection	457	457	457
Major inspection every five years	2,283	849	849
Annual energy losses in TS (WL)	732	732	732
Annual calibration of chargers	4,566	4,566	-

Table 3 Fixed operating costs.^c

Since the transformer station causes most losses, the empirical formula given by CSN 341610 standard is used for the estimation of annual losses in the transformer station:

$$T_L = \left[0.2 \frac{T_m}{T_0} + 0.8 \left(\frac{T_m}{T_0} \right)^2 \right] \cdot T_0 = \left[0.2 \frac{1,958}{8,760} + 0.8 \left(\frac{1,958}{8,760} \right)^2 \right] \cdot 8,760 = 741 \text{ [hours]} \quad (31)$$

$$W_L = P_{nl} T_0 + P_{kn} \frac{S_m^2}{S_n^2} T_L = 0.6 \cdot 8,760 + 6.5 \cdot \frac{606^2}{630^2} \cdot 741 = 9,721 \text{ [kWh]} \quad (32)$$

^b TS = transformer station; VAT = value added tax 21%; exchange rate: 1 EUR = 26.5 CZK.

^c TS = transformer station; VAT = value added tax 21%; exchange rate: 1 EUR = 26.5 CZK.

Although the technical part shows that one transformer provides sufficient power for residents but only with a 75% success rate of full charging for residents, the percentage of refused nonresidents creates significant NCF. Therefore, the previous tables also contain additional annualized costs of deploying one more transformer. The sum of these annualized costs indicates whether it is advantageous to deploy a second transformer. The economic part aims to determine the levelized costs of electricity (LCOE) for both the nonresident and resident groups.

$$LCOE = \frac{N_i + \sum_{t=1}^n (M_t + N_{Et})(1+r)^{-t}}{\sum_{t=1}^n E_t(1+r)^{-t}} \approx \frac{C_A + M + F_t}{E_A} \quad (33)$$

Here, the variable N_i denotes the initial investment in the equipment; M denotes the annual maintenance expenditures, and N_E is the electricity bill in the year t . Providing that the values are not changed year-on-year, the variables C_A and F_t can be set. C_A indicates the annualized costs for the corresponding discount rate r , and F_t denotes the annual electricity bill. E represents annual electricity sold (kWh).

4.8 Results

The following chapter presents the results of the model applied to real data obtained from the Letňany car park, Prague, and the users' charging needs from the ŠKO-ENERGO charging station data. The values of levelized costs of electricity showing the competitiveness of charging points are presented.

4.8.1 LCOE of Charging Tariff Rate

As the LCOE are mainly dependent on the discount rate and the fixed operating cost ratio, the following results show minimum user tariff rate dependence. Furthermore, the tables contain additional thresholds for the investor's more qualified decision.

The initial decision regarding construction of a charging point is to plan the installed capacity of the transformer station. Figure 14 shows the share of uncovered costs caused by the nonresidents with respect to the annualized costs of an additional transformer.

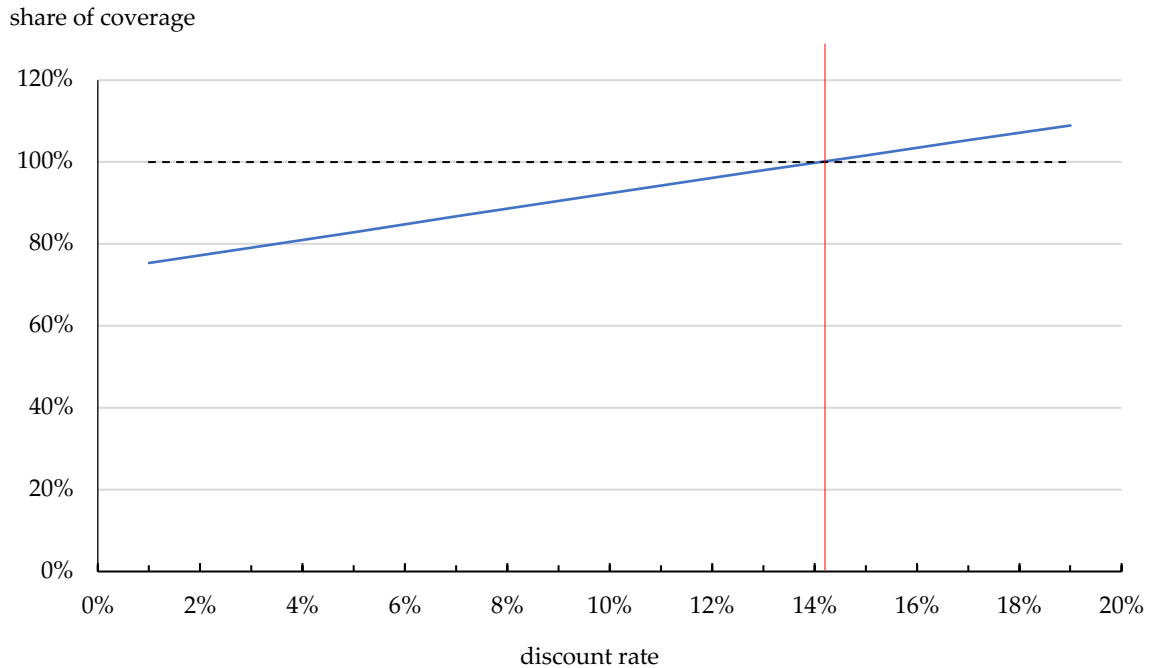


Figure 14 Share of coverage of annualized costs of additional TS.

The first threshold is marked in Figure 14. The share of coverage of annualized costs of additional TS is marked with the red line and is the boundary for the decision to increase the installed capacity of transformers. It follows from the results of the case study that an additional transformer for a discount rate higher than 15% should be installed. This boundary is also shown in Table 4 and Table 5.

Both tables show the LCOE value according to Equation (33) for the case of installation of two transformers. For a discount rate lower than 15%, it is profitable to install one transformer only. For the case of one transformer, the values highlighted in yellow are replaced with the LCOE values.

The table also shows the monetary limits per kWh depending on the number of installed transformer stations. The rate of 0.19 EUR/kWh was chosen as a reference value, which corresponds to the price of home charging. The red area indicates the monetary limits in the case of installation of one transformer. On the contrary, the green area indicates the same limit for installation of two.

		Discount Rate													
		%	5	7	9	11	13	15	17	19	21	23	25	27	29
Share of inclusion of fixed costs in residential price	0	0.08 ¹	0.08 ¹	0.08 ¹	0.08 ¹	0.08 ¹	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08
	10	0.09 ¹	0.09 ¹	0.09 ¹	0.09 ¹	0.09 ¹	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
	20	0.10 ¹	0.10 ¹	0.10 ¹	0.10 ¹	0.11 ¹	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.12
	30	0.11 ¹	0.11 ¹	0.11 ¹	0.11 ¹	0.12 ¹	0.12	0.12	0.12	0.12	0.12	0.13	0.13	0.13	0.13
	40	0.12 ¹	0.12 ¹	0.12 ¹	0.13 ¹	0.13 ¹	0.13	0.13	0.13	0.14	0.14	0.14	0.14	0.15	0.15
	50	0.13 ¹	0.13 ¹	0.13 ¹	0.14 ¹	0.14 ¹	0.14	0.14	0.15	0.15	0.15	0.16	0.16	0.16	0.16
	60	0.14 ¹	0.14 ¹	0.14 ¹	0.15 ¹	0.15 ¹	0.15	0.16	0.16	0.16	0.17	0.17	0.17	0.18	0.18
	70	0.15 ¹	0.15 ¹	0.15 ¹	0.16 ¹	0.16 ¹	0.16	0.17	0.17	0.18	0.18	0.18	0.19 ²	0.19 ²	0.20 ²
	80	0.16 ¹	0.16 ¹	0.16 ¹	0.17 ¹	0.17 ¹	0.18	0.18	0.18	0.19 ²	0.19 ²	0.20 ²	0.20 ²	0.21 ²	0.21 ³
	90	0.16 ¹	0.17 ¹	0.17 ¹	0.18 ¹	0.18 ¹	0.19 ²	0.19 ²	0.20 ²	0.20 ²	0.21 ²	0.21 ²	0.22 ³	0.22 ³	0.23 ³
	100	0.17 ¹	0.18 ¹	0.18 ¹	0.19 ¹	0.19 ¹	0.20 ²	0.20 ²	0.21 ²	0.22 ²	0.22 ³	0.23 ³	0.23 ³	0.24 ³	0.25 ³

Table 4 Dependence of residential LCOE on discount rate and on share of inclusion of fixed costs in residential price in case two TS are installed.^d

		Discount Rate													
		%	5	7	9	11	13	15	17	19	21	23	25	27	29
Share of inclusion of fixed costs in residential price	0	0.14 ¹	0.14 ¹	0.15 ¹	0.15 ¹	0.15 ¹	0.16	0.16	0.17	0.17	0.17	0.18	0.18	0.19 ³	0.19 ³
	10	0.14 ¹	0.14 ¹	0.14 ¹	0.14 ¹	0.15 ¹	0.15	0.15	0.16	0.16	0.16	0.17	0.17	0.18	0.18
	20	0.13 ¹	0.13 ¹	0.14 ¹	0.14 ¹	0.14 ¹	0.14	0.15	0.15	0.15	0.16	0.16	0.16	0.17	0.17
	30	0.12 ¹	0.13 ¹	0.13 ¹	0.13 ¹	0.13 ¹	0.14	0.14	0.14	0.14	0.15	0.15	0.15	0.16	0.16
	40	0.12 ¹	0.12 ¹	0.12 ¹	0.12 ¹	0.13 ¹	0.13	0.13	0.13	0.14	0.14	0.14	0.14	0.14	0.15
	50	0.11 ¹	0.11 ¹	0.12 ¹	0.12 ¹	0.12 ¹	0.12	0.12	0.12	0.13	0.13	0.13	0.13	0.13	0.14
	60	0.11 ¹	0.11 ¹	0.11 ¹	0.11 ¹	0.11 ¹	0.11	0.11	0.12	0.12	0.12	0.12	0.12	0.12	0.13
	70	0.10 ¹	0.10 ¹	0.10 ¹	0.10 ¹	0.10 ¹	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.12
	80	0.10 ¹	0.10 ¹	0.10 ¹	0.10 ¹	0.10 ¹	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
	90	0.09 ¹	0.09 ¹	0.09 ¹	0.09 ¹	0.09 ¹	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09
	100	0.08 ¹	0.08 ¹	0.08 ¹	0.08 ¹	0.08 ¹	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08

Table 5 Dependence of nonresidential LCOE on discount rate and on share of inclusion of fixed costs in residential price in case two TS are installed.^e

^d ¹ One TS is sufficient; ² two TS, price exceeds 0.19 EUR/kWh; ³ one TS, price exceeds 0.19 EUR/kWh.

^e ¹ One TS is sufficient; ³ one TS, price exceeds 0.19 EUR/kWh.

4.8.2 Setting of Minimum Blocking Tariff Rate

If we accept that users in one group can exceed the parking time and thus block others in the other group, then the size of the NCFC is based on the LCOE of the opposite group of users. The following tables (Table 6 and Table 7) show the amount of NCFC depending on the discount rate and the share of fixed costs included in the price according to Equations (2) and (4).

		Discount Rate														
		%	5	7	9	11	13	15	17	19	21	23	25	27	29	31
Share of fixed costs included in residential price	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	10	0.4	0.4	0.4	0.4	0.4	0.5	0.5	0.5	0.5	0.5	0.5	0.6	0.6	0.6	0.6
	20	0.7	0.7	0.8	0.8	0.9	0.9	1.0	1.0	1.0	1.1	1.1	1.1	1.2	1.2	1.3
	30	1.1	1.1	1.2	1.2	1.3	1.4	1.4	1.5	1.6	1.6	1.7	1.7	1.8	1.9	1.9
	40	1.4	1.5	1.6	1.7	1.7	1.8	1.9	2.0	2.1	2.2	2.2	2.3	2.4	2.5	2.6
	50	1.8	1.9	2.0	2.1	2.2	2.3	2.4	2.5	2.6	2.7	2.7	2.8	3.0	3.1	3.2
	60	2.1	2.2	2.4	2.5	2.6	2.7	2.9	3.0	3.1	3.3	3.3	3.4	3.6	3.7	3.9
	70	2.5	2.6	2.7	2.9	3.0	3.2	3.3	3.5	3.7	3.8	3.8	4.0	4.2	4.3	4.5
	80	2.8	3.0	3.1	3.3	3.5	3.6	3.8	4.0	4.2	4.4	4.4	4.6	4.7	4.9	5.1
	90	3.2	3.4	3.5	3.7	3.9	4.1	4.3	4.5	4.7	4.9	4.9	5.1	5.3	5.6	5.8
	100	3.5	3.7	3.9	4.1	4.3	4.6	4.8	5.0	5.2	5.5	5.5	5.7	5.9	6.2	6.4

Table 6 Nonresident blocking tariff rate in EUR/night.

		Discount Rate														
		%	5	7	9	11	13	15	17	19	21	23	25	27	29	31
Share of fixed costs included in residential price	0	0.9	1.0	1.0	1.1	1.1	1.2	1.3	1.3	1.4	1.4	1.4	1.5	1.6	1.6	1.7
	10	0.8	0.9	0.9	1.0	1.0	1.1	1.1	1.2	1.2	1.3	1.3	1.4	1.4	1.5	1.5
	20	0.7	0.8	0.8	0.9	0.9	1.0	1.0	1.1	1.1	1.2	1.2	1.2	1.3	1.3	1.4
	30	0.7	0.7	0.7	0.8	0.8	0.8	0.9	0.9	1.0	1.0	1.0	1.1	1.1	1.1	1.2
	40	0.6	0.6	0.6	0.7	0.7	0.7	0.8	0.8	0.8	0.9	0.9	0.9	0.9	1.0	1.0
	50	0.5	0.5	0.5	0.5	0.6	0.6	0.6	0.7	0.7	0.7	0.7	0.8	0.8	0.8	0.9
	60	0.4	0.4	0.4	0.4	0.5	0.5	0.5	0.5	0.6	0.6	0.6	0.6	0.6	0.7	0.7
	70	0.3	0.3	0.3	0.3	0.3	0.4	0.4	0.4	0.4	0.4	0.4	0.5	0.5	0.5	0.5
	80	0.2	0.2	0.2	0.2	0.2	0.2	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
	90	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.2
	100	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 7 Resident blocking tariff rate in EUR/day.

4.9 Discussion

The data analysis obtained from real chargers shows some important information: Users leave their EVs parked and connected to the charger for a longer time than is necessary for recharging the battery. A shorter charging time would be sufficient for almost 90% of the 330 EV user sample to charge fully. Users could even use a 3.6 kW AC charger to achieve the same recharging level in the same amount of parking time.

These results also correlate with the studies [40], [133] focusing on the average daily distance users travel by car. The average daily distance travelled by a user varies between 48 km and 50 km, and this range also corresponds to the charging requirements in our analysis.

Therefore, in terms of the development of the charging station installation, a sufficient number of chargers is a priority in urban and suburban areas rather than the construction of fewer chargers with higher charging power. The same consideration must be applied when charging infrastructure is built in a P + R car park. Due to the long parking in the daytime, this type of car park is a suitable candidate for constructing a sufficient number of low-power chargers in an urban area.

Our model shows that equipping a car park with chargers is a simple way to increase parking place efficiency. Due to the high occupancy during the daytime and the low occupancy overnight, P + R car parks have a great potential for increasing by installing chargers and introducing a night reservation system. In addition, the evening/night reservation ensures a sufficient number of parking places for EV owners living close to the P + R car park but having no parking place or garage.

The reservation provides user comfort and ensures charging of the EV for the next day comparable to owners of private garages or parking places. By comparison, home charging in the Czech Republic ensures EV owners to use the special electricity tariff D27d [159]. This tariff provides eight-hour charging in the interval from 6 pm to 8 am with a price per kWh approaching 0.08 EUR.

As shown in the economic part of the case study, our solution offers a twelve-hour charging span for a constant price between 0.09 and 0.21 EUR per kWh. This price depends on the discount rate and percentage distribution of non-covered costs between the resident and nonresident groups.

The proposed solution increases the efficiency of existing parking places situated in urban areas, where car parks are usually insufficient. Furthermore, the proposed solution does not dissuade potential new EV owners having no private parking from the purchase of a new EV. Thus, the development of electromobility is significantly supported.

Based on the case study results, the dimensioning of local transformer station power is more in accordance with the EV charging requirements of users arriving during the daytime (nonresidents). Insufficiently dimensioned local transformer station power and the need for simultaneous use of a smaller number of chargers result in financial losses.

The threshold for investors to increase the power of the local transformer station is set by comparing the annualized costs of an additional transformer and total non-covered costs from unsold electricity. Under the conditions described in the case study for a discount rate higher than 15%, the non-covered costs exceed the annualized costs of increasing the local transformer station power. In such cases, the investment in the additional transformer is profitable.

Increasing the power of the local transformer station is beneficial not only for nonresidents, whose percentage of refusal is reduced, but also for the residents, whose guaranteed charging hours may be prolonged. Therefore, doubled installed power allows simultaneous charging of a larger number of EVs, and guarantees up to twice the number of charging hours (Tg).

The model considers installation of oil-immersed transformers, which, unlike the dry type, require a higher degree of fire safety and measures against possible oil leakage. However, if we take into account the same price category, their advantages prevail. Compared to the dry type, the oil-immersed transformer achieves both lower short-circuiting, lower no-load loss and lower noise, guarantees thermal stability during operation at higher loads, and offers the possibility of continuous operation at the rated load [160]. We assume that installing this type of transformer near the P + R car park will meet all the requirements defined by the fire safety standard.

It is evident that an analysis of the behaviour and requirements of specific EV users both living near the site and often using the daytime parking services will be required to achieve a better setting of the parameters of the whole model. A limiting factor

of the input data is that they describe only the car park occupancy, losing the information about arrivals and departures within the measured five-minute interval. However, the occupancy data used have been adjusted for public holidays and vacations. Still, it is unknown whether these values may have been affected by, e.g., cultural events which tend to be organized near the car park during the year.

4.10 Conclusions

The paper analyses the technical and economic potential of installing low-power chargers in an existing car park. The assumed model of a car park equipped with chargers offers a solution to one of the most common obstacles of potential EV users when they decide whether to buy an EV: the absence of a private charging place. Furthermore, the model solves the problem of the lack of chargers in densely populated districts by installing the charging stations in an existing car park.

Generally, the model defines two groups of users. The first group (nonresidents) are users arriving randomly in the daytime who commute to the site for work or other purposes. Nonresidents usually leave cars parked there for a longer time. The second group (residents) live close to the car park and rent parking places primarily for overnight charging.

However, the major difference between the resident and nonresident groups is that nonresident users' priority is parking rather than charging. The nonresidents' EVs are charged if the current load of the transformer station makes this possible. Contrarily, the resident users' priority is the guaranteed charging. The model is based on real user parking behaviour, which then complements the requirements for recharging. The modelling results are the percentage of satisfaction of individual groups (especially nonresidents) under specifically selected charging infrastructure parameters.

The case study in the paper uses recharging data from the company ŠKO-ENERGO and parking place occupancy data for a P + R car park in Prague Letňany. The charging data contain three months of testing data from the year 2020, 330 charging iterations in total from seven charging points. All charging points were equipped with 22 kW DC power chargers, four of which could also charge with 50 kW DC. The parking occupancy data describe the car park, with a capacity of 650 parking places, in five-minute intervals from the 1st quarter of 2013 to the 4th quarter of 2016. The charging analysis shows that users left the EVs parked and connected to the charger for a longer

time than required to recharge the battery. Comparing charging and time spent at the charger, almost 90% of the tested EV users would have done with a shorter charging time to recharge the required energy. They could even use a 3.6 kW AC charger to achieve the same recharging level in the same amount of parking time.

Knowing the above information, the model designs the optimal size of charging equipment. By creating a reservation system for residents, the LCOE of nonresident charging at a discount rate of 15% will drop from around 0.15 EUR to 0.11 EUR, which competes with the price of other types of public charging. The simulation results show that although the model uses low-power chargers with an output of 3.6 kW, the daytime parking time in the P + R car park studied is sufficient to fully charge to 96% for nonresidents. However, in order to guarantee 6 h of resident charging and thus achieve a 95% success rate of full charging, it is necessary to add another transformer to the local transformer station.

Another benefit of the presented solution, in addition to more efficient use of parking places, is ensuring the stability of the EG during the charging of a large number of EVs in one place by dividing the power between them. Dividing the power between randomly placed charging stations of different owners within the power grid would not be as easy as dividing the power within the charging stations in one car park. In the case of demand for charging a group of EVs concentrated in one place, the local power grid would be significantly overloaded. Then, it is possible to support the overall stability of the local power grid with battery ESS, which would smooth out peaks in the load.

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Conflicts of Interest: The authors declare no conflict of interest.

Variables

\hat{A}	Vector with distribution of arrivals of nonresidents in five minutes during the
E	Electricity sold per year [kWh]
E_r	Total resident recharging requirement [kWh]
$E_r(x)$	Recharging requirement of resident x [kWh]
E_{TR_YX}	Energy that can be provided in interval from Y to X by local transformer [kWh]
ch_{par}	Maximum number of chargers used simultaneously
L	Length of nonresidential stay [h]
$LCOE$	Levelized costs of electricity
L_{p_kWh}	Non-covered fixed costs for unsold kilowatt hours [EUR]
M	Annual maintenance expenditures [EUR]
N_E	Electricity bill in year t [EUR]
N_i	Initial investment in equipment [EUR]
N_{var}	Unit price per kWh [EUR]
N_w	Number of EVs waiting to start recharging
P	Transformer station output power [kW]
P_{CH}	Power of one charger [kW]
P_{ch_par}	Power consumption of all chargers used simultaneously ch_{par} [kW]
P_{kn}	Short-circuit transformer losses [kW]
P_n	TS output power [kW]
P_{nl}	Power transformer no-load loss [kW]
q	Quantity
Q	Number of parking places occupied at weekends
Q_{pl}	Number of parking places in car park
Q_r	Parking places reserved for residents
R	Tariff rate for exceeding the parking time [EUR]
r	Discount rate [%]
S_m	Maximum apparent-power load of transformer [kVA]
S_n	Apparent power of transformer station [kVA]
t	Time step

T_0	Annual operating time of transformer station [h]
T_g	Guaranteed charging time for residents [h]
T_l	Last morning hour of guaranteed h
T_L	Time equivalent of losses at maximum transformer load per year [h]
T_{LT}	Lifetime [years]
T_m	Utility factor [h]
T_o	Average daily use of one charging station [h]
$T_r(x)$	Charging time of x-th resident [h]
$T_w(x)$	Waiting time in queue
W_L	Annual energy losses in transformer
X	End of interval reserved for residents
Y	Beginning of interval reserved for residents

5. Simulation of Electric Vehicle Charging Points Based on the Efficient Use of Chargers and Using Recuperated Braking Energy from Trains

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Keywords: Recuperated braking energy; train power system; varying the charger charging power; sharing economy; car park; low-power chargers; electric vehicle

The aim of this article is to explore the potential of using alternative energy sources to power EVs in areas where the local substation capacity cannot be increased. One such energy source is the energy produced by train networks that use catenary conductors.

