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Herausgeber: J. Biethahn† • L. M. Kolbe • M. Schumann

Johannes Schmidt

Demand-Side Integration Programs for Electric Transport Vehicles

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Demand-Side Integration Programs for Electric Transport Vehicles

Dissertation

zur Erlangung des wirtschaftswissenschaftlichen Doktorgrades

der Wirtschaftswissenschaftlichen Fakultät der Georg-August-Universität Göttingen

vorgelegt von

M. Sc. Johannes Schmidt

aus Wolfenbüttel

Göttingen, 2015

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Preface

Applying demand-side integration (DSI) programs for electric vehicles (EVs) is important for improving system reliability and assisting in integrating renewables into the energy system. At the same time, EV users are attracted to DSI programs due to their financial benefits. However, despite the promise of applying DSI programs for EVs, there are several barriers to the realization of DSI programs in this application context – most notably the substantial investment required for constructing infrastructure, user acceptance problems, and extensive regulatory requirements on energy markets. An application context for applying DSI programs for EVs that has not yet been investigated but seems to hold great potential is heavy-duty electric transport vehicles (ETVs) operating in closed transport systems. A particularly favorable characteristic in this area of application is the possibility of pooling these vehicles – each with a considerable battery storage capacity – on company grounds.

This cumulative dissertation primarily aims to identify and assess feasible and suitable DSI programs for an ETV fleet that is employed exclusively within the walls of a fulfillment or distribution center. Based on this, it is possible to determine the extent of DSI's economic value for the ETV fleet operator. To ensure the practical relevance of the results, the analyses were based on a large-scale electric mobility project conducted in a container terminal. It was found that the load-shifting potential of the ETV fleet can be used for a broad range of DSI programs, the most promising of which resulted in a significant potential for cost saving (>30%) compared to uncontrolled charging with fixed electricity prices. Furthermore, the analyses reveal that an ETV fleet can be more profitable than a comparable diesel-powered one, and applying DSI programs can increase the cost-efficiency of the ETV fleet even further. Overall, the results have the potential to convince further fleet operators to use ETVs and adopt DSI solutions, which is crucial for shaping a sustainable transport and energy sector.

This work would not have been possible without the support and help of many others whom I would like to thank in the following.

First and foremost, I want to thank all my co-authors in particular Matthias Eisel and Lars-Peter Lauven. During our common paper projects, I not only benefit from your professional skills but also enjoyed the successful collaboration. Furthermore, I want to thank Rachael Garcia for her excellent proofreading service and the linguistic revision of all studies.

My sincere thanks go to Prof. Dr. Lutz M. Kolbe, my doctoral advisor, for his support during my dissertation project and his friendly cooperation. He granted me the freedom to develop my own ideas and also provided an excellent and professional research environment. Furthermore, I am very thankful to Prof. Dr. Jutta Geldermann and Prof. Dr. Johann Kranz, my co-advisors, for their helpful suggestions and efforts in evaluating my work.

I would also like to express my gratitude to all partners from the BESIC research project in Hamburg, in particular Serge Runge, Norman Ihle, and Claas Meyer-Barlag. During the last three years, I had the opportunity to learn a lot about energy economics and logistics in practice. This knowledge helped me tremendously in writing my studies.

Furthermore, I would like to thank all my colleagues from the Chair of Information Management and the Chair's SMRG for the enjoyable collaboration, motivating work atmosphere, and great experiences during the conferences we participated in all over the world. In particular, I want to thank Matthias Eisel and Simon Trang for their scientific input during my research endeavor.

Besides my colleagues, I also want to thank my family and friends. First of all, I am thankful for the continuous encouragement and considerable trust of my parents. I hope you know how much I appreciate your support not only during the last few years but also during the course of my study, international internships, and during my school days. Without your backing, I would not have been able to write this thesis. I also want to thank Runhild with all my heart for her unconditional support and understanding in difficult times. Your trust in me encouraged me to start and successfully complete my dissertation project. Finally, I want to thank all my friends, particularly Dominik, Lars, Stefan, Viktoria, Katharina, Gunnar, and Susanne for all the leisure activities, including holidays, concerts, and pub crawls, which helped me gather new strength for my research projects.

Göttingen, October 2015 *Johannes Schmidt*

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Acronyms

AGV	Automated guided vehicle
Ah	Ampere-hour
AMCIS	Americas Conference on Information Systems
AMI	Advanced metering infrastructure
B2M	Battery-to-(regulation)-market
B-AGV	Battery-powered automated guided vehicle
BDEW	Bundesverband der Energie- und Wasserwirtschaft
BESIC	Battery electric heavy goods vehicles within intelligent container terminal operation
BEV	Battery electric vehicle
BMU	Bundesministeriums für Umwelt, Naturschutz, Bau und Reaktorsicherheit (engl.: Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety)
BMWi	Bundesministerium für Wirtschaft und Energie (engl.: Federal Ministry for Economic Affairs and Energy)
BSS	Battery-swapping station
CTA	Container-Terminal Altenwerder
dena	Deutsche Energie-Agentur (engl.: German Energy Agency)
DOE	Department of Energy
DR	Demand response
DSI	Demand-side integration
DSM	Demand-side management
EEG	Erneuerbare-Energien-Gesetz (engl.: Renewable Energy Sources Act)
EEX	European Energy Exchange
EMS	Energy management system
ETV	Heavy-duty electric transport vehicle operating in closed transport systems
EU	European Union
EV	Electric vehicle
FERC	Federal Energy Regulatory Commission
GHG	Greenhouse gas

GW	Gigawatt
HDV	Heavy-duty vehicle
HHLA	Hamburger Hafen und Logistik AG
ICEV	Internal combustion engine vehicle
ICT	Information and communication technology
IfD	Institut für Demoskopie
IPCC	Intergovernmental Panel on Climate Change
IS	Information system
KBA	Kraftfahrt-Bundesamt
KPI	Key performance indicator
kW	Kilowatt
kWh	Kilowatt-hour
LOGMS	International Conference on Logistics and Maritime Systems
MADM	Multi-attribute decision-making
MAPE	Mean absolute percentage error
MW	Megawatt
NIST	National Institute of Standards and Technology
NPC	Net present costs
NPE	Nationale Plattform Elektromobilität (engl.: National Platform for Electric Mobility)
OECD	Organisation for Economic Co-operation and Development
PHEV	Plug-in hybrid electric vehicle
PNC	Plug-and-charge
REN21	Renewable Energy Policy Network for the 21st Century
SC	Smart charging
SOC	State of charge
StromNEV	Stromnetzentgeltverordnung
TCO	Total cost of ownership
TEU	Twenty-foot equivalent unit
TOU	Time-of-use
TSO	Transmission system operator

TWh	Terawatt-hour
UCTE	Union for the Co-ordination of Transmission of Electricity
UNCTAD	United Nations Conference on Trade and Development
U.S.	United States
V2G	Vehicle-to-grid
VDN	Verband der Netzbetreiber
VHB	Verband der Hochschullehrer für Betriebswirtschaft
VRLA	Valve-regulated lead–acid

A. Foundations

The first part of this cumulative dissertation is divided into two chapters. Chapter A.I explains the general motivation of this work and presents the research questions, structure, research context and anticipated contributions of this thesis. Afterwards, Chapter A.II provides the reader with relevant background information.

I. Introduction

The first section in this chapter highlights the relevance of the research topic, followed by a description of the research questions and the structure of the thesis. Afterwards, Section A.I.4 explains the research context and design. Finally, Section A.I.5 concludes this chapter with a description of the anticipated contributions for research and practice.

I.1 Motivation

During recent years, there has been a fundamental paradigm shift in the energy sector in many industrialized countries around the world. In this regard, several governments – including those of Germany and the USA – are aiming to establish a future energy system that includes sustainable energy generation, reduced energy intensity of demand, and a more effective and sustainable use of energy (REN 21, 2015; Harmelink et al., 2006). The main drivers for this development are the irreversible depletion of fossil fuels, the threat of climate change, and the increasing environmental pollution caused by the use of fossil fuels (Elliot, 2011; IPCC, 2007). A further push comes from the recent prioritization of environmental sustainability as a societal goal (Melville et al., 2010).

In particular, Germany's government has defined ambitious energy- and climate-related targets to shape a sustainable energy system. One of the most important of these is increasing the share of renewable energies to at least 80% of the total energy production by 2050 (BMWi and BMU, 2010). To date, wind and solar power are among the most widely installed and supported types of renewable energy, with a share of more than 55% of the total renewable electricity generation in Germany in 2014 (BMWi, 2014a). However, due to fluctuations in their energy supply and limited predictability, the integration of intermittent renewable energy resources into the energy grid poses enormous challenges (Ketterer, 2014). These challenges are expected to become even more formidable for grid operators as the discrepancy between power supply and demand widens (Pecas Lopez et al., 2007).

One possibility for realigning electricity supply and demand is provided by the concept of demand response (DR), which refers to the consumer's ability to alter his or her energy consumption pattern in response to external signals, such as time-dependent electricity prices or incentive payments (U.S. DOE, 2006). In broader terms, demand-side integration (DSI) also includes programs for increasing energy efficiency as well as power control procedures with the goal of optimizing demand independently of external signals (International Energy Agency, 2003). DSI programs are associated with several energetic benefits: in addition to supporting the increased deployment of renewable energy by smoothing out power fluctuations, system reliability can be improved by reducing electricity demand at critical load times (Bradley et al., 2013; FERC, 2008).

Electric vehicles (EVs) are a valuable resource for DR and DSI programs because they remain idle (in parking mode) for the greater part of the day (Kempton and Tomić, 2005a); the corresponding charging processes can then be shifted to periods in which overall electricity demand is low and the grid is unstressed or power generation from renewables is high, referred to as smart charging (Valentine et al., 2011). Furthermore, EVs' batteries can provide utility services by supplying power to the grid for stabilization and peak-time supply, known as the vehicle-to-grid (V2G) concept (Mullan et al., 2011). Hence, applying suitable DSI programs for EVs can contribute to ensuring the security of energy supply and promoting the development of renewables (Lund and Kempton, 2008).

At the same time, DSI programs seem compelling from the point of view of EV users due to their financial benefits; the application of DSI programs can make a valuable contribution to ensuring that EVs become economically competitive with conventional internal combustion engine vehicles (ICEVs) by significantly decreasing energy procurement costs or creating revenues by providing utility services (Kempton and Tomić, 2005b). Hence, applying DSI programs could also promote the market penetration of eco-friendly vehicles and would support the German government's objective of achieving a sustainable transport system, as about a quarter of greenhouse gas emissions in the European Union in 2011 was produced by road transport (European Environment Agency, 2012).

Most research (e.g., Mullan et al., 2011; Wang et al., 2011a; Andersson et al., 2010) has focused on (privately) used EVs for the application of DSI programs. Despite the promising potentials for the energy industry, EV users, and policymakers, there are several complications obstructing the realization of DSI programs in this application context – most notably the substantial investment required for constructing infrastructure, user acceptance problems, lack of incentives, and extensive regulatory requirements on energy markets (Geelen et al., 2013; Sovacool and Hirsh, 2009; Strbac, 2008).

A promising, emerging field of application for DSI programs in the domain of electric mobility can be found in commercial heavy-duty EV fleets operating in closed transport systems, such as aircraft tractors, forklift trucks, or container transport vehicles. Battery-powered heavy-duty vehicles represent an innovative transport technology and appear to have decisive economic, technical, and ecological advantages in closed transport systems. Furthermore, focusing on this application area is an important first step toward the implementation of DSI programs for EVs due to the following reasons:

1) Many larger commercial fleet operators have already implemented the smart grid and ICT technologies necessary for applying DSI programs;
2) Economies of scale result from the aggregation of numerous vehicle batteries, each with considerable storage capacity compared to privately used EVs;
3) EVs can be pooled on company grounds to exploit energetic and economic synergies;
4) The operation times of EVs can be adapted to optimally charge the batteries in a smart grid system; and
5) The energy consumption of EVs can be forecasted more precisely based on order confirmations, delivery dates, or arrival times.

Finally, the flexible load of EVs can be used for company-internal purposes, such as optimizing the company's load curve. Hence, companies adapting DSI programs for their EV fleets can utilize the flexible load for a broad range of DSI programs and are not limited to the established DSI programs for EVs, such as the V2G concept or smart charging. Due to the promising potentials of applying DSI programs in this field of application, this thesis focuses on quantifying the financial impacts of applying DSI programs for one special subtype of EVs: Commercial heavy-duty electric transport vehicles operating in closed transport systems, referred to in the following as an ETV fleet. To this end, data from a large-scale electric mobility project conducted in a container terminal that uses automated ETVs to transport containers on company grounds is analyzed to assess the feasibility and economic potential of several DSI programs.

This work contributes to the field of smart grid research (Sioshansi, 2011) by adding new insights regarding the value of DSI programs that reduce energy procurement costs for fleet operators and ensure the security of energy supply. In doing so, this thesis provides useful information for fleet operators about the economic value of applying DSI programs. This is important because DSI for EVs has experienced only moderate expansion in Germany, due in part to a limited understanding of the benefits of such DSI solutions as well as an uncertainty regarding the extent of DSI's economic value (Goebel et al., 2014; Aghaei and Alizadeh, 2013; Bradley, 2013; Strüker and van Dinther, 2012; Strbac, 2008). Furthermore, technical, operational, and in particular regulatory requirements for implementing DSI programs are given particular consideration in this dissertation. Based on these analyses, it also becomes possible to provide commercial fleet operators with guidelines regarding how to best participate in DSI programs. Simultaneously, valuable information can be given to policymakers regarding how to design a future energy market that also allows smaller flexible consumers to participate. This is essential because the question of how to integrate distributed energy resources such as flexible loads into existing energy markets remains unanswered (Goebel et al., 2014).

Overall, the results of this work have the potential to convince flexible consumers, such as E(T)V fleet operators, to adopt DSI solutions, which is crucial for an economically efficient and technically secure operation of a power system with a high share of intermittent generation sources.

I.2 Research Gaps and Research Questions

Applying DSI programs for EVs is important for improving system reliability and assisting in integrating renewables into the energy system. Furthermore, E(T)V users can expect financial benefits from applying DSI programs. Despite its potential, DSI for EVs has experienced only moderate expansion in most countries (see Section A.I.1). Adapting these thoughts, this thesis has two overarching goals. First, it aims to determine the extent of DSI's economic value for different actors from the demand and supply sides of an energy system, including EV fleet operators, ETV fleet operators, and energy suppliers. At the center of this work are fleet operators using heavy-duty electric transport vehicles, as this application context seems particularly suitable for DSI under current conditions. Second, this thesis investigates how to integrate flexible loads, such as ETV fleets, into existing energy markets, considering in particular the energy market design and regulatory requirements for applying DSI programs.

Based on this analysis, suggestions can be derived for policymakers on how to redesign the energy market in order to utilize flexibility options on the demand side to a greater extent.

To achieve both goals, four related main research questions should be answered in this thesis. As seen in Figure A:1 and elaborated in detail in the next section, RQ 1 provides an energy supply-side perspective on DSI programs, while RQs 2 and 3 provide a demand-side perspective on DSI programs with a focus on heavy-duty fleet operators. Finally, RQ 4 provides a governance (policymakers) perspective on DSI programs.

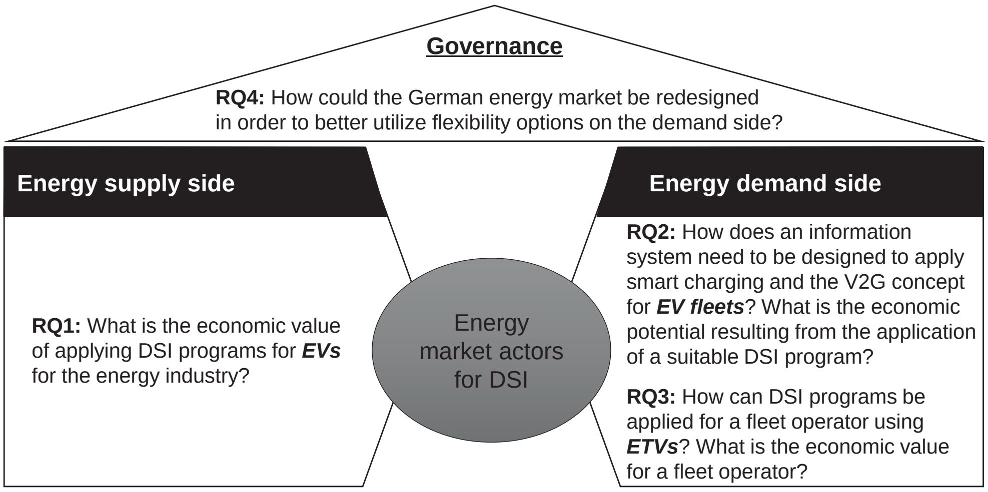

Figure A:1. Overview of all RQs included in this thesis.

From the point of view of the **supply side,** the energy industry can expect financial benefits from applying DSI programs for EVs in general. In this regard, it is assumed that charging a large number of EVs in an uncontrolled manner would create a significant load that could jeopardize the security of energy supply, in turn forcing power producers to increase power plant capacities. However, necessary power plant capacity adjustments could be reduced or even prevented by the implementation of DSI programs for EVs. To date, there is no study assessing the cost-saving potentials resulting from the application of DSI programs for EVs for the energy industry. This leads to the first research question:

1) ***What is the economic value of applying DSI programs for EVs for the energy industry?***

Aside from the supply side, this cumulative dissertation focuses on quantifying the economic potential of applying DSI programs for the **demand side**, represented by EV and in particular ETV users. In general, fleet vehicles within an existing business relationship (e.g., parcel delivery fleets) seem to be good candidates for initial DSI applications, mainly because they offer the possibility of exploit economic and energetic efficiencies through the aggregation of a large number of E(T)Vs (Williams and Kurani, 2007). There are some studies (De Los Rios et al., 2012; Han et al., 2010; Tomić and Kempton, 2007) estimating the financial profits of applying two classical DSI programs for EV fleets: smart charging and the V2G concept. To control a charging process (e.g., interruption during price peaks), however, the fleet operator must consider electricity prices beforehand and be able to predict electricity demand, allowing him to determine the margin for load shifting per charging process in advance (Geelen et al., 2013). Surprisingly, this fact has not been given much attention so far. Furthermore, hardly any study investigating the potential of DSI programs for EV fleets use real-world data and thus the results lack external validity. Therefore, the following research question is addressed:

2) ***How does an information system need to be designed to apply smart charging and the V2G concept for EV fleets? What is the economic potential resulting from the application of a suitable DSI program?***

An application context for applying DSI programs for EV fleets that has not yet been investigated but seems to hold great potential is heavy-duty electric transport vehicles operating in closed transport systems (intralogistics sector). Unlike EV fleets that are used to deliver goods outside the premises, these ETV fleets are employed exclusively within the walls of a fulfillment or distribution center. They are operated in diverse areas of application, such as in warehouses (forklifts), at airports (aircraft tractors), and at ports (container terminal vehicles). A particularly favorable characteristic for applying DSI programs in this area of application is the possibility of pooling the ETVs – each with a considerable battery storage capacity – on company grounds (see Section A.II.2.2). To ensure the practical relevance of the thesis' results, the analyses are based on a large-scale electric mobility project conducted in the largest container terminal in Germany. These issues are transformed into the following research question, which represents the focus of this thesis:

3) ***How can DSI programs be applied for a fleet operator using ETVs? What is the economic value for a fleet operator?***

From this central research question, four partial research questions are derived, answered in four corresponding articles (see Section A.I.3). The central research question is answered in Section B.II.5 by consolidating the findings from all subordinated research questions.

As mentioned above, the two most studied DSI programs for EVs are smart charging and the V2G concept. While the economic potential of these DSI programs has already been estimated for EV fleets used to deliver goods outside the premises, transferring these DSI program to the environment of closed transport systems and quantifying the economic benefits for fleet operators still appear underresearched and thus present a research gap. Hence, the following questions emerge:

3a) How can smart charging and the V2G concept be adjusted and transferred to the environment of closed transport systems? What is the economic value for a fleet operator?

To be able to realize DSI actions in practice, one must accurately forecast the ETVs' electricity demand and charging flexibility (duration an ETV is available for charging) for a certain period. Otherwise, an ETV might be unavailable due to an insufficient battery status, which could lead to enormous costs for a commercial fleet operator. This leads to the following research question:

3b) How can electricity demand and the resulting load-shifting potential from ETVs operating in closed transport systems be forecast in order to apply DSI programs?

A particular benefit that arises from the application of DSI programs to ETV fleets operating in closed transport systems is the ability to use the resulting charging flexibility for a broad range of DSI programs. For example, the flexible load can also be used for company-internal purposes, such as optimizing the load curve of the transport company. Therefore, the following research question is investigated:

> *3c) Which kinds of DSI programs are applicable for ETV fleets in general? What is the economic potential resulting from technically feasible DSI programs for a fleet operator?*

At this stage, one can determine the most promising DSI program for making use of the charging flexibility and quantify the economic benefits for a fleet operator. However, it is also useful to evaluate the influence of the resulting cost-saving potentials on the total cost of ownership (TCO) of an ETV fleet. Moreover, some studies (e.g., Propfe et al., 2012; Thiel et al., 2010) have revealed that the economic viability of EVs is currently constrained, mainly because their acquisition costs are significantly higher than those of ICEVs. However, little is known about the economic potential of ETVs operating in container terminals. The corresponding research question can hence be formulated as follows:

> *3d) What is the TCO of an ETV fleet? How can DSI programs reduce the TCO for the closed transport system?*

Based on this analysis, it becomes possible to measure the financial impact of applying DSI programs for ETV fleets and to evaluate the profitability of using ETVs in closed transport systems in general.

Answering the research questions above allows for both the provision of guidelines for adjusting and transferring DSI programs to the environment of closed transport systems as well as an assessment of the economic potential of applying DSI programs to this application context. On the basis of the information gained within the frame of the overall research project, it is also possible to derive important recommendations for **policymakers**. In this regard, the current energy market design in Germany seems ill-suited for smaller providers of flexible loads, such as ETV or EV fleet operators. The corresponding research question can hence be formulated as follows:

> ***4) How could the German energy market be redesigned in order to better utilize flexibility options on the demand side?***

I.3 Structure of the Thesis

This work is a cumulative dissertation and contains three parts (see Figure A:2). The middle portion (Part B) covers all studies. As seen in the figure, each research question (marked with a star) presented in Section A.I.2 is answered in a particular section.

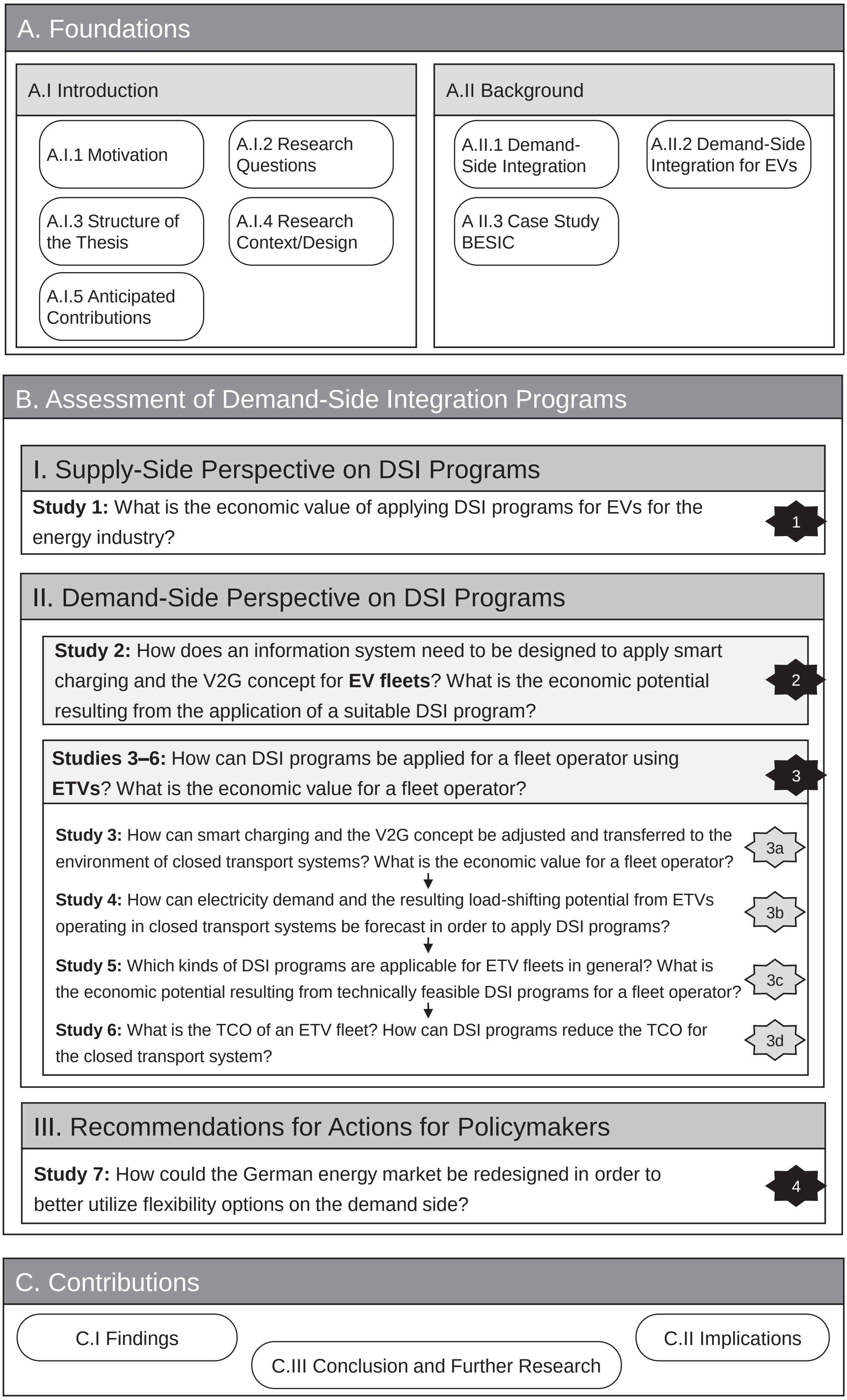

Figure A:2. Structure of the thesis (each star indicates a research question).

Part A covers the motivational introduction for this research endeavor and then details the research gaps and resulting research questions. In addition, the research context and design, thesis structure, and anticipated contributions are presented. The next subsection lays the foundation for a comprehensive understanding of DSI programs in general as well as those concerning the particular case of EVs. It also briefly addresses previous work from the context of applying DSI programs for E(T)Vs and ends with an introduction of the case study used to assess the potential of applying DSI programs for ETVs.

The following **Part B** represents the main body of this cumulative dissertation, comprising seven studies. All of the studies (see Table A-1) address the general topic of DSI programs for electric (transport) vehicles. Two of these essays have been published in leading energy journals and one has been submitted to a renowned transportation journal (Status August 2015: under review). Furthermore, two studies have been published in a leading international IS conference proceeding, and one has been published in an international energy conference proceeding. Finally, one piece has been presented at an international logistics conference.

Table A-1. Overview of studies included in the thesis.

No	Outlet	Status	Ranking (VHB)	Section	RQ	Main contribution
1	Americas Conference on Information Systems 2013	Published	D	B.I	1	Recommendations are given for the energy industry regarding whether investments in DSI programs for EVs are a suitable alternative to an expansion of power plant capacities.
2	Americas Conference on Information Systems 2015	Forth-coming	D	B.II.1	2	An IS design is developed, enabling fleet operators to apply established DSI programs for an EV fleet that operates outside the premises.
3	Energy Policy 2014	Published	B	B.II.2	3a	Suggestions are offered for applying certain DSI programs for ETV fleets, and the cost-saving potentials of applying DSI programs for ETV fleets are revealed.
4	International Conference on Logistics and Maritime Systems 2014	Presented	n.a.	B.II.3	3b	A simulation model for forecasting the logistic processes and the related electricity demand of the ETVs is developed.
5	International Journal of Energy Sector Management 2015	Forth-coming	B	B.II.4	3c	The most promising DSI programs for utilizing the charging flexibility of the ETVs under realistic conditions are identified and assessed, considering technical, regulatory, and economic aspects.
6	Research in Transportation Business & Management	Submitted (under review)	n.a.	B.II.5	3d	The commercial viability of ETVs is assessed, and two strategies that can be used to increase the profitability of an ETV fleet are developed.
7	Erasmus Energy Forum 2015	Published	n.a.	B.III	4	Several recommendations for policymakers are given for enabling smaller providers of flexible loads to participate in DSI.

Part B is divided into three chapters that represent different perspectives on DSI programs for EVs, with a particular focus on ETVs. The first **Chapter I** offers an energy supply-side perspective on DSI programs for all kind of EVs and thus provides an answer to RQ 1, regarding whether and to what extent energy suppliers can benefit economically from applying DSI programs for EVs. To answer this research question, a simulation study is conducted to determine whether the necessary power plant capacity adjustments can be reduced or even eliminated through the implementation of DSI programs for EVs.

In contrast, **Chapter II** provides a demand-side perspective on DSI programs with a predominately economic focus, representing the core of this thesis. The insights gleaned from this part contribute to answering RQs 2 and 3, which inquire how DSI programs should be applied for a fleet operator using E(T)Vs and how fleet operators can benefit economically from the application of DSI programs. This first study of this chapter focuses on applying two established DSI programs (smart charging and the V2G concept) for "normal" EV fleets that operate outside the premises and thus provides answers to RQ 2. Furthermore, it develops an IS artifact that can be used by fleet operators to apply DSI programs for their EV fleets under realistic conditions. For the economics of this DSI program, real-world data from a car-sharing operator are evaluated.

Four related studies (Studies 3–6) focus on fleet operators using ETVs to answer RQ 3: "How can DSI programs be applied for a fleet operator using ETVs, and what is the economic value for a fleet operator"? The German electric mobility project BESIC (see Section A.II.3) serves as a business case in this chapter, both to ensure the feasibility of the DSI programs presented here as well as to evaluate economic implications. The connections among these studies – which represent the main part of this thesis – are illustrated in Figure A:3.

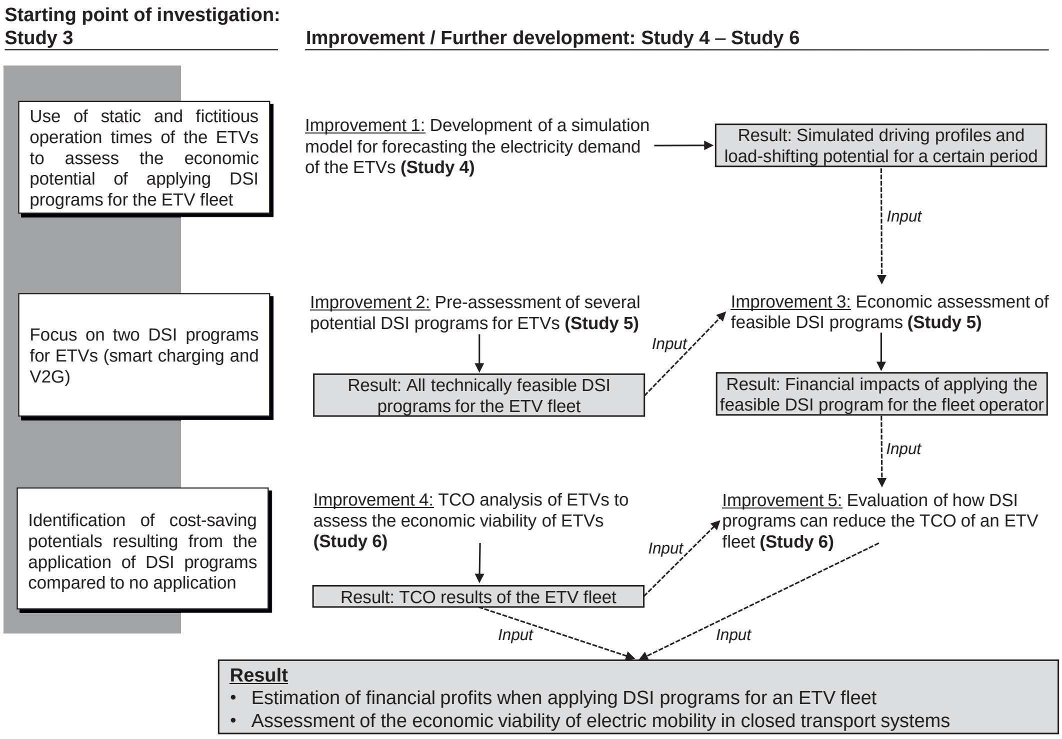

Figure A:3. Connections among the studies to answer RQ3.

The first study in this chapter, which focuses on ETV fleets (Study 3), represents the starting point of the investigation. In this study, the cost-saving potentials of applying two DSI programs are assessed using static and fictitious operation times of an ETV fleet. This work is extended and improved in the following studies, each of which builds upon the results of the previous studies. First, a fleet operator needs information about the ETV batteries' power consumption and the time frame in which a battery is available for charging to apply DSI programs in practice. Therefore, a simulation model for forecasting the related electricity demand of the ETVs for a certain period is developed in Study 4. Furthermore, the charging flexibility of the ETV fleet can be used for a broad range of DSI programs – e.g., to optimize the load curve of the transport company – and is not limited to the two typical DSI programs for EVs investigated in Study 3. Hence, the fifth study explicitly concentrates on assessing the feasibility of several further potential DSI programs considering the technical, regulatory, and operational requirements of the fleet operator. Moreover, dynamic driving profiles on the basis of the simulation model (Study 4) are used as input data to conduct an economic assessment of feasible DSI programs. Based on this analysis, it is possible to determine the most promising DSI program for making use of the charging flexibility of the ETV fleet and to quantify the benefits for a fleet operator in economic terms. Finally, the sixth study investigates how the application of DSI programs can reduce the TCO for the ETV fleet using input data from Study 5. It also assesses whether eco-friendly (heavy-duty) transport vehicles are a viable alternative to conventional diesel-powered transport vehicles in closed transport systems on the basis of a TCO analysis. Based on these four studies, it is possible to estimate the financial profits from applying DSI programs for an ETV fleet and to evaluate the economic viability of electric mobility in closed transport systems.

The last **Chapter III** of Part B focuses on providing policy recommendations; insights from this section contribute to answering Research Question 4, i.e., how to redesign the energy market in order to encourage smaller providers of flexible loads, such as EV or ETV fleet operators, to participate in DSI programs.

Although Chapters I, II, and III of this thesis each provide a different perspective on DSI programs for E(T)Vs (see Figure A:4), all parts contribute to answering the two overarching objectives of this thesis (see Sections A.I.1 and A.I.2). A detailed discussion of each study's contribution to achieving the overarching goals of this thesis in given in Section C.I.4.

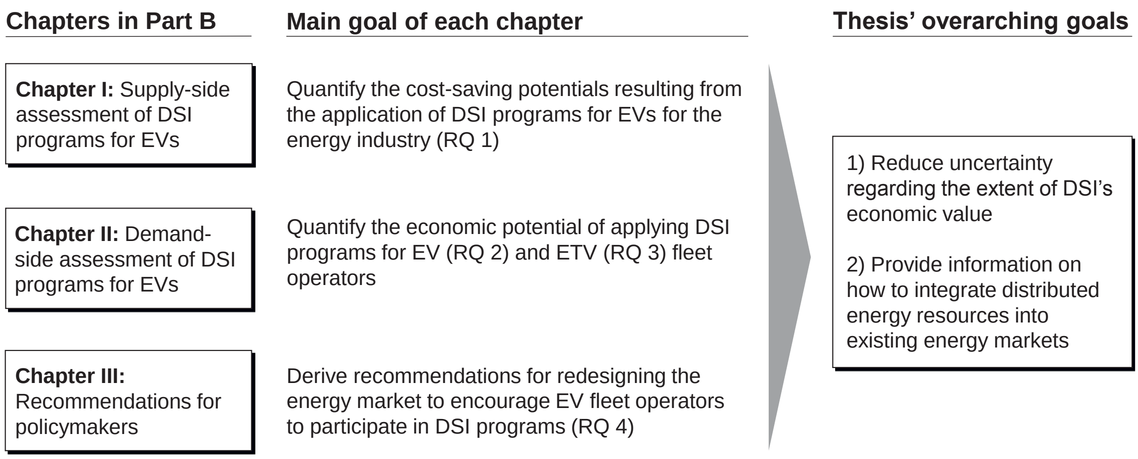

Figure A:4. Main goal of each chapter of this thesis' main Part B.

Finally, in **Part C**, the findings of this research endeavor are discussed. Afterwards, implications for researchers and practitioners are given, leading to the overall conclusions and limitations of this study. The thesis closes with suggestions for further research.

I.4 Research Context and Design

This thesis deals with energy economics-related research. A broad definition of energy economics is given by Sickles (2008), who defines this research stream as “a wide scientific topic zone that contains subjects associated to energy supply and energy demand in societies.” Energy economics is not a self-contained educational subject, as it is intertwined with several subdisciplines of economic science, such as econometrics, environmental economics, finance, macroeconomics, and resource economics. According to Bhattacharyya (2011), this interdisciplinary research field can be defined as a “branch of applied economics where tools are applied to ask the right questions and to analyze them logically and systematically to develop a well-informed understanding of the issues.” In principle, energy economics is not different from any other branch of economics; it is concerned with the basic economic issue of allocating scarce resources (in the given context, energy) in the economy (Stevens, 2000). However, the energy sector/system is complex mainly because the constituent industries tend to be highly technical in nature and each industry of the sector has its own specific feature (Bhattacharyya, 2011). Demand for energy economics research in Germany arises because the provision of an environmentally sound, reliable, and affordable energy supply is seen as one of the major challenges of the twenty-first century (BMWi, 2011). Hence, the practical relevance of this research stream is high, garnering significant attention from policymakers or practitioners.

In this thesis, the focus lies on the microeconomic field of energy economic, which is concerned with energy supply and demand (Pindyck, 1979). More precisely, this thesis concentrates on one of the main topics of energy economics: energy demand-side management (DSM). Demand-side management of energy can be defined as the “systematic utility and government activities designed to change the amount and/or timing of customer’s use for the overall benefit of the society” (CRA, 2005). Even before the liberalization of the electricity market, grid operators supported peak load avoidance and the shifting of demand into time ranges with lower prices through peak load–based tariffs and distinct day and night tariffs. DSM has evolved considerably over the last three decades due to a rapid expansion of renewable energies and steadily rising energy consumption in many countries (see Section A.II.1).

Energy economics is a complex and interdisciplinary research field; the influence of operations research, engineering sciences, business administration, and information systems research has been profound (Erdmann and Zweifel, 2010). Therefore, various methodological approaches are applied in this thesis to answer the introduced research questions (see Table A-2).

Table A-2. Overview of research design and core research questions.

No	RQ	Research design	Data collection	Method of data analysis
1	1	Techno-economic analysis	Secondary data	Simulation and economic analysis
2	2	Techno-economic analysis	Primary and secondary data	Prediction model and optimization
3	3a	Techno-economic analysis	Primary and secondary data	Optimization and economic analysis
4	3b	Mathematical model	Primary data	Simulation
5	3c	Techno-economic analysis	Primary and secondary data	Optimization and economic analysis
6	3d	Techno-economic analysis	Primary and secondary data	Optimization and economic analysis
7	4	Case study	Primary and secondary data	Interviews, field observations and analysis of documents

Regarding the applied research design, techno-economic analyses are performed in several studies; such methods are often applied in energy demand analysis, either alone or in conjunction with econometric methods. Unlike a "pure" econometric approach, techno-economic analyses can incorporate engineering and technical characteristics of energy consumption into their modeling (Bhattacharyya, 2011). Techno-economic analyses are suitable for this thesis as the focus lies on assessing several technologies, e.g., demand-side integration techniques. Furthermore, a broad range of technical characteristics (e.g., energy per vehicle, charging efficiency, or motor efficiency) is considered in this thesis.

Most studies in this thesis combine primary and secondary data sources. This is necessary because some data had to be collected specifically for this investigation (e.g., trip information and energy flows to and from the batteries [e.g., Section B.II.1]), while other data (e.g., energy prices) was already available to be used for this research endeavor. A variety of quantitative methods, such as optimization models, prediction models, and simulation studies are used to analyze the collected data. Finally, one qualitative method (case study) is applied in this thesis.

I.5 Anticipated Contributions

Although this thesis is scientific in nature, it addresses both research and practice. To ensure the practical relevance of the results, most analyses are based on a comprehensive electric mobility project conducted in a container terminal (see Section A.II.3.3). First of all, the thesis is directed to several groups in practice.

- **Transport sector**: Several suggestions – validated both practically and scientifically – should be offered to fleet operators, enabling them to apply DSI programs for their electric (transport) vehicle fleet. The methods developed in this study should also help fleet operators assess the economic potential of applying these programs to their fleets. Furthermore, valuable information should be provided regarding the economic viability of a novel transport technology in closed transport systems: heavy-duty battery electric transport vehicles in combination with a battery-swapping station.
- **Energy industry**: General information should be provided on how to integrate distributed energy resources, such as flexible loads, into existing energy markets. Furthermore, there is detailed information in this thesis about the value of applying DSI programs to ensure the security of energy supply.

- **Policymakers**: Information about the deficits of the current energy market design are revealed and suggestions can be made how to redesign the energy market in order to utilize flexibility options on the demand side to a greater extent. The need for such investigation has recently been highlighted by the publication of a Green Book "A Power Market for the Energy Reform," which is meant to promote the public debate about a new power market design (BMWi, 2014b). Finally, several policy recommendations can be given on the basis of the thesis' investigation to promote the market penetration of ETVs.

Another key contribution of this thesis is anticipated to be providing **energy researchers** with a sound knowledge base and consolidating the scarce research efforts in the application domain of demand side management (see Section A.I.2). This study is the first to investigate a broad range of DSI programs for ETVs operating in closed transport systems. Furthermore, new techno-economic and econometric approaches investigating the economic profitability of applying DSI programs for E(T)Vs are developed in this thesis. This is significant because most prior analyses do not consider the energy market design and are thus based on unrealistic assumptions. A detailed description of this thesis' contribution to theory and practice is given in Section C.II.

II. Background

As described in the previous chapter, this work focuses on DSI programs that can be applied for electric (transport) vehicles. Therefore, this chapter presents the fundamentals and related literature of DSI in general and DSI programs for EVs and ETVs.

II.1 Fundamentals of Demand-Side Integration

The energy system consists of both supply-side activities (generation, bulk transmission, and distribution) and demand-side activities. For many years, the focus on the energy system lay on the supply side; the objective was to arrange for an adequate energy supply so that energy demand – which was considered as given and uncontrollable – could be satisfied (Sioshansi and Vojdani, 2001).

Today, however, the energy system is developing from a centralized, constant, and fossil-based energy-generation base to a more decentralized, environmentally friendly, and intelligent electricity system, known as smart grid (Geelen et al., 2013). Many countries have been stimulating this transition of the electric power system, mainly through the promotion of renewable energies. For example, the European Union has issued a target for renewables to make up 20% of the total electricity generation by the year 2020 (European Union, 2009). For the energy industry, this trend indicates a fundamental paradigm shift; whereas in the past supply attempted to meet demand, electricity demand must now increasingly adjust to the intermittent supply from renewable energies (Pecas Lopes, 2007). Furthermore, technical innovation in the field of information and communication technology (ICT) – such as advanced metering infrastructure (AMI) or smart meters with a communication gateway – enables energy customers to play a more active role in the future energy market by adapting energy consumption according to the information received (e.g., energy prices) or incentives (Kranz, 2011; Daim and Iskin, 2010). It is thus becoming evermore apparent that the focus on the energy system will lie on demand-side activities in the future.

One possibility for balancing power supply and demand while simultaneously increasing energy efficiency and allowing customers to play a more active role in the energy system is provided by the concept of demand response. According to the U.S. DOE (2006) and the FERC (2009), DR can be defined as “changes in electric usage by end-use customers from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized.”

DR is part of the more general concept of demand-side integration, which also includes energy efficiency programs and load management programs (e.g., peak clipping) with the goal of optimizing energy demand without reacting to external price signals or incentive payments (Bradley et al., 2013; dena, 2013; York and Kushler, 2005). For example, energy customers can optimize their internal load curves to reduce the grid fees that depend on peak loads. Alternatively, energy customers can optimize their own distributed generation system that uses renewable energy by shifting energy demand in periods when power generation from renewables is high. The overall goals of DSI are hence to alter the timing, level of instantaneous demand, or total electricity consumption to ensure that demand meets available generation and the grid’s power-delivery capabilities at any time (Ipakchi and Albuyeh, 2009).

In principle, energy end-users have three possibilities for adjusting their electricity usage (Mohagheghi et al., 2010; Gellings and Parmenter, 2008; Albadi and El-Saadany, 2007):

1) Reduce demand for energy during on-peak hours through load curtailment strategies (peak clipping);
2) Move energy consumption from on-peak to off-peak periods, often on the basis of pricing information (load shifting); and
3) Use onsite standby generation or energy storage systems, thus limiting customers’ dependence on the main grid.

The basic principle of the two commonly used DSI options, i.e., peak clipping and load shifting, are illustrated in Figure A:5.

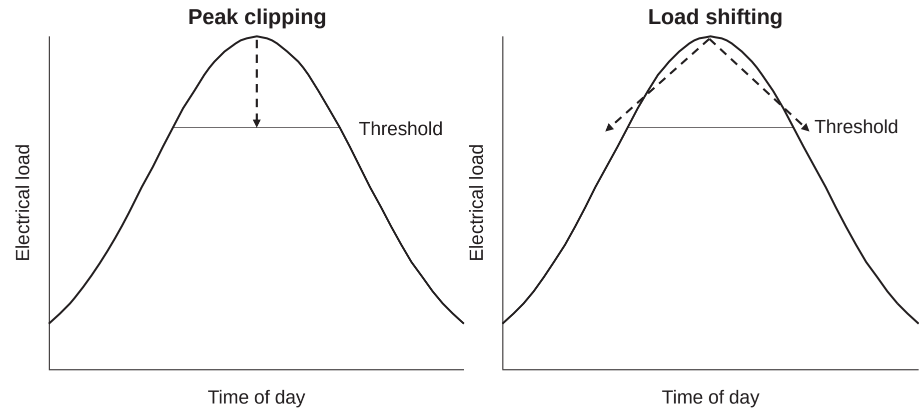

Figure A:5. Two demand-side integration options: peak clipping and load shifting (adapted from Bhattacharyya, 2011).

II.1.1 Demand-Side Integration Programs

Customers can participate in DSI through the application of a variety of programs that can be divided into three different groups of influencing behavior on the consumer side. Figure A:6 provides an overview of the various programs and respective techniques.

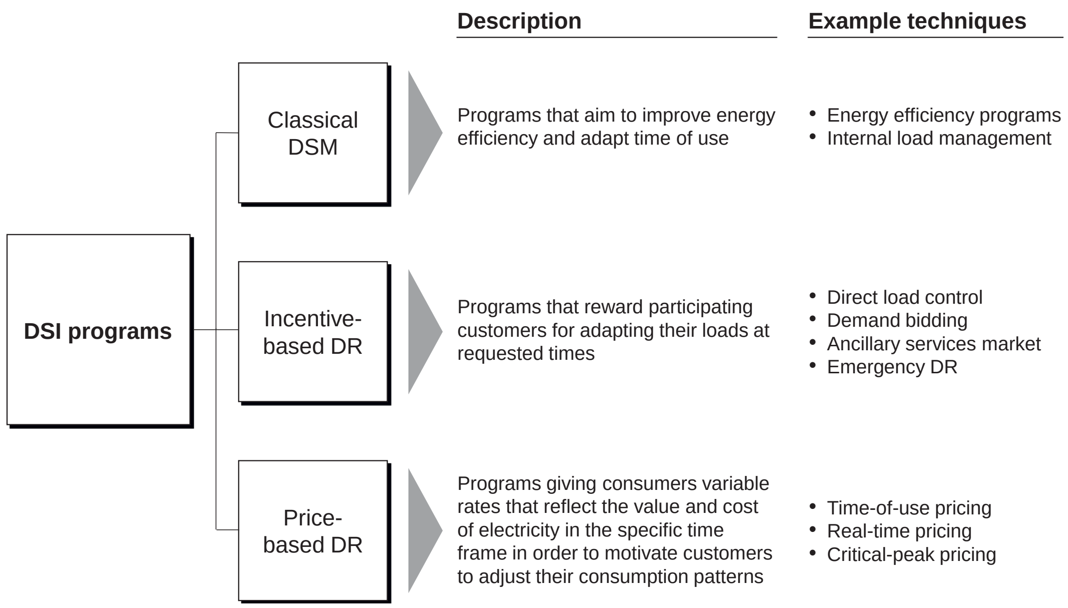

Figure A:6. Classification of DSI programs (adapted from Palensky and Dietrich, 2011; Albadi and El-Saadany, 2007; U.S. DOE, 2006).

Classical DSM programs are generally applied to optimize the in-house load management and energy efficiency of a company or household. In contrast, customers applying incentive-based or price-based DSI programs can participate directly or indirectly in the energy market. On the one hand, end-users with a modest energy demand usually participate indirectly in organized energy markets (e.g., wholesale electricity markets), as they are aggregated by intermediaries or utilities (Chui et al., 2009). For example, an intermediary can aggregate a larger number of energy end-users to act on the capacity market by providing load reductions as substitutes for system capacity (Siano, 2014). Furthermore, a utility can offer real-time pricing rates for its customers that vary continually in response to wholesale market prices (Albadi and El-

Saadany, 2007). On the other hand, large commercial and industrial customers can participate directly in either wholesale or retail electricity markets. Real-time pricing can be realized by these customers by procuring the required energy on electricity spot markets, where hourly (volatile) prices are determined by day-ahead auctions (Zachmann, 2013). Alternatively, larger customers can provide control reserve power in ancillary service markets and receive incentive payments from a grid operator for agreeing to reduce loads on request. A detailed description of possible markets and techniques for DSI is given in Sections B.II.2 and B.II.4.

II.1.2 Benefits of Demand-Side Integration

Several benefits associated with DSI can be identified for energy customers, the energy industry, and the energy system as a whole. First, customers undertaking DSI actions are rewarded financially. Incentive-based DSI programs reward consumers for reducing or increasing loads in specific periods, while consumers participating in price-based programs can reduce their electricity bills by shifting electricity consumption to off-peak periods (U.S. DOE, 2006).

Second, there are also several potential benefits of DSI for the energy industry (energy supply side), particularly for transmission and distribution operators (grid operators), energy producers, and retailers. In most cases, one of these actors offers DSI programs. Transmission and distribution operators benefit from reduced transmission network investments by reducing network congestion (Strbac, 2008). Furthermore, DSI programs usually use mechanisms encouraging customers to reduce demand in order to limit peak load or shift energy consumption to periods in which electricity demand is low, thus contributing to the improvement of distribution network and operation efficiency and increasing grid reliability (Siano, 2014). The most important benefit of DSI for energy producers and grid operators in the near future is likely its ability to facilitate the balancing of energy supply and demand, which is particularly important with intermittent generation (Ipakchi and Albuyeh, 2009). In this regard, it is becoming increasingly important that demand accommodate the shape of the fluctuating supply, as reliable operation of the electricity system necessitates a perfect balance between supply and load in real time (Strbac, 2008). For retailers, DSI seems compelling because it reduces price volatilities on the energy wholesale market by smoothing out power fluctuations (FERC, 2008).

Finally, there are several market-wide DSI benefits. Savings in variable supply costs for all energy end-users can be achieved through a more efficient use of electricity. In this regard, shifting energy demand outside of peak hours reduces demand from expensive peak-load power plants and thus contributes to lower wholesale and retail electricity prices (FERC, 2008). Moreover, benefits in terms of displacing new or additional generation, transmission, or distribution infrastructure investments arise from using DSI to shift peak demand (Bradley et al., 2013). The avoided or deferred costs will likely be reflected in the electricity price for all energy consumers. On top of this, there are environmental benefits that arise from the reduction of emissions from generation plants during peak periods (U.S. DOE, 2006). A final benefit of DSI that affects all market participants is reliability. For example, system reliability can be improved through DSI by reducing electricity demand at critical load times (Strbac, 2008).

An overview of the most important benefits of DSI for the energy demand side, the energy supply side, and the energy market as a whole is given in Table A-3.

Table A-3. Benefits of demand-side integration.

Recipient	Benefit
Energy demand side	▪ Incentive payments ▪ Electricity bill savings
Energy supply side (energy industry)	▪ Distribution network and operation efficiency benefits ▪ Increased penetration of renewable energy sources ▪ Reduced energy generation during peak times ▪ Reduced price volatilities
Market wide	▪ Reduced prices for electricity ▪ Avoided/deferred infrastructure costs ▪ Environmental benefits ▪ Reliability benefits

II.1.3 Customers of Demand-Side Integration

Different types of customers of DSI can be classified according to energy consumption within their facilities (NIST, 2010; Chiu et al., 2009):

1) Large industrial and commercial customers (e.g., refrigerated warehouses or large office buildings);
2) Small commercial and industrial customers (e.g., manufacturing facilities or medium offices); and
3) Residential customers (e.g., households).

Various studies identify large industrial and commercial customers – in particular, energy-intensive industries (aluminum, chemistry, or cement) – as primary target groups for DSI programs (Paulus and Borggrefe, 2011; Roon and Gobmaier, 2010). This is mainly because of the immense quantities of energy required and the often already implemented smart grid and ICTs necessary for applying DSI programs. The suitability of DSI for small commercial and industrial customers must be considered on an individual basis because some seem more like residential customers while others share many characteristics with commercial and industrial customers (Siano, 2014).

Residential customers are characterized by a relatively small energy demand. Several studies (e.g., Prüggler, 2013; Vasirani and Ossowski, 2013; Gudi et al., 2012; Lujano-Rojas et al., 2012; Gottwalt et al., 2011) investigate the possibilities and economic potentials for household consumers when using DSI; the estimated saving potentials reach as high as 20% for households. However, residential customers grapple with several obstacles that exacerbate the widespread adoption of DSI programs. The main factors discouraging households from participating in DSI programs are the significant technological costs for DSI, a generally limited understanding of DSI solutions, an inappropriate market structure, and the considerable regulatory requirements in place (Geleen et al., 2013; Kim and Shcherbakova, 2011).

EVs represent important new types of loads that show great promise for DSI as they offer capabilities that can be used for shaping the distribution system load (Gu et al., 2013; Ipakchi and Albuyeh, 2009). As assessing the potential of demand-side integration for EVs embodies the center of this thesis, the fundamentals and related work of demand-side integration programs that can be applied for EVs are discussed in detail in the next section.

II.2 Demand-Side Integration for Electric Vehicles

Electric vehicles are considered as one of the most promising DSI resources for future smart grids because they remain idle for the greater part of the day, and it is thus possible to control – within a certain range – the point in time when a vehicle's battery is recharged (Kempton and Tomić, 2005a). This is illustrated in Figure A:7, which depicts the charging process of a typical EV on an illustrative day when using a plug-and-charge approach (batteries begin charging immediately after being connected to the grid). The representation assumes the EV's trip ends at 8 p.m. with a fully depleted battery (assumed capacity = 20 kWh) and that the EV is needed again in operation at 6 a.m., fully charged. Using a domestic power outlet, a full charging cycle takes approximately five hours. As the total available charging time (10h) is longer than the time necessary to fully charge the battery, it is possible to shift the charging process when required by grid operators or energy suppliers. Because of the resulting load-shifting potential (here: five hours), EVs are generally considered as flexible loads.

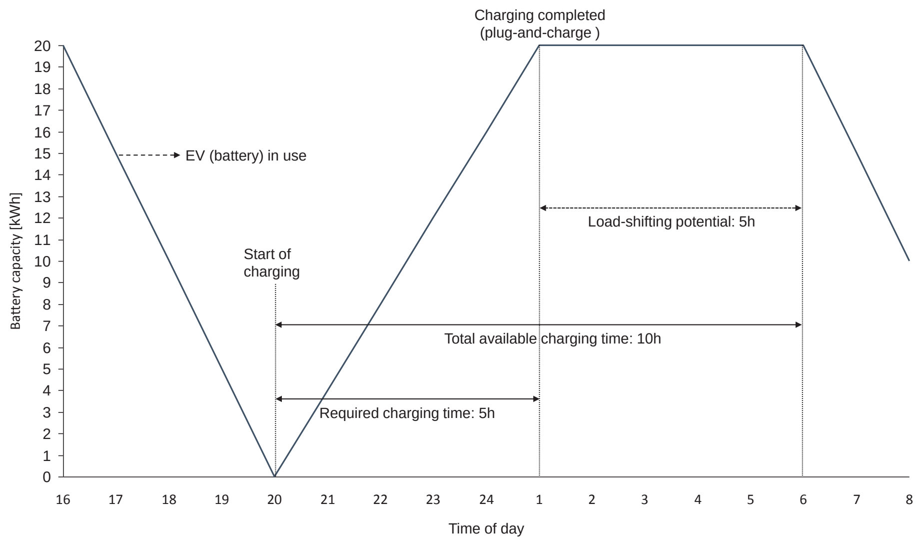

Figure A:7. Depiction of a charging process on an illustrative day.

Another reason why EVs seem predestined for participating in DSI programs is because they are already equipped with the charging controllers and on-board metering devices necessary for applying DSI (Kempton and Tomić, 2005b).

Although several DSI programs may be applicable for EVs, most research has focused on two kinds of DSI programs for EVs in the private sector: smart charging (a type of price-based DSI) and the vehicle-to-grid concept (a type of incentive-based DSI). Within the V2G concept, EVs are meant to provide utility services by supplying power to the grid for stabilization and peak-time supply (Letendre and Kempton, 2002). Most studies consider the provision of regulation services on ancillary markets to keep the frequency in energy grids stable to be the most profitable application for V2G (e.g., De Los Rios et al., 2012; White and Zhang, 2011; Guille and Gross, 2009; Sovacool and Hirsh, 2009; Brooks, 2002). When there is a surplus of energy in the grid, EVs can provide regulation down by charging their batteries and, vice versa, EVs can provide regulation up by supplying power to the grid when it is lacking (Mullan et al., 2011). Several studies have been performed on the use of EVs with V2G (e.g., Dallinger 2011; Andersson et al., 2010; Williams and Kurani, 2007; Kempton and Tomić, 2005a). Depending on the assumptions chosen and market considered, V2G can be profitable for an EV user. Further studies have found that V2G allows for integration of much higher levels of intermittent energy generation by proving assistance in frequency control problems caused by intermittent energy sources (e.g., Lopes et al., 2009; Lund and Kemtpon, 2007). A detailed description of the V2G concept and its implementation is provided in Sections B.II.2 and B.II.4.

The main goal of smart charging is to shift charging processes to times when electricity prices are low and the grid is not stressed or power generation from renewables is high. Some studies have shown the potential of smart charging to reduce load peaks, balance intermittent energy generation (particularly wind), and reduce power system costs (e.g., Valentine et al., 2011; Wang et al., 2011a). Other work has focused on the potential economic benefits of EVs participating in DSI (e.g., Goebel, 2013; Flath et al., 2012; Sioshansi, 2011; Rotering and Ilic, 2010). Considering the case of California, for example, Goebel (2013) and Rotering and Ilic (2010) find that optimal smart charging can help to reduce daily energy costs for EV users by up to 50%. Some analyses have been performed to assess the impact of EVs on distribution system performance, i.e., in terms of potential overloads or voltage deviations (e.g., Milano and Hersent, 2014; Masoum et al. 2011; Lopes et al., 2010). In general, it has been found that controlled charging (mainly based on pricing information) can help to integrate a higher number of EVs in the same distribution grid. Applying DSI programs for EVs is also becoming increasingly relevant because it is uncertain whether the existing generation capacity is able to meet the rapid development of EVs, as each vehicle represents a difficult to predict and sizeable load (Luo et al., 2011; Lopes et al., 2010). Through the application of DSI for EVs, possible investments in additional energy generation capacity can be reduced by shifting charging processes to off-peak hours, thus reducing system peaks.

As explained in Section A.II.1.3, however, there are various barriers to a broad implementation of DSI programs in the residential sector. There are also several further concerns and uncertainties that discourage individual EV users from participating in DSI programs. First, economic efficiency is a key challenge for DSI program designers because applying DSI for EVs requires substantial investments in infrastructure, which can hardly be compensated by the expected profits (Lyon et al., 2012). Therefore, the willingness of most EV users to invest in DSI technology has been low. Furthermore, the feasibility of most DSI programs is limited because regulatory and technical requirements on the majority of energy markets are too strict. With the V2G concept, an EV user can provide control reserve in order to guarantee a stable system frequency. However, an actor on the ancillary market in Germany must offer a minimum of 5 MW of power for at least 4 hours (Regelleistung, 2014a). Under current market conditions, it is therefore necessary to aggregate thousands of independent and dispersed EVs simultaneously to apply the V2G concept. In addition, the aggregation of dispersed EVs requires tremendous coordination on the part of the DSI provider. Even the application of simple price-based DSI programs (e.g., time-of-use pricing) is difficult because a single EV cannot enter the electricity wholesale market and there are almost no time-variable pricing tariffs on electricity markets for private users (Verbong et al., 2013). A detailed description of the regulatory and technical requirements for applying a certain DSI program is given in Section B.II.4.