Train stations, typically located in city centres, offer a unique opportunity to set up charging points for EVs. The construction of charging sites near train stations connected to the catenary conductor networks can also utilize the recuperated braking energy (RBE) generated by trains as they slow down when approaching a station. This recovered energy can then be used to charge EVs, reducing emissions by substituting some of the electricity required from the electricity distribution grid (EDG).

Unfortunately, the effective use of RBE is not always achieved on many railway segments. This is due to the lack of equipment such as energy storage systems (ESS) or power systems with the capability to transfer RBE back to the EDG. In such cases, RBE is often wasted by being converted into heat in the train's onboard resistors.

Several studies have explored the effective use of train RBE, with a focus on transferring the recovered energy from one railway segment to neighbouring segments, storing the RBE in ESSs, optimizing the schedule to achieve the lowest electricity consumption from the EG, and using RBE stored in battery ESSs to charge EVs.

Our proposed solution takes a different approach, offering an efficient use of RBE without the need to install an ESS, which would significantly increase the initial investment in the system. The model we have developed adjusts the charging power of each charger using a variable charging power function, ensuring that the RBE is always used in an efficient manner and does not overflow back into the EDG.

The article also highlights the results of monitoring the operation of the Tesla Model 3 EV in the Czech Republic in partnership with Solops. The data collected from

July 2020 to July 2021 showed that the current energy mix and operation of EVs in the country does not meet EU emission limits. This highlights the need for a change in the energy mix and more efficient use of electricity in order to meet European climate targets.

5.1 Abstract

Electric vehicles represent an innovation in mobility that can help significantly reduce greenhouse emissions and mitigate climate change. However, replacing internal combustion with electric vehicles is not enough. This replacement needs to be complemented with a change in the energy mix of individual countries towards renewable energy sources and efficient use of electricity generated as a secondary product. Recuperated braking energy from trains can serve as one source of such secondary energy. Following an analysis of recuperative energy generated and analysis of charging requirements of individual electric vehicles, the paper proposes a model of a charging site near train stations. Using this energy to charge electric vehicles helps to reduce energy consumption from the EG and thus reduce carbon emissions. Compared to other articles, the proposed model ensures the efficient use of recuperated braking energy from trains by using the variable charging power function; thereby, the installation of additional battery storage is eliminated. Our model results show that the benefits of a car park with a reservation system near train stations increase the car park efficiency, provide a sufficient number of private charging points, contribute to efficient use of recovered energy, and reduce carbon emissions.

5.2 Introduction

Following the European Union's (EU) 2030 targets [3] and the need to reduce one of the main sources of air pollution, namely the transport sector [9], [22], [161], many subsidy programs have been suggested to support electric vehicles (EVs) sales and construction of charging stations [22]. The main benefit of promoting EVs and associated construction of charging stations is to reduce emissions produced by the transport sector, especially in urban areas with a high concentration of both cars and inhabitants [31]. The operation of EVs directly meets this requirement, as they have zero local emissions [75].

However, transforming internal combustion engine cars into EVs will not be sufficient to reach the climate neutrality goals without a fundamental change in the energy

mix of individual countries towards a significant contribution from renewable energy sources (RESs) [3]. Achieving the emission reduction targets in the transport sector (and ultimately the climate neutrality objectives) will require both a transition from fossil fuel electricity generation [14], [15], [38], [132] and, in line with the energy efficiency first principle [162], also ideally increasing the efficiency of using recovered energy [43].

The CO₂ emission targets for 2025 and 2030 are defined as a percentage reduction from the EU fleet-wide target in 2021, with a reduction of 37.5% in the passenger car sector and 31% in the van sector in 2030 [3]. Several studies (e.g., [8], [14], [16], [163]) have therefore focused on the use of RESs such as wind or solar power plants for EV charging in an effort to reduce the carbon footprint associated with a kilowatt-hour charged in an EV.

However, respecting the energy efficiency first principle, using energy that would otherwise be wasted is another good option [9], [43], [44]. However, this has been much less explored so far [9], [43]–[46], [164]–[166].

Therefore, this paper takes this approach and focuses on reducing the CO₂ associated with each kilowatt-hour charged into an EV battery using recuperated braking energy (RBE) from trains, which is generated while a moving train is slowing into a station [9]. Using this energy for EV charging is another way to use it efficiently and not to waste it (usually converted to heat in onboard resistors/rheostats) [9], [43], [44]. Additionally, the paper considers the use of RBE by varying the charging power of EV chargers without the necessary additional installation of an energy storage system (ESS).

The objective of this paper is to find out what the economic and environmental effects of using the recuperated braking energy (RBE) to charge electric vehicles (EV) are. We do so by defining the following research questions:

1. How efficiently (in terms of %) can a charging system installed in an existing car park near a train station use RBE and how successfully (in %) can RBE be used for charging EVs?
2. How will RBE reduce the amount of CO₂ associated with kWh charged into an EV, especially with respect to the Czech Republic's energy mix?
3. How can a charging system using RBE achieve the price per kWh that users with private garages and chargers enjoy?

5.3 State of the art

Many car manufacturers have already responded to the EV demands and supported the shift from internal combustion engine cars to EVs with their strategy [167]. However, despite subsidies for the purchase of EVs [168], which vary from one EU country to another [7], there has not been a significant change in the fleet towards EVs [169], [170].

There are several reasons why users do not choose EVs, but the three main reasons are as follows: (i) high purchase price, (ii) users' concerns about the short range of EVs, and (iii) users' concerns about the uncertainty of recharging an EV before the next trip [7], [22], [24], [133].

The price of an EV is still high for a wide group of users, as has been confirmed by Xu et al. [133], who, among other things, considered the ratio between the percentage of registered EVs of California car owners and their annual salary level. The study states that 45% of car owners with an annual salary above the \$150,000 threshold have a registered EV, but only 15% of car owners whose annual salary does not exceed this threshold have a registered EV. Although the purchase price of EVs is still higher than that of internal combustion engine cars in the same category [171], the costs of EVs can be expected to fall in the future [9], [172]. This expectation is also reflected in the current trend of falling prices of batteries [9], one of the most expensive components of EVs [75]. If we compare the price of a battery between 2010 and 2020, we see that the price has fallen by 89%, and in 2020 the price reached USD 100 per kWh of battery capacity [173].

The second important issue for potential EV users is the short mileage range of EVs due to the small capacity of the installed batteries [40]. Studies [40], [133], [174] report that the average daily distance travelled by a user living in Beijing, California, and the Czech Republic is no more than 50 km. Taking into account all currently available battery EV models, with an average installed battery capacity of 60 kWh [137] and average energy consumption of about 20 kWh/100 km [138], the mileage range of the EV on one charge can belittle this concern. In fact, these users with an average daily mileage of no more than 50 kilometres get an opportunity to travel for up to six days without recharging.

The third important issue for many respondents is the charging of EVs and the question of a dense network of charging stations [7], [22], [24], [25], [133], [174].

In other words, the reason for not deciding to buy an EV is often the absence of a private garage or parking space equipped with a charging station that would enable the user to recharge the battery before the next journey.

One of the aims of this article is to contribute to the solution of the third issue. The solution for these EV customers who do not have their own charger-equipped parking space could be a dense network of strategically located public charging stations or the possibility of sharing or reserving either public or private chargers [40], [49], [50], [135]. Unfortunately, building a dense network of public charging stations would require breaking the vicious circle [132]. The reason for the small number of charging stations is that many investors are still reluctant to build more charging stations because the number of EVs in operation is below the level the investors economically require [132], [168]. However, sharing charging stations can be a solution.

Nevertheless, sharing of private charging stations, similar to the construction of new public ones, also has its limitations. Shared private charging stations can be divided into two categories. The first category is sharing chargers by individual EV owners who have a charger located in a private garage or parking space. The advantage of this type of sharing can be seen in many charging points being randomly distributed in the city [40], [49]. The disadvantage is the owner's responsibility for the charging station provided [40]. However, a significant disadvantage of this sharing is the probability of a charging requirement overlap between the owner and the potential customer in the afternoons and evenings [62], [174]. The second sharing category, to which the present paper also contributes, is constituted by sharing a larger number of charging stations in car parks, such as company car parks, car parks near hospitals, schools and shopping centres, or even car parks on the outskirts of cities [174]. These car parks are mostly used between 7 am and 7 pm and minimally outside this time span [175]. Therefore, the benefit of these car parks, such as the large capacity of parking spaces with chargers and lower occupancy in the evenings, diminishes the number of refused charges, mostly in the desirable evening hours [51], [133], [176]. Selecting a suitable place for the construction of a charging point, optimising the number and power of chargers, and using RESs are therefore critical [9], [50], [62], [75], [132], [164], [174], [177].

Concerning dimensioning both the power and the number of chargers in relation to the installation place and charging requirements, Dvořáček et al. [174] conclude that a higher number of chargers is for city centres and suburban areas a higher priority than

high power when building charging stations. Based on the analysis of charging requirements [154], users leave EVs parked and connected to chargers located in urban areas for a longer time than required to recharge the battery. This can be demonstrated by the fact that it was possible to charge the battery of an EV with a lower-power 3.6 kW charger during the same parking time [174].

However, this statement should not be applied to dimensioning a charging point for specific groups such as EV taxi drivers [178]. The same rules for dimensioning charging points along highways and other expressways apply to these groups with specific charging requirements. In these cases, high charging power and consequently short charging times are a priority [179].

Besides optimization of the number and power of charging stations, there are other criteria such as (i) good access from the viewpoint of transport infrastructure [135], (ii) installation near more attractive points of interest (POI) [135], and (iii) focusing on the capacity of the site's electrical connection to the distribution system and the stability of the local distribution system [14], [62], [132], [133], [145].

The stability of local electricity distribution grids (EDG) by supplementing energy storage systems (ESS) or a new source of renewable energy was addressed in [180]–[185]. Both the ESS and the new energy source should be built as close as possible to the EV charging point [186]. Due to the nearby installation, there are no frequently long-distance energy transmissions that would overload the grid and also contribute to energy transmission losses [14], [184]. In addition, the benefits of ESS include smoothing of peaks in the consumption pattern and accumulation of energy produced from RES that is not directly consumed [185].

Similarly to the EDG, power peaks also occur in the train power system and threaten its stability. There are generally two types of catenary conductor feeding compared to the distribution network: DC and AC power supply, while the power feeding system is still not united [187]. For instance, in the Czech Republic, the catenary conductors in the southern part of the country are fed by AC, and DC still feeds the northern part [188]. However, a change towards AC power technology is a trend bringing the advantage of DC for powering an extended segment of the catenary conductor from a single feeder due to lower transmission losses over longer distances [187]. The AC-powered catenary conductors can thus be 40 km to 60 km long [189].

These segments can be fed by a reversible substation from one side or both sides. The advantage of these reversible substations is the possibility of transferring the unconsumed RBE back to the EDG [44]. The disadvantage of transferring the recuperated energy via reversible substations back to the EDG is the possible instability of the grid and the generation of AC harmonics [44]. One of the limitations on effective RBE use is the impossibility of transferring this energy between neighbouring segments without additional modern technologies [45], [165]. Therefore, it is advantageous to consume the RBE directly in the given segment. According to the benefits of AC compared to DC, we will focus in our article only on AC power systems and RBE consumption directly in the given railway segment with the reversible substation.

The research gap to which this article responds is the construction of charging points for EVs in car parks near train stations, with efficient use of existing catenary conductor networks [9]. Furthermore, in order to achieve more efficient use of these charging stations, reservation of charging stations at night is used [174]. In consideration of occupancy profiles of these car parks near train stations [175], evening reservations for EV charging are directly offered. After all, these car parks are mainly occupied throughout the day [175], when they are used by people arriving by car and travelling on by train [190]. In the evenings, these car parks are often unused [175] and can be offered to returning users who live in the area around the train station and do not have their own private charger.

The high power levels of catenary conductor networks and their stability [43], [44], [189], [191], as well as the location of train stations, typically in city centres [190], directly offer this opportunity for building EV charging points. Furthermore, the construction of charging sites for EVs near train stations connected to the catenary conductor networks offers the possibility of using recuperated braking energy (RBE) of trains [9]. The RBE is generated while a moving train is slowing into a station and can charge EVs. Since there are no CO₂ emissions from the generation of RBE, by consuming and efficiently using this energy, the amount of CO₂ associated with the need for each kilowatt-hour of energy is reduced significantly. Moreover, the contribution of this recovered energy to the charging of EVs helps reduce emissions by substituting some of the electricity required from the distribution grid [43].

However, RBE is very often not used effectively on many segments of railway lines. On railway segments equipped with neither ESS nor a power system with

the facility to transfer RBE back to the EDG, RBE is wasted by conversion to heat in the train onboard resistors (rheostats) [9], [43], [44]. Fernández-Rodríguez et al. [9] showed that the inefficiently used RBE on a selected Italian train line was up to 15 MW per day (roughly 10% of all daily RBE). On a selected Spanish railway line, the daily inefficiently used RBE was 10.28 MWh (roughly 13% of all daily RBE). Fernández-Rodríguez et al. [9] further reported that the maximum inefficient use of RBE on the railway lines was observed, particularly when the time intervals between trains were long. In the peak periods during the day, when the time intervals between trainsets were short, and hence RBE consumers were numerous, up to 98% of RBE was used efficiently [9].

Effective use of train RBE has also been the subject of other studies [9], [43]–[46], [164]–[166]. The studies can be divided into three categories. The first one wants to transfer the recovered energy from one separately fed railway segment to neighbouring segments at the same time [45], [165]. This transferred energy will replace part of the electricity consumed by starting or accelerating trains on the other segments, thereby reducing the electricity consumed from the EDG and, consequently, carbon emissions [43]. The second group of studies [9], [44], [191] focuses both on storing the RBE in ESSs and on schedule optimization to achieve the lowest electricity consumption from the grid while efficiently using the RBE. These ESSs also contribute to smoothing out any power fluctuations in the catenary conductor networks and thus ensure the stability of the traction power system. The ESSs typically used to accumulate RBE are capacitors, which have better charge and discharge rates, durability and life cycles than batteries [44]. The third group of studies [9], [164], [189] focuses on the possibility of using RBE stored in battery ESSs to charge EVs.

Our proposed solution and the developed model approaches EVs charging with the same objective to efficiently use the RBE as in the studies mentioned above, but with no need to install an ESS, which would significantly increase the initial investment in the whole system.

5.4 Model of EV charging site using RBE

From the viewpoint of the EV user, car parks near train stations are among the most sought-after points of interest (POIs) and thus a place with a high population density [192]. In terms of charging time for EVs, charging stations at train station car

parks bring users the benefit of effective use of the long parking time when an EV is unused, and charging it thus contributes to increased user comfort. Building charging stations at such locations is therefore of great importance. Therefore, our model considers constructing a charging point at a strategically located car park at a train station where the battery capacities of the individual EVs being charged directly replace the ESS capacity. The recuperated energy thus supplies a significant part of the energy absorbed by the EV batteries, but simultaneously the electricity available from the railway line power is also used for charging.

5.4.1 Scheme of EV charging site with variable charging power function

In addition to more efficient use of charging stations through user reservations in the evenings, the model considered uses the variable charging power function of charging stations. Due to charging power variation, the model is able to better respond to fluctuations in the RBE and thus uses this energy with more efficiency for charging EVs. The charging power level is adjusted based on the number of simultaneously charging EVs and the amount of predicted RBE at the same time (Figure 15).

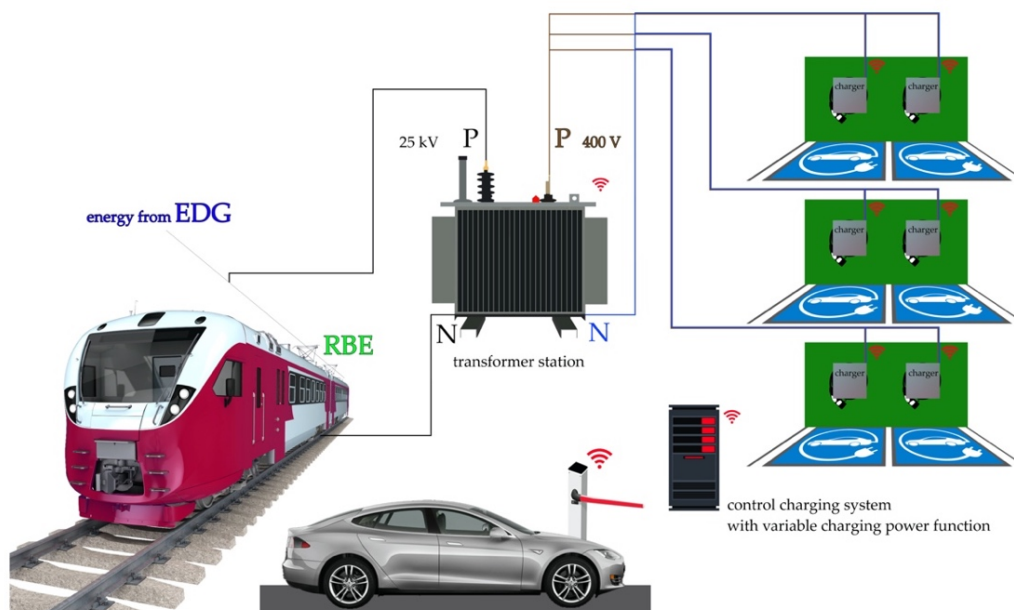


Figure 15 Car park model equipped with single-phase chargers and variable charging power function.

In the model, individual parking lots are equipped with single-phase AC charging stations with a power ranging from 3.6 to 7.4 kW. We chose these types of charging stations based on testing results provided by the company Ško-energo [154]. Their results confirmed that the variation in charging power with the AC type and the given power range is not blocked by the EV onboard system. AC charging stations with charging

power up to 11 kW could also be used for charging, but the standard three-phase design limits their implementation. To achieve 11 kW AC charging power would require modifications to charging station manufacturing and production of an AC charging station that would achieve this power on one phase with a 50 A current [193]. In terms of current limits, chargers taking 50 A do not affect train power systems operating at tens of kiloamperes, unlike the EDG.

When considering the use of a DC charging station with a power exceeding 50 kW, we are confronted with the problem of the choice of the charging power level, which is set by the EV onboard charging system in this case according to the OCPP standard [194]. The maximum charging power value is adjusted depending on the type of battery cells used, their actual temperature and life cycle [194]. The charging station's request for an increase in charging power would thus not be accepted.

5.4.2 Model input parameters

The input parameters for a model car park equipped with low-power chargers fed by a railway line power system with the benefit of using RBE are as follows:

- maximum number of parking places in the car park assumed (Q_{PL});
- EV arrivals on weekdays;
- data describing demand for electricity by arriving EV users;
- data describing fluctuation of recuperated braking energy (RBE) in the railway line segment.

The model of charging infrastructure for a car park near a train station consists of a 25kV/400V single-phase AC transformer station (TS), a switch disconnector and isolator, a circuit breaker, a fuse, cabling, a charging control system and chargers.

The model considers the following aspects: The charging issue is always related to the maximum load of a single-phase transformer, where model input parameters such as a fixed number of chargers (n) and the maximum power level of the charging station used (p) define the required transformer power (P_{CH}). The nominal apparent power (S_n) of a suitable transformer depends on the power factor ($\cos \varphi$).

This dimensioning of the transformer power is very important due to the variable charging power function used. For efficient use of RBE, the charging power of the chargers is adjusted to ensure that the energy generated by RBE is fully exploited.

$$S_n \geq \frac{P_{CH}}{\cos \varphi} \quad (34)$$

$$P_{CH} = n \cdot p \quad (35)$$

$$Q_{PL} \geq n \quad (36)$$

5.4.3 Variable charging power function

The charger and the EV communicate using the OCCP protocol from the start of the charging process [195]. During this communication, the charging station gets information about the specific parameters of the connected EV and the amount of energy needed to fully charge its battery [195]. These charging processes are primarily beneficial for the EV's battery life, where the battery temperature stays at optimal levels. Consequently, the batteries are ready to increase the charging power. A further benefit brought by continuous EV charging consists in keeping the electricity consumption of the train charging system free of significant fluctuations in its load.

The issue of charging power variation is divided into three scenarios in the model which differ by the number of charging EVs and the amount of RBE. However, the same basic charging power of the AC chargers, which does not decrease below the minimum power level of the charger is used for all scenarios.

The first scenario describes a situation where RBE is zero, and the basic power of AC chargers is used to charge all EVs.

The second charging scenario describes a situation where RBE becomes higher than zero but does not exceed the energy consumed by EVs charged by the basic power of AC chargers. In this scenario, the RBE replaces part of the energy that would have to be supplied from the EDG to the train power system and then consumed by the chargers.

The third scenario describes a situation in which RBE becomes higher than zero and simultaneously exceeds the energy consumption by EVs charged by the basic power of AC chargers. In this case, the model sets the required power increase for all used chargers within the range limited by their maximum charging power to use the RBE efficiently.

Furthermore, there are variations in the chargers' charging power in the specific case where RBE is higher than zero, and at the same time, there are cars in the group of charging EVs with a demand for energy that the charger can supply when using the maximum charging power. In this case, RBE is used preferentially to recharge these cars.

5.4.4 Description of users

A fundamental issue in setting up a model car park located near a train station equipped with chargers is to dimension and adapt its equipment to the requirements of individual groups of EV users. Generally, car park users can be divided into two main groups. The first group consists of EV users who commute to a car park near a train station to continue to work or other destinations by train. The second group consists of users (residents) who live close to the train station and rent a parking space mainly for charging in the evenings. As far as residents are concerned, the reservation of a parking space equipped with a charger offers them a similar convenience as to people living in family houses who have their own garage or private parking space equipped with a charger.

Our model assumes that the first group of EV users (nonresidents) use the car park in the daytime when, especially in the morning at (X) o'clock, they leave their EVs in the car park and use the train service to continue their journey. Nonresident EVs are thus parked and can be charged until the nonresidents return from work or other journeys at (Y) o'clock. Therefore, nonresident users' priority is parking rather than charging, which is not mandatory for them. Before parking, each nonresident user chooses whether he/she wants to charge his/her EV. After leaving the parking place, the user pays an appropriate hourly parking rate and the energy bill. Since the train station car park is not primarily intended as a public charging site, nonresidents are not guaranteed fully charged batteries. Parking only increases the energy level in the EV; the problem of full recharging is solved by home charging or by other means.

For the second group (residents), the car park model offers the possibility of renting parking places with a charger during evening hours. If the residents arrive no later than at the set evening time (T_{SCH}), they are guaranteed minimum charging power for the entire parking time and the appropriate amount of energy (Ch_R). Therefore, the rules for the resident group require a different setting. It is assumed that residents want to rent a parking place due to the absence of private charging points and the guaranteed battery charge before the next trip.

Compared to nonresidents, residents are financially motivated to use the car park to charge their EVs. The proposed principle to encourage residents to charge their EVs is to introduce a minimum flat rate for residential parking. Under the flat fee, residents are guaranteed energy recharge regardless of actual usage. Charging beyond the guaranteed

energy recharge is then calculated per kWh. The flat rate will ensure a reduction in the risk of non-covered fixed costs (NCFC) due to blocking cars with little need for charging. Another source of risk is the mutual blocking of users; this issue is addressed in the following section.