Finally, EV users' acceptance of DSI programs represents a considerable obstacle that constrains the application of DSI for EVs. It is generally uncertain whether EV users are willing to accept possible changes in their energy consumption behavior (Sovacool and Hirsch, 2009). Even simple day–night electricity tariffs are viewed critically by many customers. It therefore seems likely that many EV users would not allow any external control over the charging process (Geleen et al., 2013). Closely related to this barrier are EV users' concerns about privacy issues. For most DSI programs, DSI providers need information about the time and duration that an EV is available for charging in order to forecast the load-shifting potential (charging flexibility). On the basis of this information, it is possible to schedule a charging process and react to external signals. However, many EV users are likely unwilling to provide information about their driving patterns to energy suppliers. DSI providers would therefore be forced to charge EVs immediately to ensure that the users' daily mobility needs are not restricted due to an insufficient battery status (Fridgen et al., 2014; Verbong et al., 2013).

II.2.1 Demand-Side Integration for Electric Vehicle Fleets

Due to the difficulties associated with applying DSI programs for individually (privately) used EVs, fleet vehicles within an existing business relationship (e.g., vehicles from a logistics service provider) seem to be good candidates for initial DSI applications. The basic idea is to aggregate the electric fleet vehicles to exploit economic, energetic, and operational efficiencies. A particular economic advantage behind such aggregation is represented by the possibility of spreading infrastructure costs, such as energy management systems and smart grid technologies, across a large number of EVs. Additional economic benefits accrue as a result of economies of scale; the fleet operator can act as a single entity on energy markets and can undertake transactions with considerably lower transaction costs than an individual EV owner (Guille and Gross, 2009). The energetic advantages are the aggregation of capacity and energy supply into sizeable loads, up to several megawatts (Williams and Kurani, 2007). Fleet operators owning a sufficient number of vehicles can even act by themselves on energy markets, as they exceed minimum bid sizes (Kempton and Tomić, 2005a). A sizeable aggregation of EVs can also provide considerable support to grid operators by providing load reductions or supplying power back to the grid when needed (e.g., for ancillary services). Operational advantages in the implementation include the possibility of predicting the EVs' energy consumption on the basis of order confirmations, delivery dates, or arrival times. In some cases, the fleet vehicles even operate at fixed times. Furthermore, the EVs' operation times can be adapted in some cases to optimally charge the batteries in a smart grid system. Finally, user acceptance problems are irrelevant in this (commercial) application context. There are several studies investigating the economic potential of applying DSI programs for EV fleets (e.g., De Los Rios et al., 2012; Han et al., 2010; Tomić and Kempton, 2007). However, all publications lack both coherent real-world data and a simulation/prediction model to forecast the load-shifting potential (charging flexibility) of the EV fleet required for the application of DSI program in practice.

At first glance, EV fleets seem to be particularly suitable for a broad implementation of DSI programs. However, there are several complications obstructing the actual realization of DSI programs for EV fleets under current conditions. First of all, the small size of a single battery makes it necessary for a fleet operator to aggregate thousands of EVs to act independently on energy markets. It is also extremely difficult for a fleet operator to precisely predict future trips and the resulting charging flexibility, particularly if there are no regularly scheduled events. Furthermore, external events (e.g., accidents, traffic jams, or weather events) may undermine the fleet operator's energy demand forecast. Finally, the limited range of an EV complicates the implementation of DSI programs. If the required average daily trip distance is too high for an EV, a fleet operator would probably not use one. Alternatively, the EV must be recharged outside the fleet operator's premises, thus making it nearly impossible to apply DSI programs.

II.2.2 Demand-Side Integration for Electric Transport Vehicles Operating in Closed Transport Systems

The application context of (heavy-duty) electric transport vehicles operating in closed logistic systems – which are used in diverse areas of application (see Section A.I.2) – appears to offer significant potential for applying DSI programs for EV fleets. In general, the electrification of vehicles operating in closed transport systems offers great potential as almost one million industrial trucks were ordered worldwide in 2012 (Statista, 2014a).

Several favorable characteristics for applying DSI programs in this area of application can be identified. When focusing on ETVs, the benefits of aggregated EV fleets explained above can generally be exploited. Further advantages include the possibility of pooling the vehicles and batteries on company grounds and the predefined operation range of the vehicles. Furthermore, electricity demands of the ETV fleet operating in closed transport systems can be forecast more precisely than for EV fleets that might also operate outside the premises. This is mainly due to the lesser degree external interference, such as traffic jams or accidents. In combination, these three aspects greatly facilitate coordination in the realization of DSI programs. Energetic and economic benefits result from the aggregation of numerous vehicle batteries, each with considerable storage capacity. Thus, the currently unrealistic assumption of thousands of aggregated EVs essential to act on energy markets under current conditions is avoided. Heavy-duty electric transport vehicles are generally equipped with significantly larger battery systems than normal EVs because they are used to transport heavy goods (e.g., containers) or equipment (e.g., airplanes).

Despite the promise of applying DSI programs for ETV fleets for both the energy industry as well as fleet operators, there still seems to be a research gap concerning the identification of feasible and suitable DSI programs and the quantification of their economic benefits.

II.3 Case Study BESIC (Battery Electric Heavy Goods Vehicles within Intelligent Container Terminal Operation)

This thesis primarily aims to identify and assess feasible and suitable DSI programs for a (heavy-duty) electric transport vehicle fleet that is employed exclusively within the walls of a fulfillment or distribution center. Based on this, it is possible to determine the extent of DSI's economic value for the ETV fleet operator. To this end, data from a comprehensive electric mobility project (called BESIC) with one of the largest container terminal operators in Europe are analyzed in four related studies (Sections B.II.2–B.II.5). In the first two parts of this section, the fundamentals and recent developments of container terminal operation are presented. Afterwards, the background and main goals of the research project are explained.

II.3.1 Fundamentals of Container Terminal Operation

According to Krieger (2005), container logistics can be defined as "the integrated planning, coordination, execution and control of all flows of standardized ISO 668 steel boxes (containers) and of the related information from the origin to the final destination." Besides the overseas transport of containers on deep-sea container vessels, container logistics also includes stripping (unloading), stuffing (loading), storing, and handling containers as well as hinterland transportation (Kemme, 2013). The primary function of the container terminal is the transshipment of containers from one mode of transportation to another, with the container terminal representing the interface between overseas and hinterland transport (Steenken et al., 2004). As the direct transshipment from one mode of transportation (e.g., ship) to another (e.g., train) is nearly impossible, the temporary storage function of containers is of particular importance for the performance of a container terminal (Saanen, 2004).

Although hundreds of different container terminal layouts, most of their subsystems have a similar arrangement. According to the related operations and equipment involved, container terminal systems can be divided into four subsystems (Kemme, 2013; Rijsenbrij and Wieschemann, 2011; Lee and Kim, 2010; Steenken, 2004):

1) Ship-to-shore subsystem: In this area, quay cranes are used to load and unload containers from arriving or departing ships.
2) Horizontal-transport subsystem: This subsystem is designed to transport full or empty containers between the quay cranes and storage yard via horizontal-transport vehicles.
3) Storage subsystem: The storage subsystem is where containers are temporarily stored using reach stackers, forklifts, or different variants of yard cranes.
4) Hinterland-connection subsystem: This subsystem is responsible for the transport of containers from the storage area to the hinterland. Containers arriving/departing by road or railway at/from the terminal are handled within the truck and train operation area.

An overview of the different subsystems of a container terminal is given in Figure A:8.

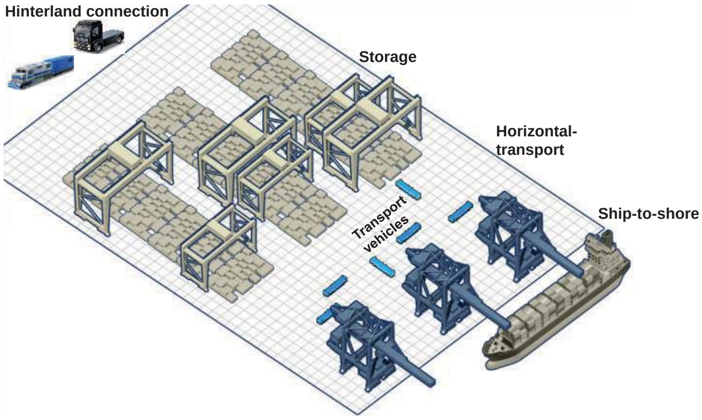

Figure A:8. Schematic terminal layout (adapted from Kemme, 2013).

II.3.2 Recent Developments in Container Logistics

International sea freight container transportation has grown dramatically over the last two decades. Nowadays, container logistics play a major role in the supply chain of most production companies. This is mainly because of the increasing globalization, worldwide economic growth, and widening geographical distribution of business activities (Saanen, 2004). Furthermore, the overseas transport costs of containers have been reduced substantially in recent decades due to economies of scale, mainly resulting from ever-growing vessel sizes (Hecht and Pawlik, 2007).

As illustrated in Figure A:9, the container volume handled worldwide has increased steadily in recent years, with an annual average rate of more than 3%. In 2013, the total world container throughput first surpassed 650 million 20-foot equivalent units (TEU = volume of a 20-foot-long container) (UNCTAD, 2014). The brief decline in growth can be explained by the economic crisis of 2008 and 2009.

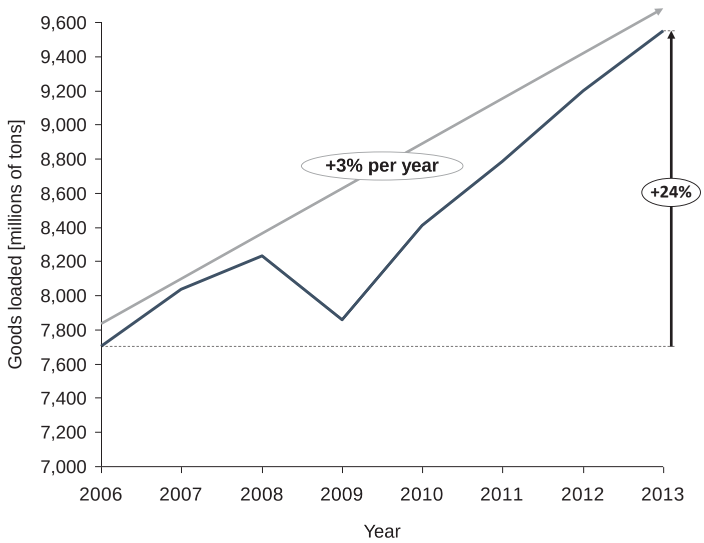

Figure A:9. World seaborne trade, 2006–2013 (UNCTAD, 2014).

However, this growth comes along with several emerging challenges for container terminals. First, the increasing number of containers being processed at ports forces container terminal operators to expand their handling capacities. However, the expansion of port capacity is often constrained due to the scarcity of land close to the seaports and escalating environmental concerns, especially for urban center ports (Le-Griffin and Murphy, 2006). Second, rising customer demands (e.g., shorter berth times or greater container-handling capacity) pose new and intricate problems for terminal-operating companies. In this regard, the capacity of container vessels has increased considerably in recent years, from a maximum of 6,000–8,000 TEU in 2000 to 18,000 TEU in 2013 (Rodrigue et al., 2013). To manage larger container vessels, container terminals must maximize their handling capacities and thus avoid a significant increase in the turnaround time of container vessels.

European terminal operators are faced with two further challenges. With their lower rates, Asian container terminals are placing growing cost pressure on European container terminals (Kemme, 2013). Furthermore, rising labor costs in many European countries are causing enormous economic difficulties for European container terminal operators (Rijsenbrij and Wieschemann, 2011). In order to meet these challenges and thus remain competitive, container terminal operators must increase their productivity and efficiency to achieve high container throughput at low costs. One means for increasing efficiency and reducing operational costs is to provide an advanced level of automation in container terminals, especially in high-wage countries (Liu et al., 2004). According to Xin (2014), a container terminal is referred to as automated when the equipment can be controlled fully automatically without any human intervention. Famous automated container terminals are located in Hamburg (HHLA) and Rotterdam (ECT Delta or ECT Euromax). In general, it has been shown that significant cost-saving potentials of up to 25% (including labor, operation, and capital costs) can be realized through advanced terminal automation (Kemme, 2013).

In these container terminals, automated (driverless) guided vehicles (AGVs) are mostly used for the transportation of containers between quay cranes and the container storage. Each AGV is capable of carrying either one 40-foot or two 20-foot containers. The advantages of employing AGVs include labor cost savings, predictable and continuous operation, high reliability, and the reduction of error rates of transport processes due to the high degree of automation (Gelareh et al., 2013; Vis and Harika, 2005). To date, this kind of transport is normally executed with diesel-powered vehicles that consume large quantities of fossil fuel. However, battery-powered AGVs (B-AGVs) represent an emerging transport technology for this application context that appear to have decisive economic, technical, and ecological advantages in container terminals.

Environmental benefits mainly result from the possibility of reducing greenhouse gas emissions. Terminal operators can also improve their green image and develop environmental strategies. Furthermore, noise pollution and local gas emissions can be reduced by using B-AGVs, which is especially important for ports located in urban centers as the high local traffic density on ports (often more than 100 AGVs operate at one terminal) causes high emission concentrations and noise exposure. From an economic point of view, the use of B-AGVs offers potentials because their lower maintenance costs and electricity costs relative to fuel costs make them cheaper to operate than conventional ones. Finally, B-AGVs seem to be particularly suitable for a broad implementation of DSI programs (see Section A.II.2.2).

The HHLA (Hamburger Hafen und Logistik AG) Container Terminal Altenwerder was the first to test a prototype of a fully electric AGV. Within the frame of the BESIC research project (see next section), the HHLA procured a fleet of B-AGVs and a battery-swapping station. One of the central project goals is to assess the possibility of coordinating charging times with operational requirements and the occurrence of peak loads. The project thus seems well-suited to assess the potential of applying DSI programs for (heavy-duty) ETVs.

II.3.3 Description of the Project Setting

The main aim of the BESIC project is twofold: First, it should be examined whether the use of electric transport vehicles (B-AGVs) makes economic sense in closed logistic systems in combination with the implementation of a battery-swapping station. Second, the feasibility and economic potential of applying DSI programs for the ETV fleet should be investigated. The project partners are the largest port operator in Germany (HHLA Container Terminal Altenwerder), one of the largest utilities in Europe (Vattenfall), an international heavy-equipment manufacturer (Terex Port Solutions), and three universities (Göttingen, Oldenburg, and Clausthal).

Within the frame of the project, 10 of the terminal's 80 diesel-powered automated guided vehicles were replaced by B-AGVs in order to perform fleet tests under actual conditions and technically compare both means of transport. In principle, a B-AGV is quite similar to a traditional AGV; in both types the drive system is electric. The difference lies in from where the energy is retrieved. In a diesel-powered AGV, a diesel engine generates the energy, while in a B-AGV the energy is retrieved from a battery system. An illustration of a B-AGV (length: approx. 15 m; max speed: 6m/s) is presented in Figure A:10.

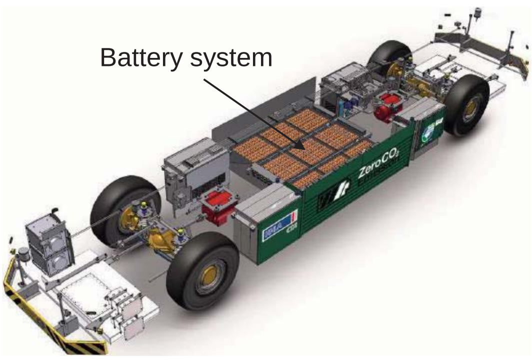

Figure A:10. Schematic illustration of a battery-powered AGV (internal project data).

The terminal operator requires that B-AGVs have similar performance characteristics to diesel-powered AGVs; a B-AGV should therefore operate for at least 12 hours with one battery cycle. To meet the defined transport requirements, each B-AGV was equipped with nine large and interconnected lead–acid batteries, resulting in a total capacity of 289 kWh per battery system. An illustration of a whole battery system is given in Figure A:11.

Figure A:11. Battery system of a B-AGV (internal project data).

Lead–acid batteries were preferred to new types of lithium–ion or nickel–metal hydride batteries because they have already been used in several ETVs (e.g., forklifts) and are therefore standardized to a higher degree. Furthermore, lead–acid batteries of this size are almost five times cheaper than similar state-of-the-art lithium–ion batteries and are fully recyclable.

One important aspect that had to be considered is that a (B-)AGV usually operates more than 5,000 hours per year at the container terminal – sometimes even 24 hours a day. For the container terminal operator, it is necessary to ensure continuous operation of the transport vehicles. In this regard, even small delays of transport orders lead to enormous costs for the transport company (based on penalty costs or port charges). To prevent the fulfillment of daily logistic tasks from being restricted by the charging processes – which can take several hours – a fully automated battery-swapping station (BSS) was installed. If the state of charge (SOC) of a battery in use drops below a certain threshold (20%), the terminal operating system automatically sends the B-AGV to the BSS. Here, the depleted battery can be exchanged automatically for a fully charged one in less than five minutes. Thus, the overall performance of the B-AGV system is equivalent to a diesel-driven system with comparable interruptions of operating times for a refueling process. Finally, the charging rate was fixed at 1/6 C-rate (charging power 48 kW), making it possible to fully charge a battery system in six hours. The BSS that was installed at the container terminal is illustrated in Figure A:12.

Figure A:12. Battery-swapping station installed at the container terminal (internal project data).

To use a BSS, the mobility system must have more batteries than the number of vehicles deployed so that the stock of charged batteries is sufficient to replace the depleted ones. As explained above, it is necessary to ensure continuous operation of the B-AGVs. Hence, enough spare batteries must be procured to ensure that all B-AGVs can obtain full batteries without waiting, even if the terminal is at maximum capacity for days at time. Currently, there are two battery systems available per vehicle, resulting in a total of 20 lead–acid battery systems.

The B-AGVs represent a valuable resource for DSI for two main reasons. First, because a certain number of batteries is always in the BSS, the combined storage capacity can be defined as quasi-stationary, which facilitates the application of DSI programs. Second, the average usage time with one fully charged battery system (approx. 17 hours) is significantly longer than the time necessary to fully charge it. Therefore, the charging processes can be shifted when required, creating a load-shifting potential. Although it would be conceivable to reduce the number of spare batteries, previous practical applications within the research project have shown that there is little scope for this, especially when the terminal is working at full capacity.

Using data from the research project, this thesis is primarily concerned with identifying the most promising DSI program for making use of the load-shifting potential without negatively affecting the logistic processes of the terminal operator (the so-called “logistic premise”). To this end, the efforts necessary for implementing several DSI programs are assessed considering regulatory complexity as well as operational and technical requirements. Furthermore, several DSI programs are compared economically on the basis on optimization methods and economic analysis (Section B.II.2–B.II.4). It is also investigated how the application of DSI programs can reduce the TCO for the ETV fleet and whether B-AGVs are a viable alternative to conventional diesel-powered transport vehicles in closed transport systems (B.II.5). Finally, on the basis of the information gained from the research project, recommendations are given on how to redesign the German energy markets to better utilize flexibility options on the demand side (Section B.III).

B. Assessment of Demand-Side Integration Programs

As explained in detail in Part A, this cumulative thesis at hand aims to achieve two overachieving goals within three different chapters in this part. First, it aims to quantify the financial impacts of applying DSI programs for EVs and (heavy-duty) ETVs for two groups: energy suppliers (Chapter I: Study 1) and fleet operators (Chapter II: Studies 2–6). At the center of this work are fleet operators using heavy-duty electric transport vehicles (Studies 3–6), as this application context seems particularly suitable for DSI under current conditions. Second, the thesis aims to offer policymakers suggestions on how to integrate flexible loads, such as ETVs, into existing energy markets (Chapter III: Study 7). The last study is based on knowledge gained from the previous studies, as regulatory requirements for applying DSI programs were given particular consideration throughout the whole thesis

Although each chapter in this part provides a different perspective on DSI programs for E(T)Vs – energy supply side, energy demand side, and policymakers – all chapters contribute to answering the two overarching objectives of this thesis. A detailed discussion of each study's contribution to achieving the overarching goals of this thesis in given in Section C.I.4.

I. Supply-Side Perspective on DSI Programs – Study 1: The Value of IS to Ensure the Security of Energy Supply

In the first study of this part, the financial impacts of applying DSI programs for electric vehicles in general are quantified from a supply-side perspective. Applying DSI programs for EVs is becoming increasingly relevant for energy suppliers because it is uncertain whether the existing generation capacity is able to meet the rapid development of EVs (see Section A.II.2). DSI programs can contribute to reducing or even eliminating possible investments in additional energy generation capacity by shifting charging processes to off-peak hours, thus reducing system peaks. To date, there is no study assessing the cost-saving potentials resulting from the application of DSI programs for EVs for the energy industry. To fill this research gap, a simulation study and economic assessment are performed in this section to estimate these financial benefits. In doing so, the first research question of this thesis can be answered.

Table B-1. Fact sheet of study no. 1.

Title	The Value of IS to Ensure the Security of Energy Supply
Authors	Johannes Schmidt*, Sebastian Busse Chair of Information Management, University of Göttingen, Platz der Göttinger Sieben 5, 37073 Göttingen, Germany *Corresponding author. Tel.: +49 551 3921177. E-mail address: jschmida@wiwi.uni-goettingen.de
Outlet	Proceedings of the 19th Americas Conference on Information Systems (AMCIS) 2013, Completed Research Paper
Abstract	Replacing the internal combustion engine through electrification is regarded as crucial for future mobility. However, the interactions between a higher number of electric vehicles and the impacts on power plant capacities have not been sufficiently investigated yet. Hence, this paper develops an approach to evaluate the energetic impacts on current power plant capacities that result from a higher market penetration of electric vehicles by 2030. The key aspect of the approach is the quantification of smart charging processes in energetic and economic perspectives. It was found that the implementation has significant energetic and thus economic benefits because of an improved integration of the additional electricity demand. The value of information systems – which enable smart charging processes – is shown by the calculated cost-saving potentials, resulting from a reduced expansion of the power plant system.
Keywords	Electric Mobility, Smart Charging Processes, Security of Energy Supply, Economic Appraisal

I.1 Introduction

Over the last decades, there has been continuous growth of the demand for individual mobility, seen particularly in increasing car sales. However, recent trends indicate a fundamental paradigm shift in the automotive industry. This trend has been initiated by a gradual substitution of electric vehicles[1] (EVs) for vehicles with a combustion engine (Urbschat and Bernhart, 2009). The main motivations for this development are political and social, with the most important being environmental requirements of future mobility. In this regard, the introduction of electric vehicles is seen as an important strategy to achieve climate protection goals. Concurrently, the German electricity industry is undergoing a period of technological and structural upheaval as a result of the German Federal Government's "Energy Concept for an Environmentally Sound, Reliable, and Affordable Energy Supply" (BMWi and BMU, 2010). The increasing demand for electric vehicles poses further challenges for the electricity industry. In this context, the rising electricity demand could force power producers to increase their power plant capacities. The associated additional investments could significantly reduce the attractiveness of the electric mobility concept. Moreover, any expansion of the fossil power plant system is in contradiction with climate protection goals. In this respect, the intelligent utilization of green Information Systems (IS) can contribute to higher energetic and environmental sustainability (Watson et al., 2010). For example, investments in smart charging technologies to realize controlled charging processes are a potential substitute for investments in the power plant system. By reducing the need for increases in power plant capacities, IS can therefore create significant saving potentials. Due to these reasons, our paper focuses on two research questions:

1) Which power plant capacity might result from an increasing electricity demand of EVs by 2030 and what are the energetic and economic impacts on the current power plant system in Germany?
2) Are investments in smart charging technologies to control charging processes of EVs a suitable alternative to an expansion of power plant capacities?

The analysis presented in this paper is based on data for the German energy market, which may serve as test market for many approaches as ours.

I.2 Research Background and Related Work

The need for an analysis of the security of energy supplies can be seen in the influence a higher market penetration of EVs would have on the future electricity demand. Several studies have investigated the impact of an increasing number of EVs for the electricity sector. A lot of basic grid related research, due to the additional electricity demand, has been conducted (e.g., Green et al., 2011; Freire et al., 2010; Kempton and Tomić, 2005b). Additionally, some studies examined possibilities of vehicle-to-grid (V2G) concepts (e.g., Rezania and Pruggler, 2012; Tomić and Kempton, 2007; Kempton and Tomić 2005a); the basic idea is that EVs provide power to the grid while parked. Studies that examine the impacts of a future higher number of

[1] In this paper, we focus on battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs).

electric vehicles on power plant capacities mainly focusing on technical effects while neglecting the economic impacts (e.g., Clement-Nyns et al., 2010; Perujo and Ciuffo, 2009). These studies also discuss the question whether energy security can be ensured despite a higher market penetration of EVs. However, no existing study investigates the economic costs to ensure security of energy supply by adjusting power plant capacities to meet the additional future electricity demand. We deal with this topic, comparing the cost/benefit ratio of a possible power plant capacity adjustment to the cost/benefit ratio of an alternative smart grid technology adoption (see, e.g., Corbett, 2011 for DSM application).

Table B-2. Research contribution.

	Security of energy supply	**EV usage impact on**		**Focus**		
Publication		Power plant capacity	Smart grid / Smart technology	Grid	Economical	Technical
Clement-Nyns et al., 2010	X	X		X		X
Perujo and Ciuffo, 2009	X	X		X		X
Green et al., 2011	X			X		X
Corbett, 2011			X		X	X
Lund and Kempton, 2008			X	X		X
Kempton and Tomić, 2005a			X		X	
Kempton and Tomić, 2005b		X	X	X	X	
Tomić and Kempton, 2007				X	X	
Rezania, 2012			X	X	X	
Freire et al., 2010				X		X
This paper's research contribution	**X**	**X**	**X**		**X**	

Security of energy supplies is warranted if all consumers can be supplied with uninterruptable electricity to meet their demands. A power plant capacity bottleneck is defined by insufficient capacities of the electricity producers to fulfill a given demand (Costantini et al., 2007). One of the main parts of a green electricity strategy and one instrument to increase the security of energy supply is demand side management (DSM) that helps to reduce or time-shift demand (Browne et al., 2009). This concept plays a key role within the electric mobility concept since it controls the charging processes of EVs to integrate the additional electricity demand as optimally as possible into the existing load pattern. However, advanced information systems are a prerequisite for the realization of controlled charging processes. An implementation requires the ability to communicate between the EV and charging station, as well as the charging station and energy supplier (Parry and Redfern, 2010).

I.3 Research Design

The research design is based on an approach to evaluate the energetic impacts on current power plant capacities that result from a higher market penetration of electric vehicles by 2030.

The structure consists of two parts. The first part includes the calculation of various load profiles of EVs on a given day, based on a simulation. This simulation was developed with the simulation tool "Matlab/Simulink" for the reference years 2020 and 2030, considering different assumptions of the future development of key model parameters. For this, the main factors influencing the demand for electricity from EVs were combined to simulate whole-day load profiles resulting from the charging process of EV-batteries on a given day. This model-based approach also facilitates the demonstration and evaluation of a chosen load management system.

In the second part of the approach, whole-day residual load reserves were calculated. These can be defined as unused power plant capacities after electricity demand, which are thus available for current and future charging processes of EVs without expanding the power plant capacities. Through combining the whole-day residual load reserves with the predicted load profiles of the EVs one can make reliable predications about potential capacity bottlenecks. Moreover, it is possible to calculate the exact amount of capacity adjustments necessary to ensure the security of energy supply, despite the additional demand for electricity, depending on various scenarios. The energetic results were then used to analyze the economic impacts on the electricity industry by 2030. To achieve this, additional revenues from the increased electricity demand were compared with the investments necessary to avoid a possible capacity bottleneck, analyzing two alternatives. Finally, the energetic potentials of load management systems were converted into financial saving potentials. The following figure illustrates the above described model's approach.

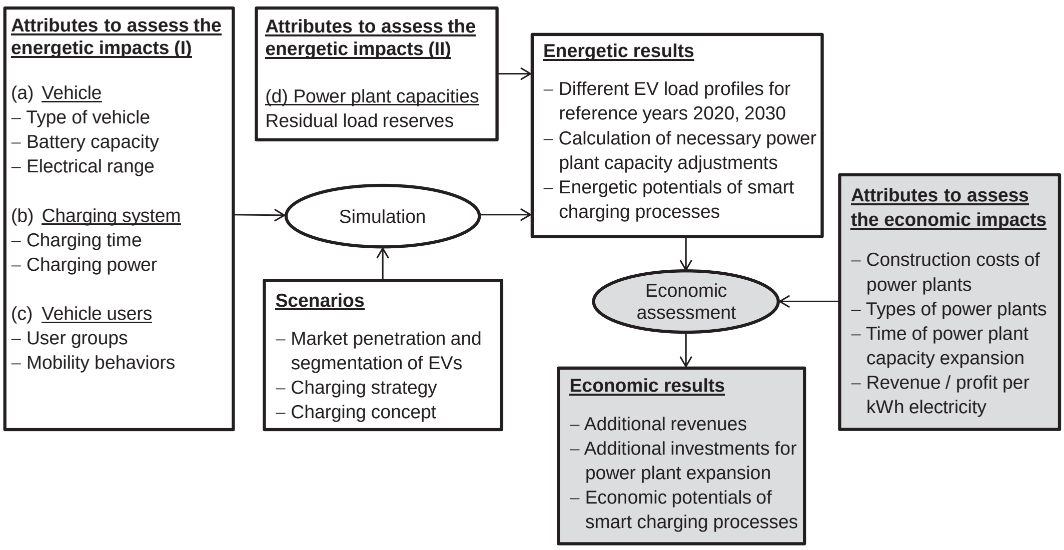

Figure B:1. Approach of the simulation and economic appraisal (shaded grey).

The central objective of the model is the quantification of the benefits of smart charging processes, as part of demand side management, from energetic and economic perspectives. It is assumed that the implementation of a proper load management system could significantly reduce the required investments of possible power plant capacity expansions. Thus, it could be an alternative solution to conventional investment strategies.

I.4 Assumptions for an Assessment of the Energetic Impacts on Power Plant Capacities

The analysis of the energetic impacts by 2030 was based upon data for the basis year 2008 (aggregated German energy data: BDEW, 2013a). Based on several studies, for all calculations it was assumed that electricity demand (excluded additional electricity demand of EVs) and supply remain at a constant level throughout the period examined (Klaus et al., 2010; Matthes and Ziesing, 2008). Furthermore the model incorporates values of a medium-sized BEV (Volkswagen Golf blue-e-motion) and PHEV (Toyota Prius plug-in-hybrid) as reference EVs. For the simulation, private charging with two different current levels was considered. As we specifically want to assess a worst case scenario, it was assumed that the users have no possibility to recharge the EV during the day and connect their vehicles after the last trip has ended. For this purpose, all EVs plug in at 6:00 p.m., as previous analyses have shown that the majority of trips (89.6%) are finished by this time. Certain impact factors that influence the demand for electricity due to the charging processes of EVs can be varied within the framework of the simulation. This is intended to develop different load curve scenarios of EVs on a given day. For this reason, two different charging strategies were examined. “Daily charging after the last trip” describes the strategy in which all vehicle owners recharge their vehicles each day after finishing their last journey. In contrast, the “adjusted charging after the last trip” strategy compares the range of one battery charge with the average daily driving distance. From this, one can calculate the actual frequency with which the cars must be charged.

For this paper, two different charging concepts were examined. The first concept is uncontrolled charging, in which the charging process of the EVs starts immediately after the vehicle is connected to the grid. The second and more sophisticated charging strategy is the implementation of smartly controlled charging processes. We examine the simplest smart charging strategy in which the initial charge of the EVs is delayed to avoid the evening demand peak and realize load shifting (Parks et al., 2007). Since the number of EVs has a considerable influence on electricity demand, two market penetration scenarios are generated. The “expected” scenario (a) assumes a moderate market penetration, for which the federal government’s goals of introducing one million EVs by 2020 and six million by 2030 is used (German Federal Government, 2009). Currently, these goals seem difficult to achieve. However, purchase price incentives, rising oil prices and low energy costs for EV are still assumed to stimulate the market for electric vehicles and thus lead to a significant increase in future sales (Propfe et al., 2013). The “optimistic” scenario (b) assumes a considerably higher market penetration of EVs. Moreover, the ratio of PHEVs to BEVs is changed during the observation period. An overview of the relevant impact factors and their respective parameters is illustrated in Table B-3.

Table B-3. Impact factors and parameters of the model.

Impact factor	Parameter	Modifiable in simulation?
Technical data	$Capacity_{Bev}$ = 26.5 kilowatt hours [kWh] / $Capacity_{PHEV}$ = 5.2 kWh	-
Market penetration of electric vehicles	2020 (a): 500,000 BEVs, 500,000 PHEVs; (b) 750,000 BEVs, 750,000 PHEVs 2030 (a): 4,000,000 BEVs, 1,000,000 PHEVs; (b) 6,000,000 BEVs, 1,500,000 PHEVs	✓
Time of battery charge	Plug-in of EV = 6 p.m. Load shifting = Depending on load concept; latest end of charging 4:30 a.m.	✓
Charging power	Charging $power_{Normal}$ = 3.7 kilowatts [kW]; Charging $power_{Fast}$ = 11 kW	-
Average electric distance driven daily	Electric driven daily distance BEV = 39 km Electric driven daily distance PHEV = 31.2 km (80% of average driven distance)	-
Charging concept	Uncontrolled and smart charging	✓
Charging strategy (I)	EV_{daily} = Daily charging; $BEV_{adjusted}$ = Every 3.85 days; $PHEV_{adjusted}$ = Daily	✓
Charging strategy (II)	Fast charging = 20% of all BEV owners	-

The calculation of residual load reserves was based on the day with the maximum peak load from the basis year 2008; the additional demand must not cause a power outage even on this day with an already very high electricity demand. By combining the simulated “load profiles of EVs on a given day” with the “residual load reserves on a given day” it is possible to make exact statements about the impacts of a higher market penetration of EVs on power plant capacities; if the power producers can cover the additional demand even on the day with the maximum peak load, it seems plausible that the electricity demand can also be covered on all other days of the year. For this, the key performance indicator of the “maximum electricity deficit” is introduced. This measure can be used to calculate the necessary amount of power plant capacity adjustments, to secure energy supplies. We denote the total load of all electric vehicles in gigawatt (GW) by P^*_{max} and the residual load reserves of the power plants in GW by $C^{\sim}_{Power\ Plants}$.

Maximum electricity deficit (P^*_{max}): Highest positive difference between total load of EVs and residual load reserves (in GW) occurs at the same time on a given day, per day and scenario

$$P^*_{max} = max\,\{P_{EV} - C^{\sim}_{Power\ Plants}\}\,;\; P^*_{max} > 0. \tag{B.1}$$

I.5 Assumptions for an Assessment of the Economic Impacts

An increasing number of EVs creates a sales potential for the electricity industry due to the higher demand for electricity. Corresponding calculations start from 2009, when the first marketable EVs were launched. The forecast of the additional revenues requires knowledge of the 2008 to 2010 statistically recorded (electric sales data: Destatis, 2013) and predicted (2011–2030) average price per kWh, as well as the additional electricity demand per year by 2030. For the calculation of the additional electricity demand from 2009 to 2030 (cumulative total load of EVs in terawatt hours [TWh] = $\mathrm{E}_{\mathrm{EV,cumulative}}$), let n be the number of electric vehicles in units and $\overline{\pi}$ the average yearly electric driven distance in km. Moreover, we denote the actual average energy consumption of the EVs (in consideration of charge losses) in TWh per km by $\Phi_{\mathrm{Real,EV}}$.

Finally, we use the following formula to calculate the additional electricity

$$E_{EV,cumulative} = n_{PHEV} \times \Phi_{Real,PHEV} \times \bar{\pi}_{Electric,PHEV} + n_{BEV} \times \Phi_{Real,BEV} \times \bar{\pi}_{Electric,BEV}. \quad \text{(B.2)}$$

For the calculation of the additional profits for the electricity producers, a calculated margin derived from the electricity production costs is used. The profit per kWh of electricity is assumed to be constant during the observation period. The expected investments by 2030 for the electricity industry focus on the measurements required to sufficiently cover the additional demand for electricity by EVs, and thus prevent a blackout. Investments can either be made by expanding existing power plant capacities or by implementing a DSM system.

I.5.1 Additional Investments: A Necessary Increase of the Power Plant Capacities

We suppose that investments in increasing power plant capacities depend solely upon the construction costs of building new or expanding existing peaking power plants. Focusing on peaking power plants is reasonable although the share of renewable energies is around 25% in Germany and shall increase to even 50% by 2035. In this regard, peaking power plants generally run when there is a high demand for electricity, such as in the early evening. This is suitable due to the previous assumption that EVs are connected to the grid in the early evening. Moreover, in contrast to renewable energies, these types of power plants entirely belong to the secured power plant capacities. The forecast of the composition of the peak load power for the reference years is based on existing studies (Schlesinger et al., 2011). The same applies for the determination of the construction costs for the basis year 2008 (Groscurth and Bode, 2009; Panos, 2009). Capital expenditures for run-of-the-river power plants and pumped-storage plants can differ considerably. For this reason, a distinction is made between new and modernized plants, as well as location conditions. The average construction time was determined to be five years. By multiplying the respective shares of the power plants in the total peak power generation with the construction costs, it is possible to calculate the average capital expenditures for the construction of a peaking power plant with an output of one GW for the reference years. The estimation for the remaining years is based on a regression analysis. For the calculation of overall additional investments, the previously calculated “maximum electricity deficit” was used; the existing stock of power plants has to be increased by this amount of electricity to prevent a power outage. For simplification, it was assumed that the entire capacity expansion necessary is conducted by the year the first bottlenecks are expected.

I.5.2 Additional Investments: Implementation of a Load Management System

Investments in smart charging technologies and therefore in advanced information systems realizing controlled charging processes are a potential substitute for investments in power plant capacity as described above. Through this alternative, an increase of power plant capacities can be either reduced or prevented. The cost analysis was based on data from the power company RWE (eMobility products RWE: RWE eMobility, 2013). It was found that static charging processes can now be realized without extensive capital investments, but with only a simple home charging station connected with the respective electricity supplier. The costs of this charging station range from 500 to 2,000 Euros. However, users must bear the purchasing costs of the charging stations. Not considered here are operation costs for load management systems (e.g., permanent control of the load profiles).

I.5.3 Economic Appraisal: Expand Power Plant Capacities vs. Invest in Smart Charging Technologies

The associated economic appraisal compares the expected additional profits from the higher demand for electricity with the investments necessary to prevent a power outage by 2030. The focus regarding the expenditures is on two previously examined alternatives: (1) an increase in power plant capacities and (2) the implementation of smart charging processes. However, it must be noted that power plant capacities must be expanded in some scenarios, even if charging processes are controlled. The costs were calculated by straight-line depreciation from the first year of construction. The economic lifetime of the power plants considered is determined to be 35 years (Torres, 2011; Hannemann et al., 2009).

I.6 Results

I.6.1 Energetic Results

The table below displays the summarized model results, including the “first year a power outlet is expected due to a capacity bottleneck” and the “maximum electricity deficit” by 2030. The most important findings follow:

- The first capacity bottlenecks are expected around 2020 when using uncontrolled charging processes;
- Power producers must increase their capacities to around 30 GW to prevent a power outage in a worst-case scenario;
- Necessary power plant capacity adjustments can be reduced considerably or even prevented by the implementation of smart charging processes.

Table B-4. Energetic results depending on market penetration of EVs (a = expected scenario, b = optimistic scenario), charging strategy and concept.

Scenario	Charging strategy	Charging concept	Expected date of capacity bottleneck	Maximum electricity deficit by 2030 in GW
a	Daily charging	Uncontrolled	2022	17.65
a	Adjusted charging	Uncontrolled	2023	2.37
b	Daily charging	Uncontrolled	2021	29.76
b	Adjusted charging	Uncontrolled	2022	6.9
a	Daily charging	Rigidly controlled	2026	9.13
a	Adjusted charging	Rigidly controlled	-	-
b	Daily charging	Rigidly controlled	2023	21.25
b	Adjusted charging	Rigidly controlled	-	-
a	Daily charging	Flexibly controlled	-	-
a	Adjusted charging	Flexibly controlled	-	-
b	Daily charging	Flexibly controlled	2029	2.55
b	Adjusted charging	Flexibly controlled	-	-

I.6.2 Economic Results

➢ *Additional Expected Revenues and Profits for the Electricity Industry*

The following table shows the additional expected revenues and profits for the reference years resulting from a higher demand for electricity due to the charging processes of the EVs. The table also contains the forecasted cumulative additional revenue and profits by 2030. In total, this means that the revenue for the reference year 2030 (calculated revenues: 64.1 billion Euros) in the expected scenario will increase relative to the total revenue of the electric companies for the basis year 2008 (61.0 billion Euros: BDEW, 2013a) by just 1.02%. Even in the optimistic scenario (calculated revenues: 66.15 billion Euros), the revenues are only expected to increase up to 6.7%. According to these results, the electricity companies cannot expect a considerable increase in sales.

Table B-5. Additional revenue and profit by 2030.

	Additional revenue [billions of €]		**Additional profit [billions of €]**	
Year	Scenario (a)	Scenario (b)	Scenario (a)	Scenario (b)
2008	0 (Basis year)		0 (Basis year)	
2020	0.62	0.94	0.05	0.08
2030	4.10	6.15	0.29	0.44
Cumulative by 2030	**21.6**	**34.5**	**1.69**	**2.91**

➢ *Additional Expected Financial Burden for the Electricity Companies*

Table B-6 shows the predicted additional expenditures for the power companies. As mentioned previously, these result solely from necessary investments in power plant capacity adjustments by 2030 (I_{2030}) to prevent a capacity bottleneck. Additionally, the average capital expenditures for the construction of a peaking power plant with a one-GW capacity in Euros ($I_{\emptyset}$) in the year construction commenced are illustrated.

Table B-6. Additional expenditures for the power companies by 2030.

Scenario	**Charging strategy**	**Charging concept**	**Start of construction**	**P^*_{max} in GW**	**$I_{\emptyset,\text{Start of construction}}$ [billions of €]**	**I_{2030} [billions of €]**
a	Daily	Uncontrolled	2017	17.65	1.03	18.1
a	Adjusted	Uncontrolled	2018	2.37	1.03	2.45
b	Daily	Uncontrolled	2016	29.76	1.02	30.22
b	Adjusted	Uncontrolled	2017	6.9	1.03	7.07
a	Daily	Smart	2021	9.13	1.06	9.72
a	Adjusted	Smart	-	-	-	-
b	Daily	Smart	2018	21.25	1.03	21.99
b	Adjusted	Smart	-	-	-	-

As seen this table, capacity expansions of the power plants can be reduced substantially by using smart charging processes. Regarding scenario (b), power producers have to invest 30.22 billion Euros by 2030 to prevent a capacity bottleneck if the EVs will be charged uncontrolled; the necessary investments by 2030 can be reduced substantially by the implementation of smart charging processes in the same scenario (necessary investment: 21.99 billion Euros) allowing a cost-saving potential of 8.23 billion Euros in this scenario. Therefore the utilization of IS, as precondition for the implementation of smart charging processes, creates significant saving potentials.

➢ *Economic Appraisal*

The summarized results for the economic appraisal can be seen in the following table. Here, the alternatives of “increasing the power plant capacities” and “implementation of a DSM system” are compared with regard to their economic benefits. To gauge this, the additional expected profits by 2030 (P_{2030}) are compared with the respective input costs, converted over straight-line depreciation by 2030 (Dep_{2030}).

Table B-7. Economic appraisal.

Charging type		**Expected scenario (a)**			**Optimistic scenario (b)**		
Charging strategy	Charging concept	P_{2030} without capacity adjustments [billions of €]	Dep_{2030} [billions of €]	P_{2030} including capacity adjustments [billions of €]	P_{2030} without capacity adjustments [billions of €]	Def_{2030} [billions of €]	P_{2030} including capacity adjustments [billions of €]
Daily	Uncontrolled	1.69	6.72	-5.03	2.91	12.09	-9.18
Adjusted	Uncontrolled	1.69	0.84	0.85	2.91	2.63	0.28
Daily	Rigidly controlled	1.69	2.50	-0.81	2.91	7.54	-4.63
Adjusted	Rigidly controlled	1.69	x	1.69	2.91	x	2.91

As a result, the electric companies must expect additional costs of 9.19 billion Euros in the worst-case scenario. On the other hand, the “best case” results in additional profits of 2.91 billion Euros by using smart charging processes. Moreover, one can see that the estimated costs exceed the profits in all scenarios when considering the “daily charging strategy”. In summation, it can be concluded that, from the perspective of the electric industry, increasing electric mobility in combination with uncontrolled charging processes tend to have negative consequences by 2030. Hence, the value of IS lies in setting free cost-saving potentials, resulting from a reduced expansion of the power plant system by using smart charging processes.

I.7 Conclusion

In this paper, we have presented the economic and energetic effects of an increasing share of electric vehicles on the German market on existing power plant capacities. The question – whether and to what extent the existing power plant capacities must be adjusted to prevent a power outage by 2030 – was one focus of the energetic analysis. Moreover, one kind of smart charging processes for an optimal integration of the additional demand for electricity into the existing load pattern was examined. The most important findings were:

- The first capacity bottlenecks are expected around 2020 when using uncontrolled charging processes;
- A necessary extension of power plant capacities by 2030 is made considerably smaller by using smart charging processes.

The focus of the economic analysis was an economic appraisal that compared the necessary capital expenditures to prevent a blackout by 2030 with the additional profits due to the increased electricity demand. For this assessment, two alternatives to ensure the security of energy supplies were examined: (1) power plant capacity adjustments and (2) implementation of a demand side management system to realize smart charging processes. The following conclusions can be made:

- Electric companies cannot expect a considerable increase in revenue and profits by 2030;
- Using uncontrolled charging processes from EV users may lead to significant additional costs for the electricity industry due to a considerable necessary increase of power plant capacities;
- The implementation of smart charging processes has cost-cutting potentials up to 8.2 billion Euros by 2030 because of an improved integration of the additional electricity demand.

In summation it was concluded that the investments in a demand side management system, and therefore in information systems as precondition for the implementation, would have positive effects due to the arising saving potentials. Therefore we recommend focusing on measures to realize smart charging strategies instead of power plant capacity expansions. This would also offer ecological benefits as a result of a reduced use of peaking power plants. Hence, smart charging processes would also indirectly promote the development of renewable energies. However, further research is required to calculate the costs for the implementation more precisely. Associated economic analysis should also include the operational costs and consider further smart charging strategies. One of the major challenges for power producers is to find a solution how users can be convinced to invest in smart charging technologies. Since power producers' profit considerable by the implementation of smart charging processes, it appears appropriate that they also bear a share of the costs. For example, power producers could offer reduced electricity tariffs, if EV users give them the possibility to postpone the charging process. Further study is needed to answer this question. Moreover, it could also be examined if renewable energies are suitable to cover the additional demand. Finally, future studies should also employ driving patters in the model to perform a stochastic simulation for the determination of the probable “time of battery charge”.

II. Demand-Side Perspective on DSI Programs

Similarly to the previous Chapter I, this chapter aims to reduce uncertainty regarding the extent of DSI's economic value. However, while in the last chapter the focus was on the energy supply side, this parts concentrates on estimating the financial profits for actors from the energy demand side: EV and in particular (heavy-duty) ETV fleet operators. Besides the quantification of financial profits for E(T)V fleet operators, this part investigates how best to integrate these kinds of flexible loads into existing energy markets, considering the regulatory, operational, and technical requirements for applying DSI programs.

The first study of this chapter focuses on applying DSI programs for EV fleets that operate outside the premises. While there are several studies investigating the economic potential of applying DSI programs for EV fleets, all publications lack both coherent real-world data and a simulation/prediction model to forecast the load-shifting potential of the EV fleet. Therefore, an IS is designed in Section B.II.1 to derive the optimal decision for shifting energy demand at a given time without restricting daily mobility needs. Furthermore, real-world data from a car-sharing operator in Germany is used to realistically assess the economic potential of applying one suitable DR program for a fleet operator. In doing so, the second research question of this thesis can be answered (How does an information system [IS] need to be designed to apply smart charging and the V2G concept for EV fleets, and what is the economic potential resulting from the application of a suitable DSI program?).

The following four studies focus on assessing the potentials resulting from applying DSI programs for an emerging transport technology: (heavy-duty) ETVs. Despite the promise of applying DSI programs for ETV fleets for the energy industry and fleet operators (see Section A.II.2.2), there still appears to be a research gap concerning the identification of feasible and suitable DSI programs and the quantification of their economic benefits. The main objective of this thesis – expressed in RQ 3 (How can DSI programs be applied for a fleet operator using ETVs, and what is the economic value for a fleet operator?) – is to close this research gap by analyzing data gained within a comprehensive research project (see A.II.3). The connections among the four studies to answer this Research Question 3 were explained in detail in A.I.3.

1 Study 2: Applying Demand Response Programs for Electric Vehicle Fleets

Table B-8. Fact sheet of study no. 2.

Title	Applying Demand Response Programs for Electric Vehicle Fleets
Authors	Johannes Schmidt*, Björn Hildebrandt, Matthias Eisel, Lutz M. Kolbe Chair of Information Management, University of Göttingen, Platz der Göttinger Sieben 5, 37073 Göttingen, Germany *Corresponding author. Tel.: +49 551 3921177. E-mail address: jschmida@wiwi.uni-goettingen.de
Outlet	Proceedings of the 21th Americas Conference on Information Systems (AMCIS) 2015, Completed Research Paper
Abstract	In this study, we demonstrate the contribution of IS-supported demand response (DR) programs to the development of a sustainable transport sector. Based on the energy informatics framework, we develop an IS artifact that can be used to apply DR programs for electric vehicle (EV) fleets. Furthermore, we quantify one DR program in economic terms by analyzing data gathered in an electric mobility project with a car-sharing provider that uses EVs. The findings indicate that fleet operators can expect significant cost savings when applying DR programs; energy procurement costs can be reduced significantly by adjusting the time of energy use. Applying DR programs therefore has the potential to make EV fleets economically sensible because the already existing operational cost advantage can be further increased. Consequently, DR for EVs can foster sustainable development, as higher profitability could promote the market penetration of eco-friendly vehicles.
Keywords	Demand Response, Green IS, Energy Informatics, Electric Vehicles

1.1 Introduction

Many governments currently aim to establish a future energy system that includes sustainable energy generation, reduced energy intensity of demand, and a more effective and sustainable use of energy (REN 21, 2011; Harmelink et al., 2006). The main drivers for this development are the irreversible depletion of fossil fuels, the threat of climate change, and increasing environmental pollution caused by the use of fossil fuels (Elliot, 2011; IPCC, 2007). Therefore, some governments, such as Germany's, have determined various energy- and climate-related targets in order to shape a sustainable energy system. One of these goals is to reduce CO_2 emissions in the transport sector by at least 80% by 2050 compared to the 2008 level (BMWi and BMU, 2010). This is deemed necessary because road transport is responsible for one-fifth of greenhouse gas emissions in the European Union (European Environment Agency, 2012). Electric vehicles (EVs) are seen as an important factor in reducing road emissions. However, as their economic viability is constrained, the market penetration of EVs is still very low; several studies (e.g., Propfe et al., 2012; Thiel et al., 2010) have shown that the higher initial acquisition costs of EVs compared to conventional vehicles cannot be offset by the lower operating costs. One possibility for meeting this challenge is applying demand response (DR) programs for EVs. In general, DR refers to the consumer's ability to alter his or her energy consumption pattern in response to time-dependent electricity prices (Strbac, 2008). Applying DR for EVs thus offers the opportunity to reduce energy procurement costs by shifting charging processes to off-peak hours (Lyon et al., 2012). In addition, DR programs create energetic advantages because they can be used for balancing power supply and demand (Albadi and El-Saadany, 2007).

Various studies identify energy-intensive industries as primary target groups for DR programs (e.g., Paulus and Borggrefe, 2011; Roon and Gobmaier, 2010). Technical innovation in the field of information and communication technology (ICT) – such as advanced metering infrastructure (AMI) or smart meters with a communication gateway – also enable households and small commercial consumers to engage in DR programs (Kranz, 2011). However, additional information systems (IS) are required for DR to compute the difference between expected and actual electricity wholesale prices and derive the optimal decision to shift demand at a given time (Feuerriegel et al., 2012). These kind of IS fall under the umbrella of Green IS as they form a base for DR and enable end users to take part in the smart grid (Melville et al., 2010).

IS are also required to enable fleet operators – for example, car-sharing operators using EVs – to participate in DR programs. To control a charging process (e.g., interruption during price peaks), however, it is necessary for the fleet operator to predict electricity demand and thus know the margin for load-shifting per charging process in advance (Geelen et al., 2013). In addition, electricity prices must be known beforehand. Surprisingly, most studies investigating the potential of DR programs for EV fleets ignore these facts. In line with these thoughts, our paper introduces a novel IS artifact that can be used to apply DR programs for EV fleets without restricting mobility needs. This leads us to the first research question:

1) How does an information system need to be designed to apply DR for EV fleets?

By significantly decreasing energy procurement costs, the application of DR programs can make a valuable contribution to ensuring that these vehicles become economically competitive. Most related publications assessing the economic potential of controlled charging concepts, however, lack real-word data and therefore the results are missing external validity. To overcome this issue, we use data from a car-sharing operator in Germany to realistically assess the economic potential of applying a DR program for fleet operators and address the following second research question:

2) What are the economic potentials resulting from the application of a suitable DR program for an electric vehicle fleet?

Our study thus addresses the issue of how IS-supported DR programs for EVs can save energy procurement costs for a company using EVs, thereby acting as a driving force for sustainable solutions in organizations. The remainder of this paper is organized as follows. Section B.II.1.2 examines the fundamentals of DR in general and DR programs for EVs. Section B.II.1.3 then presents an IS artifact that can be used to apply DR for EV fleets. In Section B.II.1.4 we develop a prediction model required for the application of DR programs and then quantify one DR program in economic terms; the corresponding results are provided in Section B.II.1.5. In Section B.II.1.6 we discuss the findings and limitations of our research endeavor, which leads us to the conclusion presented in Section B.II.1.7.

1.2 Background

1.2.1 The Role of Demand Response in Energy Informatics

Demand response can be defined as “changes in electric usage by end-use customers from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized” (U.S. DOE, 2006). There has been a growing number of IS-related research publications on DR since Watson et al. (2010) emphasized the importance of IS research in increasing the efficiency of energy demand and supply systems. Subsumed under the terms ‘Green IS’ and ‘Green IT,’ research efforts have been made to reveal and apply the potential advantages of IS to sustainability dimensions, especially at the interface of IS and energy (Kossahl et al., 2012). For instance, Feuerriegel et al. (2012) and Bodenbenner et al. (2013) analyze how IS designs can contribute to the realization of demand response systems. In addition, Corbett (2011) reveals how IS may increase energy efficiency, while Watson et al. (2013) present a conceptual design for a DR system based on the trading of consumption rights. Strüker and van Dinther (2012) establish that IS play an important role in applying DR, as investments in smart grid technologies and ICT are required to interact with customers. For example, communication systems are responsible for smooth and standardized real-time data exchange between all DR partners (e.g., utility, grid operator, and consumer). Furthermore, customers need information about electricity prices and the required usage alteration. To do so, an AMI including hardware, software, communication, and data management is used, enabling two-way communication between the utility's network and the customer's smart meters (Strüker et al., 2011).

Several benefits associated with DR can be identified. First, it supports the deployment of renewable energy by smoothing out power fluctuations (Azami and Fard, 2008). Adapting electricity demand to volatile supply also leads to a reduction of price volatility in the electricity spot market. Furthermore, system reliability can be increased by reducing electricity demand at critical load times (Bradley et al., 2013; Strbac, 2008). In general, DR programs can be divided into two categories that influence behavior on the consumer side: incentive-based programs and price-based programs. Incentive-based programs offer payments to participating customers (e.g., bill credits) to reduce their electricity consumption as required by the program sponsor; this may be triggered by grid reliability problems or price peaks. Price-based programs provide participating customers time-dependent rates reflecting the costs of generating and delivering electricity (Palensky and Dietrich, 2011).

1.2.2 Demand Response of EVs

Several studies (e.g., Geelen et al., 2013; Wang et al., 2011a) have identified EVs to be particularly suitable for participating in DR because, on average, they are used only during 4% of the day; the resulting idle times can be exploited by shifting the corresponding charging processes (Gu et al., 2013). Furthermore, charging a large number of EVs in an uncontrolled manner results in a significant load that would probably jeopardize power grid security (Schmidt and Busse, 2013; Luo et al., 2011).

To date, most research has focused on two DR programs for EVs: the vehicle-to-grid (V2G) concept and smart charging. Within the V2G concept, EVs can provide utility services (incentive-based DR programs) by supplying power to the grid for stabilization and peak-time supply (Kempton and Tomić, 2005b). The feasibility of this DR program for EVs, however, is limited because regulatory requirements on most energy markets are too strict. For example, an actor on the ancillary market in Germany must offer a minimum of 5 MW of energy (Regelleistung, 2014a). Moreover, technical requirements (e.g., regarding reaction time) are too high for smaller providers of flexible loads (Schmidt et al., 2014). Therefore, this DR program cannot be realized for EVs under the prevailing conditions.

The main goal of smart charging concepts is to shift energy consumption from peak to off-critical hours. To achieve this goal, electricity suppliers can give customers monetary incentives (e.g., real-time pricing) to alter their consumption behavior (Faruqui et al., 2010). However, this method requires advanced meters because energy suppliers need information about actual driving behavior to schedule a charging process (Goebel, 2013).

Despite the promise of controlled charging concepts for both the energy industry and EV users, it is uncertain to what extent the load-shifting potential can actually be used. In this regard, many EV users might not allow any external control on the charging process (Geleen et al., 2013). Moreover, implementing DR requires substantial investment in constructing infrastructure such as energy management systems and smart grid technologies, thus probably diminishing economic benefits (Lyon et al., 2012). From an information management perspective, participation in DR programs for private EV users is challenging because energy suppliers need information about the time and duration that an EV is available for charging (Fridgen et al., 2014).

1.3 Designing a Demand Response System for Fleet Operators

In this section, we conceptualize an IS artifact used to determine optimal charging times for an EV fleet without restricting mobility needs. We focus on EV fleets, as they seem to be particularly suitable for a broad implementation of IS-supported DR programs. In this regard, many larger commercial fleet operators have already implemented smart grid and the required ICT technologies (Paulus and Borggrefe, 2011). Furthermore, larger energy customers or fleet operators with a sufficient number of EVs can benefit directly from prevailing electricity price fluctuations by purchasing the required energy from the day-ahead spot market for electricity and using it on the next day (Hill et al., 2012).

Our research model is positioned within the energy informatics framework by Watson et al. (2010) which partitions an intelligent energy system into four basic elements:

- A **flow network** represents the transport components (e.g., wiring of power grids) that support or enable the movement of continuous matter (e.g., energy) or discrete objects (e.g., cars). In this study, we focus on a flow network that solely permits the flow of electricity.
- A **sensor network** is a set of connected, spatially distributed devices (e.g., smart meters), whose purpose is report on the status of the flow network. In this study, we consider an AMI that, inter alia, receives and reports data on electricity prices.
- **Sensitized objects** are capable of reporting data about their use. For our case, modern vehicle telematics in the form of data loggers are needed to constantly sense and report the status of the EVs as well as, inter alia, trip information and energy flows to and from the batteries. In addition, load control devices are required for managing the electricity demand, i.e., interrupting the charging process during price peaks.
- The “heart” of the framework is an **information system** that serves as an integrator and ties together the above-described elements. We focus on one of the main functions of IS in the framework, described as “manage supply and demand to avoid high costs resources” (Watson et al., 2010).

Figure B:2 illustrates the interactions between all elements within our study.

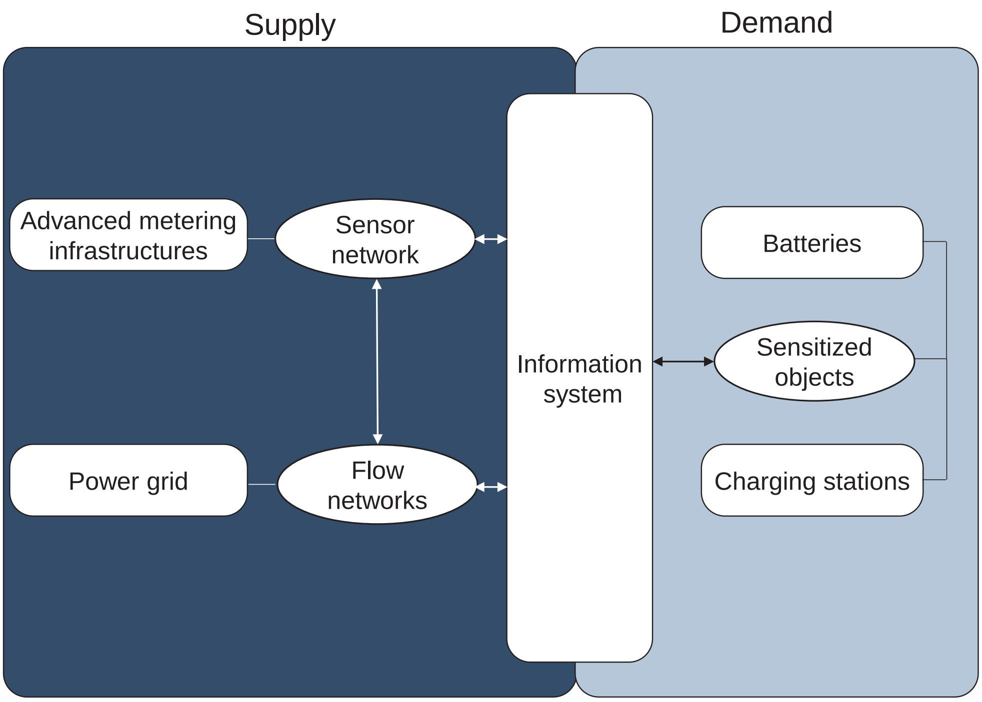

Figure B:2. Embedding the DR program into the energy informatics framework (adapted from Watson et al., 2010).