5.4.5 Blocking issues

To completely prevent charger blocking, additional installation of chargers in each parking place is assumed. Moreover, the model sets a maximum number of reserved parking spaces for residents to avoid blocking between the nonresident and resident groups. The limiting factor for determining the number of resident parking spaces in a car park is the number of spaces available at (X) am or (Y) pm, with a probability exceeding 90%. Then the number of resident spaces is defined by choosing a smaller number when comparing the available parking spaces at (X) o'clock in the morning or (Y) o'clock in the evening.

The smaller number of resident parking spaces than the number of nonresident ones and the ability to reserve resident memberships for a specific day mostly solve a potential problem of mutual parking space blocking. Besides, the model allows residents to reserve membership in a parking group rather than a specific parking space to avoid a resident parking space being blocked by a nonresident's delayed departure.

Since the primary purpose of a car park located near a train station is to provide parking space for nonresident users who leave their EVs in the car park and use the train service to continue their journey, it is necessary to consider possible blocking by residents using the car park overnight. Therefore, residents who choose not to leave before (X) am are charged a special daytime rate. The minimum rate per each blocking hour ($R_{resident}$) is set as the product of the NCFC per unsold kWh ($L_{P_kWh_nonresident}$) and the average nonresident charging power ($P_{ACH_nonresident}$).

$$R_{resident} = L_{P_kWh_nonresident} \cdot P_{ACH_nonresident} \quad (37)$$

Otherwise, if a nonresident decides not to leave and blocks a resident after (Y) pm, the special nighttime rate is charged. The minimum rate per each blocking hour ($R_{nonresident}$) is set as the product of the NCFC per unsold kWh ($L_{P_kWh_resident}$) and the average resident charging power ($P_{ACH_resident}$).

$$R_{nonresident} = L_{P_kWh_resident} \cdot P_{ACH_resident} \quad (38)$$

5.5 Economic aspects of proposed model

Besides the technical aspects, economic factors must also be taken into account when constructing charging infrastructure in an existing car park near a train station. One of the key issues is the competitiveness of the project compared to other charging methods, such as public charging stations as well as home charging with private chargers. We assume that the main priority of the model is to maximize the use of RBE in order to reduce the amount of energy purchased from the EDG. Reducing the amount of energy purchased from the EDG using RBE reduces the cost per kilowatt-hour for both residents and nonresidents. The minimum price per kilowatt-hour sold is then compared with both the kilowatt-hour prices of charging at competitive public chargers and the prices users pay when charging at home.

In order to assess the economic effectiveness, the model uses the levelized costs of electricity (LCOE) to recalculate individual capital expenditures (CAPEX) with different lifetimes and operating expenses (OPEX) converted to a unit price per kWh. The CAPEX include a HV/LV single-phase transformer, switch disconnectors and isolators, circuit breakers, fuses, cabling, installation material, chargers, connection fees, installation work and a charging control system. The OPEX are generally divided into two items, the first one consisting of maintenance and the second one associated with electricity consumption.

Since the TS is responsible for significant losses, the following empirical formula given by the standard CSN 341610 is used for the estimation of annual losses in the TS.

$$T_L = \left[0.2 \frac{T_m}{T_0} + 0.8 \left(\frac{T_m}{T_0} \right)^2 \right] \cdot T_0 \quad (39)$$

where T_L is the annual time of full transformer losses, T_m is the utility factor, and T_0 is the annual operating time of the TS.

$$W_L = P_{nl} T_0 + P_{kn} \frac{S_m^2}{S_n^2} T_L \quad (40)$$

where W_L is the annual energy losses in the transformer, P_{nl} is the power transformer no-load loss, T_0 is the annual operating time of the TS, P_{kn} is the short-circuit transformer losses, S_m is the maximum apparent-power load of the transformer, S is the apparent power of the TS, and T_L is the time equivalent of losses at the maximum load of the transformer per year.

These transformer losses affect both the energy supplied from the EDG and the RBE energy generated by braking trains. The losses caused by the transformation decrease the efficiency of the RBE energy use and consequently have an impact on both the price of a kilowatt-hour charged to EVs as well as the increase in CO₂ emissions associated with it.

The objective of the economic evaluation of the model is to determine the levelized costs of electricity (LCOE) for both nonresident and resident charging groups.

$$LCOE = \frac{\text{sum of costs over lifetime}}{\text{sum of electrical energy sold}} = \frac{N_i + \sum_{t_y=1}^{T_{LT}} (M_{t_y} + N_{E t_y}) (1 + r)^{-t_y}}{\sum_{t_y=1}^{T_{LT}} E_{t_y} (1 + r)^{-t_y}} \quad (41)$$

where the variable N_i denotes an initial investment in the equipment; M denotes the annual maintenance expenditures, and N_E is the electricity bill in the year t_y , r is the discount rate, T_{LT} is lifetime and E denotes electricity sold in the year t_y [kWh].

5.6 Case study

The following chapter deals with an application of the model to real data. The chapter consists of four subchapters. The first two present and analyse the real data entering the model. They are followed by a technical evaluation of the case study data (the third subchapter) and an economic evaluation (the fourth subchapter).

5.6.1 Car park description

Data from a car park located at the Praha Holešovice train station with 64 parking spaces were selected for the survey. The data capture the car park occupancy in five-minute intervals from 2013 to 2018. The car park occupancy data do not include data for holidays and public holidays, which would significantly alter occupancy information for the days in question. The parking data do not include any private residents.

For further processing, information about the car park occupancy in five-minute intervals was divided into weekdays (from Monday to Friday) and weekends (Saturday and Sunday). The average weekday and weekend occupancy levels were calculated for each five-minute interval based on this six-year study.

Subsequently, a comprehensive data analysis was performed to identify significant differences in car park occupancy between weekdays (Monday to Friday) and weekends.

The analysis of weekdays shows that user behaviour is almost identical on weekdays. Conversely, significant differences were observed when comparing the behaviour of users on weekdays and weekends, especially in the full occupancy interval of the car park. On weekdays, the car park was almost full between 6 am and 2 pm, while its occupancy reached a maximum between 1 and 3 pm during the weekends. Assuming a daily occupancy of the car park from $X = 6$ am to $Y = 7$ pm, the rate of deviation (the ratio of the standard deviation occupancy to the average occupancy) between individual working days does not exceed 13% (Figure 16).

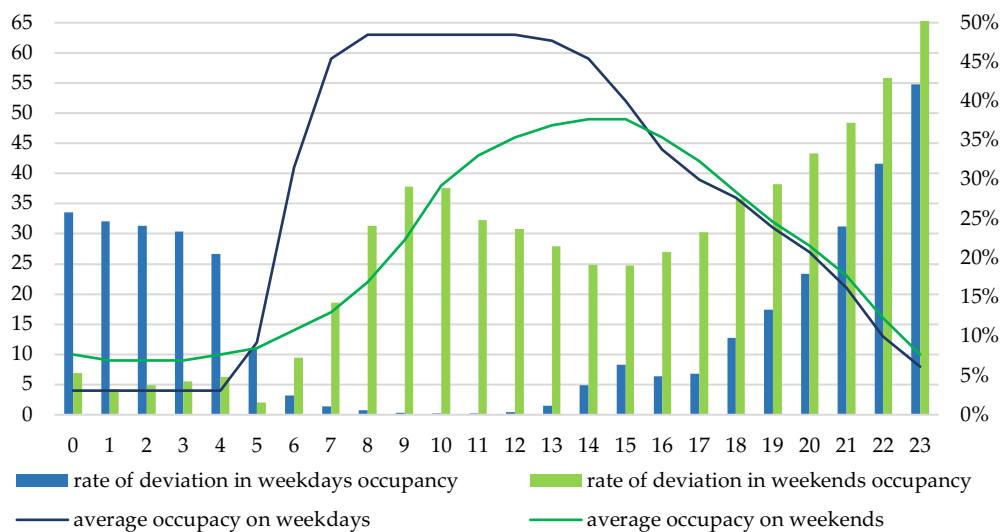


Figure 16 Similarity of parking occupancy data between weekdays and weekends

Considering a daily occupancy of the car park from $X = 6$ am to $Y = 7$ pm, the rate of deviation (the ratio of the standard deviation occupancy to the average occupancy) between the reference years 2013 to 2018 is less than 15% (Figure 17).

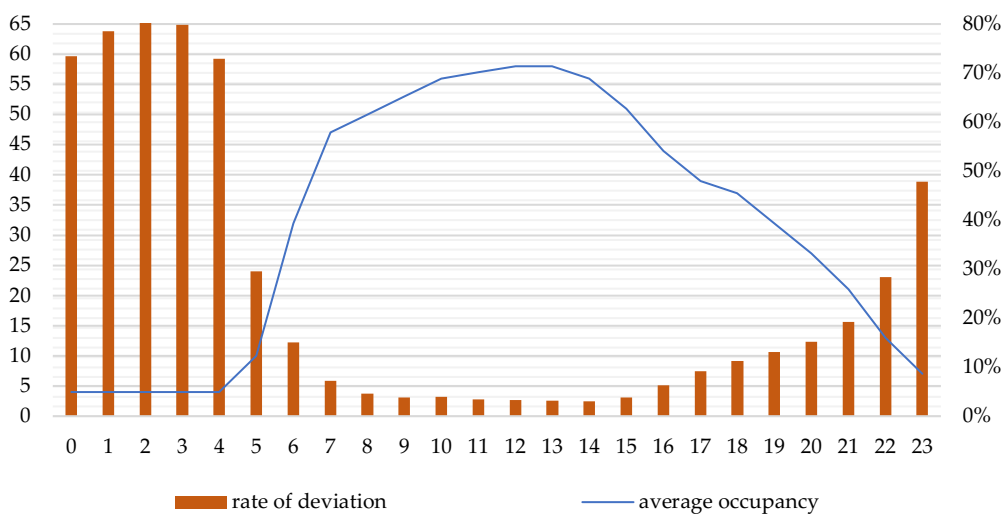


Figure 17 Similarity of parking occupancy data among years

The disadvantage of the data used to characterize the car park occupancy is that the data do not track the arrivals and departures of individual cars at five-minute intervals but only reflect car park occupancy. Thus, at five-minute intervals, when the number of departing cars equals the number of arriving ones, the car park occupancy tracking shows zero change and consequently introduces inaccuracies into our modelling. Therefore, the model tries to approximate the parking occupancy curve by generating vehicle arrivals and their parking times to achieve the real occupancy of the Praha Holešovice station car park. The departure time was modelled using a Gaussian distribution with a mean and a standard deviation described in the following paragraph.

The purpose of the train station car park and requirements of its users during the day had to be taken into account in the modelling. It is assumed that users (nonresidents) arriving at the car park before 9 am use it for all-day parking until they return from work or other journeys. Therefore, for nonresidents arriving before 9 am, a Gaussian function with a 6-hour mean and a standard deviation of 3 hours was used for parking time modelling. A Gaussian function with a 2-hour mean and a standard deviation of 1 hour was used to model the parking time of users (nonresidents) who used the car park after 9 am.

The data obtained from the charging stations operated by PRE [196] (Prague, Czech Republic) were used to simulate the demand for recharging of EVs. During the one-year measuring from November 2019 to November 2020, data on 3,000 charging iterations from various types of EVs were obtained.

The charging data were obtained from seventy-seven charging points, each equipped with a 22 kW DC power charger. At eleven of these seventy-seven charging points, it was also possible to use a 50 kW DC charger. Six of the seventy-seven charging points were equipped with 75 kW DC chargers. The most powerful supercharger with 150 kW DC was installed only in two of the seventy-seven charging points.

A more in-depth analysis of the data provided information about the time spent in the car park and the time required for sufficient charging (Figure 18). The analysis shows that users left their EVs parked and connected to the charger for periods longer than needed to recharge the batteries. This can also be demonstrated by the fact that it is possible to recharge the required energy to fully charge the EVs' batteries by using a charger with a lower power over the same parking time. The only exception was for

charging iterations shorter than 30 minutes, where the results of the analysis were affected by the 150 kW supercharger. During these charging iterations, the EV batteries were supplied by energy for which a 3.6 kW charger would take almost twice as long.

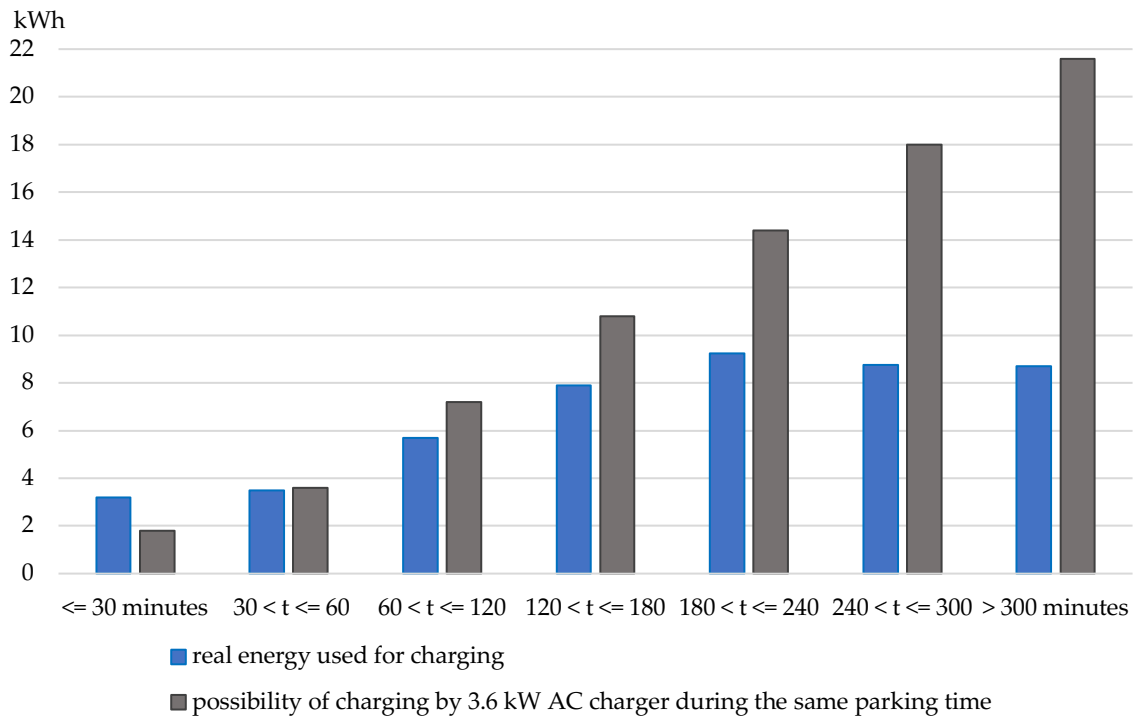


Figure 18 Pražská energetika (PRE) charging stations ([196], calculated by authors)

Figure 18 shows that users park longer than necessary to recharge the battery to the full capacity after less than 30-minute charging iterations, and therefore they unnecessarily block the possibility of recharging other EVs.

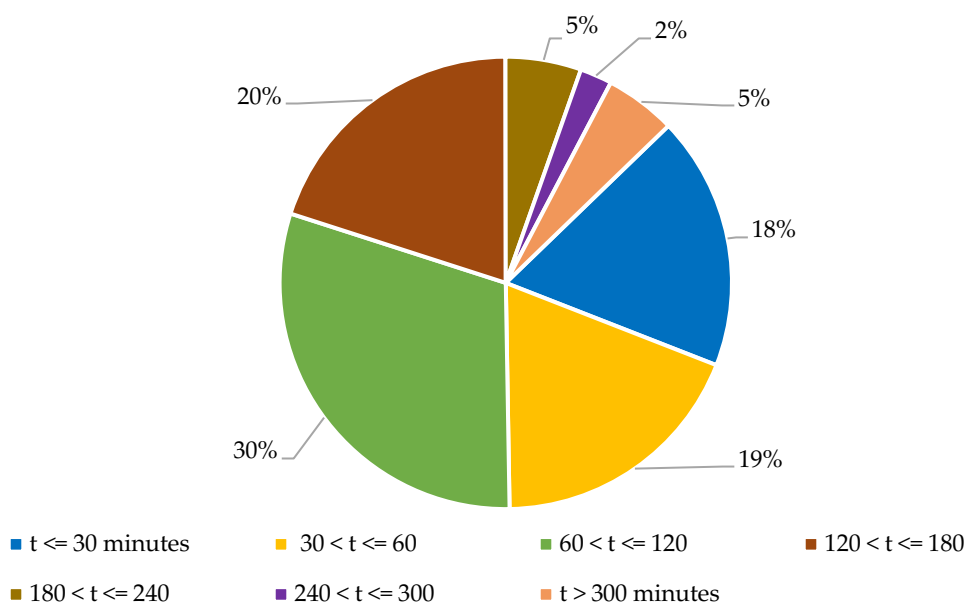


Figure 19 Parking time at PRE charging stations ([196], calculated by authors)

Figure 18 and Figure 19 show that more than 80% of the car users analysed could have done with a shorter charging time to recharge the required energy or using a 3.6 kW AC charger to achieve the same recharging level in the same amount of parking time.

The EV charging sample also offers a valuable outline of the demand for electricity recharging. The data obtained from 3000 charging iterations were sorted based on the energy consumed and subsequently used to calculate the cumulative distribution function (CDF).

The most frequent groups (12%) are EVs with a charging requirement of 6 kWh and 7 kWh, followed by a group of EVs (11%) with a charging requirement of 9 kWh. The charging requirements show that 90% of arriving EVs require less than 13 kWh to recharge, corresponding to approximately 4 hours of recharging with a 3.6 kWh charger (see Figure 20).

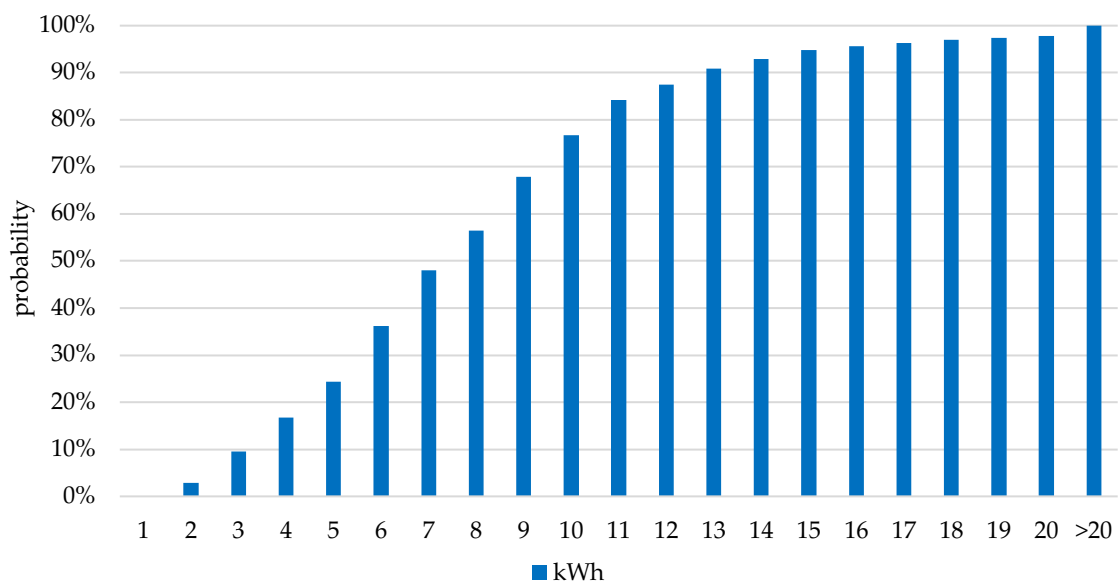


Figure 20 Cumulative distribution function of charging requirements [kWh] ([196], calculated by authors)

Data capturing the RBE overflows on the busiest train line between Prague and Brno were used for the simulation [197]. The RBE overflow data were captured at five-minute intervals during the yearly monitoring at the feeder, which is the connection between the EDG and the train power system.

For further processing, the average levels were calculated for each five-minute interval based on annual monitoring of RBE overflows on weekdays.

The data capturing RBE during weekends were not available for the busiest train line between Prague and Brno. The absence of the weekend RBE data from this train line

is also the reason why the case study focuses, in the following, on simulating both the car park operation and the recuperated energy consumption only for weekdays.

5.6.2 Analysis of input users' data

The case study considers the integration of charging infrastructure into an existing car park near the Praha Holešovice train station with 64 parking spaces (Q_{PL}) in Prague. The input data vector describing the car park occupancy during one day was composed of 288 five-minute intervals. The analysis of the real data showed that with more than 90% probability, 20 parking spaces are available in the car park on weekdays at 6 am and 27 parking spaces at 7 pm. Therefore, 20 parking spaces (Q_R) can be reserved from $Y = 7$ pm to $X = 6$ am for residents out of the total capacity of 64 parking spaces (Q_{PL}).

The number of nonresidents in the car park at a given five-minute interval (t) is estimated by using a Gaussian distribution function. The mean and the standard deviation of the Gaussian distribution ($A(t)$) were obtained from the input occupancy data on weekdays in a given five-minute interval (t).

$$\hat{A}(t) \sim N(\mu_A(t), \sigma_A(t)) \quad (42)$$

Similarly, the time spent by a nonresident in a parking lot is estimated by using a Gaussian distribution function where the mean and the standard deviation depend on the occupancy time interval. For nonresidents arriving at the car park before 9 am, a 6-hour mean and a standard deviation of 3 hours were used for parking time modelling. A Gaussian function with a 2-hour mean and a standard deviation of 1 hour was used to model the parking time of users (nonresidents) who used the car park after 9 am. The median value of 8 hours and a standard deviation of 30 minutes were used to model the time spent by a resident in a parking lot. The departure time of residents is around 6 am.

The parking requirements are described as follows:

$$L(x) \sim N(\mu_L, \sigma_L) \quad (43)$$

where for nonresidents arriving in the car park at the time t :

- 6 am < t < 9 am: $\mu_L = 6$ h, $\sigma_L = 3$ h
- $t > 9$ am: $\mu_L = 2$ h, $\sigma_L = 1$ h

and residents arriving in the car park at the time t :

- $t > 8:30$ pm: $\mu_L = 8$ h, $\sigma_L = 0.5$ h

The nonresidents' charging requirement ($E_N(x)$) assumed a distribution function, which correlates with real requirements obtained from charging stations of PRE [196] (Prague, Czech Republic) during the annual measuring.

The charging requirements are described as follows:

$$E_N(x) \sim PDF(\text{real requirements obtained from charging stations}) \quad (44)$$

Since no data were obtained describing evening arrivals and morning departures of residents living close to the considered car park at Praha Holešovice station, the case study models only the charging requirement of the residents' group. The charging demands are obtained from the study results [198] focused on the PDF of the daily distance driven by a car (Figure 21). We obtain information about the required energy charge (E_R) by dividing the daily distance driven by cars by the average EV consumption of 20 kWh per one hundred kilometres [138].

$$E_R(x) \sim PDF(\text{Pareschi's study focused on the daily range of users}) \cdot 20 \text{ kWh} \quad (45)$$

The reason for adjusting the residents' charging requirements is that the parking cost increased by the guaranteed amount of energy (Ch_R) is too high for users with a lower charging demand. The increase motivates residents to use the car park for evening parking as well as charging when they really need to recharge their EVs battery. Residents with a requirement to charge a small amount of energy (units of kilowatt-hours) are able to recharge their EV at public charging points during their journey in a short time and without significant inconvenience.