Adapting these thoughts, we design an IS to optimize DR decisions for fleet operators using EVs, based on two components: a prediction model and an optimization model. As a necessary precondition for applying DR programs, one must accurately forecast electricity demand from the EVs and the DR potential (charging flexibility) for a certain period. Otherwise, an EV might be unavailable due to an insufficient battery status. Surprisingly, most studies investigating the economic profit of smart charging concepts (e.g., Milano and Hersent, 2014; Lyon et al., 2012; Schuller et al., 2012; Deilami et al., 2011) do not consider this fact. Information systems can help alleviate this problem by collecting information about EV usage patterns and the battery status; relevant data are detected and reported by sensitized objects and afterwards analyzed. To gather information about mobility requirements, a prediction model based on historic data is needed for forecasting vehicle use times and energy consumption in a certain period. Thus, the IS requires information on how long the battery must be charged (depending on the current state of charge [SOC] of the battery and distance of the next trip) and when the vehicle is needed again in operation. Furthermore, information on electricity prices is required for a certain period in advance. In Germany, electricity spot market prices can be obtained from the European Energy Exchange (EEX), where hourly prices are determined by day-ahead auctions (Ellersdorfer, 2005). Alternatively, fleet operators can receive information about the energy price at a certain time of use from their utility company through AMI.

Using the input data described above, the IS derives **optimal decisions to shift electricity usage** at a given time and thus manages the interdependencies between the supply and demand sides.

1.4 Research Methodology

Having described the IS artifact used to apply DR programs for EV fleets, we adapt it for a medium-sized car-sharing operator in Germany. Our pilot case company provides users access to a fleet of 87 company-owned conventional vehicles including 7 EVs. Within the car-sharing operator's business model, the users must pick up and return the vehicles to one of the stations distributed in the operator's area.

Our methodological approach consists of two steps. In the first step, we establish a prediction model forecasting the average hourly distances driven for the EVs considered. As explained in the previous section, it is necessary to forecast the electricity demand of the EVs within a defined time window because the load-shifting potential must be known in advance. The second step involves an economic assessment of applying one DR program (smart charging) to the car-sharing operator's EV fleet. To do so, we perform an optimization of charging costs to reduce energy procurement costs for the pilot case company. The economic assessment of this DR program is based on actual driving profiles of the car-sharing operator's EVs for the reference year of 2014. Additionally, information about the EVs' energy consumption per trip was available, as we constantly monitored and tracked all batteries' SOCs in the reference year.

1.4.1 Prediction Model

To estimate the vehicles' usage, we establish a prediction model forecasting the average distances driven per hour for the K vehicles considered. The resulting electricity demand $d(k,l)$ of one EV k for a certain trip l can be calculated by multiplying the energy consumption per km c by the distance of a certain trip $D(l)$

$$d(k,l) = c \cdot D(l). \tag{B.3}$$

The data used to establish our prediction model are booking data of the pilot case company gathered within a time frame of $T = 380$ days (05.31.2011–06.30.2012). As the maximum reachable distance of EVs is approximately 120 km, we focus on completed tours under this distance. The time frame was subdivided into two intervals. The data from the first interval (300 days, starting on 05.31.2011) are considered as training data, while the second interval's data (80 days, ending on 06.30.2012) are considered as test data. In the first step, we accumulate the distances travelled per one-hour time slot within the training data time frame, which is illustrated for one day and one vehicle in Figure B:3. The points represent the exact values and the line a respective maximum likelihood estimation. There is a peak around midday, while in the morning and evening few kilometers were driven.

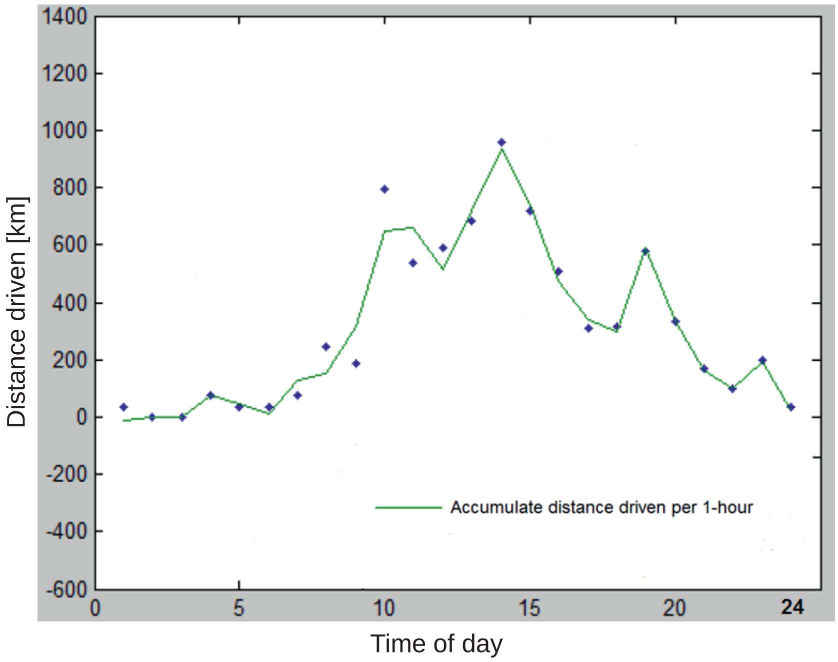

Figure B:3. Kilometers driven for each hour of the day for one vehicle.

Next, we determine the average distances driven per one-hour slot by dividing the accumulated distances by the number of days within the test data time frame. Generally, the consequences of underestimating the future EV demand are worse than those of overestimating. If future demand is underestimated, a trip might not be realized, because the battery is insufficiently charged. To avoid overfitting, an estimator is used (polynomial of degree n), minimizing the distance between the average values and the estimator itself. The polynomial's degree is dependent on the error measure MAPE (mean absolute percentage error); the polynomial with the lowest MAPE is used for the prediction model. To calculate the MAPE, the differences between the estimators $\mathrm{F}_{k,t}$ for vehicle k on day t from the training data and the actual values $\mathrm{A}_{k,t}$ from the test data are generated for every one-hour time slot (within the corresponding time frame) using

$$\mathrm{MAPE}_i = \frac{1}{\mathrm{T}} \sum_{t_{start}}^{t_{end}} \left| \frac{\mathrm{A}_{k,t} - \mathrm{F}_{k,t}}{\mathrm{A}_{k,t}} \right|. \qquad (B.4)$$

Accumulating the modified average values for every one-hour time slot indicates the average distance traveled by a particular time of day, if the vehicle was actually used. To take into account short trends and changes in usage behavior, the prediction model suggested is divided into two parts: a short-term and a long-term component, both weighted with 50%. The short-term component reflects bookings of the last four weeks. In this regard, data from the same weekday and time of day of the previous week is weighted by 50%. Moreover, data from the same one-hour time slot two, three, and four weeks before are considered with weightings of 25%, 12.5%, and 12.5%, respectively. The average distance driven by a particular time of day for one vehicle is illustrated in Figure B:4.

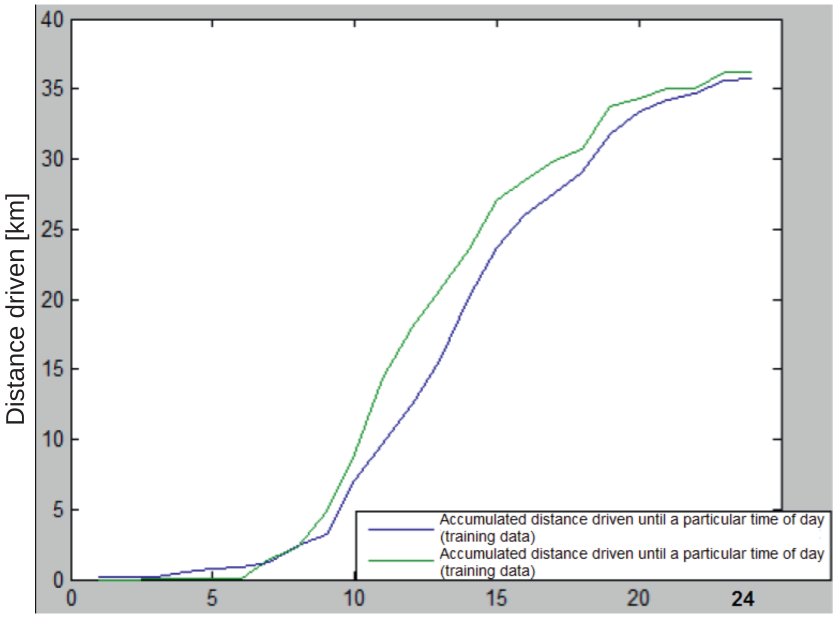

Figure B:4. Average distance driven until a particular time of day.

Our prediction model allows for a forecast of average distances traveled per hour. These values can then be converted into forecasted electricity demand, using Eq. (B.3). The availability of this information is a prerequisite for applying DR programs for EVs, as explained in the previous section.

1.4.2 Optimization Model

In order to evaluate the results of our optimization approach, we first calculate annual energy procurement costs when charging the EV fleet in an uncontrolled manner (plug-and-charge concept) C_{pnc}. Let d_{Fleet} be the annual electricity demand of the EV fleet and $\bar{p}_{el}$ be the average electricity price for the reference year. To ensure comparability between this charging concept and the smart charging concept, we consider the average wholesale price for the fleet operator as it is the only component of the final retail price that can be influenced by smart charging; the other price components (e.g., electricity taxes or grid fees) are fixed (BDEW, 2014). Furthermore, the charging efficiency η is considered by adjusting the demand parameter. Thus, we derive

$$C_{pnc} = \bar{p}_{el} \frac{d_{Fleet}}{\eta}. \tag{B.5}$$

The application of the DR program for the EV fleet is based on energy procurement on the spot market for electricity. As seen in Figure B:5, the electricity spot market exhibits high price volatility and frequent extreme price peaks in Germany. Consequently, the aim is to charge the EVs during the hours with the lowest possible prices.

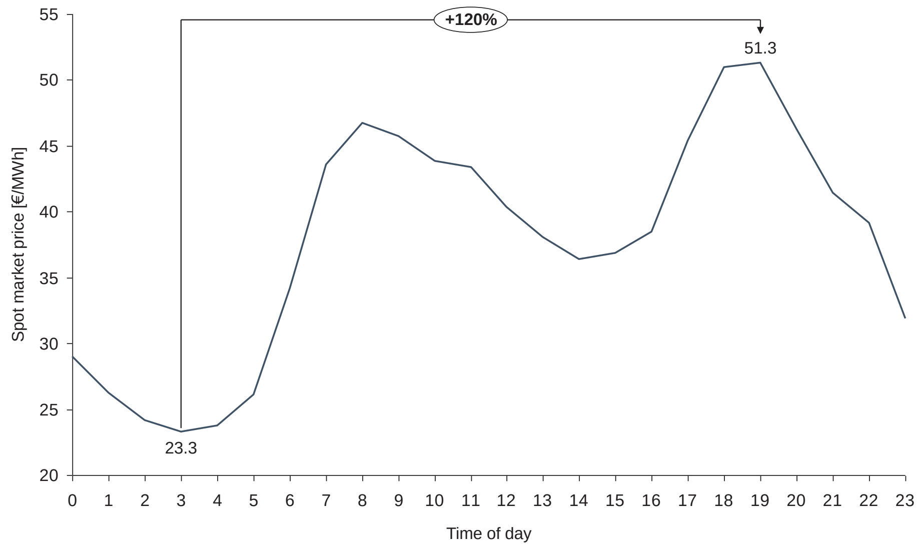

Figure B:5. Average electricity spot prices per hour and resulting price spread in Germany (in 2013).

In the first step of the optimization model, the load-shifting potential per charging process must be defined. For this evaluation, we use historical data from the pilot case company (e.g., tour start and end as well as tour distance) as well as data relating to the charging status $SOC(k,i,t)$ of the EVs' batteries within the reference year. To calculate the electricity demand $d(k,i,t)$ of one EV k in hour i on day t, we use information concerning the maximum battery capacity C_{max} and the charging efficiency η

$$d(k,i,t) = \frac{C_{max} - SOC(k,i,t)}{\eta}. \quad \text{(B.6)}$$

The time available for each charging process depends on the idle time between two bookings. Furthermore, let N be the number of minutes necessary to fully charge the battery. This value is dependent on the vehicle's electricity demand $d(k,i,t)$ and the charging power W

$$d\big(d(k,i,t)\big) = 60 \cdot \frac{d(k,i,t)}{\mathrm{W}}. \quad \text{(B.7)}$$

In order to optimize energy procurement costs per charging process, we shift all charging processes to the time slots in which the electricity spot market prices $p_{spot}(i,t)$ are lowest. This is feasible, because electricity spot market prices are determined by day-ahead auctions. In the interest of constraining the charging processes to the hours with lowest prices for electricity procurement, we use the following function as a decision variable

$$H(k,i,t) = \begin{cases} 1 \; for \; charging \; the \; EV \; k \; in \; hour \; i \; on \; day \; t \\ 0 \; for \; not \; charging \; the \; EV \; k \; in \; hour \; i \; on \; day \; t. \end{cases} \quad \text{(B.8)}$$

The car-sharing operator requires that the fulfillment of all booking requests always has priority over reducing charging costs. Therefore, the battery must always be charged sufficiently in order to realize the next trip. The energy procurement costs per charging process $C_{ep}(k,i,t)$ can be calculated by multiplying the electricity demand $d(k,i,t)$ with the spot market prices $p_{spot}(i,t)$ that prevail during the time in which the batteries are charged, under consideration of the decision variable $H(k,i,t)$. The corresponding optimization problem for minimizing energy procurement costs for the whole fleet resolves to

$$\min_{H(k,i,t)} C_{ep}(H(k,i,t)) \sum_{k=1}^{K} \sum_{i=0}^{23} \sum_{t=1}^{365} p_{spot}(i,t) d(k,i,t) H(k,i,t), \quad \text{(B.9)}$$

subject to

$$\sum_{i=0}^{23} H(k,i,t) = N\big(d(k,i,t)\big)\ \forall\ H(k,i,t) \in \{0,1\}; k \in \{1,\cdots,K\}; i \in \{0,\cdots,23\};\ t \in \{1,\cdots,365\}. \quad \text{(B.10)}$$

1.5 Results

The parameters necessary for assessing the smart charging DR program are presented in Table B-9 for the fleet of seven EVs.

Table B-9. Parameters used to economically assess the DR program in the reference year.

Charging strategy	Parameter	Value	Comments	Data source
Plug-and-charge concept	d_{Fleet}	4881	Annual electricity demand of the EV fleet [kWh]	Project data
	η	.90	Charging efficiency	Project data
	p_{el}	7.31	Average electricity wholesale price [€/kWh]	BDEW [2014]
Smart charging	W	11	Charging power [kW]	Project data
	p_{spot}	[-87.52 – 265.3]	Electricity spot market prices in the reference year [€/MWh]	EEX [2014]
	C_{max}	18.70	Maximum battery capacity [kWh]	Project data

The annual costs when charging the EV fleet in an uncontrolled manner with fixed electricity prices can be calculated using Eq. (B.5) and the parameters listed in Table B-9 to be €356.80. It must be taken into account that we calculate annual charging costs using the wholesale electricity price, which is roughly 25% of the retail price for electricity in Germany (BDEW, 2014). Therefore, to obtain the consumers' retail prices for electricity, further price components – such as grid fees (5.9 cents/kWh) or apportionments for the promotion of renewable electricity (6.2 cents/kWh) – must also be included. Considering the wholesale price, however, allows for an economic assessment of applying the suggested DR program to the EV fleet.

In this regard, the economic assessment of the smart charging DR program is based on the assumption that the fleet operator procures the required energy on the spot market and charges the batteries during the hours with the lowest possible prices. The optimization approach for one vehicle on an exemplary day is illustrated in Figure B:6, in which the trip ends at 2 p.m. with a SOC of 3 kWh. Furthermore, the EV is needed again in operation at 9 p.m. (total charging time available = 7 hours) with a SOC of 15 kWh. Having an available charging power of $W = 11$ kW and a charging efficiency of $\eta = 0.9$, the batteries can be fully charged in 95 minutes. Hence, the charging process takes place during the 1.58 hours with the lowest spot market prices.

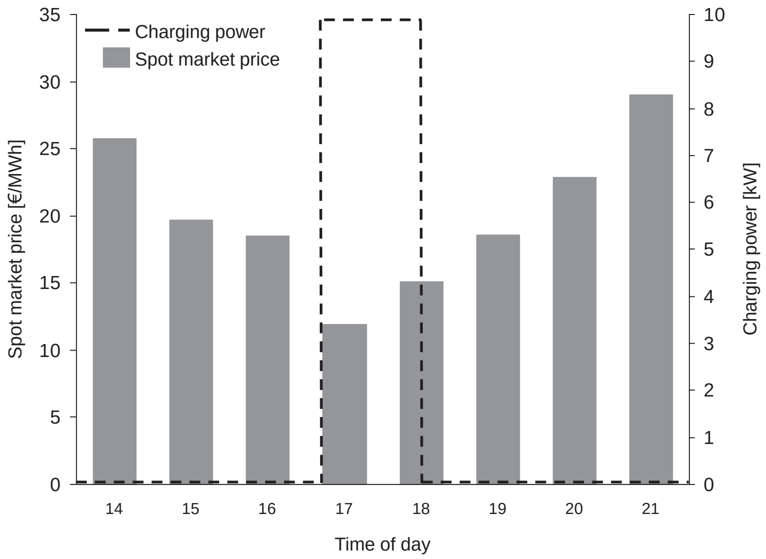

Figure B:6. Optimization procedure for one charging process and one EV on a certain day.

The car-sharing operator can expect significant cost savings when applying the suggested DR program. The annual charging costs were calculated to be €206.50 using Eq. (B.9).

If the whole 87-car fleet of our car-sharing operator were electrified, the annual cost savings would amount to €1,868 (annual charging costs uncontrolled charging = €4,434 / annual charging costs smart charging = €2,566).

1.6 Discussion

Our analysis is based on a business case with a car-sharing operator in Germany. Nevertheless, our suggested IS design for applying DR to EV fleets can be adopted by all kinds of companies with characteristics similar to those of our pilot case company, including logistics providers, parcel delivery firms, or outpatient nursing services. As part of the IS, a prediction model was used to forecast the vehicles' usage times and energy consumption. This information is a prerequisite for deriving the optimal decision to shift demand at a given time. Precise predictions for upcoming but not already executed bookings are particularly important for car-sharing providers applying DR because incorrect predictions of EV demand may lead to additional costs. In this context, it must be noted that the main goal of a car-sharing operator is to fulfill all booking orders rather than optimizing energy procurement costs.

Using an optimization approach, we demonstrated that fleet operators can expect significant cost savings when applying DR programs for their EV fleets. Within our suggested DR program, charging processes are interrupted during spot market price peaks and shifted to the hours in which the spot market prices are the lowest. This results in cost savings of at least 42% in comparison to a simple plug-and-charge approach. Thus, applying DR programs has the potential to make EV fleets economically sustainable, as the already existing operational cost advantage can be further increased. Furthermore, fleet operators using EVs can expect reputational benefits from adopting eco-friendly technology. The combination of these aspects could promote the market penetration of EVs, thereby supporting the government's objective of reducing transport emissions. In particular, the electrification of car-sharing vehicles offers great environmental potential, as almost 0.5 million people used car-sharing services regularly in Germany in 2014 (IfD Allensbach, 2014), and it can only be assumed that the number of users will increase.

The DR program presented is also associated with energetic benefits. It is generally known that charging a large number of EVs in an uncontrolled manner is likely to jeopardize the security of energy supply because of an expected increase of peak load. This can be avoided by shifting charging times into time ranges in which electricity prices are low. Because electricity prices are particularly low when a large amount of renewable energy is available or electricity demand is low, the DR program would also indirectly promote the development of renewable energies. The German government's intention to increase the share of renewable energies (BMWi and BMU, 2010) influences DR programs in two ways. Discrepancies between power supply and demand can be expected to increase, which means that this DR program could make an important contribution to enhancing the security of energy supply. Furthermore, price volatilities on the spot market are also likely to increase (Ketterer, 2014), which would have a positive effect on the profitability of this DR program.

Our study contributes to IS research in three major ways. First, we appear to be the first to investigate how smart charging programs can be applied for fleet operators under realistic conditions. To do so, we conceptualized a comprehensive IS artifact that can be adopted by other companies using EVs. Second, we followed the call by Watson et al. (2010) and Dedrick (2010) by contributing to the research stream of energy informatics. In this regard, our approach helps to increase energy efficiency and match supply and demand in the grid. Third, our approach can contribute to assessing the economic value of IS-supported DR programs (Strüker and van Dinther, 2012).

However, the following limitations should be considered. As the investigation is based on a case study, the results cannot be expected to be representative for all kinds of users. Furthermore, we assumed that the fleet operator itself can act on the spot market. Under current energy market conditions, however, an intermediary offering access to the energy stock is required. Alternatively, a utility company can offer time-variable electricity tariffs, but both approaches would diminish the economic benefits. Finally, we established a prediction model to forecast the electricity demand of an EV. However, it is challenging to precisely predict future trips based on historical driving patterns, particularly if the EVs are used at irregular intervals.

1.7 Conclusion

In this study, we designed an IS artifact that can be used by fleet operators to apply DR programs for battery charging based on two components: a prediction model and an optimization model. Using real-world data from a car-sharing operator that uses EVs, we demonstrated that fleet operators can expect significant cost savings when applying DR programs for their EV fleets. Applying DR programs for EVs can thus make a valuable contribution to ensuring that these vehicles become economically competitive. This finding is significant because it addresses one of the main barriers of EV adoption, i.e., their significantly higher purchasing prices in comparison to conventional vehicles. Along with economic benefits, the implementation of controlled charging concepts also brings energetic benefits as DR promotes the development of renewables. However, the application of DR programs currently faces barriers, as most EV users have a limited understanding of the benefits of DR solutions. As our study revealed the potential for significant cost saving through the use of DR, this might convince further companies to adopt DR solutions.

Summarizing, we illustrated how IS research can foster sustainable development. Given the rapid expansion of renewable energies it is important that in the future smaller, flexible consumers participate in DR and respond to the intermittent supply of energy. From a fleet operator's point of view, DR seems compelling because energy procurement costs can be reduced by, for example, adjusting the time of energy usage. A useful extension of this work is to investigate the application of DR programs in further areas of applications, such as at logistics providers. Further, our IS must be expanded in future so that car-sharing users can supply information on future trips. This would increase the forecast reliability of EV energy demand for a certain period and thus facilitate the application of DR programs for EV fleets.

2 Study 3: Assessing the Potential of Different Charging Strategies for Electric Vehicle Fleets in Closed Transport Systems

Table B-10. Fact sheet of study no. 3.

Title	Assessing the Potential of Different Charging Strategies for Electric Vehicle Fleets in Closed Transport Systems
Authors	Johannes Schmidt*, Matthias Eisel, Lutz M. Kolbe Chair of Information Management, University of Göttingen, Platz der Göttinger Sieben 5, 37073 Göttingen, Germany *Corresponding author. Tel.: +49 551 3921177. E-mail: jschmida@wiwi.uni-goettingen.de
Outlet	Energy Policy 2014, Vol. 74, Completed Research Paper
Highlights	• We model various charging strategies for electric transport vehicles. • The economic assessment is based on a field experiment with a port operator. • We consider the special market design of spot and ancillary service markets. • All charging strategies presented provide substantial cost-saving potentials. • Optimizing energy procurement is more profitable than offering control reserve.
Abstract	A key reason for the low sales volumes of electric vehicles is their significantly higher purchasing price in comparison to conventional vehicles. However, various charging strategies can be applied to make these vehicles more profitable. In this paper, controlled charging concepts are transferred to commercial fleets operating in closed transport systems, as we found this field of application particularly well-suited for the implementation of charging strategies. We analyzed data gathered in a field experiment conducted in an European port using electric vehicles in combination with a battery-swapping station to calculate the economic potentials of three charging scenarios: (1) optimizing energy procurement (2) trading load-shifting potential on control markets, and (3) a combination of the two. The findings indicate that all approaches are appropriate for reducing economic disadvantages of electric transport vehicles. Furthermore, we find that adjusting charging processes to avoid price peaks is more profitable than offering control reserve. Finally, focusing on the combination of both strategies seems to be most promising from an economic perspective. In this context, operational cost savings of more than 65% can be achieved compared to a similar diesel-powered vehicle when applying this strategy.
Keywords	Electric Transport Vehicles, Closed Transport Systems, Charging Strategies

2.1 Introduction

Since the substitution of conventional vehicles with electric vehicles (EVs) is seen as an important factor in achieving a sustainable mobility sector, governments around the globe have defined target numbers of EVs. With the transport sector accounting for about one-fifth of greenhouse gas (GHG) emissions in the European Union and the United States, increasing the proportion of EVs in use holds great potential for reducing such emissions. Several studies identify the environmental advantages of EVs in reducing GHG emissions (e.g., Samaras and Meisterling, 2008) and for the energy system through facilitating the integration of intermittent renewable energy generation (e.g., Lund and Kempton, 2008). However, the efforts of many governments – including those of the USA, China, and Germany – in supporting electric mobility projects or creating various incentive systems to promote electric vehicle sales have not brought the expected success (Zhang et al., 2014; Rascoe and Seetharaman, 2013; NPE, 2012). In this regard, the significantly higher purchasing cost of EVs relative to conventional cars is a key barrier for user adoption. Even the lower lifetime operating costs of EVs cannot compensate for this economic disadvantage (Propfe et al., 2012). One possibility for meeting this challenge is to apply suitable charging strategies (e.g., vehicle-to-grid [V2G] or smart charging) that save energy costs or even create revenue by feeding in electricity to the grid, ensuring that these vehicles are economically competitive.

These concepts have been described in the literature mainly for privately owned electric vehicles (e.g., Andersson et al., 2010; Kempton and Tomić, 2005a; Letendre and Kempton, 2002). Little research has been conducted on how to transfer these charging strategies to commercial fleets in closed transport systems. However, the electrification of vehicles operating in closed transport systems offers great potential as almost one million industrial trucks were ordered worldwide in 2012 (Statista, 2014a). Furthermore, commercial fleets operating in closed transport systems seem to be particularly suitable for the broad implementation of controlled charging concepts. The key reasons for this are the economies of scale resulting from the aggregation of a large number of EV batteries, the possibility of using a battery-swapping station on company grounds, and significantly better prediction of energy consumption and vehicle operating times compared to privately owned EVs. Besides the economic benefits, controlled charging concepts are also associated with energetic benefits. For example, charging processes can be shifted to periods in which overall electricity demand is low or power generation from renewables is high. A valuable contribution to ensuring the security of energy supply or promoting the development of renewables can thus be achieved.

In order to assess the economic potential of these charging concepts, we analyze data gathered in a field experiment conducted at one of the largest European ports (Hamburg), where an electric vehicle fleet is used to load and unload containerships. This enables us to examine whether electric transport vehicles are a viable alternative to diesel-powered transport vehicles in closed transport systems. The aim of our research is thus to adjust and transfer charging strategies to the environment of closed transport systems and calculate the economic potential. In addition, we discuss the energy-related impacts.

The remainder of this paper is organized as follows. Section B.II.2.2 examines charging strategies, the energy market design in Germany, and characteristics of electric mobility fleets in closed transport systems. In addition, methods are developed for quantifying the charging strategies presented in economic terms with respect to the business case. In Section B.II.2.3, we present the economic results when applying the suggested charging strategies. Afterwards, Section B.II.2.4 evaluates these strategies in terms of economic potential and practicability. Section B.II.2.5 concludes the paper with a discussion of the main findings and implications for further research.

2.2 Material and Method

2.2.1 Charging Strategies

Various charging strategies, such as smart charging and vehicle-to-grid, can be applied for reducing the operational costs of EVs. From a user's perspective, smart charging concepts generally attempt to take advantage of the variation in electricity prices throughout the day (DiUS, 2013). Charging processes can be shifted from critical to non-critical load hours to exploit the lower costs, depending on the situation in the grid (Valentine et al., 2011). Hence, customers can reduce their energy procurement costs while energy companies and transmission system operators (TSOs) benefit from reduced system costs due to load shifting (Wang et al., 2011a).

Another approach to reducing the economic disadvantages of EVs that has received significant attention is known as the vehicle-to-grid concept (V2G). The basic idea is that battery electric vehicles (BEVs) connected to the grid store surplus energy when necessary or supply energy during off-peak periods (Letendre and Kempton, 2002). The V2G approach plays an important role for the integration of renewables into the power grid since the aggregation of several BEVs results in large virtual-electricity storage (Larsen et al., 2008). From the EV user's point of view, the V2G approach seems compelling, as the total cost of utilization can be reduced by the additional profits resulting from participation in ancillary markets (Kempton and Tomić, 2005a).

2.2.2 Energy Market Design

The realization of smart charging and V2G requires acting on different energy markets. Smart charging is usually realized by energy purchases on electricity spot markets. In Germany, electricity spot prices are obtained from the European Energy Exchange (EEX), where hourly prices are determined by day-ahead auctions. Based on demand and supply, one uniform market price for all actors (market-clearing price) is determined (Ellersdorfer, 2005). As pointed out above, it is possible to take advantage of price differences (e.g., off-peak charging) due to the flexibility of the charging processes (Tirez et al., 2010). However, the minimum order size on this market is 1 MW in Germany.

On the other hand, the V2G concept can be realized by acting on ancillary energy markets. Many studies (e.g., Guille and Gross, 2009; Sovacool and Hirsh, 2009; Brooks, 2002) consider the provision of regulation services as the most profitable for V2G. EVs can generally provide regulation up (positive control reserve) by feeding electricity back into the grid when overall electricity demand is higher than supply and a frequency reduction is required. Analogously, EVs can also provide regulation down (negative control reserve) by charging the batteries to achieve the required frequency reduction (Kempton and Tomić, 2005b). In Germany, three different types of control reserves are used to keep the frequency stable, depending on the required demand and response time. For this, German TSOs procure ancillary services through public market auctions on a common Internet platform. All bidders on control markets must pass a pre-qualification procedure according to UCTE (Union for the Co-ordination of Transmission of Electricity) requirements before bidding (Riedel and Weigt, 2007).

In this study, we focus on tertiary control reserve in order to transfer the V2G concept to commercial fleets in closed transport systems. This kind of control reserve is used in case of a large imbalance between demand and supply, when other control types would be insufficient to bring the frequency down. In general, tertiary control reserve is the most realistic option for any provider that collects electric vehicles to act on German control markets; technical requirements according to the pre-qualification are much higher for primary and secondary control reserve, resulting in few actors on these markets (Hirth and Ziegenhagen, 2013). In this regard, primary and secondary control reserve must be fully deployed automatically within 30 seconds and 5 minutes, while tertiary control reserve is usually activated manually within 15 minutes (Swider, 2007). Moreover, the procurement auctions for tertiary control reserve take place daily while primary and secondary reserve is allocated in contracts that last for one week (Regelleistung, 2013a). Accordingly, when offering secondary or primary control reserve, vehicle availability for the one-week period must be known ahead of time, which is extremely difficult to forecast in reality.

The tertiary reserve auction is divided into six time slices, each consisting of four consecutive hours (time slice 1: 00:00 a.m. to 04:00 a.m., and so on). An offer must be submitted day-ahead, while it is activated in schedules of 15 minutes. Furthermore, the offers supplied must exceed a minimum supply of 5 MW in Germany, though pooling is possible within a control area (Regelleistung, 2013a). An actor on the tertiary control market can be paid in two ways: the mere provision of capacity is funded over a given contract period with the capacity price, while an energy price is paid in case of selling regulation up and down for the actual amount of energy dispatched (Müller and Rammerstorfer, 2008).

An important challenge for participation in control markets is the special tendering procedure following the concept of merit order (Riedel and Weigt, 2007). In the first step, the TSO sorts all bids by capacity price (in €/MW), beginning with the lowest. Bids are accepted until the predicted demand for tertiary control is satisfied. The tendering procedure is similar when the power reserve is actually needed: the TSO sorts all orders by ascending energy prices (in €/MWh), and all bids are accepted according to the second merit order. Contrary to the spot market, all actors are paid their individually offered prices in a pay-as-bid system. The tendering procedure for the capacity price is illustrated for a representative day (November 15, 2011) in Figure B:7. Every actor’s bid with an offered price lower than the highest accepted price (stop-out-price; here, 11.98 €/MW) is accepted.

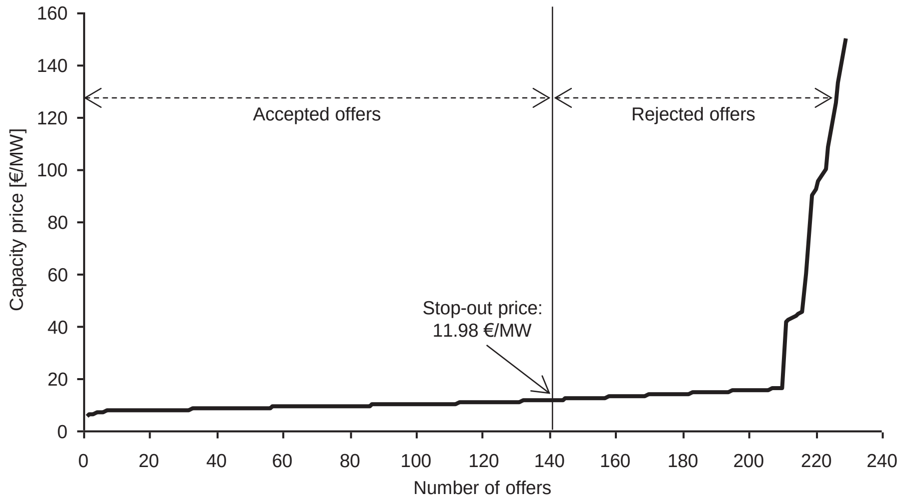

Figure B:7. Illustration of the capacity-tendering procedure on a representative day.

Surprisingly, most studies investigating the economic profitability of the V2G concept in Germany (e.g., Dallinger et al., 2011; Andersson et al., 2010) do not consider the special tendering procedure on control markets. Moreover, most V2G results are based on annual average capacity and energy prices, or even market-clearing prices (e.g., Williams and Kurani, 2007; Tomić and Kempton, 2007). However, the actual profit generated by the V2G approach depends directly on the bidding strategy, defined as the tender price for a certain time slice for the next day. In this context, the tender price influences both the probability of a bid being accepted and the revenue per time slice. Therefore, bidding strategies for participating successfully in the tendering procedure are developed in Section B.II.2.2.5.3.

2.2.3 Electric Mobility in Closed Transport Systems

Generally, fleets are particularly well-suited for controlled charging concepts because it is possible to exploit economic and energetic efficiencies by aggregating a large number of EVs (Guille and Gross, 2009). Previous calculations have indicated that providing V2G power from EV fleets is likely to be profitable (e.g., De Los Rios et al., 2012; Han et al., 2010; Tomić and Kempton, 2007). One proposed business model is based on the aggregation of dispersed vehicles within an existing business relationship (e.g., vehicles from a logistic service provider). Alternatively, an independent party can serve as an aggregator for dispersed EVs. Fleet operators with a sufficient number of vehicles can act by themselves on energy markets as they exceed minimum bid sizes on the spot market or ancillary service markets. In addition, aggregators benefit from economies of scale resulting from larger purchasing orders on electricity markets. Furthermore, with more vehicles aggregated, changes in individual driving times would be nearly negligible in capacity planning for energy procurement and provision of V2G services. However, fleet operators also grapple with obstacles that exacerbate the widespread adoption of controlled charging: detailed information about energy consumption is required for applying these approaches to fleets, and user acceptance problems occur because the aggregator is able to influence the charging processes of their properties. Moreover, achieving a critical mass of EVs is also essential for successfully implementing a business environment of additional services around dispersed vehicle fleets.

When focusing on closed transport systems, the benefits of aggregated V2G and smart charging can generally be exploited. At the same time, the problem of individual driving times and mobility demands complicating their implementation occurs less frequently. In this regard, energy consumption forecasts can be made more precise based on order confirmations, delivery dates, or arrival times. If the transport vehicles operate at fixed times, it is easy to develop beneficial smart charging routines and use these vehicles for V2G (Williams and Kurani, 2007; Kempton and Tomić, 2005b). Additional favorable characteristics in this area of application include the possibility for pooling to take place on company grounds and that the vehicles have a predefined operation range. In combination, these two aspects greatly facilitate coordination in the realization of both V2G and smart charging. Furthermore, the operation time of transport vehicles can be coordinated to a certain degree, creating a load-shifting potential that can be marketed according to either concept. For these reasons, focusing on commercial fleets in closed transport systems as a further business model for aggregation services is a reasonable first step towards the broad implementation of smart charging and the V2G concept.

2.2.4 Description of the Business Case

The German electric mobility project BESIC (Battery Electric Heavy Goods Vehicles within Intelligent Container Terminal Operation) serves as a business case to ensure the viability of the charging strategies presented here and to evaluate economic implications. Within the scope of the project, a battery-swapping station was implemented to guarantee continuous operation of the battery automated guided vehicles (B-AGVs) by decoupling charging processes from operation time. Currently, 10 of the 80 AGVs (automated guided vehicles) operating within the terminal have been substituted by B-AGVs. Lead–acid batteries were chosen because they are sufficient for the transport requirements (operation time with one battery charge: 12 hours). Furthermore, they are significantly cheaper than similar state-of-the-art lithium–ion batteries. For each battery, an additional (twin) battery was deployed to ensure continual operation. This results in a total of 20 lead–acid batteries with a useable capacity of 223 kWh each. Finally, the charging rate was fixed at 1/6 C-rate, making it possible to fully charge the batteries in six hours. Because a certain number of batteries are always in the swapping station, the combined storage capacity can be interpreted as quasi-stationary. Furthermore, the average operation time with one battery charge is six hours longer than the number of hours necessary to fully charge the batteries. For these reasons, the resulting load-shifting potential can be marketed according to the V2G or smart charging concept. The overall goal of this paper is to determine for this business case how the resulting load-shifting potential can best be economically exploited by evaluating various charging strategies.

2.2.5 Application of the Charging Strategies

In this section, we adjust and transfer four charging strategies to the environment of closed transport systems and calculate the resulting economic potentials for the reference year of 2012. These charging strategies are referred to as:

1) Plug-and-charge: uncontrolled charging processes based on fixed electricity prices;
2) Smart charging: charging during the cheapest hours of the day (off-peak hours), realized by energy procurement on the spot market;
3) Battery-to-(regulation)-market (B2M): provision of control reserve on regulation markets by batteries located in the swapping station; and
4) A combination of smart charging and B2M: provision of control reserve and necessary pre- and recharging in the least expensive remaining hours.

The most important requirement for charging-strategy development is compliance with the logistic premise of the fleet operator; influencing the charging processes (e.g., by providing control reserve) must not lead to limitations in the execution of daily logistic tasks due to an insufficient battery status. Based on the project characteristics, further assumptions are presented. Each day is divided into two 12-hour time frames, according to the operation times of the 10 B-AGVs used. In order to best offer control reserve, the time frames are chosen to be from midnight to noon and vice versa (see Section B.II.2.2.2). As illustrated in Figure B:8, both time frames thus consist of three four-hour time slices. Moreover, all batteries in use are assumed to enter the battery-swapping station completely discharged, at the same time (12:00 a.m. and 12:00 p.m.) and must be fully charged at the end of each time frame. Accordingly, we assume full utilization of the 10 B-AGVs used. These assumptions are realistic as not all AGVs will be replaced by B-AGVs in the project and it is therefore possible to match the operation times with the time frames. The control of the vehicles' operation times according to the time frame presents the additional benefit of having the maximum number of discharged batteries located in the swapping station at the same time, available for providing control reserve. Finally, handling energy purchases on the spot market can be simplified due to the predictable charging times of the whole fleet.

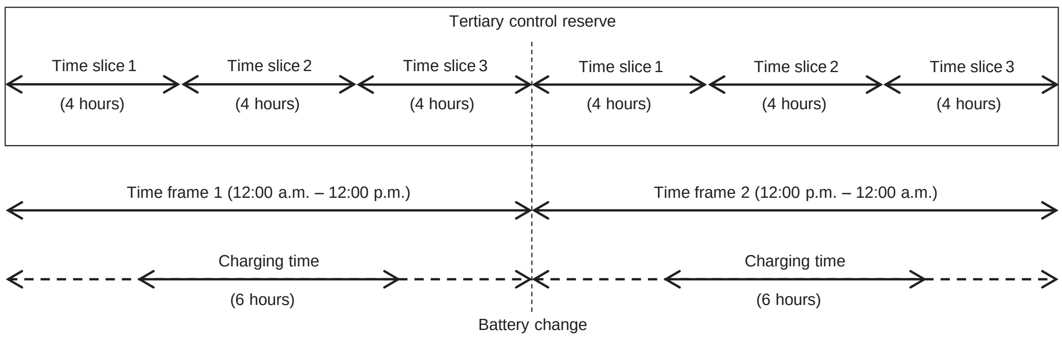

Figure B:8. Division of the day into two time frames and six time slices.

Moreover, we assume a linear battery charge and discharge. Battery changing times are not considered in the calculations. Therefore, the batteries can be charged without loss of time in the battery-swapping station. Finally, we assume that there is neither a minimum supply offer on control markets – which can be justified since pooling of single offers is possible on the German control market – nor the existing minimum order size on spot markets.

2.2.5.1 Plug-and-Charge Strategy

When implementing this plug-and-charge strategy (PnC), the B-AGVs batteries begin charging immediately after being connected to the grid and stop when the batteries are fully charged (Parks et al., 2007). According to the 12-hour operation time of each battery, they remain unused for 6 hours in the swapping station after completing their charging processes. This strategy is used as the basic scenario because it is easy to implement in business logistic sequences. The resulting charging process is illustrated in Figure B:9.

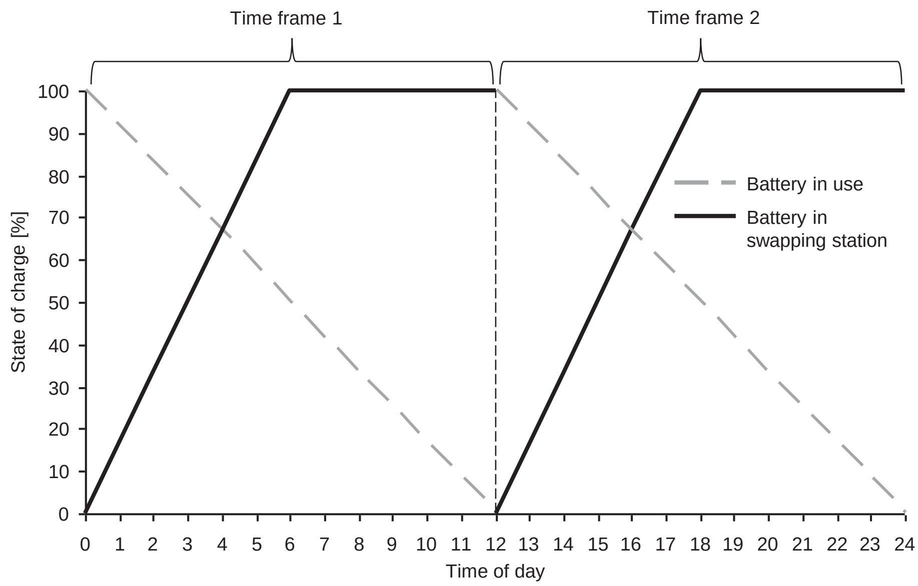

Figure B:9. Illustration of the plug-and-charge strategy during a full day.

The calculation of charging costs C_{TF} per time frame and day for using this strategy is based on the average electricity retail price for the industry sector $p_{industry}$ in 2012, the respective electricity demand of one battery d_{bat} per time frame, and the number of batteries available in the battery-swapping station n_{bss}. The electricity demand corresponds to the usable capacity of the storage device because all batteries are assumed to be fully discharged when entering the swapping station and must be fully charged by the end of a time frame. However, the charging efficiency η must be considered by adjusting d_{bat}. The parameter n_{bss} is not dependent on time as there are always 10 batteries available in the swapping station that can be charged simultaneously (see Section B.II.2.2.5). Based on these parameters, we use the following equation to calculate the charging costs per time frame

$$C_{TF} = p_{industry} \frac{d_{bat}}{\eta} n_{bss}. \tag{B.11}$$

The annual costs C_{PnC} resulting from this charging strategy can thus be described by

$$C_{PnC} = 2 \sum_{t=1}^{365} C_{TF}. \tag{B.12}$$

2.2.5.2 Smart Charging Strategy

Contrary to the plug-and-charge strategy, when implementing the smart charging strategy, charging processes do not necessarily start immediately after plug-in. In this context, the overall goal is to fully charge the batteries during the hours with the lowest possible electricity prices, thereby avoiding load peaks (Galus et al., 2010). One way to make use of the price differences between peak load and off-peak hours is to purchase energy on the spot market. In general, it is possible to optimize energy procurement costs for a certain day since hourly spot market prices for electricity are published on the previous day.

For the calculation of annual charging costs C_{SC}, we computed minimal charging costs for all time frames of the reference year. Let $M = 6$ be the number of hours necessary to fully charge the batteries and $I = 12$ be the number of hours in each time frame f on day t. The optimization of charging costs per time frame and day $C_{TF}(f,t)$ can be achieved by shifting charging times to the M hours with the lowest spot market prices for electricity within each time frame.

In order to obtain a realistic variable price profile, one must add further fixed price components p_{fix} to the hourly spot market prices per day $p_{spot}(i,f,t)$. In this context, the spot market price for electricity only represents the wholesale price for a certain amount of energy (usually a multiple of 1 MW), while the retail price for electricity in Germany consists of two further components that must be considered: grid and additional fixed fees (e.g., apportionments for the promotion of renewable electricity) and electricity taxes (Traber et al., 2011). The equation for calculating the time-dependent retail price for electricity $p_R(i,f,t)$ is given below

$$p_R(i,f,t) = p_{spot}(i,f,t) + p_{fix}. \tag{B.13}$$

One must determine whether to charge during a certain hour of each time frame based on hourly spot market prices. In order to make this decision and thus charge in the hours with lowest spot market prices, we use the following functions

$$H(i,f,t) = \begin{cases} 1 \text{ if the batteries are charged in hour i within time frame f on day t} \\ 0 \text{ if the batteries are not charged in hour i within time frame f on day t.} \end{cases} \tag{B.14}$$

Next, we calculate the hourly electricity demand $d_{bss}(H(i,f,t))$ for the n_{bss} batteries in the swapping station. Again, we use the electricity demand d_{bat} of one battery per time frame and the charging efficiency η. Finally, $d_{bss}(H(i,f,t))$ is obtained from

$$d_{bss}\big(H(i,f,t)\big) = n_{bss}\frac{d_{bat}}{\eta M}H(i,f,t), \tag{B.15}$$

with $M = 6$ hours necessary to fully charge the battery. The corresponding optimization problem for one time frame resolves to

$$\min_{H(i,f,t)} C_{TF}(f,t) \sum_{i=1}^{I} p_R(i,f,t)d(H(i,f,t)), \tag{B.16}$$

subject to

$$\sum_{i=1}^{I} H(i,f,t) = M \,\forall\, H(i,f,t) \in \{0,1\}; i \in \{1,\dots,I\}; f \in \{1,2\}; \text{and } t \in \{1,\dots,365\}. \tag{B.17}$$

Finally, the calculation of annual charging costs is performed by considering both time frames of the reference year

$$C_{SC} = \sum_{t=1}^{365}\sum_{f=1}^{2} C_{TF}(f,t). \tag{B.18}$$

2.2.5.3 Battery-to-Market Strategy

Because of the load-shifting potential (see Section B.II.2.2.4), it is possible to offer control reserve in selected time slices of four hours. In this study, we focus on tertiary control reserve for the implementation of the B2M approach (see Section B.II.2.2.2). Furthermore, we decide to only offer regulation down. The batteries are charged when selling regulation down (contrary to regulation up where power flows from vehicle to grid) so that further battery degradation is limited (Tomić and Kempton, 2007). This is particularly important for our business case since lead–acid batteries have a lower cycling capability than comparable lithium–ion batteries. Furthermore, various studies have revealed that earning potentials in Germany from selling regulation down are higher than those from selling regulation up (Hirth and Ziegenhagen, 2013; Jochem et al., 2013; Dallinger et al., 2011; Andersson et al., 2010).

Of particular importance for determining this charging strategy is compliance with the logistic premise (see Section B.II.2.2.5). In this context, control reserve cannot be offered during the third time slices. A provider must guarantee capacity for the four hours within a time slice, since a permanent activation of control reserve must be expected. However, if energy is not permanently dispatched for regulation down (the batteries are permanently charged), the batteries will not be fully charged at the end of a time frame. Therefore, the focus for offering control reserve lies on the first and second time slices of each time frame. However, considering the extreme scenario of no control reserve activation within either time slice, there would not be enough time left to fully charge the batteries. Hence, it is not possible to offer control reserve in both of the first two time slices within the same time frame. In order to identify the most promising time slice for the offer of control reserve and thus be able to make recommendations for optimally applying the B2M approach, we calculate annual expected revenues in each possible time slice.

As explained in Section B.II.2.2.2, submitting (day-ahead) capacity and energy prices is necessary for participation in the tendering procedure. Thus, a bidding strategy must be applied in order to submit the best offer for a certain quantity, given the information available. In general, each accepted bid generates revenue. For most companies using the B2M approach as a secondary business, building up their own energy-trading department would be too costly. Consequently, simplified bidding strategies based on historical data must be developed. Referring to Wagner and Oktoviany (2012), we use two bidding strategies to determine the tender price. A combination of daily and weekly seasonality is taken into account by considering successful bids during the same time slice from the corresponding day in the previous week. The “mean strategy” used is based on the arithmetic mean of all successful bids from the same time slice of the previous week. In contrast, we offer the stop-out price from the same time slice of the previous week when using the “marg strategy”. The application of these bidding strategies is illustrated in Figure B:10 for time slice 1 with the example of the mean strategy.

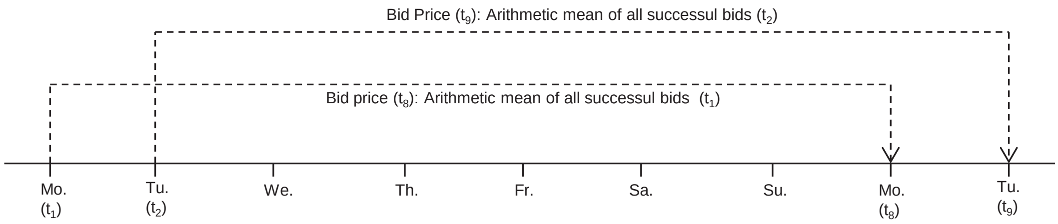

Figure B:10. Application of bidding strategy “mean” for the first time slices on two selected days.

Comparing both strategies, it can be assumed that the probability of being accepted with a bid is higher when using the mean strategy. However, prices of successful bids are higher when using the marg strategy. Therefore, we apply both strategies to calculate revenues from the B2M approach for each possible time slice of the reference year.

Of particular importance when calculating profits is distinguishing between capacity and energy payments and considering the special tendering procedure on control markets (see Section B.II.2.2.2). According to the two-stage merit order principle, a submitted bid for capacity would be fully rejected when the bid price $p_{cap}(k,t)$ for time slice k at day t (based on capacity prices of the corresponding day and time slice in the previous week) exceeds the stop-out price of that day $p_{cap,stop}(k,t)$. Thus, no revenue would be generated. If the bid price for capacity is lower than the stop-out price of that day, capacity payments $R_{cap}(k,t)$ are ensured. These revenues are calculated for each four-hour time slice. In order to distinguish between acceptance and rejection of the bid, the function below is used

$$H_{cap}(k,t) = \begin{cases} 0 \text{ if } p_{cap}(k,t) > p_{cap,stop}(k,t) \\ 1 \text{ if } p_{cap}(k,t) \leq p_{cap,stop}(k,t). \end{cases} \tag{B.19}$$

In the event that the bid was accepted, we multiply the bid price for capacity with the power available W. This power depends on the deliverable power of each connector W_{con} in the swapping station, the charging efficiency η, and the number of batteries n_{bss} available in the battery-swapping station for regulation services and is denoted by

$$W = n_{bss} W_{con} \eta. \tag{B.20}$$

We then derive the revenues per time slice via

$$R_{cap}(k,t) = H_{cap}(k,t) W p_{cap}(k,t). \tag{B.21}$$

When regulation down is needed in power systems, additional revenues from selling regulation down can be generated if the bid price $p_{Rd}(k,t)$ is lower than the current stop-out price $p_{Rd,stop}(k,t)$. However, if the bid price $p_{Rd}(k,t)$ exceeds the current stop-out price, the bid will be rejected and no additional profits can be generated. In addition, the necessity of a previously accepted capacity offer must be taken into account. As the activation of tertiary control reserve takes place in time slots j of T=0.25 h each, the number of stop-out prices $\mathrm{p_{Rd,stop}(j,k,t)}$ within a time slice k accordingly increases from 1 to 16 (where $\mathrm{j} \in [1,16]$ characterizes the current time slot within a time slice). However, it is necessary to submit one uniform price for the whole time slice. In order to distinguish between acceptance and rejection of the bid, we use the following function

$$\mathrm{H_{Rd}(j,k,t)} = \begin{cases} 0 \text{ if } \mathrm{p_{Rd}(k,t) > p_{Rd,stop}(j,k,t)} \\ 1 \text{ if } \mathrm{p_{Rd}(k,t) \leq p_{Rd,stop}(j,k,t)}. \end{cases} \quad \text{(B.22)}$$

Moreover, two price effects of regulation down must be considered. Positive energy prices can be interpreted as extra payment when charging the batteries. This has two economic advantages: savings potentials due to free charging $\mathrm{S_{free}\,(k,t)}$ and actual revenues from selling regulation down $\mathrm{R_{Rd}(k,t)}$. The latter can be calculated for $\mathrm{p_{Rd}(k,t) > 0}$ with

$$\mathrm{R_{Rd}(k,t) = H_{cap}(k,t) W T p_{Rd}(k,t) \sum_{j=1}^{16} H_{Rd}(j,k,t).} \quad \text{(B.23)}$$

In addition, free charging must be considered. The related savings $\mathrm{S_{free}(k,t)}$ for positive prices $\mathrm{p_{Rd}(k,t) > 0}$ are denoted by

$$\mathrm{C_{TF} = \; p_{industry} \frac{d_{bat}}{\eta} n_{bss}.} \quad \text{(B.24)}$$

On the other hand, negative energy prices for regulation down are associated with costs when providing control reserve. As long as these energy prices are lower than the actual retail prices for electricity, savings can be realized due to reduced energy procurement costs. In order to determine the related cost savings from the decreased charging costs $\mathrm{S_{low}\,(k,t)}$ within the time of activation, we use the following expression with $\mathrm{-p_{industry} < p_{Rd}(k,t) \leq 0}$

$$\mathrm{S_{low}(k,t) = H_{cap}(k,t) W T \left(p_{industry} + p_{Rd}(k,t)\right) \sum_{j=1}^{16} H_{Rd}(j,k,t).} \quad \text{(B.25)}$$

Finally, the resulting charging costs for using this strategy can be calculated by considering both revenues and savings compared to the charging costs for using the simple plug-and-charge approach. Comparing the two possible time slices for offering control reserve within both time frames allows one to determine the most beneficial time slice within each time frame k. Hence, the following expression for the annual charging costs in the battery-to-market strategy is obtained

$$\mathrm{C_{B2M} = C_{PnC} - \sum_{t=1}^{365} \sum_{k=1}^{2} \left(S_{low}(k,t) + S_{free}(k,t) + R_{B2M}(k,t)\right).} \quad \text{(B.26)}$$

2.2.5.4 Combination of Smart Charging and Battery-to-Market Strategy

This charging strategy represents a combination of the previously mentioned smart charging and battery-to-market approaches. The overall goal is to improve profitability of the B2M approach, which can be achieved by shifting necessary pre- or reloading processes (at least two hours) to the hours with the lowest spot market prices. We essentially followed the same approach explained in Section B.II.2.2.5.3 in order to identify the most promising time slices for the offer of control reserve. The calculation of profits due to capacity payments and selling regulation down is identical to the "pure" B2M approach. However, minor adjustments must be made in order to calculate savings potentials due to free charging $\tilde{S}_{free}$ or lowered charging costs $\tilde{S}_{low}$. In this regard, one must replace the average electricity price for the industry sector $p_{industry}$ by the time-dependent retail price for electricity $p_R(i,f,t)$ in a certain hour i within time frame f on day t. This is necessary because electricity for charging the batteries is procured on the spot market within the scope of this charging strategy. Hence, saving potentials with variable energy prices can be calculated with

$$\tilde{S}_{free}(k,t) = H_{cap}(k,t)WTp_R(i,f,t)\sum_{j=1}^{16} H_j(p_{Rd}(k,t))\text{, and} \tag{B.27}$$

$$\tilde{S}_{low}(k,t) = H_{cap}(k,t)WT(p_R(i,f,t) + p_{Rd}(k,t))\sum_{j=1}^{16} H_j(p_{Rd}(k,t)). \tag{B.28}$$

Furthermore, one must consider a slight modification for smart charging costs. The number of possible hours $i(k)$ in which the batteries can be charged within a time frame f will decrease from twelve to eight (neglecting four possible charging hours depending on the chosen time slice k for the provision of control reserve). Thus, we obtain a modified expression for calculating smart charging costs $\tilde{C}_{TF}(k)$ per time frame

$$\min_{H(i(k),f,t)} \tilde{C}_{TF}(k) \sum_{i(k)}^{I} p_R(i,f,t)d(H(i(k),f,t)), \tag{B.29}$$

subject to

$$\begin{aligned} &\sum_{i(k)}^{I} H(i(k),f,t) = M \ \forall\ H(i(k),f,t) \in \{0,1\}; k \in \{1,2\}; i(k) \\ &\in \begin{cases} \{5,\dots,I\} & \text{if } k = 1 \\ \{1,\dots,4,9,\dots,I\} & \text{if } k = 2 \end{cases}; \quad f \in \{1,2\}; t \in \{1,\dots,365\}. \end{aligned} \tag{B.30}$$

The resulting annual smart charging costs are denoted by $\tilde{C}_{SC}(k)$, depending on the chosen time slice k for the provision of control reserve

$$\tilde{C}_{SC}(k) = \sum_{t=1}^{365}\sum_{f=1}^{2} \tilde{C}_{TF}(f,t). \tag{B.31}$$

In order to calculate the annual costs for using the combined charging strategy, we subtract potential cost savings and profits from the modified smart charging costs

$$C_{B2M/SC} = \tilde{C}_{SC}(k) - \sum_{t=1}^{365} \sum_{k=1}^{2} \left(\tilde{S}_{low}(k,t) + \tilde{S}_{free}(k,t) + R_{B2M}(k,t) \right). \tag{B.32}$$

2.3 Results

The parameters and values necessary for the assessment of the charging strategies presented are summarized in Table B-11. All results below are based on these parameters.

Table B-11. Parameters used to calculate annual charging costs for the charging strategies in the reference year.