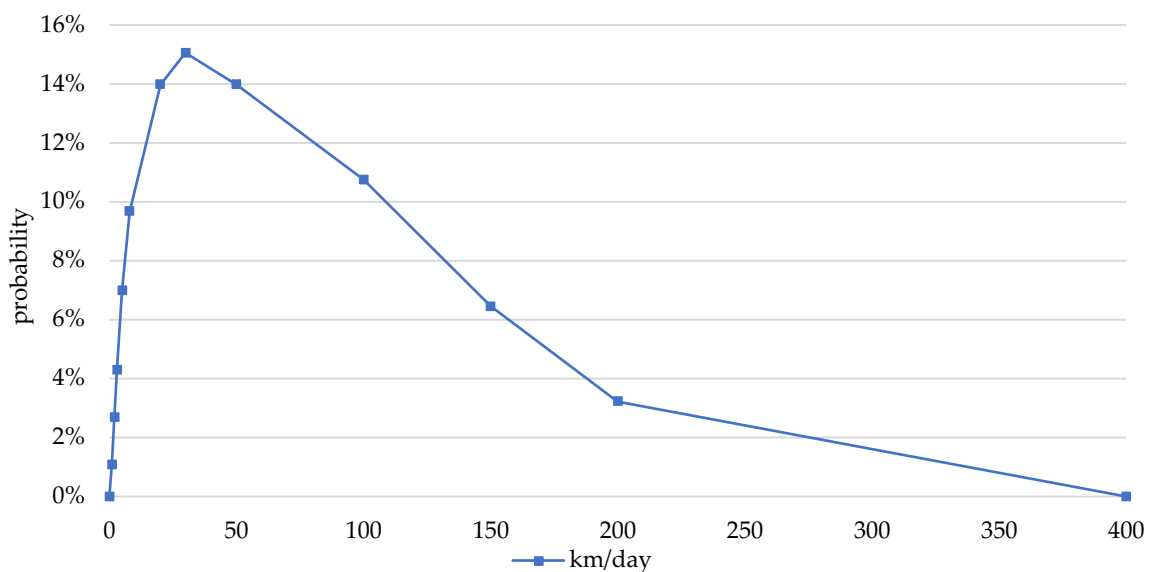


Figure 21 Probability density function of daily distance driven by car [198]

When focusing on the time required to fully charge a residents' EV battery, it is necessary to consider the energy losses incurred during the charging process. Depending on the charging station power, 10 to 25% of the energy is converted into heat. However, it can be assumed that charging with a low-power AC charger in the range from 1.38 kW to 7.4 kW results in losses close to 10%.

The minimum charging current required to ensure a charging process without interruption is set to 6A according to the standard CSN EN IEC 61851. This corresponds to a charging power of 1.38 kW when considering a single-phase charger. Concerning this standard, the minimum charging power for residential charging is set at 1.38 kW in the case study. This reduction in the minimum charging power from 3.6 kW to 1.38 kW ensures that the resident charging process is kept as long as possible during parking. Due to the charging of twenty resident EVs, the power flexibility of the system ranges from 27.6 kW to 148 kW. Thanks to the low charging power level, the system also has sufficient available capacity in the batteries of the charged EVs and therefore it can efficiently respond to RBE peaks, especially in the morning hours. Then a simple increase in the power of the charging stations is sufficient to use RBE efficiently since all EVs are ready to consume the supplied energy immediately during continuous charging until their batteries are fully charged.

From the residents' charging point of view, shifting the start of their charging depends on the effective use of RBE by charging nonresident vehicles. Although residents can arrive at the car park starting at 7 pm, the charging process for them does not start until the nonresident consumption falls below the RBE level. Considering the input data of this case study, resident charging starts at around 8:30 in the evening. From this moment, the charging process is initiated at each resident EV successively. It continues without interruption until all cars are fully charged or leave around 6 o'clock in the morning of the following day. In addition, resident departures are considered to have a Gaussian distribution, where the mean value equals 6 hours, and the standard deviation is 30 minutes.

Since the minimum charging power of the charger in the resident mode is 1.38 kW and the resident parking time is roughly 9 hours, the guaranteed amount of energy (Ch_R) is set to 12 kWh. Furthermore, this amount of energy will cover the users' 60 km daily driving range with an assumed average consumption of 20 kWh/100 km [138]. Besides Pareschi's study, other studies focusing on the daily range of users [40], [133], [174] have

confirmed that the range does not exceed 50 kilometres. Therefore, the 12 kWh guaranteed amount of energy should be entirely sufficient concerning the average daily mileage.

5.6.3 Technical aspects of system dimensioning

The capacity of the single-phase transformer is dimensioned with regard to both the number and the maximum power of the chargers considered. This dimensioning ensures that the transformer parameters do not limit the possibility of increasing charging power at all chargers to their maximum in case of a large increase in RBE. It is important to mention that due to the number of EVs charged and the level of RBE, it would be sufficient to install a single-phase transformer with a lower capacity. However, in the dimensioning of the transformer capacity in this case study, the possibility of using the full power potential of the charging stations, and thus full RBE utilization, while avoiding unwanted overflows of this energy back into the EDG is a higher priority for us.

For the installation of the charging system at the Praha Holešovice station car park, the case study considers equipping all 64 parking spaces (n) with a 7.4 kW maximum charging power (p); thus, a single-phase 25/0.4 kV transformer with a capacity (S_n) of 500 kVA must be installed for the connection to the 25 kV catenary.

$$S_n \geq \frac{P_{CH}}{\cos \varphi} = \frac{473.6}{0.95} \text{ [kVA]} \quad (46)$$

$$P_{CH} = n \cdot p = 64 \cdot 7.4 = 473.6 \text{ [kWh]} \quad (17)$$

Furthermore, a parking management system is considered which directs residents arriving especially in the evenings to charging stations available at which the resident charging mode with a basic charging power of 1.38 kW is activated. In terms of charging issues for both user groups, the case study assumes that all nonresidents require both parking and charging of EVs.

5.6.4 Economic analysis of case study

The previous chapter has shown that the use of RBE for EV charging is technically feasible, and almost all the energy from RBE can be used for EV charging. Since RBE is considered to be carbon-free, the total CO₂ emissions per EV recharge are reduced as well.

From the economic point of view, it is necessary to include the financial parameters of the model and verify the competitiveness of the price for the charging and parking with respect to conventional charging. Finally, the minimum consumer price per kWh will be defined by the levelized costs of electricity (LCOE) for the nonresident and resident groups.

$$LCOE = \frac{N_i + \sum_{t_y=1}^{T_{LT}} (M_{t_y} + N_{E t_y}) (1+r)^{-t_y}}{\sum_{t_y=1}^{T_{LT}} E_{t_y} (1+r)^{-t_y}} \approx \frac{C_A + M + F_{t_y}}{E} \quad (48)$$

Here, the variable N_i denotes the initial investment in the equipment; M denotes the annual maintenance expenditures and N_E is the electricity bill in the year t_y . Providing that the values do not change from one year to another, the variables C_A and F_{t_y} can be set. C_A indicates the annualized costs for the corresponding discount rate r , and F_{t_y} denotes the annual electricity bill. E represents annual electricity sold (kWh).

The key issue is to correctly set the ratio of the CAPEX division between nonresidents and residents. The case study presents the range of recharging costs depending on how CAPEX (Table 8) are distributed among users.

	T_{LT} [Year]	q	Unit price [EUR]	Total annual costs [EUR]
TS 22kV/0.4kV	35	1	13,208	3,303
Disconnecter and isolator	35	1	566	142
Circuit breaker BH400	35	1	453	113
Fuses PM45 16A	35	1	74	19
Cabling [m]	50	400	9	925
Installation material	35	1	377	94
Charging control system	35	1	37,736	9,438
Charging station	10	64	755	13,528
Labour	35	1	45,283	11,325

Table 8 Investment costs.^f

The costs associated with the electricity consumption (OPEX) differ from a standard connection to the EDG since the charging system in the car park is connected to the train power system. The OPEX are shown in Table 9 and Table 10.

^f TS = transformer station; exchange rate: 1 EUR = 26.5 CZK

	Unit	Unit costs (incl. VAT)	Total annual costs
Energy	EUR/MWh	117.5	107.98
Distribution services	EUR/MWh	44.68	41.06
System services	EUR/MWh	3.52	3.23
RES fee	EUR/month	22.6	20.76
Electricity tax	EUR/MWh	1.29	1.19

Table 9 Annual electricity bill [199], [200].^g

Table 10 shows the fixed operating costs related to transformer maintenance and overhauls as well as the annual energy losses incurred.

	Costs incl. VAT [EUR]	Total annual costs [EUR]
Annual inspection	457	457
Major inspection every five years	2,283	849
Annual energy losses in TS (WL)	630	630
Annual calibration of chargers	4,566	4,566

Table 10 Fixed operating costs.^h

Compared to a standard connection to the EDG, the connection to the train system does not include a fee for reserved power. The price per kilowatt-hour consumed from the train power system consists of the catenary transmission fee, the price of energy, system services and RESs and the electricity tax. The unit cost of purchasing electricity from the train power system is shown in Table 9. The unit price per kilowatt-hour taken from the train power system is EUR 4.15 without VAT. Since no financial revenue is provided for the train power system operator for RBE overflows back to the EDG, the model also assumes a zero cost for each kWh from RBE.

Since the weekend RBE data are not available, only weekday car park operations were considered. The calculation of annual transformer losses (empirical formula given by the standard CSN 341610) corresponds to the weekday car park operation, where transformer operation and losses are considered only in 250 days of the year.

$$T_L = \left[0.2 \frac{T_m}{T_0} + 0.8 \left(\frac{T_m}{T_0} \right)^2 \right] \cdot T_0 = \left[0.2 \frac{861}{250 \cdot 24} + 0.8 \left(\frac{861}{250 \cdot 24} \right)^2 \right] \cdot (250 \cdot 24) = 271 \text{ [hours]} \quad (49)$$

$$W_L = P_{nl} \cdot T_o + P_{kn} \cdot \frac{S_m^2}{S_n^2} \cdot T_L = 0.6 \cdot (250 \cdot 24) + 6.5 \cdot \frac{498.5^2}{500^2} \cdot 271 = 5,351 \text{ [kWh]} \quad (50)$$

^g VAT = value added tax 21%; exchange rate: 1 EUR = 26.5 CZK

^h TS = transformer station; VAT = value added tax 21%; exchange rate: 1 EUR = 26.5 CZK

5.7 Results

The following chapter presents the results of the model applied to the real data obtained from the car park near Praha Holešovice train station, the data capturing the RBE overflows on the busiest train line (between Prague and Brno) and users' charging needs from the PRE charging station data. The percentages of RBEs in both resident and nonresident recharge requirements are presented. Consequently, the use of RBEs is also associated with reducing the amount of CO₂ emissions that would have been generated by supplying electricity from the EDG to cover the charging requirements, and last but not least, the levelized costs of electricity values are also presented to show the competitiveness of the charging points.

Figure 22 presents an average electricity consumption in the car park during weekdays, where the total energy consumed by the charging point in a given time interval exceeds the amount of RBE supplied due to the minimum charging power requirement of each EV (indicated by black bars). Using the variable charging power function, the model then adjusted the charging performance of each charger to ensure that the RBE was always used as efficiently as possible and did not overflow back to the EDG.

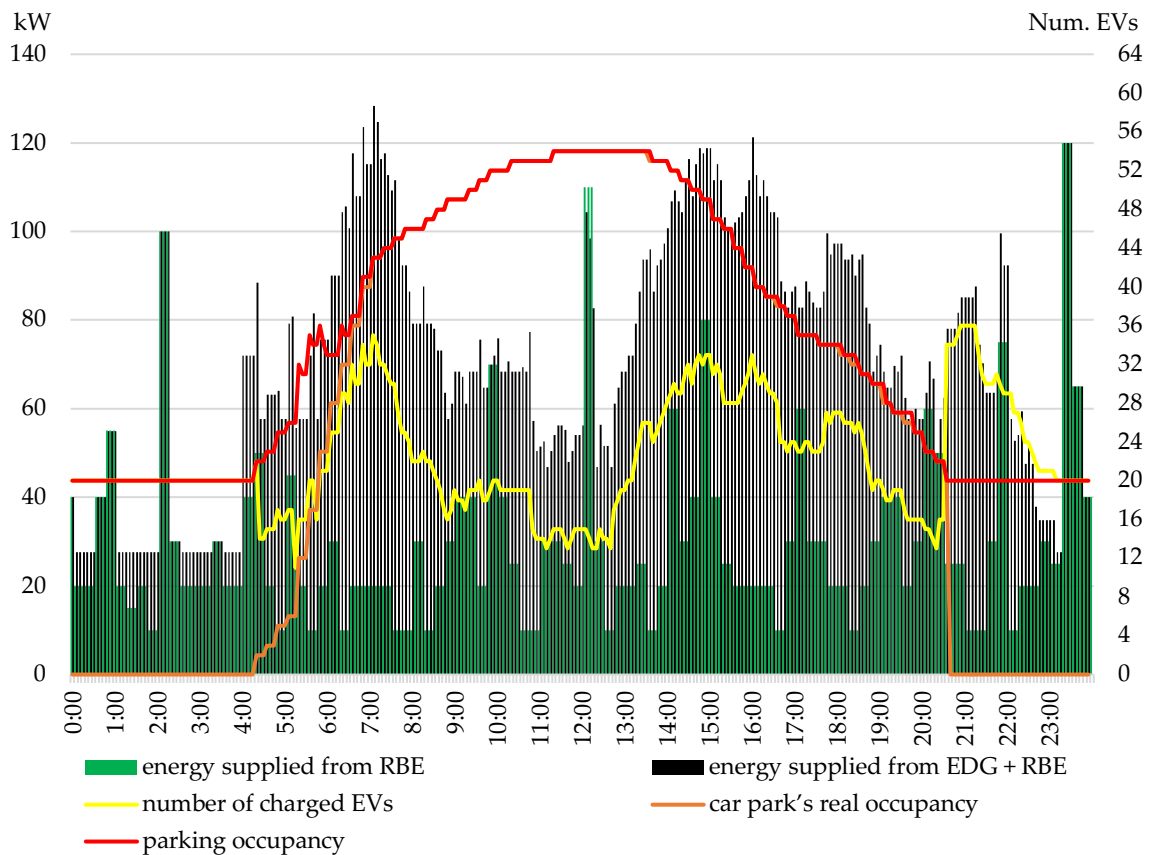


Figure 22 Average electricity consumption in the car park during weekdays

The same set of 40 simulations was performed to obtain reliable results, but with different charging requirements and parking lengths for each participant. Focusing on the fluctuation of the user arrivals and departures modelled, on the basis of an approximation of the real car park occupancy during weekdays, the average number of nonresidents served is 215. The number of residents served is limited to a fixed number of 20.

In terms of the car park electricity consumption during weekday operation, the total energy consumption did not exceed 1,694 kWh. This amount of energy already includes losses incurred in the transformer given by the standard CSN 341610.

From the total of 1,694 kWh of energy, the 20 residents consumed 350 kWh on average, and a further 1,344 kWh was consumed during the day by nonresidents' charging requirements. A more in-depth analysis of the total car park consumption data shows that RBE supplied 775 kWh of energy on average. These RBE energy supplies covered 199 kWh of residents' energy requirements, corresponding to 57% of the residents' total consumption. Nonresident RBE energy covered 577 kWh, equivalent to 43% of the total nonresidents consumption (Figure 23). The remaining amount of energy needed to cover the charging requirements of both user groups was purchased and supplied from the EDG. Regarding the power load on the train power system due to the purchase of energy required to operate the chargers in addition to the energy obtained from RBE, the power load did not exceed 110 kW during the nonresident charging on the given day. Furthermore, the power load did not exceed 52 kW during the resident charging on the given day.

Focusing on the efficiency of RBE consumption and the use of this energy for EV charging, it was found that all RBE was used for nonresident charging, and there was no overflow into the EDG. RBE was used for residential charging with a 99.7% success rate. Due to earlier morning departures of some residents, RBE was not fully used. Therefore, less than 1 kWh of RBE overflowed into the EDG.

The charging station power level changes within the range from 3.6 to 7.4 kW for nonresidents and from 1.38 kW to 7.4 kW for residents with the objective of using the RBE efficiently. The reason for the increase in the charging power level was the train braking and simultaneous generation of RBE. In terms of the increasing charging power, the average charging power for each of the 215 resident cars was

identified as 2 kW. As might be expected, when charging a group of 20 resident cars, which is nearly one-eleventh the number of nonresidents, the average charging power for each EV was 3.78 kW. Focusing on the success rate of charging residents' vehicles to the full battery charge, we find out that, on average, 18 out of 20 residents are satisfied in this way, and the success rate is therefore 80%.

All residents are guaranteed a 12 kWh energy amount if they arrive in the car park at the required time. However, the simulations found that due to the RBE energy on the train line between Prague and Brno being considered, each resident's EV can get 22 kWh of energy due to the increasing charging power of the chargers.

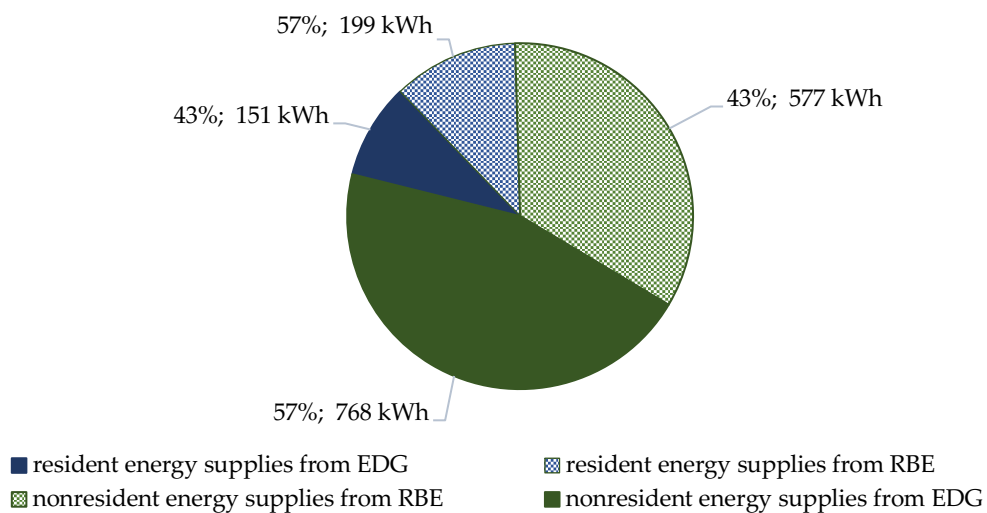


Figure 23 Proportion of RBE and EDG in car park electricity consumption during weekday operation

The fundamental benefit of charging at the car park considered compared to charging at a public charging station or at home without renewables is the lower amount of CO₂ emissions associated with each kilowatt-hour charged into the battery. The average amount of emissions correlated with each kilowatt-hour supplied by the distribution network in the Czech Republic in 2019 is equal to 428 gCO₂. Since both electricity from the EDG and RBE are used to charge the EVs at the car park in question, the emissions associated with the charging are lower than those from the energy supplied from the distribution network in terms of CO₂ emissions. Therefore, each kilowatt-hour charged to the EV battery, regardless of the charging time at the car park in question, is equivalent to 228 gCO₂ (Figure 24). Assuming an average EV consumption of 20 kWh/100km, an EV charged in the car park has emissions of 46 gCO₂ per kilometre.

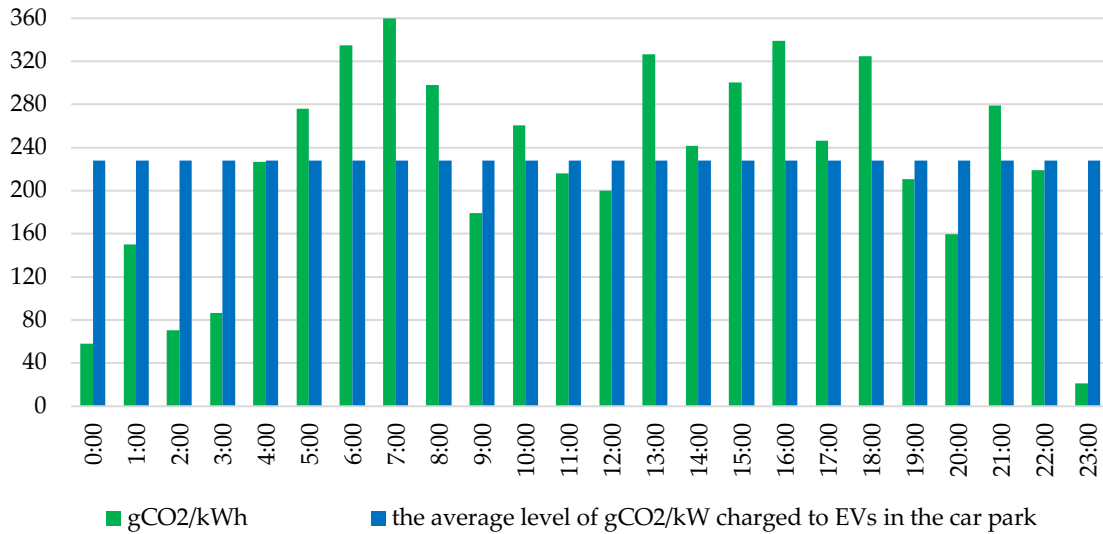


Figure 24 Emissions correlated with each kWh charge to EVs at the car park

A more detailed analysis of the CO₂ emissions associated with a kilowatt-hour in the resident and nonresident groups found that 46% of the energy used to cover the charging requirements of the resident group came from RBE. Therefore, the emissions associated with a kilowatt-hour recharged by the resident charging group reached the level of 181 gCO₂/kWh. However, the emissions associated with a kilowatt-hour of nonresident charging, where RBE supplied 43% of the 1344 kWh, reached 240 gCO₂/kWh. Considering an average EV consumption of 20 kWh/100km, a resident's EV charged in the car park in question has emissions of 48 gCO₂ per kilometre. In contrast, a kilometre driven by a nonresident's vehicle results in emissions of less than 38 gCO₂.

Compared to the emissions of an EV recharging at a public charging station that uses only electricity from the EDG, the amount of gCO₂ produced by each kilometre of a resident driving is lower by almost 37 gCO₂. A resident charging at the car park in question produces almost 49 gCO₂ less per kilometre than a user who charged their EV at a public charging station.

5.7.1 Results of economic part

Table 11 and Table 12 below present the LCOE dependence on the two most important input parameters: the yield of the project (discount rate) and the share of inclusion of fixed costs (CAPEX) between the user groups being considered.

Before presenting the final prices per kWh in the modelled car park, it is necessary to illustrate the conditions of home charging, which is the main competitor.

Home charging in the Czech Republic provides EV owners with a special electricity rate known as D27d [201]. This rate offers eight hours of charging between 18:00 and 8:00 with a price per kWh close to €0.09 in the low rate bracket and close to €0.2 in the high rate bracket.