Charging strategy	Parameter	Value	Comments	Data source
General	η	95	Charging efficiency [%]	Project data
	n_{bss}	10	Number of batteries available in the battery-swapping station	Project data
Plug-and-charge	$p_{industry}$	140.2	Average electricity price for the industry sector [€/MWh]	Statista [2013a]
	d_{bat}	0.22	Electricity demand of one battery per time frame [MWh]	Project data
Smart charging	p_{spot}	[-87.52 – 265.3]	Electricity spot market prices in the reference year [€/MWh]	EEX [2013]
	p_{fix}	70.03	Fixed electricity price components [€/MWh]	Statista [2013b]
	p_t	[-17.22 – 335.6]	Time-dependent retail price for electricity [€/MWh]	Own calcluation
	d_{bss}	0.04	Electricity demand in each hour all batteries in the swapping station are charged [MWh]	Project data
Battery-to-market	$p_{cap,stop}$	[0 – 188.21]	Stop-out price for capacity [€/MW]	Regelleistung [2013b]
	$p_{cap,mean}$	[0 – 121.34]	Mean capacity price of all accepted offers [€/MW]	Regelleistung [2013b]
	$p_{Rd,stop}$	[-22.65 – 1,500]	Stop-out price for regulation down [€/MWh]	Regelleistung [2013b]
	$p_{Rd,mean}$	[-36.55 – 990.68]	Mean price for regulation down of all accepted offers [€/MWh]	Regelleistung [2013b]
	W_{con}	0.51	Power of each connector in the swapping station [MW]	Project data
	T	0.25	Activation time of tertiary control reserve [h]	Regelleistung [2013b]

2.3.1 *Plug-and-Charge Strategy*

Based on Table B-11 above, the parameters and respective values required for calculating annual charging costs can be extracted. The resulting costs for fully loading a B-AGV is €32.97, using constant electricity prices for the industry sector in 2012. The annual charging costs with the plug-and-charge strategy are calculated via Eq. (B.12) to be $C_{PnC} = €240{,}670$ for the entire fleet of 10 B-AGVs.

2.3.2 *Smart Charging Strategy*

This charging strategy was developed by optimizing energy procurement costs individually for each time frame and day of the year. Accordingly, the charging processes of each time frame are adjusted to charge the batteries in the hours with the lowest spot market prices. Most charging processes of the first time frame thus take place in the first hours (12:00 p.m. to 6:00 a.m.) as spot market prices are lower in off-peak hours. Regarding the second time frame, the charging processes are mostly interrupted from 4:00 p.m. to 10:00 p.m. to avoid the evening peak. Annual charging costs of €88,706 in time frame 1 and €96,773 in time frame 2 were calculated using Eq. (B.18) and the parameter listed in Table B-11. The charging costs in the first time frame are lower because the absolutely lowest prices per day normally prevail between 12:00 p.m. and 4:00 a.m.. This results in annual charging costs of $C_{SC} = € \, 185{,}479$ for using smart charging with all 10 B-AGVs. Hence, cost savings for using the smart charging approach are calculated as €55,191 for the entire fleet (compared to the plug-and-charge strategy).

2.3.3 Battery-to-Market Strategy

Based on two bidding strategies for the offer of control reserve, we calculate revenues resulting from the provision of control reserve in the first two time slices of each time frame for the reference year 2012. Annual expected profits from capacity provision per time slice was calculated using Eq. (B.21) with the parameters listed in Table B-11, while annual revenues from selling regulation down of the 10 batteries available in the swapping station were calculated using Eqs. (B.23) to (B.25).The results are summarized in Table B-12.

Table B-12. Annual revenues for using the B2M approach for the whole fleet.

		Annual revenues resulting from capacity payments [€]		**Annual revenues resulting from selling regulation down [€]**	
Time frame	Time slice	marg strategy	mean strategy	marg strategy	mean strategy
I	1	2,665	3,004	2,303	2,116
	2	2,870	**3,038**	**5,848**	4,297
II	1	916	984	4,888	2,938
	2	869	**896**	**5,027**	3,448
Maximal revenues (I+II)		**14,809**			

Comparing the two bidding strategies, mean strategy generates higher earnings for the provision of capacity. However, annual profits resulting selling regulation down in the reference year are higher when using the marg strategy. Probabilities to be accepted with a capacity bid are higher when using the mean strategy (average of 57.6% [mean] and 34.6% [marg]). On the other hand, higher profits per accepted bid can be achieved when using the marg strategy as a result of the higher tender price. Based on Table B-12, it seems reasonable to submit a bid for capacity by using the mean strategy while higher profits can be expected when submitting a bid for regulation down by using the marg strategy.

Given the logistic premise, it is only possible to offer tertiary control reserve in the first or second time slice per time frame. As revealed in the table above, it appears suitable to focus on the second time slice of each time frame because it represents the highest expected overall revenues. Therefore, one can expect overall annual revenues (including savings) of €8,886 in time frame 1 and €5,923 in time frame 2 when using the mean strategy for capacity bids and marg strategy for energy bids. Altogether, financial benefits of €14,809 can be generated.

According to Eq. (B.26), the resulting annual charging costs for using the B2M approach were calculated to be $C_{B2M} = €225{,}861$.

2.3.4 Combination of Smart Charging and Battery-to-Market Strategy

The calculation of annual revenues due to the provision of control reserve in the first two time slices of each time frame is similar to the "pure" B2M approach, but with additional attention paid to energy procurement costs on the spot market. In order to identify the most promising time slice for the offer of control reserve, we present the economic results for the B2M approach with variable prices for electricity in Table B-13.

Table B-13. Annual revenues for using the combined charging strategy for the whole fleet.

		Annual revenues resulting from capacity payments [€]		**Annual revenues resulting from selling regulation down [€]**	
Time frame	Time slice	marg strategy	mean strategy	marg strategy	mean strategy
I	1	2,665	3,004	1,851	1,470
	2	2,870	**3,038**	**4,867**	2,032
II	1	916	984	4,255	2,246
	2	869	**896**	**4,344**	2,736
Maximal revenues (I+II)		**13,145**			

Revenues for providing capacity are equal to those in the "pure" B2M approach. Nevertheless, revenues resulting from selling regulation down are different, as the reference price decreases from a constant value to a flexible one according to Eqs. (B.27) and (B.28). Total annual revenues (including savings) decrease slightly to €7,905 in time frame 1 and €5,240 in time frame 2, resulting in total revenues of €13,145. Just as with the "pure" B2M approach one can expect the highest revenues when offering tertiary control reserve in the second time slice of each time frame, using the mean strategy for capacity bids and marg strategy for energy bids. Based on these results, an optimal charging strategy that combines smart charging and B2M is as follows:

1) Pre-charging in the two cheapest hours of the first time slice;
2) Offering tertiary control reserve in the second time slice of each time frame (time frame I: 4:00 a.m. – 8:00 a.m.; time frame II: 4:00 a.m. – 8:00 p.m.); and
3) Optional recharging (depending on actual activation) in the last time slice for both time frames (time frame I: 8:00 a.m. – 12:00 a.m.; time frame II: 8:00 p.m. – 12:00 p.m.).

As the average activation time of regulation down is almost negligible (calculated as less than five minutes per day), we assume that energy is purchased day-ahead for the entire duration of the charging strategy. This is especially important for a realistic development and economic assessment of this charging strategy as we cannot precisely forecast the activation time of tertiary control reserve. Costs for smart charging are calculated to be €93,153 in time frame 1 and €98,550 in time frame 2, resulting in annual costs of $\tilde{C}_{SC} = €191{,}703$. Accordingly, charging costs are slightly higher when considering flexible electricity prices in time slices 1 and 3 compared to "pure" smart charging (Section B.II.2.3.2).

The resulting annual charging costs for the combination of B2M and smart charging were found using Equation Eq. (B.32) to be €85,248 in time frame 1 and €93,310 in time frame 2, resulting in total annual charging costs of $C_{B2M/SC} = €178{,}558$. For a complete economic assessment of this charging strategy, one must examine whether the additional revenues resulting from the B2M approach can compensate for possible higher electricity procurement costs. In this regard, the batteries are not necessarily charged in the lowest price intervals per time frame. According to the economic results from the smart charging strategy (Section B.II.2.3.2), it is clear that the additional revenues can compensate for the higher energy procurement costs. In this regard, annual charging costs are lower in both time frames when using the combination of B2M and smart charging.

2.3.5 Economical Comparison of the Charging Strategies

An economic evaluation of the charging strategies suggested is based on the comparison of annual charging costs. These consist of annual energy purchase costs due to the electricity demand from the B-AGVs and the reduction of energy costs by offering tertiary control reserve. The summarized results for the charging scenarios evaluated are given in Table B-14.

Table B-14. Economic assessment of the presented charging strategies (in €) for the whole fleet.

	Plug-and-charge	**Smart charging**	**Battery-to-market**		**B2M + Smart charging**	
Bidding strategy	-	-	Capacity bid = mean	Energy bid = marg	Capacity bid = mean	Energy bid = marg
Annual energy purchase cost	240,670	185,479	240,670		191,703	
Additonal revenues and savings	0	0	14,809		13,145	
Total energy costs	**240,670**	**185,479**	**225,867**		**178,558**	

It is apparent that total energy costs can be reduced significantly when using smart charging processes with flexible prices instead of charging at a fixed price with a full supply contract. The greatest cost-saving potential can be achieved by using the combination of B2M and smart charging for the charging process. However, these results must be discussed in detail.

2.4 Discussion

The results of the investigated charging strategies are based on a business case from the biggest port operator in Germany. However, it can be assumed that the basic characteristics of this company do not differ significantly from other transportation companies. Therefore, it is possible to derive recommendations for other companies, with a particular focus on airports, railway operators, and larger private transport companies. The evaluation of all charging strategies is based on three characteristics: efforts for implementation, economic potential, and energetic benefits with a focus on grid stability. A comparison of the charging strategies discussed in this section is presented in Table B-15.

Table B-15. Summarized evaluation of the presented charging strategies.

Characteristics	PnC	SC	B2M	SC+B2M
Efforts for implementation	++	+	-	--
Energetic benefits	--	+	+	++
Opportunity for cost savings	--	+	-	++
Opportunity for revenues	--	--	++	+
Annual charging costs	--	+	-	++

Among the charging strategies evaluated, plug-and-charge is the simplest but most expensive. Although no additional infrastructure is necessary for implementing this strategy, additional economic and energetic benefits cannot be generated otherwise. Compared to the annual fuel costs for an appropriate fleet of AGVs, cost savings of at least €285,000 (>54%) can be achieved, provided a tax-advantaged diesel price (approx. €0.80 per liter) for the port operator. If subsidies granted for harbor diesel were abolished, the charging strategies presented would generate even greater cost savings. This provides the opportunity for the government to foster electric mobility by narrowing the price gap between EVs and conventional vehicles.

Compared to the plug-and-charge approach, using the smart charging concept involves additional efforts and minor constraints of flexibility. Implementation of this strategy requires only slight modifications of the charging processes in order to avoid the evening peak in electricity spot market prices. It should be mentioned that energy procurement on this market was considered to be possible without any effort by transport companies. However, energy procurement must be made on the previous day and requires a minimum purchase volume. Offering more time-variable pricing tariffs could therefore be a good step for encouraging customers' participation in the smart charging concept. Altogether, using the smart charging strategy leads (under the assumptions made) to cost savings of approximately €55,000 compared to the plug-and-charge approach due to taking advantage of price differences. The average size of these price spreads has increased recently in Germany due to the development of renewable energies. In addition, it is likely that price spreads will rise while prices on the electricity spot market will drop (Genoese et al., 2010). The main cause for this development is the planned increase in the share of renewables to at least 35% in Germany by 2020 according to the Renewable Energy Sources Act (EEG). From a technical point of view, smart charging helps improve grid stability and promotes the development of renewables. In this regard, charging in off-peak hours makes a valuable contribution to balancing supply and demand. Thus, the number of necessary redispatch measures from the TSOs will be reduced (ceteris paribus), which offers potential for cost savings. Accordingly, customers could benefit from lower power grid charges.

The B2M concept generally leads to constraints in charging flexibility, as a certain battery capacity must be provided for a time slice of four hours. Additional efforts result from a necessary participation in the special tendering procedure of control markets. For reaching the minimum bid size, the project's fleet must be extended significantly. Alternatively, the minimum bid size on tertiary control markets could be lowered to provide companies the possibility of acting on control markets by themselves. As it is possible to generate revenues by offering capacity for regulation down, the related annual charging costs are lower than those for the plug-and-charge approach. Even though cost savings can be generated in addition to revenues, the B2M concept as implemented in this context is less lucrative than using the smart charging strategy. This results mainly from the almost negligible average activation time of regulation down and relatively low prices for tertiary control reserve.

However, the quantity demanded and thus the prices for negative control reserve in Germany have recently undergone an increase. This can be explained by the expansion of renewables – particularly wind energy – and the growing gap between energy demand and supply (Growitsch et al., 2010; Maurer et al., 2009). Moreover, the share of renewables is expected to surge while in addition fewer conventional power plants will be available to provide ancillary service due to the previously agreed-upon nuclear phase out. Both effects will lead to a rising demand for ancillary services (Bundesnetzagentur and Bundeskartellamt, 2013; Paulus and Borggrefe, 2011). Accordingly, a rising demand for control reserve would lead to an improvement for applying the B2M approach in closed transport systems. Thus, logistics and transport companies can develop a second mainstay due to participation in energy markets.

Similar to the implementation of the smart charging approach, B2M creates energetic advantages for the energy system. Providing capacity for tertiary control reserve is essential for balancing electricity supply and demand, since the aggregation of several B-AGVs results in large virtual-electricity storage. As the future need for intermittent renewable energy sources increases, more actors supplying control reserve are required in order to keep the grid frequency steady. A greater number of transport and logistics companies applying the B2M approach could be a suitable alternative, as these could satisfy the increasing demand for control reserve; this would make a valuable contribution to ensuring the security of energy supply. However, as the number of actors on ancillary markets would increase, earning potentials from the aggregation of energy sales may be lowered.

The most complex charging strategy examined is the combination of B2M and smart charging. Constraints in charging flexibility and efforts for implementation result from both the participation on ancillary markets and energy purchases on the spot market. In economic terms, focusing on this charging strategy seems to be most promising. Profits can be generated from the provision of control reserve while energy procurement can be economically improved. Energetic benefits result from the composition of both charging strategies explained above.

2.5 Conclusion and Policy Implications

This paper takes a comprehensive electric mobility project as case study to develop and evaluate various charging strategies for electric transport vehicles in closed transport systems. We found commercial EV transport fleets operating in a single location to be particularly well-suited for implementing controlled charging processes. Consequently, we recommend focusing on commercial fleets in closed transport systems as a reasonable first step towards the broad implementation of controlled charging concepts in the field of electric mobility. This results mainly from general fleet advantages as well as from reliable predictions of the energy consumption of these vehicles. In addition, the usage of a battery-swapping station in combination with acting on control and spot markets was identified as a suitable instrument for transferring the V2G and smart charging concepts to closed transport systems.

In general, the results indicate that all charging strategies presented are appropriate for reducing the economic disadvantages of electric transport vehicles. More specifically, our analysis revealed that even the simplest charging strategy provides a substantial economic cost-saving potential compared to the fuel costs of diesel-powered transport vehicles. The highest cost savings can be achieved by shifting battery charging to off-peak hours, although providing control reserve can generate additional revenues. Against the background of rising petrol prices, transport companies using controlled charging processes for EVs could even gain a competitive advantage. Another important aspect influencing future profitability is the development of renewables as it influences both price spreads on electricity spot markets and demand for control reserve.

For policymakers, fostering electric mobility in closed transport systems seems to be promising. Few government subsidies would be necessary to make it profitable, and thus to reach market maturity. This could promote the market penetration of electric transport vehicles and would support the government’s objective of achieving a sustainable transport system. From an environmental point of view, the substitution of conventional transport vehicles for EVs is an important and often underestimated factor for achieving climate protection objectives. The electrification of the whole transport fleet considered would result in savings of more than 3.5 million liters of fuel (diesel). Depending on the applied electricity mix, corresponding savings of up to 11,400t CO_2 eq. emissions are possible. Replacing conventional industry trucks (annual sales close to 1 million vehicles) with electrical transport vehicles thus offers a huge potential for reducing GHG emissions. Another benefit from a political perspective is the resulting decreased dependency on petroleum. For these reasons, we recommend paying more attention to electric transport vehicles as a suitable measure for fostering the government’s environmental and energy goals.

Moreover, our analysis reveals some interesting energy-related findings that could be relevant for policymakers. Charging in off-peak hours or offering capacity for control reserve can help to ensure the security of energy supply and promote the development of renewables. However, the feasibility of these charging concepts is limited due to regulatory requirements and still requires some modifications of key parameters in the two regarded power markets (see Andersson et al., 2010). In Germany, the Bundesnetzagentur (Federal Network Agency for Electricity, Gas, Telecommunications, Post and Railway) should consider decreasing the minimum bid size in control reserve markets further to facilitate the access of electric-vehicle fleet operators to control markets. In this regard, a provider in Germany must offer 5 MW of energy over a period of at least four hours, which results in a minimum size of 20 MWh. Therefore, the fleet considered in this study must be extended significantly from 10 to at least 90 B-AGVs with a capacity of 223 kWh each. In addition, offering time-variable pricing tariffs could help customers participate in the smart charging concept. Policymakers should focus on measures to better integrate EVs into the energy system, such as inducing power producers to offer more variable pricing tariffs.

As the focus of this study lies on the analysis of economic impacts, the energetic effects of the charging strategies on the power grid deserve a more detailed analysis. Furthermore, a useful extension of this work could be considering the whole electricity consumption of companies, so that charging processes could support a corporate-wide demand-side management system. Finally, a comprehensive total cost of ownership analysis should be conducted with real battery degradation data, different types of batteries, different equipment scenarios of EVs, and future development scenarios of renewables.

3 Study 4: Simulation of Power Demand in a Maritime Container Terminal using an Event-Driven Data Acquisition Module

Table B-16. Fact sheet of study no. 4.

Title	Simulation of Power Demand in a Maritime Container Terminal using an Event-Driven Data Acquisition Module
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Outlet	4th International Conference on Logistics and Maritime Systems (LOGMS) 2014, Presented, Completed Research Paper
Abstract	A simulation model for a container terminal typically includes the logistic processes in the quay area, waterside horizontal transport, yard area, landside horizontal transport and gate area for truck and rail access. We integrated a charging infrastructure model into a model of the container handling system (works with battery exchanges), in order to investigate the cost-effectiveness of the use of battery-electric transport vehicles. Moreover, we had to acquire power demand data from within our combined simulation model, but we found shortcomings in recent developments of such energy-related simulation modules. Instead of following a purely state-driven manner, we opted towards an event-driven manner for the simulation of power demand and acquisition of power demand data.
Keywords	Container Terminal Operations, Container Terminal Simulation, Energy Demand Simulation, Energy Management

3.1 Maritime Container Terminals and Electric Mobility

Maritime container terminals offer equipment and services for transshipment of cargo containers and/or bulk cargo between container ships and in most cases trucks and railroad vehicles. By virtue of an enormous growth in the container industry, container terminals are geared to perform as many transshipment operations as they possibly can in a short period of time. In recent decades, transshipment frequency has significantly increased at German container ports, so the buffer and storage areas have become scarce at first (OECD reports accordingly, 2012). At the same time national and nearby international container ports have been newly built or upgraded, so that a considerable competitive pressure has arisen (ISL and IHS, 2010). The last couple of years were more or less characterized by stagnation or even decline in container volume paired with still more heaps of container charging/discharging requests (ISL, 2013). As a result, new and more efficient tools for handling and transport of the containers are always needed. Attempts to achieve a high degree of automation are often made in countries with high labor costs (Kemme, 2013).

In order to charge/discharge huge amounts of standard containers and reduce labor costs at the same time, it has become favorable to use automated guided vehicles (AGVs). An AGV is a driverless transport vehicle, which receives a container from a crane and a crane is required to take the container off again (Vis and Harika, 2005). Most AGVs are operated in a fleet of automatically controlled transport vehicles within a fenced area on the seaside of the container terminal. Around the world HHLA Container-Terminal Altenwerder (CTA) was the first to test a prototype of a fully electrified AGV. It was found that the expenses for operating battery-powered AGVs are drastically lower than the expenses for diesel-powered vehicles; keeping up with the trend of electrifying maritime terminals, such self-contained container logistic system can be seen as one of the most promising and perhaps path-breaking application contexts for electric mobility (HHLA, 2011). Shortly thereafter, APM Terminals Maasvlakte 2 (M-2) was the first container terminal to order a fleet of 37 fully electrified automated lifting vehicles (Lift-AGVs) (Port Technology International, 2012). Besides the positive impact on the environment, using battery-electric AGVs also reduces costs. As of today diesel is one of the major cost components in operating a fleet of transport vehicles in a container terminal. In comparison between wholesale electricity prices and diesel supply prices the electricity consumption of a battery-electric AGV is more cost effective than diesel consumption of a diesel-electric AGV (Runge, 2013).

Moreover, world-class container terminals like M-2 and CTA have most profound chances to lowering energy costs even further by participating in electricity markets – the spot market as well as the balancing power market. Especially for coastal industries such as a container port the charging of battery systems for transport vehicles brings up new opportunities. They might exploit the inherently uncertain electricity generation of nearby wind and solar power plants and benefit from dynamic electricity pricing. Typically wholesale electricity prices decline whenever there is excess electricity in the transmission network. In order to carry out such energy-related management use cases, it is necessary to forecast electricity demand of container terminal operations more accurately and to build tools for energy-related optimization of battery exchange and/or stationary charging operations.

In this paper, we put forward a simulation-based approach to electricity demand forecasting. First of all, we give an overview of domain-specific simulation tools, built-in modules for energy-related analysis and some simulation projects. Secondly, we describe a concept of an event-based simulation module for the acquisition of power demand data. Third, we describe our charging infrastructure model and its integration into a container logistics model. To verify their effectiveness, both the general building blocks for the acquisition of power consumption data as well as a model of energy-related behavior of container handling equipment were applied to investigate energy demand of CTA as a whole and its subsystems, including battery-electric AGVs. We will briefly discuss first results of our simulation system and point out to future work in this field of energy-related modeling and simulation.

3.2 Container Terminal Simulation Models and Energy-Related Simulation Tools

A container terminal is often subdivided into several subsystems according to the type of operations and the container handling equipment involved. They have different layout structures depending on the level of process automation, the equipment used and the orientation of their storage blocks. Since the different subsystems are linked with one another, each subsystem should be designed and managed in such a way that the connected subsystems may be operated most efficiently (Voß et al., 2004). Due to the high demands in productivity and automation, special simulation tools have been developed for computer aided planning of container terminal design and container terminal operations. Nowadays all change and innovation processes regarding terminal structures, yard layout, general operation strategies, etc. may be accompanied by means of simulation (Schütt, 2011). A simulation model typically includes the logistic processes in the quay area, waterside horizontal transport, yard area, landside horizontal transport and gate area for truck and rail access. At the quay area, the vessels are charged / discharged by the quay cranes which are served by horizontal transport machines (Yang et al., 2004).

3.2.1 Simulation-based container terminal planning models

Quite a few simulation models are used strategically to study and compare alternative terminal layout plans, performance of different kinds of container handling equipment, chances and risk of leasing and financing policies and different management rules. Such simulation techniques are mainly used in the design and master-planning phase of a new port or extension of an existing port from a consulting point of view:

- Merkuryev et al. (1998) discuss the key issues of modeling and simulation for management of the Riga Harbour Container Terminal with ARENA. They opted to improve the logistic processes in general. Their simulation model was used for analysis purposes.

- Yun and Choi (1999) propose modeling and simulation of the Korean Pusan Container Terminal with SIMPLE++ (after that known as eM-Plant and now known as Plant Simulation). Their simulation model includes the berthing area, yard area and gate area. It is used to calculate the most commonly used key performance indicators.
- Tahar and Hussain (2000) discuss key issues of modeling and simulation of the Malaysian Kelang Container Terminal with ARENA. Their simulation model includes all processes required to operate the seaport efficiently, having a focus on the allocation of quay cranes and scheduling of truck-trailer units. It is used to retrieve detailed statistics on throughput and other utilization characteristics, in order to evaluate general management strategies and scheduling rules.

Some more examples for terminal simulation are given by Khoshnevis and Asef-Vaziri (2000) as well as Huang et al. (2007). Another overview about various simulation projects is given by Stahlbock and Voß (2007).

3.2.2 Academic container terminal simulation models

Most of the simulation models are developed to study optimization problems in planning and managing operations for an existing terminal configuration (studies are being carried out for fixed terminal layouts and sets of container handling equipment):

- Martinssen et al. (2001) developed a simulation model for HHLA Container-Terminal Altenwerder in Hamburg with Plant Simulation, formerly known as eM-Plant. Their model focusses on the quay area and the yard area. It was used to study the outcome of bio-inspired methods to optimize quay-side transshipment and horizontal transport operations. They showed in a feasibility analysis, whether it is possible to reduce demurrage that way.
- Lochana Moorthy et al. (2003) developed an algorithm for prediction and avoidance of deadlocks in container handling systems. They focused on AGV system designs with complex road layout and a fairly high number of AGVs. There are a lot of situations, in which the system may stall and most of these situations can be avoided through coordinated AGV routing. In order to test their graph-based AGV deadlock detection procedures, they used a simulation model in AutoMod.
- Grunow et al. (2006) stress that handling times of quay and stacking cranes as well as release times of transportation orders can only be roughly estimated in advance. Their simulation model focusses on the quay area and yard area where AGVs can be used in single or dual-carrier mode. They present results of a simulation study of AGV dispatching strategies in a seaport container terminal. It reveals that a pattern-based off-line heuristic clearly outperforms its on-line counterpart.
- Wei and Shaomei (2006) developed a library of object building blocks and simple planning procedures for simulation of container terminals with Plant Simulation.
- Zeng and Yang (2009) present a method for scheduling container loading operations in container terminals. At first they generate an initial sequence of containers with simple dispatching rules. Then they improve this sequence by the means of a genetic

algorithm, using their simulation model to evaluate any given schedule. Their method also includes a neural network to predict the outcome of the objective function result, such that some simulation runs can be discarded.

Some more academic simulation models as well as terminal planning/simulation models are compared by Kozan (1997). Angeloudis and Bell (2011) conduct a review of academic container terminal models, which includes both models that have served as a virtual subject of studies for terminal design or as a test-bed for results of diverse planning algorithms.

3.2.3 Energy-related container terminal simulation models

Kawakami and Takata (2012) discuss strategies for management valve-regulated lead–acid (VRLA) battery systems, which are – until now – typically used in smaller AGVs. On the one hand, side those should be charged at a lower rate and within a reasonable voltage range to avoid the deterioration and to extend battery life. On the other hand, this might turn out to more frequent charging requests, affecting the overall performance of AGVs. They developed a simulation model for evaluating battery related costs under various AGV operation modes and for designing battery management strategies. The cost of charging equipment, which determines the charging time of the batteries, was also taken into account.

Until now, power demand and/or energy consumption have not drawn so much attention with regard to modeling and simulation of container terminals. After all, some work has been spent towards the integration of energy-related modules with discrete-event simulation tools (Herrmann et al., 2011).

3.3 Towards an Event-Driven Power Demand Simulation Module

Despite other simulation platforms, Plant Simulation comes with built-in energy analysis functionalities (Heinicke, 2013). It is a discrete-event simulation tool that helps to create digital models, so that characteristics of material flow systems can be explored. In the field of logistics, especially with regard to the design and control of AGV systems, Plant Simulation is preferably used. There is a library of building blocks for modeling basic flow paths or more complex road networks with a number of AGVs, which carry various goods from one location to another. Through special building blocks control strategies can be applied in the model. The building block for the AGV itself is a movable unit of a transporter class. The library in Plant Simulation features battery-powered AGVs, including their power demand while in operation.

3.3.1 Shortcomings of a purely state-driven approach

The Energy Analyzer module can be quite useful to analyze the power demand in simple production environments, which can be modeled almost entirely with basic building blocks. As such it is well-suited to test load curtailment strategies and/or energy conservation measures by means of simulation (Stoldt et al., 2013).

And yet it has some shortcomings for capturing power demand with regard to container terminal operations:

a) Since it is based on pre-defined machine states, it is impossible to differentiate power demand according to influencing factors (e.g., weather conditions, size of a work piece) other than intrinsic factors of material flow. Whenever the basic building block is occupied by a movable unit, the represented machine is assumed to be working on a predetermined abstract level.
b) It can neither be distinguished between different classes of movable units to be processed by the machine in question (e.g., twenty-foot equivalent units are handled in the same way as forty-foot equivalent units) nor the quantity of the movable units processed in parallel (e.g., twin transport).
c) Apart from material flow any power demand (e.g., industrial lighting, cold storage yard) will go unnoticed.

One could also argue that a power demand model has to be set up for every single basic building block on its own. The Energy Analyzer settings are made in a decentralized fashion, which makes them time-consuming to maintain. In fact, it would be beneficial, if one could apply a common power demand model to a group of quay cranes, for example. There is a programmable interface of the Energy Analyzer in terms of special energy-related state attributes, though. Those state attributes might be observed by high-level methods to refine any given power demand model if needed.

3.3.2 Recommendations for an event-driven approach

To overcome those drawbacks, one would need some kind of event processing structure, which allows recognizing changes in power demand by starting from low-level events and going up to high-level events while enriching event data successively with explicit model data.

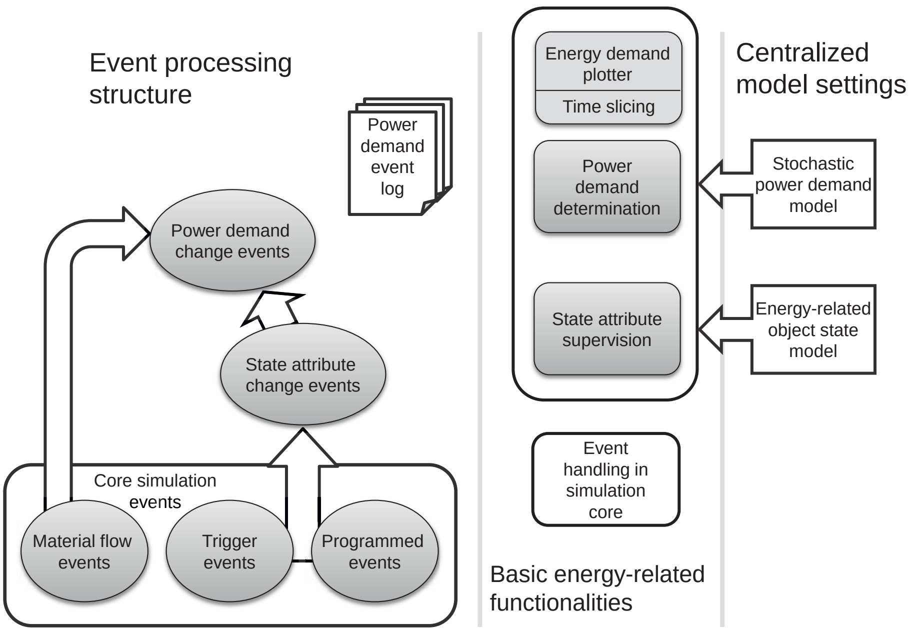

Figure B:11. Overview of a feasible event processing structure, basic functionalities and required model data for the acquisition of power demand data in the course of a simulation run.