A more in-depth analysis of the residents' table shows that in the limit case (green field), the residents' charging price per kWh in the car park reaches the low rate price per kWh of home charging. As far as the green field (the discount rates and CAPEX shares) is concerned, nonresidents have a lower price per kWh than they would have with home charging at a high rate. The blue part in both tables denotes a price per kWh that is lower than or equal to the price per kWh at the high home-charging rate. From the perspective of users who can charge at home, this price is not very profitable. However, for users with the absence of private parking, the given prices per kWh are very profitable compared to public charging stations [202]. The red part in both tables shows the area with minimal difference in price per kWh between both groups if the fixed costs are divided by the ratio of 25% for residents and 75% for nonresidents.

		Discount rate													
		5%	7%	9%	11%	13%	15%	17%	19%	21%	23%	25%	27%	29%	31%
Share of inclusion of fixed costs in residential price	0%	7	7	7	7	7	7	7	7	7	7	7	7	7	7
	5%	8	8	8	8	8	9	9	9	9	9	9	10	10	10
	10%	9	9	9	10	10	10	11	11	11	12	12	12	13	13
	15%	10	10	11	11	12	12	13	13	14	14	15	15	16	16
	20%	11	12	12	13	13	14	15	15	16	17	17	18	19	19
	25%	12	13	13	14	15	16	17	17	18	19	20	21	22	22
	30%	13	14	15	16	17	18	19	19	20	21	22	24	25	26
	35%	14	15	16	17	18	19	20	22	23	24	25	26	27	29
	40%	15	16	17	19	20	21	22	24	25	26	28	29	30	32
	45%	16	17	19	20	21	23	24	26	27	29	30	32	33	35
	50%	17	19	20	22	23	25	26	28	30	31	33	35	36	38
	55%	18	20	21	23	25	26	28	30	32	34	36	37	39	41
	60%	19	21	23	25	26	28	30	32	34	36	38	40	42	44
	65%	20	22	24	26	28	30	32	34	36	39	41	43	45	47
	70%	21	23	25	27	30	32	34	36	39	41	43	46	48	51
	75%	23	25	27	29	31	34	36	39	41	44	46	49	51	54
	80%	24	26	28	30	33	35	38	41	43	46	49	51	54	57
85%	25	27	29	32	35	37	40	43	46	48	51	54	57	60	
90%	26	28	31	33	36	39	42	45	48	51	54	57	60	63	
95%	27	29	32	35	38	41	44	47	50	53	56	60	63	66	
100%	28	30	33	36	39	43	46	49	52	56	59	62	66	69	

Table 11 Resident prices in cents.ⁱ

ⁱ Green field = competitive price with low rate price per kWh in home charging
Blue field = competitive price with high rate price per kWh in home charging
Red field = minimal difference in price per kWh between residents and nonresidents

		Discount rate													
		5%	7%	9%	11%	13%	15%	17%	19%	21%	23%	25%	27%	29%	31%
Share of inclusion of fixed costs in residential price	0%	15	16	16	17	18	19	20	20	21	22	23	24	25	26
	5%	15	15	16	17	17	18	19	20	21	21	22	23	24	25
	10%	14	15	16	16	17	18	18	19	20	21	22	22	23	24
	15%	14	15	15	16	17	17	18	19	19	20	21	22	22	23
	20%	14	14	15	16	16	17	17	18	19	20	20	21	22	22
	25%	13	14	15	15	16	16	17	18	18	19	20	20	21	21
	30%	13	14	14	15	15	16	16	17	18	18	19	19	20	21
	35%	13	13	14	14	15	15	16	16	17	18	18	19	19	20
	40%	13	13	13	14	14	15	15	16	16	17	17	18	19	19
	45%	12	13	13	14	14	14	15	15	16	16	17	17	18	18
	50%	12	12	13	13	14	14	14	15	15	16	16	17	17	17
	55%	12	12	12	13	13	14	14	14	15	15	15	16	16	17
	60%	12	12	12	12	13	13	13	14	14	14	15	15	15	16
	65%	11	11	12	12	12	13	13	13	13	14	14	14	15	15
	70%	11	11	11	12	12	12	12	13	13	13	13	14	14	14
	75%	11	11	11	11	11	12	12	12	12	12	13	13	13	13
	80%	10	11	11	11	11	11	11	12	12	12	12	12	12	13
	85%	10	10	10	10	11	11	11	11	11	11	11	11	12	12
	90%	10	10	10	10	10	10	10	10	10	11	11	11	11	11
	95%	10	10	10	10	10	10	10	10	10	10	10	10	10	10
100%	9	9	9	9	9	9	9	9	9	9	9	9	9	9	

Table 12 Nonresident prices in cents.^j

5.8 Discussion

The analysis of data obtained from real chargers shows some important results. More than 80% of the sample of 3000 charging iterations from Prague shows that users leave their EVs parked and connected to the charger for a time longer than necessary for recharging the battery. Chargers with a charging power of 3.6 kW would be sufficient for these users to charge the full battery capacity for the same parking time. The exception was the remaining 20% of the EV user sample studied, whose priority was to quickly recharge their EV and continue their way. Thus, they chose a 75 kW charger or 150 kW supercharger station to charge their EV, which satisfied their requirement. A charging station with a power range of 3.6 to 7.4 kW could not meet this requirement. In terms of developing the installation of charging stations in urban and suburban areas, a sufficient number of low-power chargers is a higher priority than building fewer chargers with higher charging power. The same consideration must be applied to building charging infrastructure in car parks near train stations. The way

^j Green field = competitive price with low rate price per kWh in home charging
Blue field = competitive price with high rate price per kWh in home charging
Red field = minimal difference in price per kWh between residents and nonresidents

these car parks are used correlates with the users' long parking times and, therefore, with the sufficient time to recharge their EVs.

Moreover, car parks at train stations equipped with charging infrastructure are suitable for evening reservations due to their minimal occupancy in the evenings. The reservations then create the same conditions for EV users who live in the area and do not have their own private parking space with chargers as users with their own garage do.

As shown in the economic section of the case study, our solution offers residents a guaranteed recharge of 12 kWh. Depending on the amount of RBE, residents could recharge up to 22 kWh during their parking. The residents' price per kWh was constant throughout the charging time and mainly depended on the discount rate and the percentage split of the investment costs (CAPEX) between the resident and nonresident groups. The smallest difference in price per kWh between the two groups was achieved with CAPEX split between users at 25% for residents and 75% for nonresidents. At these discount rates and CAPEX shares, the residents' price per kWh ranged between EUR 0.12 and EUR 0.20 per kWh.

The case study results show that using RBE from trains efficiently is possible without installing battery storage or a capacitor. The charging power management system, which varied the charging power of the chargers depending on the number of EVs being charged and the RBE size, was able to use RBE with almost 100% efficiency.

In terms of resident charging, the system is designed to use RBE as efficiently as possible. It guarantees all residents a 12 kWh energy amount if they arrive in the car park at the required time. A high priority of the modelled charging system was to use the RBE efficiently, whereas 100% recharging for residents was not fundamental to the model. Conversely, if 100% recharging for residents was a high priority and RBE covered only a part of the total energy consumed, the system would increase the charging power of the chargers to the maximum power level at times when RBE alone would not be sufficient for residents to recharge fully. The charging system would have to monitor the amount of energy required for the full battery charge of each resident vehicle during charging. When the amount of energy required approaches a limit that the charger would no longer be able to achieve without increasing the charging power to the maximum, considering the remaining parking time, the charging system

would then have to change from the resident charging mode to the maximum charging mode. This would fully satisfy all residential charging requirements but with a significant increase in energy consumption from the EDG.

Another important issue is the CO₂ emissions associated with both the production of electricity and the operation of EVs themselves. The results of many studies and the results presented in our case study highlight the importance of converting electricity generation from fossil to RESs. The part of the case study focusing on EV charging in the conditions of the Czech Republic and its current energy mix shows that for each kilometre driven by an EV, the CO₂ production does not meet the required European targets. In addition to the construction of RESs, efficient use of RBE can also contribute to reducing CO₂ emissions. RBE is generated when trains are braking and sometimes wasted by conversion to heat in the onboard resistors (rheostats).

It is evident that for a better setup of all model parameters, it will be necessary to analyse the behaviour and requirements of specific users of EVs, both those living in the vicinity of the car park and those using the car park services primary during the day. In particular, the number of resident parking spaces provided may be different depending on the arrivals and behaviour of local residents. It can be higher due to an increase in the number of residents arriving later than 7 p.m. and conversely leaving earlier than 6 a.m..

5.9 Fuel transformation vs energy mix change

Transforming the car fleet with EVs only without changing the energy mix of individual countries will not make it possible to meet the emission limits required by the EU [3]. Achieving the set objectives will require both a transition from fossil fuel electricity generation [14], [15], [38], [132] and increasing the efficiency of using recovered energy [43].

The results of the analysis presented in this article confirm the importance of changing the energy mix and efficient use of electricity. In cooperation with Solops [203], Tesla Model 3 Long-range EV operation in the Czech Republic was monitored. The annual monitoring, which captured all the charging activities between 10 July 2020 and 10 July 2021, provided information about the consumed electricity taken both from electricity meters at charging stations (tank to wheel) and from the onboard EV charger (since the last charge).

In order to calculate the carbon emissions produced by the EV during its annual operation, we captured the amounts of gCO₂ associated with one kilowatt-hour consumed in the Czech Republic for each charging activity using electricity from the EDG [204]. During the test period, there were also charging activities that used electricity generated only from the Solops photovoltaic power plant (PV) [203].

Tawalbeh et al. [205] reported that the carbon emissions of PV power plants range from 14-73 gCO₂ eq/kWh. However, the National Renewable Energy Laboratory reported that this value is closer to 40 gCO₂ eq/kWh [206]. Therefore, we assumed a pessimistic scenario for our analysis and chose PV emissions of 45 gCO₂ eq/kWh.

The users drove the Tesla for 58,405 kilometres during the annual operation, which corresponded to electricity consumption (tank to wheel) of 13,368 kWh. About 57% of this energy (7,529 kWh of electricity) was taken from the EDG of the Czech Republic. The other 7% were supplied by a combination of both the EDG and the Solops PV plant. This combination supplied 1,017 kWh, and the carbon emission contribution from both the PV plant and the distribution system had to be considered when calculating the carbon emission impact. The final 36%, corresponding to 4,822 kWh, was supplied exclusively from the PV plant.

It is important to note that for relevant carbon emissions, it is necessary to consider – for each kilowatt-hour supplied by the EDG – the losses incurred in

transmitting the electricity and the generation in the power plants themselves. According to the annual report of the Energy Regulatory Office focused on the Czech Republic's electricity grid, this loss corresponded to 7% [207].

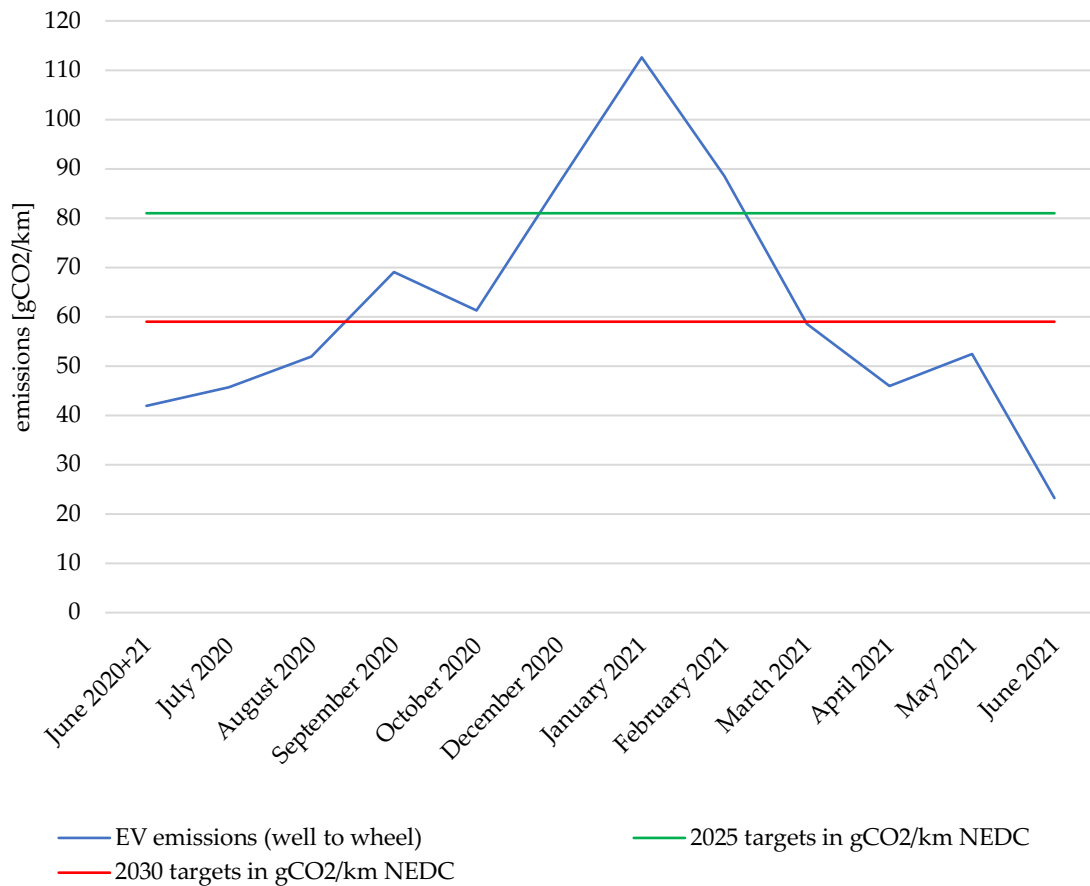


Figure 25 Tesla emissions [gCO₂/km] [203]

The current energy mix in the Czech Republic and the EV operation do not meet the emission limits set by the EU, as can be seen in Figure 25. The EV emissions exceeded the 2025 default limit of 81 gCO₂/km [3] from December 2020 to February 2021. Considering the emission limit of 59 gCO₂/km to be achieved at the beginning of the 2030s [3], the operation of the test EV in the Czech Republic would exceed the emission limit between the end of September 2020 and the beginning of March 2021.

5.10 Conclusion

The paper analyses the economic and environmental effects of using RBE to charge EVs in a car park located near a train station where additional construction of charging infrastructure is considered.

The model primarily focuses on the efficient use of RBE by adjusting the charging power of individual chargers. In general, the model defines two groups of users for which it sets the power range of the chargers. The first group (nonresidents) are users who use the car park for all-day parking. Typically, nonresidents leave their EVs at the car park near the train station in the morning and continue to travel by train. Consequently, their EVs are parked in the car park and charged until they return from work or other journeys in the evening. The second group (residents) live close to the car park and rent parking spaces primarily for overnight parking.

The charging station power level changes within the range from 3.6 to 7.4 kW for nonresidents and from 1.38 kW to 7.4 kW for residents with the objective of using the RBE efficiently. The lower power limit of the chargers during the charging of the resident group was set to ensure enough charged cars and thus providing the possibility to increase their charging power whenever needed during the resident parking time.

The case study in this paper uses recharging data from the company PRE and parking place occupancy data for a car park with 64 parking spaces near the Praha Holešovice train station. Data capturing RBE overflows on the busiest train line between Prague and Brno were used for the simulation. Building of EV charging infrastructure using RBE at the existing car park has been considered along this train line.

For the case study, annual data were taken from the charging stations between 2019 and 2020, with more than 3000 recharges from seventy-seven charging points. At each of these charging points, a 22 kW AC charger could be used for charging an EV. Eleven of these seventy-seven charging points also had a 50 kW DC charger for EV charging. Six of the seventy-seven charging points had 75 kW DC chargers. The most powerful 150 kW DC supercharger was installed at only two of the seventy-seven charging points. The remaining 20% of the studied EV users had a priority to quickly recharge their EV and continue their way. Thus, they chose a 75 kW charger or a 150 kW supercharger station to charge their EV, which satisfied their requirement.

Focusing on the efficiency of RBE consumption and the use of this energy for EV charging, it was found that due to the variable charging power function used, RBE was used with almost 100% efficiency. RBE contributed to the total daily car park consumption, equaling 1695 kWh, with more than 45%. Since there are no CO₂ emissions from the generation of RBE, by consuming and efficiently using this energy, the amount of CO₂ associated with the need for each kilowatt-hour of energy is reduced significantly.

Comparing the average amount of 428 gCO₂ emissions associated with each kilowatt-hour supplied from the distribution grid in the Czech Republic in 2019 with the amount of CO₂ emissions associated with each kilowatt-hour charged into the EV battery at the car park in question, it was found that the CO₂ emissions were reduced by more than 45%. Each kilowatt-hour charged to the EV battery using RBE, regardless of the charging time at the car park considered, is equivalent to 228 gCO₂. Assuming an average EV consumption of 20 kWh/100 km, an EV charged in the considered car park has emissions of 46 gCO₂ per kilometer. Therefore, the use of RBE would contribute to the achievement of the 50 gCO₂/km target set by the EU for the year 2050 in the energy mix of the Czech Republic, where more than 40% of the total energy was produced by coal power plants in 2019.

From the economic point of view, the results show that the residents' prices per kWh are able to compete with home charging. However, these prices are considerably dependent on the division of CAPEX between both groups of users and the required discount rate. In the presented case study, a competitive price per kWh was achieved if residents contributed 10% of the CAPEX, and the required discount rate was 7%. If the required discount rate were equal to 23%, the resident contribution to CAPEX would be only 5% to achieve a competitive price.

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Variables

\hat{A}	Parking occupancy vector with five-minute intervals
C_A	Annualized costs
$\cos \varphi$	Power factor
E	Electricity sold per year [kWh]
E_N	Total nonresident recharging requirement [kWh]
E_R	Total resident recharging requirement [kWh]
F_{ty}	annual electricity bill
Ch_R	Guaranteed amount of energy for a resident [kWh]
L	Length of EV user stay [h]
LP_{kWh}	Non-covered fixed costs for unsold kilowatt-hours [EUR]
M	Annual maintenance expenditures [EUR]
n	Number of chargers in car park
N_E	Electricity bill in year t [EUR]
N_i	Initial investment in equipment [EUR]
p	Maximum power per charger [kW]
P_{ACH}	Average charging power [kW]
P_{CH}	Minimum power of transformer station [kW]
P_{kn}	Short-circuit transformer losses [kW]
P_{nl}	Power transformer no-load loss [kW]
Q_{PL}	Number of parking places in car park
Q_R	Parking places reserved for residents
R	Minimum rate per blocking hour [EUR/hour]
r	Discount rate [%]
S_m	Maximum apparent power of group of chargers [kVA]
S_n	Nominal apparent power of transformer station [kVA]
t	Time step
T_0	Annual operating time of transformer station [h]
T_L	Time equivalent of losses at maximum transformer load per year [h]
T_{LT}	Lifetime [years]

T_m	Utility factor [h]
T_{SCH}	Resident charging start time
t_y	Year
W_L	Annual energy losses in transformer
X	End of interval reserved for residents
Y	Beginning of interval reserved for residents

6. Why Transaction Costs Do Not Decrease Over Time? A Case Study of Energy Efficiency Programmes in Czechia

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Keywords: Transaction costs; Energy efficiency programmes; Climate policy; Energy policy; Evaluation

The implementation of energy and climate policies and measures is critical to addressing the urgent challenge of climate change. However, the negative impact of transaction costs on the implementation of these policies and measures can hinder progress toward reducing greenhouse gas emissions. In particular, transaction costs can be an obstacle to the adoption of EVs and the construction of charging infrastructure, both of which are crucial to the transformation of the transport sector. Despite their significant impact, transaction costs are often not systematically tracked and evaluated in the context of energy efficiency and renewable energy policies.

The focus of this article is on the development of transaction costs over time and their impact on energy and climate policies and measures. Through empirical evidence, we aim to shed light on the impact of transaction costs on the implementation and effectiveness of these policies and measures. In order to achieve this, we defined two research questions: firstly, what is the difference in transaction costs between two programmes and two periods of time? And secondly, what are the main factors contributing to the change in transaction costs over time?

Our findings show that transaction costs increase with time, contrary to the general perception that they decrease as organizations gain more experience with programme implementation. These costs are influenced by various factors such as changes in programme administration, internal conditions of the programmes, and loss of information. This highlights the need for more systematic tracking and evaluation of transaction costs in the development and implementation of energy efficiency and renewable energy policies.

The importance of reducing transaction costs cannot be overstated, as it can significantly impact the adoption and implementation of energy and climate policies and measures. As such, this article provides valuable insights into the impact of transaction costs on energy and climate policies and measures, and the need for more systematic tracking and evaluation of these costs.

6.1 Abstract

Transaction costs have a negative impact on the implementation and effectiveness of energy efficiency policies, while they remain rarely systematically tracked and evaluated. Transaction costs should decrease over time, thanks to the ageing of the policy (and the effects of learning) and the prevalence of initial, fixed costs. However, we find that the opposite may be true.

We examine the effect of time and learning on the structure and size of transaction costs by using a data set of two programmes in two programming periods (2007–2013 and 2014–2020). We find that despite the continuity of the programmes, the burden of transaction costs in both cases increased significantly. The potential gains from learning throughout the programmes are overrun by constant internally and externally driven changes to the programme. In addition, through the course of the programmes, smaller and more complicated projects prevail. Lastly, due to internal organisational changes among the recipients, there is little institutional memory and distribution of information.

An early thorough preparatory phase of a programme and stability of the institutional environment increase the effectiveness of the programmes. Differentiating the administrative processes according to the size of projects, with simplified procedures for smaller projects, may further decrease administrative intensity.

6.2 Introduction

Transaction costs have negative impacts on the implementation of energy and climate policies and measures. Transaction costs can impede the implementation of energy efficiency and other climate mitigation measures or even prevent them from being implemented. Even though transaction costs cannot be zero, lower transaction costs are “almost always beneficial” [208].

Transaction costs are not systematically taken into account when designing energy efficiency and renewable energy policies, nor are they regularly evaluated ex-post. Therefore, the information on the overall effectiveness of (public) programmes and instruments is incomplete and leads to suboptimal decisions from the public administrator and societal point of view. There is a strong theoretical background for transaction costs [209], [210], and growing empirical evidence on the structure and levels of transaction costs of various energy efficiency and low-carbon policies [211]. The available studies

suggest that transaction costs are of non-negligible levels, averaging roughly from 10% up to 40% relative to the compared unit of measurement [212]–[214].

The factors that influence the structure and level of transaction costs are manifold [215], [216]. One of the key factors influencing transaction costs is time. The role of time may take different forms [216]. It is perceived that transaction costs decrease over time due to learning-by-doing [217] and due to the fact that many of the transaction costs are “one-off” costs connected with initial stages of a programme [218], such as the search for information and learning about the programme both from the administration body and from other participants of the programme [219]. However, empirical evidence demonstrating how exactly transaction costs develop temporally within the programmes remains scattered.

The aim of the paper is, therefore, to provide empirical evidence on how transaction costs develop over time. We do so by defining two main research questions:

- 1) What is the difference in transaction costs in two programmes and two periods of time.
- 2) what are the main factors contributing to the change in transaction costs in time.

We use a comparative analysis of two major energy efficiency (and renewable energy) support programmes, monitoring the transaction costs over two subsequent programming periods. Such a sample allows us to follow the internal development of the programme, as well as carry out a cross-comparison of the two programmes temporally. We first test the hypothesis that there are different levels of transaction costs between the two periods of time, and follow with a narrative based on desk research and interviews of the main factors influencing change in transaction costs.

We conclude that contrary to the general perception, transaction costs increase with time. Any potential learning is interrupted by changes in costs, information loss occurs in organisations and with administrators, and there are constant changes in the internal conditions of the programmes.

The paper unfolds as follows: section 6.3 provides the methodological and analytical framework for the model of transaction costs and describes the case study and data collection. Section 6.4 presents the results, providing analysis of the change in transaction costs regarding time for the chosen programmes. Section 6.5 discusses the main factors and reasons behind the changes. Section 6.6 concludes with policy implications and suggestions for further research.

6.3 Methodology

6.3.1 Theoretical framework

The theory of transaction costs stems from concepts of the new institutional economics (NIE), which stipulates that all market actors decide and act under bounded rationality. Transaction costs incur due to uncertainty and asymmetry of information [220]. The institutional framework and functioning of institutions (formal and informal) influence the effectiveness of the whole market, which can be, among other factors, expressed through transaction costs [221].

There is not one single definition of transaction costs. Instead, the task itself (an analysed market situation or policy) shapes the definition. In general, the unit for measuring transaction costs is one transaction, which can take the form of a transfer of property rights for goods and services [222], but also a transfer of information and knowledge [216]. In public policy programmes, the transaction takes place between the society (represented by the government) as “buyers” and the supported organisations as “sellers” of the projects beneficial to society [223]. McCann et al. [224] define this type of transactions as second-order transactions, as opposed to first-order transactions occurring upon the development stage of policies.

For our research, we define transaction costs as costs and resources arranging a contract *ex-ante* and monitoring and enforcing that contract *ex-post* [225], [226]. In public policies and programmes, transaction costs are understood as the costs connected to acquiring information, implementation, monitoring and evaluation, control and enforcement. Costs may take the form of time, financial costs, as well as other sources of cost, such as opportunity costs incurred by the market actors and connected to the given policy and programme [212], [227].

The factors influencing transaction costs are manifold and tend to be categorized by the specifics of the transaction and the transactor [228]. Shahab et al. [216] provide a summary of the main factors that have been identified, and subsequently offer a complex categorisation of factors. Their categorisation provides a basis for our article. We select the factors influencing transaction costs that are connected to time, presented in Table 13.

We mainly test the “age of the policy” (Table 13), but with inputs and interactions from other factors, which are often interconnected, such as the experience of the actors

or consistency of the policy. The effect is defined as the perceived or demonstrated change in the level or structure of transaction costs.

Category	Factor	Impact on transaction costs
Transaction characteristics	Timing (duration and frequency)	Upward/Downward
Transactor characteristics	Experience	Downward
Policy characteristics	Age of the policy	Downward
	Precision of the policy	Upward/Downward
	Policy consistency	Downward
	Precision of the policy	Upward/Downward
	Policy consistency	Downward

Table 13 Factors influencing transaction costs related to time [216].

6.3.2 Operational programmes

We have selected two public programmes to explore the link between transaction costs and time – the Operational Programme Environment (OP E), and the Operational Programme Enterprise and Innovation (for Competitiveness, OP EIC^k). The programmes represent the “most-similar” cases [229]. Both programmes support energy efficiency and renewable energy measures in Czechia. The energy efficiency projects in both programmes are highly unified. Most of the supported projects entail thermal properties of buildings and building renovation measures, heat, ventilation, and air-conditioning (HVAC) measures, and waste-heat recovery (cf. Figure 30).

The programmes have been in place continuously since 2007 – established in the first multi-annual financial framework from 2007 to 2013 and continued in the subsequent financing period from 2014 to 2020. They are both financed through the European structural and investment funds. The form of support in both programmes is investment grant, i.e. the programme finances a percentage portion of the total eligible costs of the projects. The grant is provided as a maximum percentage

^k In 2007–2013 the programme ran under the name of Operational Programme Enterprise and Innovation; in 2014–2020 the name was changed to Operational Programme Enterprise and Innovation for Competitiveness.

value of the total eligible project costs (typically 30–60% of the eligible costs). Both programmes follow the organisational setting and processes which are harmonized for all the operational programmes financed by the European Regional Development Fund and Cohesion Fund [230].

The programmes differ by the type of recipients, i.e. the entity that is entitled to apply for the grant in each programme. For the Operational Programme Environment, it is public entities (typically municipalities, regional authorities, health care and educational centres). The Operational Programme Enterprise and Innovation (for Competitiveness) is open to private enterprises (small, medium, and large).

In OP E, the total allocation for the programme in 2007–2013 reached over EUR 820 million, while in the following period, the total allocation amounts to EUR 529 million. Conversely, the allocation in OP EIC nearly tripled in the period 2014–2020 compared to 2007–2013 (Table 14). The increase has been more than offset by the increase in the number of applicants in OP EIC, suggesting the decreasing average size of applying projects (cf. Table 16). In OP E, the total number of applicants so far corresponds with the lower allocation of the programme in 2014–2020.

		Number of applicants	Total allocated budget [EUR]
OP E	2007 - 2013	5,490	820,293,139
	2014 - 2020	3,060 ^l	529,626,952
OP EIC	2007 - 2013	900	418,000,000
	2014 - 2020	3,833 ^m	1,217,129,658

Table 14 Number of applicants and total allocated budget of OP E and OP EIC in the programming period 2007 – 2013 and 2014 – 2020 [231]–[236].

While the total allocation of the programmes in the two programming periods varied, the success rate of projects (the ratio between submitted and accepted projects) remains stable. Figure 26 shows that in OP EIC, except for the first call in 2014–2020, 70%–80% of submitted projects have been accepted for funding. In OP E, the success rate in the first period amounted to 66% [237], and 73% in the current period [234].

^l As of June 2020, i.e. these are not final numbers for the whole programme.

^m As of June 2020, i.e. these are not final numbers for the whole programme.

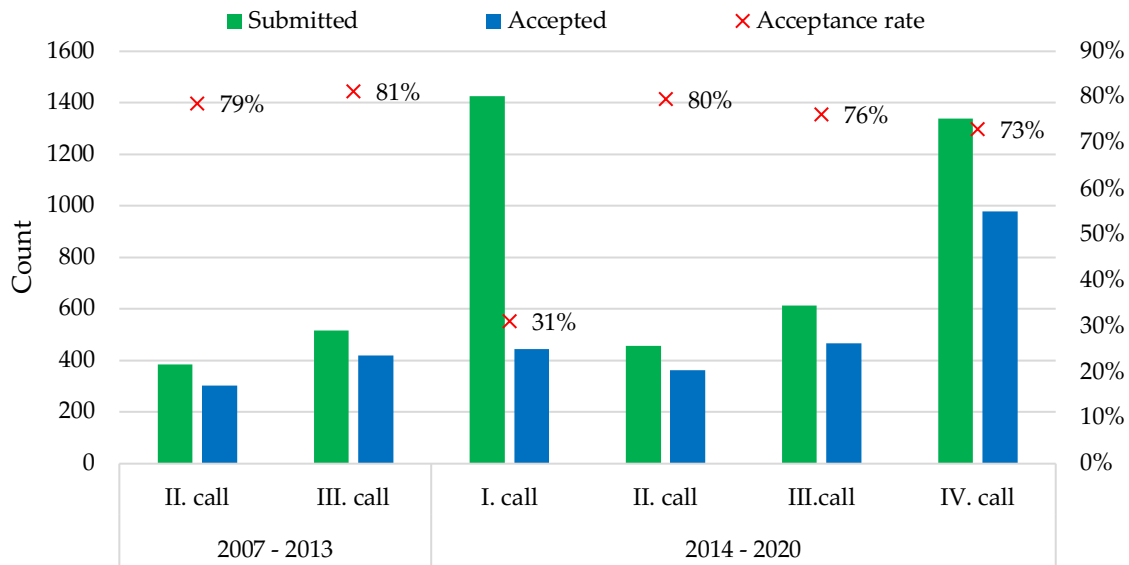


Figure 26 Supply and acceptance rate of the submitted projects in OP EIC in 2007–2013 and 2014 – 2020 [232], [233].

The data on cost-effectiveness on the supported projects in OP EIC are more detailed than in OP E and therefore allow for a meaningful comparison between the two programming periods. While the average costs per 1 GJ of energy savings ranged from 177 to 350 EUR/GJ in the calls in OP EIC (Figure 27), there is not a statistically significant difference in the means of cost-effectiveness in the two periods. The detailed data for OP E (especially for the period 2014–2020) have not been made available. However, given the similarity in the programmes, we can expect that the cost-effectiveness on OP E has also not changed substantially between the two periods either.

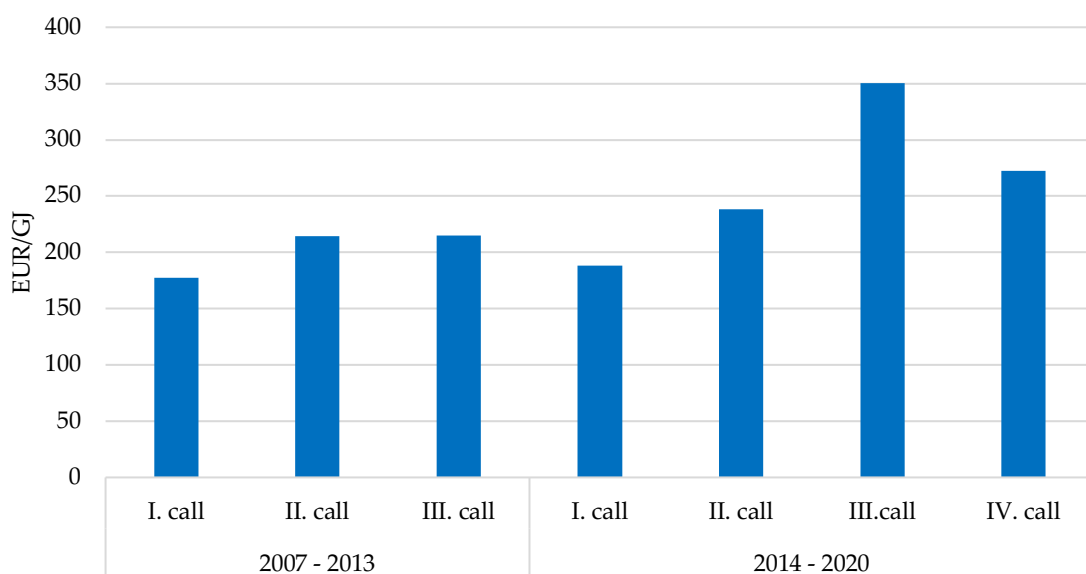


Figure 27 Average eligible costs per 1 GJ of energy savings of the submitted projects in OP EIC in 2007–2013 and 2014 – 2020 [238], [239].

6.3.3 Model of transaction costs

The transactions in the analysed public policy programmes are the energy efficiency projects. The proxy for the price of the transaction is the size of the project [211], expressed as eligible project costs.

The public programmes entail both administrative and market transactions [240]. The public programmes, by definition, do not operate as regular markets. However, while the final amount of energy efficiency projects is fixed (through the finite budget available for the programme), the conditions of the programmes are set in a way to support “reasonably” cost-effective projects. The programmes do not support both highly cost-effective projects with very high return rates and ineffective projects (with high unitary costs per energy savings). Therefore, the programmes should not support projects with negative social costs.

In order to determine the role of time on transaction costs in the two programmes, we have analysed transaction costs in two of the years within the time periods mentioned above – in 2011 and 2019. The two years represent the projects carried out since the beginning of the respective programming period (2007–2013 and 2014–2020) until the date of the survey, which also approach the end of the administration process. In practice, it means that the sample from 2011 would entail mostly projects carried out in 2008–2010, and the sample in 2019 covers projects implemented from 2016 to 2019. It, therefore, provides a good overview of how the administrative processes developed over time in the two programming periods.ⁿ

We have used a mixed-methods approach, combining qualitative and quantitative methods [241]. In line with this approach, we collected quantitative data and used qualitative research to help us explore and explain the findings from our quantitative dataset.

The research was conducted in three stages [212]: desk research, questionnaire survey, and a combination of qualitative interviews and a discussion seminar. The desk research provided insight into the operation and administration of the programmes. First, we used the analysis from [242] as a basis and focused on the changes that

ⁿ At the same time, the survey should not be implemented only after the end of the programme, as the time-lag between the end of most projects and the survey may decrease the validity of the research due to personal changes at the subsidy recipients and the mere fact of remembering the processes [242]

the programmes may have undergone over time, and that may have influenced transaction costs. Second, we conducted questionnaire surveys among subsidy recipients in the two programmes. We used an online platform (Formsite) for the surveys. The first survey was conducted in 2011 and was described in detail by [242]. The second survey was conducted in March and April 2019. Altogether, 958 subsidy recipients in the two programmes were addressed. They represented all the recipients that had reached the implementation phase of the project in the time of the survey. Only recipients with one project within the respective programme were selected. We received 229 responses, i.e. a 24% response rate (Table 15).

Programme	Year			
	2011		2019	
	Contacted	Responded	Contacted	Responded
OP E	318	84 (55) ^o	238	58
OP EIC	135	41 (38) ^p	267	46
Total	453	125 (93)	505	104

Table 15 Population and sample of the questionnaire survey – number of projects.

Summary	Year	Count	Eligible costs median <i>sample</i> [EUR]	Eligible costs median <i>all projects</i> [EUR]
OP E	2011	55	200,115	222,574
	2019	53	128,096	126,624
OP EIC	2011	35	286,538	380,577
	2019	46	201,561	240,135
Total		189		

Table 16 Count and size of the projects.

^o Number of total responses (respondents with one project)

^p Number of total responses (respondents with one project)

Semi-structured interviews and a workshop were used to both validate the survey and to provide insight into the quantitative results. In total, five interviews were conducted in 2018; three with the administrators of the two programmes, one with a subsidy recipient and one with a project facilitator.⁹ In addition, we discussed the quantitative results in a focused discussion workshop with representatives of the administrators and the energy efficiency policy experts after the completion of the survey.

In order to determine the structure and level of transaction costs, we use the Standard Cost Model [243]. Transaction costs are, therefore, structured as follows:

$$TC_n = C_t + C_{id} + C_e \text{ [monetary units]} \quad (51)$$

where TC_n are transaction costs incurred by the subsidy recipient, C_t are costs of time induced by the subsidy administration, C_e are costs of external services connected with the subsidy administration, and C_{id} are indirect costs (overheads). The costs of time are a product of the time in hours, estimated by the respondents, and hourly labour costs. We have added the indirect costs to the calculation. The recipients themselves are often unable to estimate the indirect costs. Therefore, we have used a flat rate of 20% of the sum of costs of time and external costs.

Total transaction costs related to the amount of eligible costs per individual project allow us to account for a different size in projects and show the relative burden of transaction costs (Equation (52)). The eligible costs of a project provide a good proxy for the size of the project while allowing for comparison between projects and programmes.

$$TC_r = \frac{TC_n}{EC} \times 100 \% \quad (52)$$

where TC_r is the percentage share of transaction costs on total eligible costs, and EC are eligible costs of the project.

We assume that the whole administration process and, therefore, transaction costs related to the project take place within one year, as confirmed in [242]. Having studied the transaction costs over two periods of time (2011 and 2019), we have also escalated the costs of 2011 to prices of 2019. We have used the labour costs for the sector of

⁹ In addition, there were eight qualitative interviews carried out in 2011.

public services and enterprises, and the market services price indices for the changes in price levels of the external services [244], [245].

In order to address the first research question, we formulated the hypothesis stating that the transaction costs decrease in time and with the maturity of the programme. To test the hypothesis on the difference in transaction costs in the two programmes and two periods of time, we used a model developed in [242]. Total eligible costs and time period (time of the survey) are two independent variables, while respective transaction costs are the dependent variable.

$$TC_n = f(EC; t) \quad (53)$$

where t is the binary variable defining the time period of the programme, represented by the questionnaire survey from 2011 to 2019.

Regression analysis was used to establish the relationship between the variables TC_n , EC , and t . The dataset has a lognormal distribution.^r The regression is operationalized as follows:

$$2011: \quad \ln TC_{n1} = \alpha_1 + \beta_1 \ln EC_1 + \varepsilon_1 \quad (54)$$

$$2019: \quad \ln TC_{n2} = \alpha_2 + \beta_2 \ln EC_2 + \varepsilon_2 \quad (55)$$

where ε_i are the standard i. i.d. error terms, $i = 1, 2$.

Similarly, we establish the relative transaction costs:

$$2011: \quad \ln TC_{r1} = \ln \left(\frac{TC_{n1}}{EC_1} \right) \quad (56)$$

$$2019: \quad \ln TC_{r2} = \ln \left(\frac{TC_{n2}}{EC_2} \right) \quad (57)$$

To answer our research question about the difference in transaction costs in the two programmes and two periods of time, we test the difference in mean transaction cost burden ($\ln TC_r$) of both samples. We coded 2011 as 1 and 2019 as 0, and tested the means of relative transaction costs (TC_r) for the two years to be the same:

$$1) \quad H_0: \mu_1 - \mu_2 = 0$$

^r We provide evidence for this in the next section.

2)

$$H1: \mu_1 - \mu_2 \neq 0$$

Where μ_1 is the mean of relative transaction costs $\ln TC_{r1}$ in 2011 and μ_2 is the mean of relative transaction costs $\ln TC_{r2}$ in 2019. Rejecting the null hypothesis would mean that there would be a statistically significant difference between the two means.

6.4 Results

In total, we analysed 229 responses from participants in the programmes in 2011 and 2019. However, due to the unavailability of data on eligible costs or incompleteness and other faults in the questionnaire, we used 189 responses in total for further analysis (Table 16, cf. Table 15).

The sample reflects the size of the projects in the whole population - all supported projects in the final stage of implementation and administration at the time of the survey. The median eligible costs (representing a proxy for the size of the project) in the sample are in all four cases within the range of the median eligible costs of the whole population.

In both programmes, we see that in 2019 (representing the new programming period 2014–2020) the supported projects are generally smaller than in 2011 (representing the programming period of 2007–2013). The mean size of the projects in our sample runs from EUR 128, 000 to EUR 286, 000, while it is EUR 126, 000 to EUR 380, 000 in the whole population of the analysed projects.

The set of graphs in Figure 28 and Figure 29 endorses the lognormal distribution of the sample. While the non-transformed distribution for both eligible costs and transaction costs has a declining character of a distribution of an exponential type, the logarithms of both eligible and transaction costs exhibit a shape typical for a normal distribution.

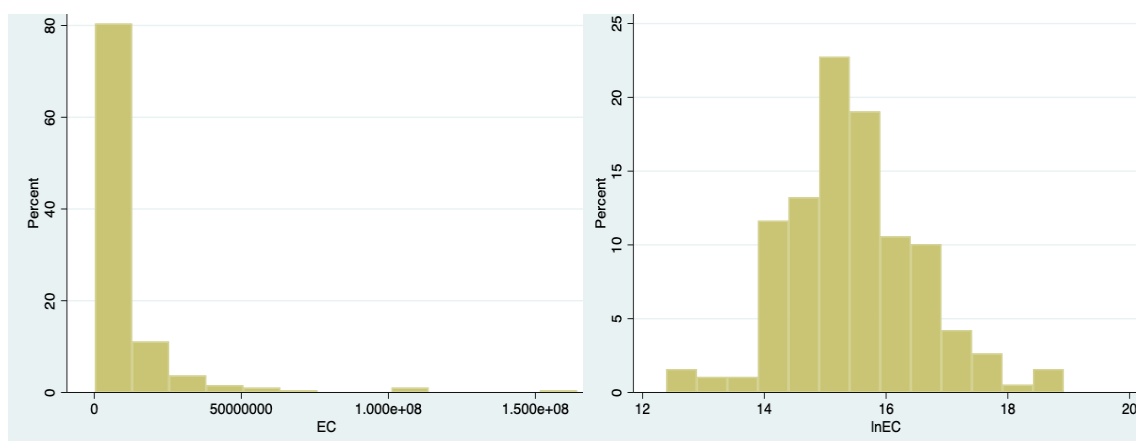


Figure 28 Distribution of eligible costs (EC) in the sample and their natural logarithms.

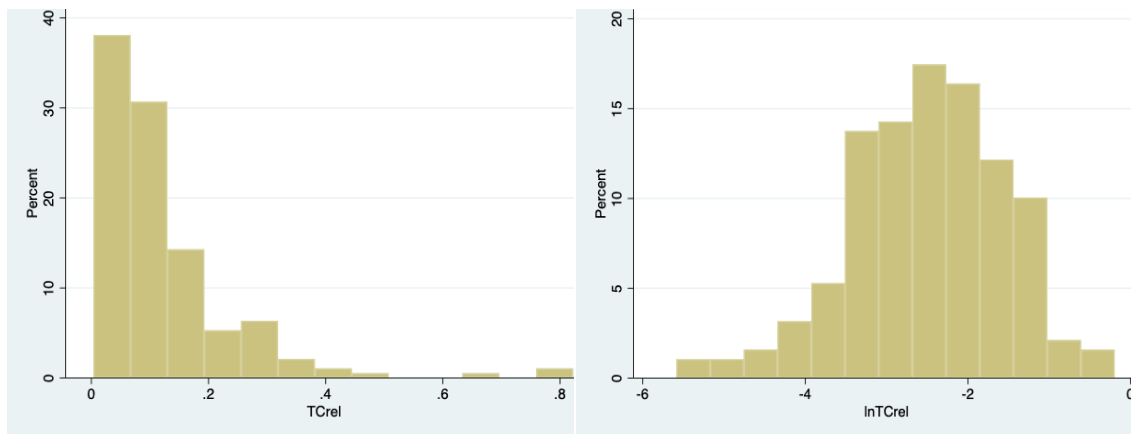


Figure 29 Distribution of relative transaction costs (TCrel) in the sample and their natural logarithms.

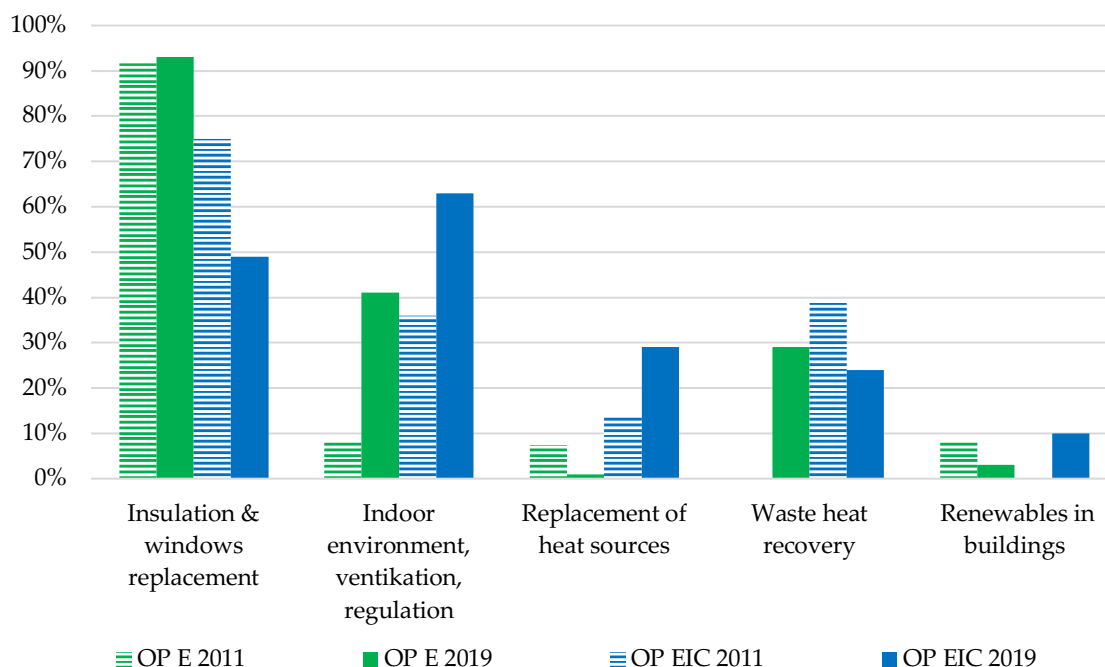


Figure 30 Structure of the supported energy efficiency and RES measures.

In both programmes, the most frequent types of supported measures are the measures improving thermal properties of the buildings (insulation and windows replacement), combined with control systems and recuperation (Figure 30). There is a larger share of waste heat recovery and technology replacement in the OP EIC, mainly due to the nature of the applicants – private enterprises improving the efficiency of their technology processes.

6.4.1 Costs of time

The time spent on administration of the subsidized projects increased in both programmes from 2011 to 2019, with an overall 45% increase in the case of the OP E (which subsidizes public sector organisations), and 40% increase in the case of the OP EIC (supporting private enterprises). We have further divided the projects according to size (eligible costs). We see the sharpest increase in time intensity in the smallest projects (up to EUR 200 thousand) in the public sector – the OP E (Figure 31).

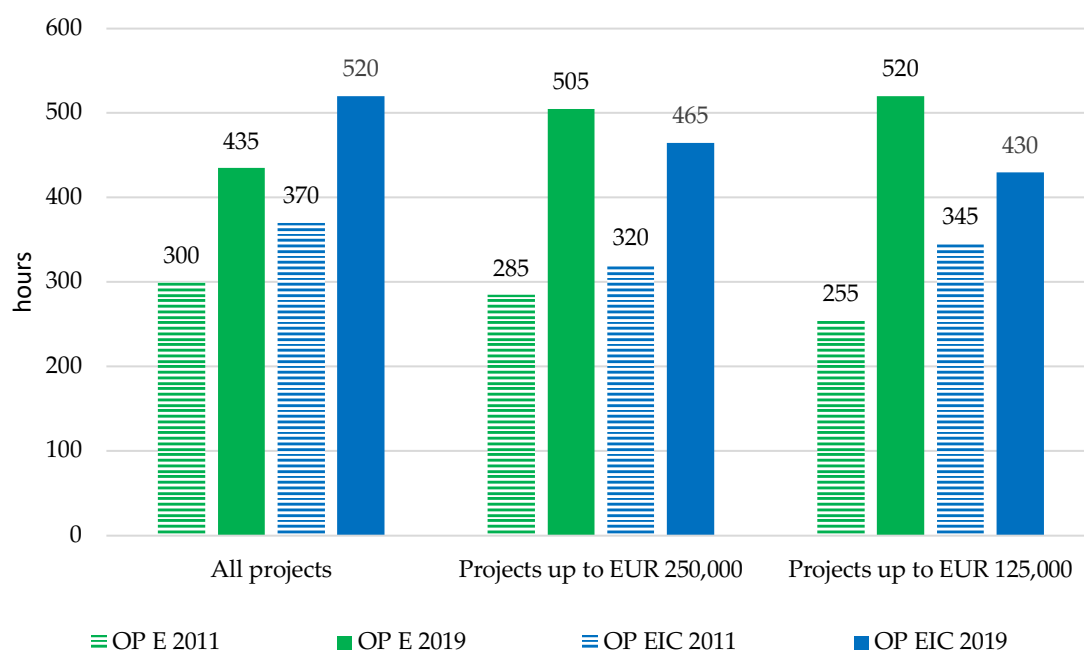


Figure 31 Time spent with the administration of the project in hours (per size of the project in eligible costs).

As both programmes are supported by EU Structural Funds and aim at increasing energy efficiency and renewable energy sources (RESs), the requirements are largely harmonized, and so are the documents and administrative processes. In both programmes and programming periods, the most time intensive activities were the application submission (including a search for information), and implementation of the project (while accounting only for the activities which would be incurred due to the fact that the project was supported by the programme).

We recalculated the time costs using average labour costs for the given NACE^s activity (public administration and industry). The respondents spent EUR 3200–3400 administering their project in 2011 while spending EUR 5300–5600 EUR in 2019, representing a 65% increase in both cases (Table 17). The difference between

^s Statistical classification of economic activities in the European Community.

the increase in hours and the increase in costs is caused by the increase of respective unitary labour costs in the studied period [244]. Between 2011 and 2019, the average labour costs increased by 14%–17% depending on the sector.

Costs of time per project [EUR]	2011	2019
OP E	3,204	5,290
OP EIC	3,389	5,590

Table 17 Costs of time per project – median [EUR].

6.4.2 Costs of external services

Almost all respondents used services from an external company for at least one of the activities connected with the administration of the subsidized project. These included namely energy assessment and project documentation (requirements of the programmes), administrative support for submission of the subsidy request, tender dossier and organisation of the tender for the supplier. While in the OP E the percentage of applicants hiring an external company grew across all services (Figure 32 and Figure 33), in the OP EIC, there was a decrease in the services connected with the administration of the project (administrative support, public tender and a tender dossier).

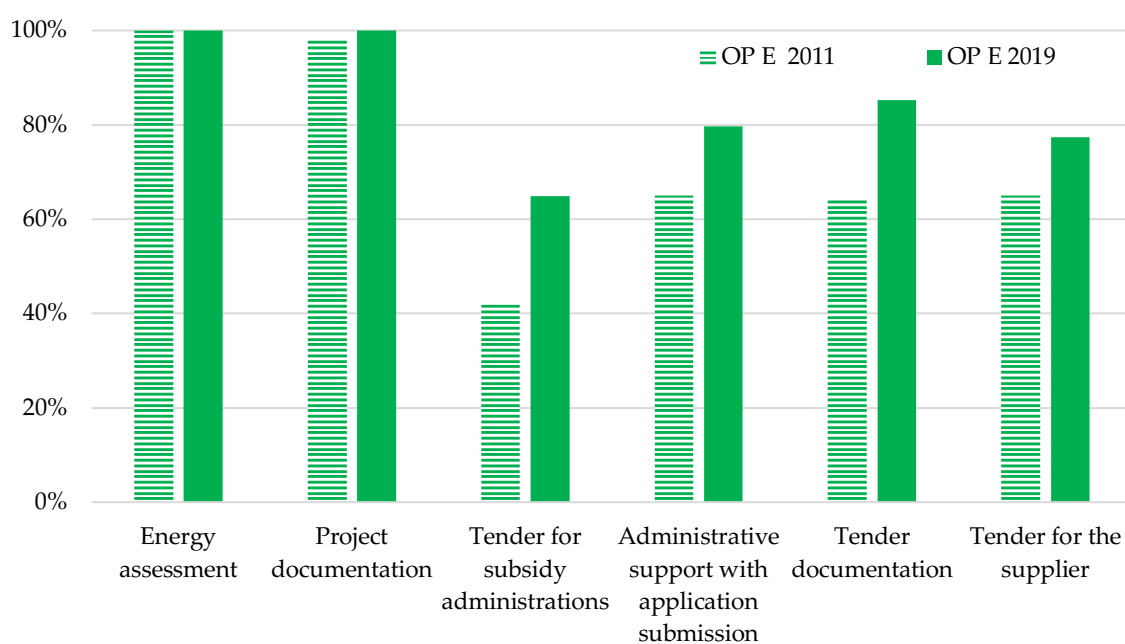


Figure 32 Percentage of applicants outsourcing the services connected with project administration (Operational Programme Environment).

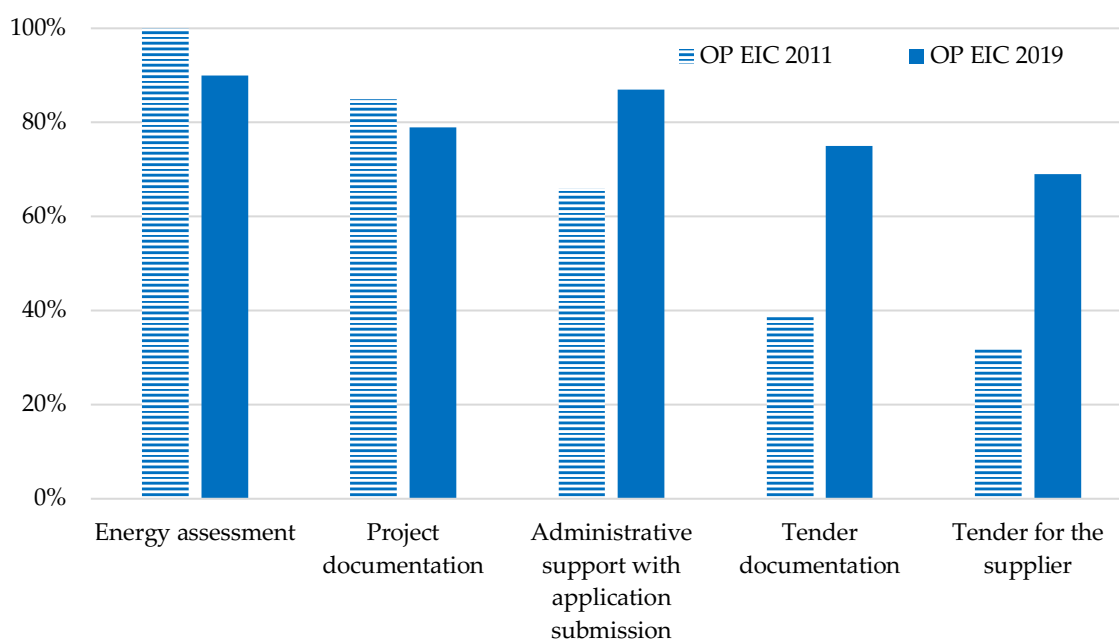


Figure 33 Percentage of applicants outsourcing the services connected with project administration (Operational Programme Enterprise and Innovation for Competitiveness).

While the costs of external services decreased in the OP EIC from EUR 15,200 in 2011 to EUR 10,000 per project in 2019, they increased in the case of the OP E from EUR 6000 to EUR 10,000 respectively (Table 18). The market services price indices in the business sector remained unchanged from 2011 to 2018 [245], therefore having close to zero effect on the costs of external services.

Costs of external services per project [EUR]	2011	2019
OP E	6,000	10,000
OP EIC	15,200	10,000

Table 18 Costs of external services per project – median [EUR].

Looking closer at the distribution of the costs of external services across the programmes and years, there is a clear shift in the OP EIC towards lower costs in 2019 as opposed to 2011 (Figure 34). The shift corresponds to the prevalence of smaller projects in 2019 compared to 2011. Even though the overall costs for external services increased in the case of the OP E, we do not see such a significant shift at the OP EIC, even though in both cases the supported projects are smaller in 2019 compared to 2011. In the OP E, the most substantial increase in external costs is observed for projects of up to EUR 250,000 of eligible costs. For the OP EIC, the decrease in external costs is driven

mainly by larger projects, whereas external costs for smaller projects (up to EUR 250,000 and even EUR 125,000) increased.

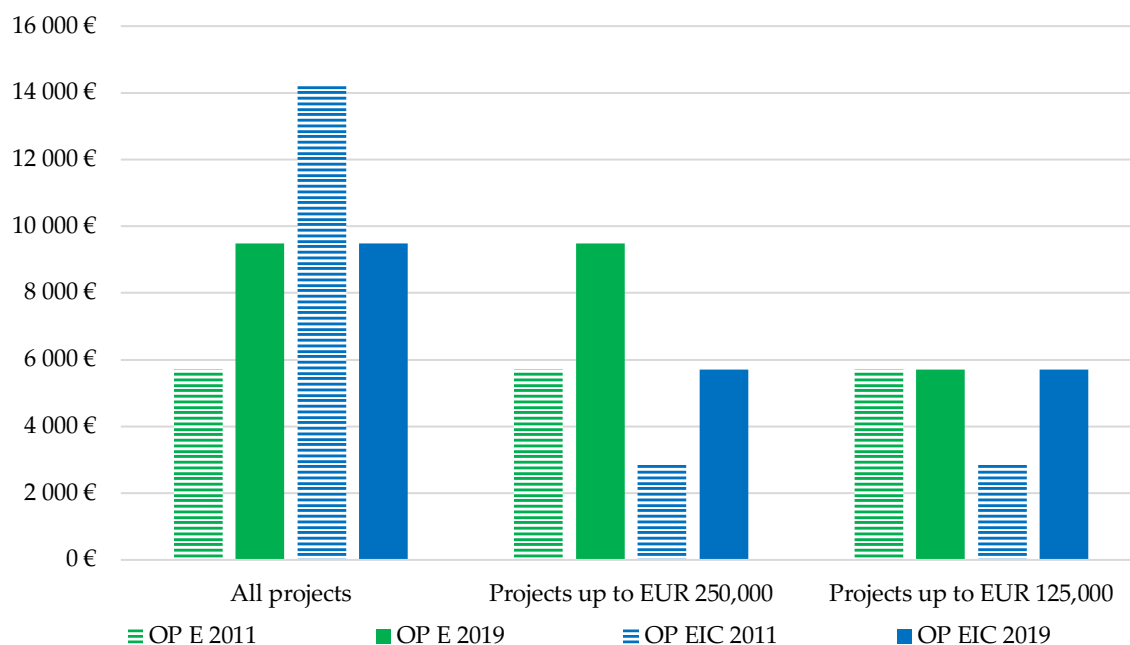


Figure 34 Distribution of costs for external services in 2011 and 2019 depending on the size of the project (eligible costs).

6.4.3 Overall transaction costs

The absolute values of transaction costs per project increased from EUR 17,000 to EUR 18,700 in the OP E, representing a 10% increase (Table 19). The transaction costs per project have decreased from EUR 18,800 to EUR 17,700 in the OP EIC (6% decrease).

Transaction costs per project	2011	2019
OP E	16,997	18,722
OP EIC	18,865	17,763

Table 19 Transaction costs per project – median [EUR].

Because there are smaller projects in both programmes in the new period (2014–2020), it means that the burden of transaction costs, expressed as the share of transaction costs on total eligible costs of the project, has increased both in the OP E and in the OP EIC from 2011 to 2019 (Figure 35). The highest increase is observable in the smallest projects (of up to EUR 125,000). For instance, at the OP E, the transaction costs increased from 9% in 2011 to 23% in 2019. That means that for every EUR 100 of project costs,

there are additional EUR 23 of transaction costs. At the OP E, the increase is less steep, from 10% in 2011 to 14% in 2019. The overall results remain unchanged when recalculating the 2011 data to 2019 prices, except for “medium” sized projects in OP EIC.

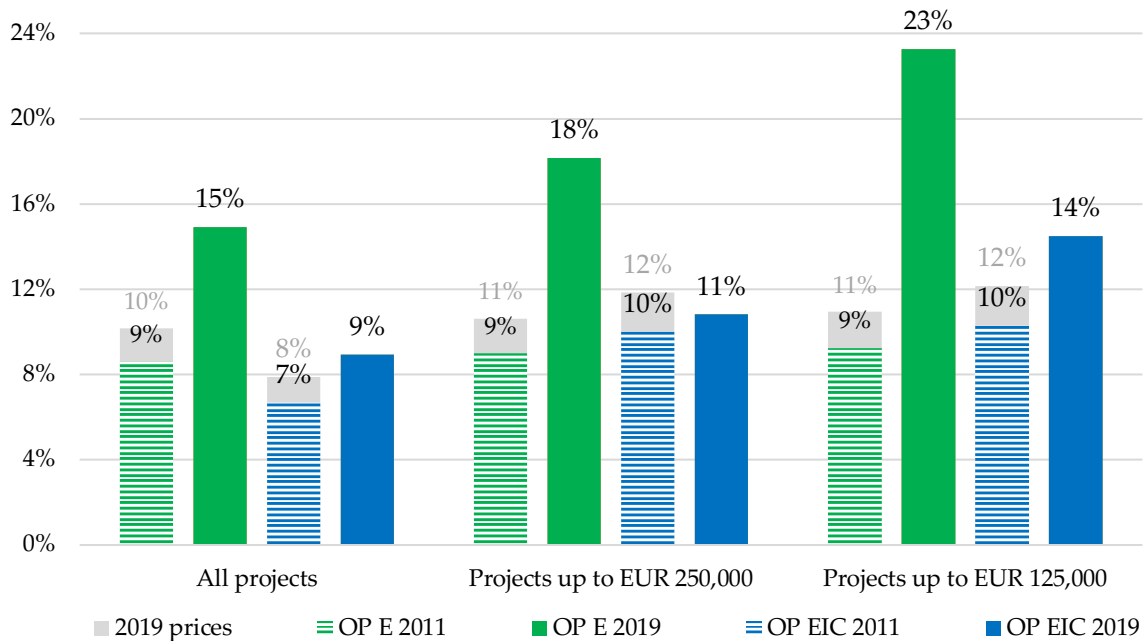


Figure 35 Share of transaction costs on eligible costs (%).

To test our hypothesis on the difference of the mean transaction cost burden ($\ln TC_t$) of both samples, we ran a two-sample t -test (with unequal variances) in which the year 2011 was coded 1 and 2019 was coded 0. The results are summarized in Table 20.

Group	Observati	Mean	Standard error
2019 (0)	99	-2.70	0.10
2011 (1)	90	-2.33	0.09
Difference		0.37	0.13

Two-sample t -test: $t(185) = 2.76$

$H_a \neq 0$: $p = 0.006$, $H_a > 0$, $p = 0.003$, $H_a < 0$, $p = 1.0$

Table 20 Results of two-sample t -test for $\ln TC_r$.

The results show that there is a statistically significant difference between the two means and that the burden of transaction costs grew from 2011 to 2019. The p -value for $H_a \neq 0$ (the means are different) is lower than 0.1. Furthermore, the p -value for $H_a < 0$ is also lower than 0.1, showing that on a 99% confidence interval level the difference

between the mean in 2019 and 2011 is greater than 0, and that the mean burden of transaction costs grew between the 2011 and 2019 samples. The difference between the two samples means (when transformed back from the log-transformed values) is **3 percentage points** for both the OP E and the OP EIC together. The difference is statistically significant for both samples; the mean difference is higher for the OP E than for the OP EIC, which is also depicted in Figure 35.

6.5 Discussion

The overall structure of transaction costs and the relative share of various stages of administration of the projects remained mostly unchanged in both programmes over the two periods. The general processes in the programmes stem from the umbrella specifications of the operational programmes' schemes under the European Structural Funds. The whole process of submission of the subsidy application accounts for a third of the total time spent, and implementation of the project, including tender dossier and organisation account for an additional 40%–45% in the whole process.

The administrative burden for subsidy recipients in both analysed programmes increased over time (Table 21). In the OP E, all parts of the transaction costs and the transaction costs burden increased. In the OP EIC, there was a decrease in costs for external services, and overall transaction costs, but similarly to the OP E, the overall burden of transaction costs increased.

	Time (hours)	Time (C _t)	External services (C _e)	Transaction costs (TC)	Relative transaction costs (TCr)
OP E	+45%	+65%	+66%	+10%	+66%
OP EIC	+40%	+65%	- 35%	- 6%	+30%

Table 21 Relative change of transaction costs in time (2019 compared to 2011).

All in all, we see that the burden of transaction costs increases with time. However, we need a closer examination of the programmes to determine why this may be happening, and why time in the analysed programmes does not play a major role in the decreasing of transaction costs. Understanding the reasons leads to specific policy implications.

First, we look at the time (and related costs) spent with the subsidized projects by the actors (subsidy recipients) internally. Despite the continuity in the programmes, there does not seem to be a downward trend of the temporal transaction costs among its participants. In both programmes, the internal time needed for administrating the project supported by a subsidy increased by almost a half in the two periods. The reasons for this are mainly two-fold. Firstly, most of the participants would be on-off participants.[†] The targeting of the programmes - investment subsidy for energy efficiency measures - means that most of the participants do not enter with the aim of further consecutive projects. Therefore, unlike in the case of, e.g. EU ETS mechanisms [218], there is little room for internal learning. Previous analyses further revealed that knowledge is rarely passed on even within different departments of the same institution [242]. The transfer of information is closely connected with institutional memory, or rather “institutional amnesia” [246]. According to Pollitt, the reasons for such “institutional forgetting”, especially in public organisations, are, among others, frequent restructuring and the inherent loss of records, as well as a high turnover of public servants. All of these factors lead not only to memory loss but, inevitably, to higher system transaction costs.

Second, despite continuous efforts to simplify the processes in the programmes (by e.g. developing templates and streamlining of processes), the programmes become more complicated. The programmes started to financially encourage some new measures, such as providing extra points for projects combining the subsidy with energy performance contracting in case of OP E. While potentially adding to the effectiveness of the projects (bringing more energy savings), the transaction costs tend to increase [216], [247]. Newly established (and sometimes politically driven) requirements, such as a requirement to provide an itemized budget at the initial stages of the project, mean that the programmes become more administratively intensive. Additionally, even though we have not examined the transaction costs on the side of the administrative body per se, the interviews with the administrators suggest that they do not perceive decreasing transaction costs. Despite the continuity of the programmes, the externally and

[†] By contrast, the external companies providing external services for the applicants tend to carry out their services in both programming periods.

internally driven changes mean an ever-present inflow of new sources of transaction costs for the administrators and, consequently, for the subsidy recipients, therefore diminishing the learning effect for the whole programme.

Conversely to costs regarding time, the development of costs of external services is more divergent. In the case of the OP EIC, the costs of external services seem to follow the decreasing size of subsidized projects. As demonstrated in Figure 33, private entities outsourced fewer activities connected with the administration of the projects (given the declining size of the projects), and carried out more of the activities internally compared to the previous period.

In the case of the OP E, by contrast, despite the decrease in the size of the projects, the costs for external services increased (by almost two-thirds). One of the likely explanations lies in the new conditions of the programme. In 2019 (representing the new programming period of 2014–2020), the OP E newly introduced a subsidy for the preparation of the project application. The subsidy amounts to 5%–15% of the eligible costs depending on the project size. There were two effects of this new opportunity. First, more applicants used an external company to help with the project preparation (cf. Figure 32), and second, the subsidy itself has served as a price setter for the services of the external companies, driving up the costs for these services.

The former effect has also led to an increasing share of external companies specializing in subsidy management exclusively, without further expertise in energy efficiency. Some of the administrators of the programmes have reportedly seen a deteriorating quality of projects and subsequently higher transaction costs for all actors. However, more research would be needed in order to confirm such a direct causality.

The burden of transaction costs (i.e. the ratio of transaction costs to the project size) increased in both programmes from 2011 to 2019. It is partially caused by the above discussed increased costs of time and external services, and partially by the fact that there are overall smaller projects supported in both programmes, therefore diminishing the effect of economies of scale [215], [242].

The increased burden suggests a prevailing share of fixed costs over variable costs, i.e. a large part of the transaction cost does not change with the size of

the project. Such fixed costs would typically entail the application procedure, in which all applicants must submit the same amount of paperwork, regardless of the size of their project. The same applies to further reporting and requests for payment, and partially to tender organisation and dossier.

The type and relative supply of projects in the programmes does not vary significantly over the analysed period. The success rate of the applications remains stable (roughly 65–75% in both programmes), leading us to a conclusion that the changes in transaction costs cannot be attributed purely to the availability of the projects. Similarly, the overall cost-effectiveness of the projects has remained mostly unchanged (showing a minor decrease with no statistical significance, cf. Figure 27). Therefore, while speculatively the “low-hanging fruit”, easy projects with high effects may have been prevalent in the first programming period (2007–2013), it does not fully explain the increase in transaction costs over time. Instead, the overall smaller size of the projects and excess of fixed costs seem to be more determinant.

The exogenous factors influence the development of transaction costs [211]. Specifically, the institutional environment sets the rules for the design and implementation of the programmes [223]. We have assumed a relatively stable overall policy environment [215] which is framed by the rules of the multiannual financial framework and implementation of the EU structural and investment funds at the national level [248]. Nevertheless, the national specifics and development of the national policy and economic framework have indeed had an impact on the transaction costs of both analysed programmes.

Firstly, the beginning of the 2014–2020 programming period was marked by high uncertainty, caused by a hasty preparatory period and late start of both programmes, thus, contributing to higher transaction costs in both programmes. There was a significant delay in the preparation of the operational programmes in the programming period 2014–2020.^u Consequently, the main parameters of the programmes were insufficiently prepared, which was reflected in poorly designed requirements of individual programmes in the initial calls for applications.

^u The first calls for applications were opened only 18–24 months after the official start of the programmes.

In the course of the programmes, a series of parameters (where possible) had to be adjusted, increasing the administrative intensity and transaction costs for the actors.^v

Secondly, the interest rates have decreased in the analysed period from 4% in 2009 and 5% in 2011 to 2–3% in 2016–2018 [249]. The decline in interest rates may have caused a higher willingness of the organisations to borrow money to co-finance the subsidized projects. We may, therefore, speculate that in case of higher interest rates (in 2009–2011), only “very good” projects would have been supported. However, first, this assumption could not be fully confirmed by the similarly higher cost-effectiveness of the projects in the prior period, and second, the projects supported through public programmes tend to be less risky for the banks in general, as they are backed by the thorough documentation proving the viability of the project. Additionally, these assumptions cannot be fully transferred to OPE participants – municipalities and other public organisations, which are bound by other budgetary and borrowing constraints.

6.6 Conclusions and policy implications

The system of structural funds offers an excellent opportunity for long-term evaluation of transaction costs and for an understanding of how programmes develop over time. We have used the two Operational programmes co-financed through the European Structural and Investment Funds to study how transaction costs develop over time, and which factors impact and possibly detour the transaction costs.

On a case study of two long-running operational programmes, we provide evidence against the prevailing downward impact of time-related factors. While the structure of transaction costs demonstrates the continuity in the programmes, the levels of transaction costs and their relative burden have increased significantly.

Effects from “learning-by-doing” in mature and continuous programmes are brought by streamlining of processes, provision of templates, and knowledge transfer. However, we have shown that these gains may be overrun by other factors, including changes in costs, information loss in the organisations, and constant changes of

^v McCann [215] notes that there is often a trade-off between ex ante and ex post transaction costs. Lower initial transaction costs may be offset by higher ex post litigation costs. However, we could not prove this to be the case for our programmes.

the programme's conditions, leading to an overall increase in transaction costs and their burden over time.

Despite the maintained overall levels of cost-effectiveness throughout the programmes, the age of the programmes in our case may also mean that “low-hanging-fruit” projects (with high cost-effectiveness) have been “collected” in the previous periods of the programmes. Smaller and more complicated projects prevail, leading to a higher burden of transaction costs in such projects.

Differentiation of the administrative procedures in such cases can improve overall effectiveness (and attractiveness) of the programmes. Simplified procedures, especially in the initial stages of the projects and in tendering procedures, can significantly decrease the administrative burden. These should be combined with a properly set up control mechanism to maintain the overall quality of the energy efficiency scheme and materiality of energy savings.

Initial, preparatory stages of the programmes, including thorough ex-ante evaluation of the policies, may improve the subsequent effectiveness and administrative intensity of the programme. Conversely, late start of the second programming period resulted in the instability of the programme, insecurity among applicants, and may have led to lower-quality projects. Therefore, not only continuity in the programmes but especially coherence – creating a safe and stable environment - are as important as the processes themselves.

Due to the character of the programmes, there is little room for intra-organisational learning by the participants. Furthermore, due to increased turnover among recipients, there is little institutional memory and distribution of information. Therefore, the potential gains from long-running, revolving activities do not translate into low transaction costs in such a way that has been observed in other types of policy instruments (such as EU ETS).

Transaction costs remain an understudied phenomenon, and empirical evidence remains scarce. Systemic tracking of transaction costs can be a powerful tool to assess the effectiveness and efficiency of energy efficiency programmes. Further research may explore what is the effect of learning, how does it impact policy change and how it translates in transaction costs.

CRedit authorship contribution statement: Michaela Valentová: Conceptualization, Methodology, Validation, Writing - original draft, review. Martin Horák: Investigation, Formal analysis, Visualization. Lukáš Dvořáček: Investigation, Formal analysis.

Declaration of competing interest:

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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7. Recommendation for Further Research

Extensive and comprehensive research in the field of EVs and charging stations is of paramount importance to overcome existing challenges and facilitate the widespread adoption of sustainable transportation. By exploring various aspects of this rapidly evolving field, researchers can contribute to the development of innovative solutions and technologies. Here are key areas that demand further investigation and exploration:

7.1 Charging Infrastructure Enhancement

The primary objective of research should be to enhance the efficiency of charging infrastructure through the optimization of design and placement, and the utilization of charging stations [39], [41], [42]. It is crucial to identify optimal locations considering travel patterns, user behaviour, and population density. Collaboration with urban planners and transportation authorities is essential in order to strategically deploy charging stations, ensuring convenient access for EV users while minimizing the need for significant infrastructure investments [39], [41], [42]. Furthermore, it is important to explore alternative charging solutions like wireless charging technologies or fast-charging to further improve the overall optimization of the charging infrastructure [108].

7.2 Smart Charging, Grid Integration, and Reservation Systems

Research efforts should focus on advancing smart charging systems to optimize charging schedules in accordance with grid conditions, electricity demand, and renewable energy generation [13], [80], [111]. The development of sophisticated algorithms and technologies for intelligent charging management, such as load balancing, demand response, vehicle-to-grid (V2G) integration, and energy storage solutions, should be a key area of investigation [57], [65], [114], [250]. Additionally, the implementation of reservation systems for charging stations can enhance user convenience by allowing EV owners to reserve a charging slot in advance. By enabling bidirectional charging capabilities, EVs not only consume energy but also have the ability to supply power back to the grid during peak demand periods, thereby contributing to grid stability and flexibility [70], [98]–[100].

7.3 Fast Charging and Battery Advancements

The improvement of fast-charging capabilities plays a crucial role in facilitating long-distance travel and minimizing charging time [10], [26], [27]. It is imperative to concentrate research efforts on advancing technologies such as higher-power chargers, enhanced cooling systems, and battery materials that enable faster charging rates. Additionally, the exploration of next-generation battery technologies, including solid-state and lithium-sulphur batteries, holds great potential for enhancing energy density, extending the range of EVs, and achieving faster charging speeds [107]–[109]. By focusing on these areas, we can significantly enhance the overall charging experience and make EVs more practical for daily and long-distance use.

7.4 Standardization and Interoperability

The establishment of universally accepted charging protocols, connectors, and communication systems is paramount for ensuring compatibility and seamless interoperability among various EV models and charging infrastructure [108]. Extensive research is required to develop global standards that not only facilitate convenient and cost-effective charging experiences but also promote interoperability across different charging networks [108]. By prioritizing standardization efforts, the industry can significantly enhance the overall EV charging ecosystem, simplifying the charging process for EV owners [108].

7.5 Renewable Energy Integration for Sustainable EV Charging

The seamless integration of RESs, including solar and wind power, into EV charging infrastructure is of paramount importance for achieving long-term sustainability [14], [16], [48], [111]. To accomplish this, research efforts should concentrate on developing effective methods for integrating renewable energy into the charging ecosystem [14], [16], [48], [111]. This includes exploring advanced technologies such as vehicle-to-home (V2H) and vehicle-to-grid (V2G) systems, which enable a bidirectional energy flow between the grid and EVs. V2H systems allow EVs to serve as temporary energy storage devices, supplying power back to homes during peak demand or power outages [251]. V2G systems, on the other hand, facilitate the utilization of EV batteries to support the grid by providing electricity during periods of high demand. By investigating and implementing these integration

methods, we can maximize the utilization of RESs, reduce carbon emissions, and create a more sustainable and resilient energy system [251].

7.6 Cybersecurity and Privacy in Connected EVs and Charging Infrastructure

With the growing connectivity of EVs and charging infrastructure, it is imperative to prioritize cybersecurity and privacy considerations. Research endeavours should focus on the development of robust security measures, encryption protocols, and authentication mechanisms to safeguard against potential cyber threats [252]–[254]. By implementing advanced cybersecurity measures, EVs and charging stations can be protected from unauthorized access, data breaches, and malicious activities. Additionally, it is essential to explore and implement privacy-enhancing technologies that guarantee secure handling and anonymization of user data [252]–[254]. By prioritizing cybersecurity and privacy in the design and implementation of connected EVs and charging infrastructure, we can instil trust, ensure user confidence, and safeguard sensitive information [252]–[254].

7.7 Economics and Business Models for Sustainable EV Charging

Research should extensively analyse the economic viability of different charging infrastructure deployment models, encompassing public, private, and shared ownership [36], [71], [112]. This assessment should include evaluating cost-effectiveness, exploring innovative business models, and understanding revenue streams associated with EV charging to attract investment and promote the growth of the EV ecosystem [36], [71], [112]. Additionally, studying the impact of EV charging on the electricity grid and implementing strategies for peak demand management, load balancing, and smart grid integration will ensure reliable and sustainable charging operations. By conducting comprehensive research in these areas, we can create an environment conducive to investment and optimize charging efficiency [36], [71], [112].

7.8 User Behaviour and Adoption

In order to effectively promote the adoption of EVs and charging infrastructure, it is crucial to conduct comprehensive research on user behaviour, perceptions, and barriers [7], [21], [118]. By understanding the factors that influence consumer choices, preferences, and attitudes towards EVs and charging infrastructure, policymakers and

industry stakeholders can develop tailored strategies to address obstacles and foster widespread EV adoption [6], [7], [20], [122]. This research should explore various aspects such as consumer motivations and concerns, the impact of pricing and incentives on purchase decisions, and the role of range anxiety and charging accessibility. By gaining insights into user behaviour and perceptions, policymakers can design effective policies, incentives, and awareness campaigns that encourage the adoption of EVs and create a user-friendly charging infrastructure [6], [7], [20], [122].

To ensure a successful transition to a sustainable and electric mobility future, it is imperative that we prioritize research in these key areas [7], [20], [21], [122]. By doing so, we can overcome the challenges currently faced, optimize the integration of EVs into the transportation system, and expedite the overall transition process. Continuous research and innovation are vital in unlocking the full potential of EVs and establishing an efficient and reliable charging infrastructure network [7], [20], [21], [122]. By dedicating our efforts to these research areas, we can pave the way for a cleaner, greener, and more sustainable transportation system that embraces the benefits of electric mobility [6], [7], [20], [21], [26], [77], [118]–[120].

8. Conclusion

In conclusion, this dissertation has provided valuable insights and solutions to address the research questions regarding EV charging infrastructure optimization, the incorporation of recuperated braking energy (RBE) from trains into EV charging stations, and the impact of transaction costs on the implementation and operation of EV charging infrastructure. The achieved results and their relevance to the research questions are summarized as follows:

1. How can electric vehicle charging points be optimized for efficient use while maintaining cost-effectiveness?

Efficient and cost-effective utilization of EV charging points can be achieved through various strategies. One effective approach is to leverage existing parking lots equipped with low-power chargers, particularly during off-peak hours when they are underutilized. By reserving parking spaces in these lots, EV owners without private garages or chargers can access charging facilities that offer comparable convenience and pricing to home charging. This solution addresses the challenge of inadequate charging stations while maximizing the potential of existing substations. Additionally, implementing power dividing between individual charging stations or utilizing deferred charging functions can help balance the load on local substations, thereby smoothing out peak demand when multiple EVs require charging. In extreme cases, integrating battery ESS can enhance stability and provide support to the local substation and the broader power grid. These measures ensure efficient utilization of charging infrastructure while considering overall cost-effectiveness.

Furthermore, an analysis of real-world data from urban charging stations revealed that EV owners tend to leave their vehicles connected to chargers for longer durations than necessary for a full recharge. This observation suggests that it is more beneficial to prioritize the installation of a sufficient number of AC chargers rather than focusing solely on the higher charging power of DC chargers. This finding holds significance for the development of charging infrastructure in urban and suburban areas, emphasizing the importance of quantity over higher power output. The same principle applies to the expansion of charging facilities in public parking lots,

including park-and-ride (P + R) car parks, where providing an adequate number of chargers is crucial for accommodating EV charging demand effectively.

When exploring optimization strategies for EV charging points, it is also essential to consider the potential for peer-to-peer (P2P) sharing among EV users for private parking and charging facilities. However, P2P sharing presents certain challenges compared to the previous approach of reserving charging spaces in public car parks, particularly in terms of ensuring consistent service quality from charging station owners. The absence of a system to penalize owners for charging station failures can result in variations in service standards. Furthermore, while P2P sharing addresses daytime charging needs, it falls short in resolving the problem of insufficient private parking spaces. During evening hours, these spaces are often occupied by owners of private charging stations.

From a cost perspective, both for the operator and the owner of an EV without a private garage, a larger charging site offers greater economic advantages compared to P2P sharing. When the charging infrastructure consists of a substantial number of chargers, the cost of these chargers can be distributed among a larger customer base, reducing the financial burden on individual EV owners. Additionally, with a larger volume of energy being consumed at the charging site, the operator has the opportunity to negotiate better prices per kilowatt-hour (kWh) with energy providers. This translates to cost savings for both the operator and the EV owners who utilize the charging facility. Therefore, opting for a larger charging site presents a more economically viable solution, benefiting all parties involved by leveraging economies of scale and enabling more favourable pricing arrangements for electricity consumption.

2. How can the incorporation of recuperated braking energy from trains into electric vehicle charging stations impact their energy consumption and operating costs?

Incorporating RBE from trains into EV charging stations presents a significant opportunity to enhance energy efficiency and mitigate the environmental impact of EV charging. When trains brake, the kinetic energy generated can be either recovered by another train accelerating on the same track segment or sent back to the distribution network. However, in less optimal scenarios, this energy is dissipated as heat through on-board resistors or rheostats, leading to energy waste and the release of surplus heat.

By capturing and utilizing this RBE, EV charging stations play a crucial role in maximizing energy efficiency. Instead of allowing the energy to be lost or converted into heat, it is harnessed towards charging EVs. This approach not only minimizes energy waste but also alleviates the load on the electricity distribution grid (EDG). By preventing excessive overflow of RBE back to the grid, the strain on the grid is reduced. Furthermore, the incorporation of RBE helps decrease the amount of energy required from the grid to charge EVs, as some of it is effectively replaced by the utilization of RBE.

Efficient management of RBE in EV charging can be achieved through different strategies. One approach is to store excess RBE in battery or capacitor ESSs, although this increases the overall infrastructure cost. Another approach involves implementing charging power management functions at individual stations, leveraging knowledge of RBE overcharging intervals to adjust charger performance for currently charging EVs.

If the charging infrastructure is operated directly by the company responsible for powering the train lines, there is an economic opportunity to sell RBE energy for EV charging at a significantly higher value compared to selling it back to the grid. This presents a potential revenue boost for the company. Conversely, the company could offer EV owners lower per kWh prices, as they can supply a portion of RBE-derived energy to the charging stations at the same low price it is fed back to the grid.

Efficient utilization of RBE in EV charging can be achieved through diverse strategies, including charging power management and pricing mechanisms. By exploring these options and avoiding the need for costly energy storage systems (ESSs), RBE integration becomes more economically viable. These approaches contribute to a more sustainable and cost-effective future for EV charging infrastructure.

3. How do transaction costs affect the implementation and operation of electric vehicle charging stations, and how can they be reduced?

Through our research, we have acquired significant insights into the influence of transaction costs on the implementation and operation of EV charging stations and the potential strategies to reduce these costs for effective and efficient infrastructure

management. We have explored the long-term development of transaction costs in the context of energy and climate policies and measures, with a specific focus on their influence on the adoption of EVs and the construction of charging infrastructure.

Our findings demonstrate that transaction costs have significant implications for the successful implementation and operation of EV charging stations. Contrary to the common assumption that transaction costs decrease over time, our research reveals that they tend to increase, influenced by factors such as changes in programme administration, internal programme conditions, and information loss. These costs can hinder the progress of energy and climate policies and impede the adoption of EVs and the development of charging infrastructure.

To mitigate the impact of transaction costs and ensure the efficient operation of EV charging stations, it is crucial to implement strategies that aim to reduce these costs. Our research suggests several approaches that can be adopted to address this challenge. These include streamlining programme administration processes, improving IMSs, fostering collaboration and knowledge-sharing among stakeholders, and implementing standardized procedures for infrastructure development.

By reducing transaction costs, we can promote the widespread adoption of EV charging stations, facilitate the transition to cleaner transportation, and contribute to the global efforts in mitigating climate change. Furthermore, our research highlights the need for a more systematic tracking and evaluation of transaction costs in the development and implementation of energy and climate policies. This will enable policymakers and stakeholders to make informed decisions and develop effective strategies to minimize transaction costs, enhance operational efficiency, and accelerate the deployment of EV charging infrastructure.



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Publications of the Author Relevant to the Thesis

- L. Dvoráček, M. Horák, M. Valentová, and J. Knápek, “Optimization of electric vehicle charging points based on efficient use of chargers and providing private charging spaces,” *Energies*, vol. 13, no. 24, 2020, doi: 10.3390/en13246750.

The author actively participated in the research presented in this paper, playing a significant role in conceiving and designing the model for the EV charging site. Furthermore, the author was responsible for analyzing the data obtained during the research process.

Shares: 55/25/10/10

- L. Dvořáček, M. Horák, and J. Knápek, “Simulation of Electric Vehicle Charging Points Based on Efficient Use of Chargers and Using Recuperated Braking Energy from Trains,” *Energies*, vol. 15, no. 2, 2022, doi: 10.3390/en15020571.

The author made substantial contributions to the research presented in this paper, including conceptualizing and designing the model. Additionally, the author was responsible for providing the essential data for the simulation and conducting a thorough analysis of the data.

Shares: 55/35/10

- M. Valentová, M. Horák, and L. Dvořáček, “Why transaction costs do not decrease over time? A case study of energy efficiency programmes in Czechia,” *Energy Policy*, vol. 147, no. March, 2020, doi: 10.1016/j.enpol.2020.111871.

The author actively participated in the investigation and conducted the formal analysis.

Shares: 55/30/15

Other Publications of the Author

Peer-Reviewed Journal Papers:

- T. Králík, J. Knápek, L. Dvořáček, and K. Vávrová, “Impact of pelleting cost on competitiveness of intentionally grown biomass for local space heating: Case example of the Czech Republic,” *Energy Reports*, vol. 6, pp. 732–737, Feb. 2020, doi: 10.1016/J.EGYR.2019.08.089.

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Invited / Awarded Proceedings Paper:

- T. Králík; J. Knápek; L. Dvořáček; K. Vavrová, “Impact of Pelleting Cost on Competitiveness of Intentionally Grown Biomass for Local Space Heating: Case Example of the Czech Republic“, In: ICEER 2019 The 6th International Conference On Energy and Environment Research Book of Abstracts. Instituto Superior de Engenharia do Porto, 2019. p. 211-212. ISBN 9789895423682.

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- M. Miltner; O. Štogl; L. Dvořáček, “Optimization of EV charging infrastructure development based on electromobility growth scenarios for a typical European developed city”, In: Proceedings of the International Student Scientific Conference Poster - 27/2023. Praha: CTU. Faculty of Electrical Engineering, 2023. vol. 1. ISBN 978-80-01-07140-3.

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- L. Dvořáček, “Benefits of Battery Storage for Charging Stations”, In: Proceedings of the International Student Scientific Conference Poster – 23/2019. Praha: ČVUT FEL, Středisko vědecko-technických informací, 2019. p. 232-235. 1. vol. 1. ISBN 978-80-01-06581-5.

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Technical Reports:

- M. Vitek; J. Knápek; J. Vašíček; M. Horák; L. Dvořáček; J. Vodrážka; Z. Brabec, “Znalecký posudek č. 159/2020 na ocenění práva využívání kmitočtů v kmitočtových pásmech 1 920-1 980/2 110-2 170 MHz”, [Technical Report] Praha: Český telekomunikační úřad, 2021. Report no. 150/2020.

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- M. Vitek; J. Knápek; M. Horák; L. Dvořáček; J. Vašíček; J. Vodrážka; Z. Brabec, “Znalecký posudek č. 160/2020 na ocenění práva využívání kmitočtů v kmitočtových pásmech 28,2205–28,4445 GHz a 29,2285–29,4525 GHz”, [Technical Report] Praha: Český telekomunikační úřad, 2020. Report no. 160/2020.

Shares: 46/11/5/5/3/15/15

Certified Methodology:

- M. Valentová; T. Králík; M. Makešová; L. Dvořáček; J. Knápek, “Metodika hodnocení nástrojů na podporu energetické efektivity z hlediska transakčních nákladů”, [Certified Methodology (for RIV)] 2020.

Shares: 20/20/20/20/20

Participation in Projects

• Technology Agency of the Czech Republic

- Models and processes for an optimal mix of support and regulatory instruments for the development of clean mobility, Project code: TK04010276
- Methodological Framework for the Future Energy Market Design of the Czech Republic, Project code: TK02010113
- Methodological tools for impact assessment of the introduction of smart metering to consumers, Project code: TK02010160

- **Student grant agency of CTU in Prague**

- Design optimization of charging sites for electric vehicles, no. SGS20/125/OHK5/2T/13
- Household electricity consumption model, no. SGS20/126/OHK5/2T/13
- Central energy storage shared within a group of small photovoltaic installations, no. SGS18/134/OHK5/2T/13

Internships and Training Schools

- **Internships**

- Institution: Porsche Engineering Services GmbH
Location: Bietigheim-Bissingen, Germany
Topic: High-Voltage System Development Division (Bereich Hochvolt-Systementwicklung)
Duration: 2022 April – 2022 September
- Institution: Workforce Development Agency - Ministry of Labor
Location: Taichung, Republic of China
Topic: Green energy course under the auspices of the Ministry of Labor in Taichung-Changhua-Nantou Regional (TCNR) Branch Taichung.
Duration: 2018 September – 2018 November

- **Training Schools**

- Institution: CTU in Prague / TU Wien: Technische Universität Wien
Location: Prague, Wien
Topic: The Future of Energy Systems in Austria and the Czech Republic