As shown in Figure B:11 there are three types of core simulation events in Plant Simulation:

- **Material flow events** occur, when a moveable unit is being moved from one processing station to another; it is being distinguished between entrance and exit of a movable unit as well as machine setup. They are parameterized with the movable unit and the processing station in question.
- **Trigger events** will change values of attributes and global variables during the simulation run according to a specified pattern and/or will invoke a user-defined callback method. From time to time it results in a change of an attribute, which is marked as an energy-related state attribute in the object state model explicitly. Then in turn a power demand chance event will be issued, which is parameterized with the simulation object that was triggered.
- **Programmed events** like a sleep command may be handled in the same way as trigger events. In Figure B:11 some functionalities of the power demand acquisition are presented, that have to be built on top of the event handling in the simulation core.
- **State attribute supervision** makes use of some fundamental settings of an energy-related object state model. Material flow events can be reissued in the form of demand change events directly. Others like state trigger events as well as programmed events might affect any public attribute or will eventually do nothing. Thus, it has to be checked for changes of energy-related attributes separately.
- **Power demand determination** adds entries to the power demand event log**.** There are supposed to be explicit settings of a power demand model, from which demand values are drawn occasionally. This makes it possible to model deterministic and even stochastic power demand of individual equipment or a machine in a centralized fashion.
- In a rolling horizon, the power demand event log will need some sort of in-line post-processing (**time slicing**), such that the power demand is being integrated over any quarter of an hour.

3.3.3 Remarks for the application of mixed approaches

During the further simulation procedure it is all a question of the flow of inbound as well as outbound containers. In our sample application model energy flow is strongly related to container flow. But there are pitfalls for a power demand data acquisition module with regard to complex simulation object models. Figure B:12 shows a model of a quay crane as an example of the necessary decomposition into basic building blocks. Note that Plant Simulation does not provide for traceable material flow events on a layer that uses network building blocks. Thus, our proposed event processing structure can either be realized in an event-driven manner depending on material flow events to be relayed from basic building blocks via network building blocks or in a purely state-driven manner. In the event-driven manner, for example, two container entities would have to be aggregated in a special moveable unit of conveyor class, such that twin transport mode can be detected appropriately. In the state-driven manner, there would have to be a twin transport state and a single transport state one by one, for example.

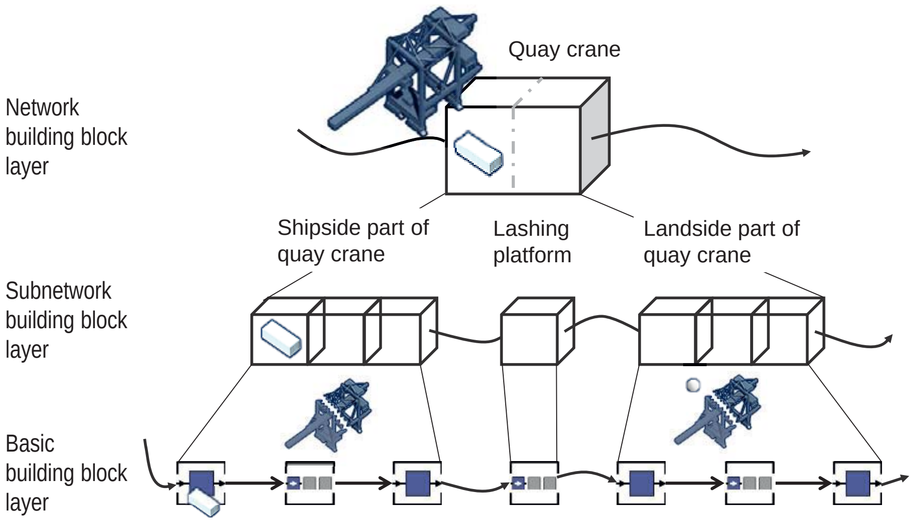

Figure B:12. Application of a power demand data acquisition module in hierarchical simulation object models.

When a container entity enters a basic building block of the quay crane, a low-level callback method is invoked as part of the platform's built-in material flow event structure. On entry of a container entity to the sea-side-most or respectively the land-side-most basic building block the quay crane network as a whole enters working state. This quay crane state transition is being supervised by a central data acquisition module. Through invocation of a high-level callback method the data acquisition module is notified about the quay crane network being working. On this higher level a power demand value is being determined with regard to parameters of the energy-related event. In case of the quay crane network the event parameters are enriched with attribute values of the container entity. We found the power demand of a quay crane is mainly influenced by the container weight. So it is best to have different power demand values drawn for one container weight category or another.

The power demand value is allocated for the quay crane network until it is revised. In order to calculate energy demand for the quay crane area, the power demand has to be integrated over time. Total energy demand may be recalculated every time the power demand value changes and new entries in the event log are made. But still the simulation module shall output quarter-hourly energy demand. So there has to be an energy-related event triggered by every quarter of an hour, such that the total energy demand counter is reinitialized periodically.

On exit of the container entity from the land-side-most or respectively the sea-side-most basic building block the quay crane network falls back into non-working state. This state transition is also reflected by the data acquisition module, which switches power demand to zero, for example (according to settings in the power demand model of the quay crane). On the other hand, the quay crane network now enters idle state, which in turn may cause some power demand. The container handling of a quay crane may be divided into two parts: one part is charging/discharging the ship and lifting the container onto the lashing platform, the second is between the lashing platform and loading/unloading the AGV. After such decomposition of the quay crane in the logistic model, the power demand model in the data acquisition module can easily be adopted.

3.4 Simulation-Based Energy Demand at CTA

At CTA some of the transport vehicles are being retrofitted to a battery electric drive chain. The project BESIC investigates cost-effectiveness of the use of battery-electric AGVs in container terminal operations. In the course of our ongoing project, a simulation model is being developed, which not only includes the conventional parts of the logistic system on the sea side like quay cranes, transport vehicles and storage cranes, but also electric mobility related parts of the local energy distribution system.

Since the prospects of applying a battery change concept will be examined, the charging infrastructure in our simulation model consists of a central charging station with some charging units and a pool of exchangeable battery systems. Through the integration of a charging infrastructure model into a model of the container handling system, the use of power demand acquisition modules, different charging strategies, and battery system exchange policies can be evaluated with regard to overall operating costs. Besides container handling equipment, like quay cranes and storage cranes, also the energy consumption of industrial lighting, container refrigerating/heating and battery systems charging are taken into account, as depicted in Figure B:13.

Input data for the simulation run is a timetable of vessel operations; the so-called sailing list includes the estimated time of arrival, the estimated shipment duration and the estimated departure time per vessel. It also states when unloading as well as loading the container ship are meant to start respectively. Furthermore the numbers of planned charging and discharging operations are annotated to the timetable. But there is no indication of the planned allocation of container ships and moorings whatsoever. From a planning perspective, the quay at CTA is divided roughly into four fixed mooring sections. This stirs up rather obvious decisions in berth allocation procedures of our model. Apart from that, the assignment of quay cranes has to be reproduced in our model in such a way, that shipment duration and departure time of the vessels are being respected.

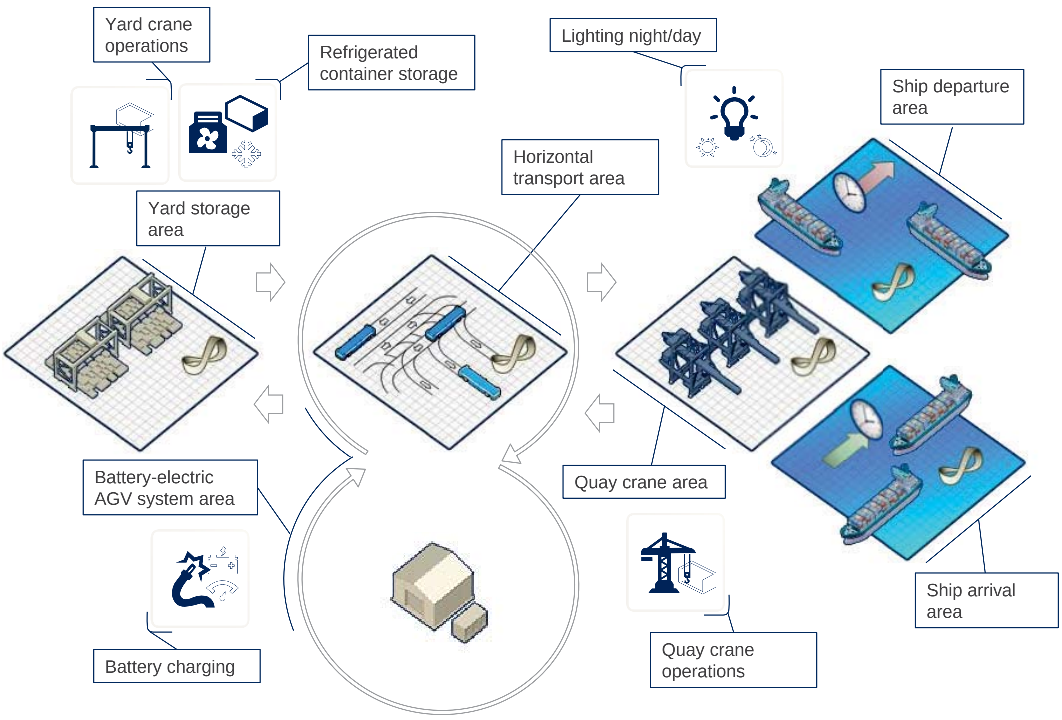

Figure B:13. Simulation components regarding container & energy flow in a maritime container terminal.

First results for CTA show that the simulated energy demand curve is a good approximation to the real energy consumption metering data, which has been gathered during everyday operations. There are good chances that simulation-based forecasting proves to be more accurate than mathematical forecasting based solely on historical energy demand. It was found that the energy demand curve of the container terminal as a whole is subject to stepwise change. Overall, it seems like terminal operations result in rather volatile energy demand. One possible explanation for this is that terminal operations rely heavily on the import and export of containers, which are brought to terminal mainly by container vessels and external trucks. When only few or small vessels are moored, there happens to be less activity in a maritime container terminal in general. The arrival times of container vessels, especially in the context of oversea transport, will be known a couple of days ahead of arrival. Thus, information about arrival time on the one hand and a cargo list on the other hand are highly utilizable as an input of a simulation run. Apparently, the number of container vessels at a glance and the number of import containers and export containers in more detail of a specific workday may deviate much from the numbers the year before. Due to the fact, that arrival of container ships and energy demand is non-repetitive in a manner of days, weeks or quarters of a year or even years, pure mathematical approaches without exogenous factors will also lead to big deviations in energy demand forecasting. An additional feature of the energy-related simulation of CTA is that we can examine the overall performance of a battery-electric AGV system and the impact of battery exchanges and charging operations.

4 Study 5: Demand-Side Integration for Electric Transport Vehicles

Table B-17. Fact sheet of study no. 5.

Title	Demand Side Integration for Electric Transport Vehicles
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Outlet	International Journal of Energy Sector Management 2015, Forthcoming, Completed Research Paper
Structured Abstract	Purpose: Demand-side integration is important for improving system reliability and assisting in integrating renewables into the energy system. In this study, we examine both the technical feasibility and the commercial viability of several demand-side integration programs to utilize the charging flexibility of electric transport vehicles in a logistic facility. Design/methodology/approach: A pre-assessment of several demand-side integration programs is performed by considering effort for implementation, costs, and economic potential. Afterwards, the most promising programs are compared economically on the basis of optimization methods and economic analysis. Our analysis is based on a comprehensive electric mobility project dealing with electric transport vehicles operating in container terminals. Findings: The pre-assessment of several potential DSI programs revealed that many of these programs are unsuitable, largely due to regulatory requirements. Although using DSI to optimize the company's load is feasible, controlled charging based on variable prices is particularly advantageous because the implementation requires modest effort while identifying significant cost-saving potentials. Practical implications: Based on our analysis, other companies using electric transport vehicles have a foundation for identifying the most promising demand-side management program. Originality/value: While most research has focused on individually used EVs, we investigate commercial electric transport vehicles operating in closed systems as we found this area of application to be particularly suitable for participation in demand-side integration programs.
Keywords	Electric Transport Vehicles, Charging Strategies, Demand-Side Integration, Demand Response

4.1 Introduction

During recent years, there has been a fundamental paradigm shift in the energy sector in Germany. The main reason for this shift is the German government's aim of establishing a future energy system with sustainable energy production, reduced energy intensity, and more efficient and sustainable energy use. To achieve this goal, policymakers have established various goals for increasing the share of renewable energies (BMWi and BMU, 2010). To date, wind and solar power are among the most widely installed and supported renewable energy technologies. However, the integration of intermittent renewable energy resources into the energy grid poses enormous challenges for the energy sector because of the expected increasing discrepancies between power supply and demand (Ketterer, 2014). Therefore, numerous possibilities for realigning electricity supply and demand are being discussed.

Energy management systems monitor business operations and, if possible, control energy demand. If the control reacts to external signals, such as dynamic prices, this process is called "demand response" (DR) (Gellings and Chamberlin, 1988). The term "demand-side management" (DSM) includes programs for increasing energy efficiency at the demand side and power control procedures such as peak clipping or load shifting with the goal of optimizing demand for company-internal purposes (Strbac, 2008). Both concepts can be summed up in the term "demand-side integration" (DSI) (BDEW, 2013b). In addition to supporting the increased deployment of renewable energy by smoothing out power fluctuations, DSI offers several further advantages. For example, system reliability can be improved by reducing electricity demand at critical load times. Furthermore, savings in variable supply costs can be achieved through more efficient use of electricity (FERC, 2008).

Significant potentials for the integration of the consumer side into energy-related activities in the context of DSI are cited in several studies (Bradley et al., 2013; Chanana and Kumar, 2010; Timilsina and Shrestha, 2008). In addition, many studies (e.g., Wang et al., 2011a; Mullan et al., 2011; Andersson et al., 2010) have found electric vehicles (EVs) to be particularly suitable for participating in DR, as they are expected to be idle 96% of the time on average; the resulting load-shifting potential can be used for DR (Kempton and Tomić, 2005a). However, there are various problems obstructing the actual realization of DR in this field of application. Of particular importance are the low profits relative to operational cost, user acceptance problems, and energy market constraints (Sovacool and Hirsh, 2009).

In this paper, we investigate the feasibility and economic potential of several DSI programs for commercial electric transport fleets operating in closed transport systems. In order to examine both the technical feasibility and commercial viability of different DSI programs with electric transport vehicles, we use data from an electric mobility project conducted in one of the container terminals of the largest port in Germany. We found this area of application to be particularly suitable for DSI because of the following reasons:

- The vehicles can be pooled on company grounds to exploit energetic and economic synergies;
- Economies of scale result from the aggregation of numerous vehicle batteries, each with considerable storage capacity;
- The vehicles' operation times can be adapted in order to optimally charge the batteries in a smart grid system;
- The energy consumption of EVs can be forecasted more precisely based on order confirmations, delivery dates, or arrival times; and
- Charging processes can be integrated in an operational demand-side management system.

From a fleet operator's point of view, DSI seems compelling for its financial benefits because it can reduce electricity bills by, for example, adjusting the time of energy usage, thus taking advantage of lower prices that prevail in certain periods. Despite the promising potentials for both the energy industry and fleet operators, identifying feasible and suitable DSI programs and quantifying the economic benefits still seems to be an open research gap for this area of application. The research questions are as follows:

(1) What kinds of demand-side integration programs are applicable for electric transport vehicles operating in closed transport systems?
(2) What are the technical and operational requirements resulting from the implementation of specific demand-side integration programs?
(3) What are the economic potentials resulting from technically feasible demand-side integration programs?

The remainder of this paper is organized as follows. In Section B.II.4.2, we discuss fundamentals of DSI and introduce our case study. Section B.II.4.3 presents the approach for determining the most promising DSI programs, while the corresponding results are provided in Section B.II.4.4. Section B.II.4.5 examines the implications resulting from our findings, which leads us to the conclusions presented in Section B.II.4.6.

4.2 Demand-Side Integration

Demand-side integration programs can be divided into different forms of influencing behavior on the consumer side (Palensky and Dietrich, 2011). Table B-18 provides an overview with general examples of the various methods. In the following sections, we identify examples of DSI programs and try to classify them according to the three categories in Table B-18.

Table B-18. Demand-side integration programs (adapted from Albadi and El-Saadany, 2007; Palensky and Dietrich, 2011; U.S. DOE, 2006).

DSI program	Description	Example technique/method
Classical DSM	Programs that aim to improve energy efficiency and adapt time of use	▪ Improving energy efficiency ▪ Load management (peak clipping, valley filling, load shifting)
Incentive-based DR	Programs that pay participating customers to reduce their loads at requested times	▪ Direct load control ▪ Demand bidding ▪ Ancillary services market ▪ Emergency DR
Price-based DR	Programs giving consumers time-dependent rates that reflect the value and cost of electricity in the specific time frame	▪ Time-of-use pricing ▪ Real-time pricing ▪ Critical peak pricing

Despite the obvious potential for income or savings through DSI programs, DSI has experienced only moderate expansion in Europe. According to Strbac (2008), there are several major challenges for the successful implementation of DSI techniques, such as the lack of IT infrastructure and incentives, limited understanding of the benefits of DSI solutions, and inappropriate market structure.

While these challenges continue to impede the expansion of DSI among households, companies and fleet operators are often in better positions to adopt DSI programs because they have the necessary IT infrastructure, smart grid technologies, and staff with the ability to analyze costs and benefits as well as manage complexity (Paulus and Borggrefe, 2011).

4.2.1 Demand-Side Integration of Electric Vehicles

As EVs are often idle for most of the day, they seem predestined for participating in DSI programs. Furthermore, charging a large number of electric vehicles in an uncontrolled manner would create a significant load that could jeopardize power grid security. In order to prevent potential power outages, EVs should primarily be charged when the grid is not stressed (Schmidt and Busse, 2013).

To date, most research has focused on two kinds of DSI programs for EVs: smart charging and the vehicle-to-grid (V2G) concept. The objective of smart charging concepts is to shift power consumption to avoid load peaks, which are related to higher electricity prices. Thus, EV users can reduce their energy procurement costs while utility companies and grid operators benefit from reduced system costs (Wang et al., 2011a). The basic idea of the vehicle-to-grid (V2G) concept is that EVs can be used to supply power to the grid for stabilization and peak-time supply (Kempton and Tomić, 2005b). EV users can thus reduce their total cost of EV utilization because of additional profits gained from participation in energy markets (Mullan et al., 2011).

However, there are various barriers to a broad implementation of DSI programs with EVs in the private sector, most notably the substantial investment required for constructing infrastructure, the limited willingness of EV users to participate, and extensive regulatory requirements. Furthermore, most DSI programs require precise forecasts about future energy consumption, which is challenging due to individual and possibly erratic driving patterns (Geelen et al., 2013).

For these reasons, EV fleets appear to be suitable for DSI because they pool a large number of EVs to participate in these programs. With more vehicles aggregated, individual driving times would have a lower impact on capacity and energy planning. Several studies have also demonstrated that providing V2G power from EV fleets can be profitable (e.g., Han et al., 2010; Tomić and Kempton, 2007).

Other literature has analyzed the problem of operating battery-swapping stations (BSS) for individual traffic with intelligent charging concepts. Yang et al. (2014) and Sarker et al. (2013) propose an optimization model for a BSS to acquire additional revenues by responding actively to price fluctuations in the electricity market. Furthermore, the operation of numerous BSS and their market interaction has been investigated by Nurre et al. (2014) using a deterministic integer program model.

Little research has been conducted on how to implement DSI programs in commercially used electric transport vehicle fleets operating in closed transport systems in combination with a BSS. However, focusing on this program context as a first step towards the implementation of DSI programs for EVs seems significant, as mentioned before.

4.2.2 Case Study: Battery Electric Heavy Goods Vehicles within Intelligent Container Terminal Operation (BESIC)

Due to the steadily increasing share of container transport in multimodal freight transportation, container terminals are in operation in ports throughout the world (UNCTAD, 2013). To date, container transportation within the terminal is often executed with diesel-powered automated guided vehicles (AGVs). There are, however, many indications that battery-powered automated guided vehicles (B-AGVs) can be cost-effective within this application context (Ihle et al., 2014). As these vehicles also offer a large potential for DSI, an assessment of both the efforts for implementation and economic potential of various DSI programs for electric transport vehicles operating in container terminals is being conducted, based on a comprehensive electric mobility project, called BESIC, with one of the largest port operators in Europe. Our pilot case company operates a fleet of 80 heavy-duty AGVs used to transport standard containers within a certain area on the seaside of a container terminal. Within the scope of this project, 10 AGVs were replaced by B-AGVs. One of the central project goals is to assess the possibility of coordinating charging times with operational requirements and the occurrence of peak loads.

In general, the pressures of both competition between container terminals as well as customer demands in terms of delivery times and reliability have increased in recent years (Saurí and Martin, 2011). To remain competitive, the number of vehicles must therefore be sufficient to ensure that all transport orders can be fulfilled on schedule because even small delays of transport orders lead to significant costs for the transport company (based on penalty costs or port charges). Accordingly, among the terminal operator’s prerequisites for the use of B-AGVs was that the availability of the vehicles must be similar to that of conventional AGVs. To prevent the fulfillment of daily logistic tasks from being restricted by the charging processes, a fully automated BSS was installed. Moreover, the vehicles were equipped with lead–acid batteries, which are already in use in several heavy electric-powered transport vehicles (e.g., forklifts). The minimum operating duration with one battery charge was set to 12 hours, resulting in a usable capacity per battery system of 289 kWh. Each battery system can be fully charged in six hours in the BSS (charging rate 48 kW). The use of a BSS makes it necessary to procure spare batteries in order to have a sufficient stock of charged batteries to replace depleted ones. Based on the company's requirements, the number of spare batteries must be sufficient to ensure that all B-AGVs can obtain fully charged batteries with almost no waiting times under any possible terminal conditions. Currently, there are 2 battery systems available per vehicle, resulting in a total of 20 lead–acid battery systems.

The charging status of the batteries is constantly monitored. If the state of charge (SOC) drops below a certain level, the B-AGVs are automatically called to the battery-swapping station and the battery system is exchanged. While the battery system is in the BSS, the charging process can be influenced via the battery administration system. The B-AGVs represent a valuable resource for DSI because the average usage time with one fully charged battery is longer than the time necessary to fully charge a battery system. Even with fewer batteries there is a possibility of load shifting whenever the container terminal is not fully utilized, because the number of batteries has been calculated for full utilization. Hence, the charging processes can be shifted when required. This is illustrated in Figure B:14, which depicts a charging process for one battery on a selected day when using a plug-and-charge approach.

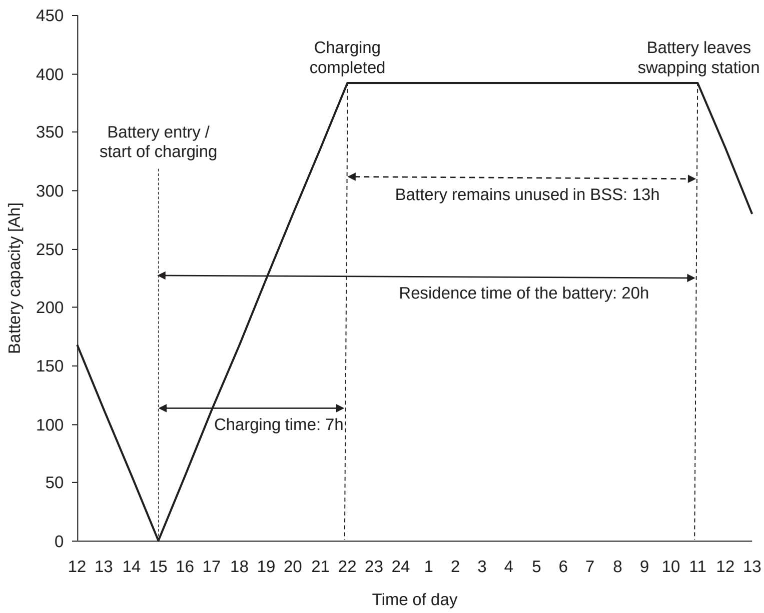

Figure B:14. Depiction of a charging process on an illustrative day.

The load-shifting potential can be used for several DSI programs. The main goal of this paper is therefore to identify the most promising DSI programs for making use of the load-shifting potential without affecting the logistic processes (logistic premise). To be able to realize short-term DSI actions, precise information about overall energy consumption and the expected retention times of the battery systems in the BSS is required. Therefore, a simulation model for forecasting the logistic processes and the related electricity demand at the container terminal for a certain period was developed within the project (Ihle et al., 2014). Based on this simulation model, it is also possible to forecast the batteries' power consumption and duration of time spent in the swapping station for a certain period. Moreover, it is possible to assess and forecast the SOC of the batteries. This is a prerequisite for optimizing the battery-charging process as the load-shifting potential must be known in advance.

Schmidt et al. (2014) assess the potential of controlled charging (realized by energy procurement on the spot market) and the provision of control reserve on regulation markets on the basis of static operation times of the electric transport vehicles. They find that controlled charging is more lucrative than offering control reserve but do not specifically consider the energy market design. Their focus is on economic aspects, assuming that the company itself can act on the energy markets. However, this is not the case for our pilot case company.

Consequently, our study considers the energy market design and regulatory frameworks in detail to ensure the effective implementation of potential DSI programs for the case study. Furthermore, we use dynamic driving profiles for an economic assessment of feasible DSI programs. Finally, the container terminal operator can participate in several further DSI programs, as the subsequent section will show.

4.3 Analysis of Demand-Side Integration Programs

Our approach for determining the most promising DSI programs for this case study consists of two parts. The first step involves a pre-assessment of several potential DSI programs for electric transport vehicles operating in container terminals. Technical and operational requirements for implementing DSI programs are given particular consideration in this paper. In addition, we assess whether there is an economic potential.

In the second step, the remaining realizable DSI programs are compared economically on the basis of optimization methods and economic analysis. To do so, cost-saving potentials expected to result from the implementation of the DSI programs are calculated in order to identify the most promising one. Based on our analysis, it becomes possible to provide commercial fleet operators with guidelines regarding how to best participate in DSI programs.

4.3.1 Pre-Assessment of Demand-Side Integration Programs

The pre-assessment of potential DSI programs for this investigation is based on three criteria, which cover the most relevant dimensions to the underlying problem. It is important to note that our pilot case company also wants to investigate how the load-shifting potential or charging flexibility can be used for internal purposes, e.g., by optimizing the company's load curve. Conversely, the load-shifting potential can be used externally, e.g., by providing ancillary services.

The first set of criteria for assessment, efforts for implementation, can be subdivided into three categories:

- Regulatory complexity: Includes, inter alia, legal aspects and market regulations as well as the need for bilateral agreements between the involved DSI partners.
- Operational requirements: Includes, inter alia, properly trained staff both for implementation and management within the company itself and for interaction with external partners, such as the grid operator or the supplier.
- Technical requirements: Includes, inter alia, energy management systems, metering and communication systems, software and load control devices.

For the second set of DSI-assessment criteria, two different kinds of costs must be considered: initial costs and running costs (Albadi and El-Saadany, 2007; U.S. DOE, 2006). Initial costs include those for enabling technology investment, such as energy management systems, metering and communication systems (upgrades), software, load control, or training for employees. The second cost category is running cost for the consumers when they respond to DSI program events; it includes lost business activity, rescheduling costs (e.g., overtime pay), and additional maintenance costs where necessary. In a logistics enterprise using EVs with battery-exchange systems, additional costs are likely to be minimal if the flexibility in battery charging can be exploited without impacting the logistic processes.

Finally, consumers are rewarded financially for participating in DSI programs. By reducing the peak load, fees for grid use can be reduced. Consumers participating in market-based DSI programs can reduce their electricity bills by shifting electricity consumption to off-peak periods. Furthermore, incentive-based DSI programs reward consumers for reducing or increasing loads in specific periods.

To enable DSI programs with battery-electric transport vehicles, several investments must be made. All DSI programs require suitable technology capable of controlling the electric devices (here, batteries in the swapping station). For example, the battery-swapping station requires a peak load limiter, which is able to respond to these signals, e.g., by interrupting the charging processes in order to provide negative control reserve power. In addition, all DSI program entities (B-AGVs, batteries, and charging points within the BSS) must be equipped with metering and communication technologies, such as smart meters. As explained in Section B.II.4.2.2, our pilot case company's vehicles already had the required technologies on board, e.g., those for monitoring the SOC and transmitting data to the BSS. This is achieved by the AGV guard and the battery administration system, which were already implemented independently of the DSI applications. Another crucial resource for the realization of all DSI applications is the software for the communication and information systems. DSI information systems are often upgrades of energy management systems (EMS). EMS are assumed to already be available within the company, and thus independent of DSI applications for the B-AGVs, because many companies in Germany are already certified according to ISO 50001:2011, which specifies the requirements for establishing, implementing, maintaining, and improving an energy management system (IMSM, 2014). In addition, the communication systems, which are responsible for smooth and standardized data exchange between all DSI application entities as well as between company and utility, are usually already available within large companies as well. Hence, investments regarding technologies for industrial consumers are relatively low.

During the research project, six DSI programs were identified to be of potential interest. These programs can be grouped as shown in Table B-19.

Table B-19. Classification of potential DSI programs.

Classification	DSI program
Internal load management	▪ Optimizing the company's load curve ▪ Optimizing the mode of operation in regard to a decentralized energy source
Balancing group management	▪ Improving the forecast quality in order to reduce balancing energy costs
Price-based DSI	▪ Implementing controlled charging based on variable prices for electricity
Ancillary service	▪ Providing control reserve power (primary, secondary, and, minute reserve control) ▪ Offering interruptible loads on capacity market

4.3.1.1 Internal Load Management

In principle, the flexible load can be used for internal load management. The first potential DSI program is *optimizing the company's load curve*. The overall objective is to reduce energy procurement costs by reducing the grid fees that depend on peak loads. In the first step of this DSI program, it must be assured that the charging processes of the batteries do not cause an increase in peak load, which would result in even higher grid fees. Moreover, electricity network operators in Germany are required to offer large companies that exceed certain minimum power consumption values an individual grid fee when achieving a particular annual usage hour threshold. The annual usage hours are defined as the ratio between the annual consumption and peak load in that year. Thus, participation in load management is explicitly supported by the legislator. In this regard, grid fees can be reduced by up to 80% when achieving 7,000 annual usage hours per year (§19 Abs. 2 StromNEV, Bundesregierung, 2014a). If battery charging does not increase the peak load, the number of annual full-load hours of the company increases. Since the share of grid fees in the total price of electricity for industrial consumers is on average 21% (Bundesnetzagentur and Bundeskartellamt, 2013), this DSI program presents a significant potential for cost saving. From a technical perspective, optimization of the load curve can be implemented with little effort. Peak load management requires suitable metering, control and communication technologies, as well as a peak load limiter (see above). Over all, the efforts for implementation seem to be modest while significant cost-saving potentials can be identified. The principle of this DSI program is illustrated in Figure B:15.

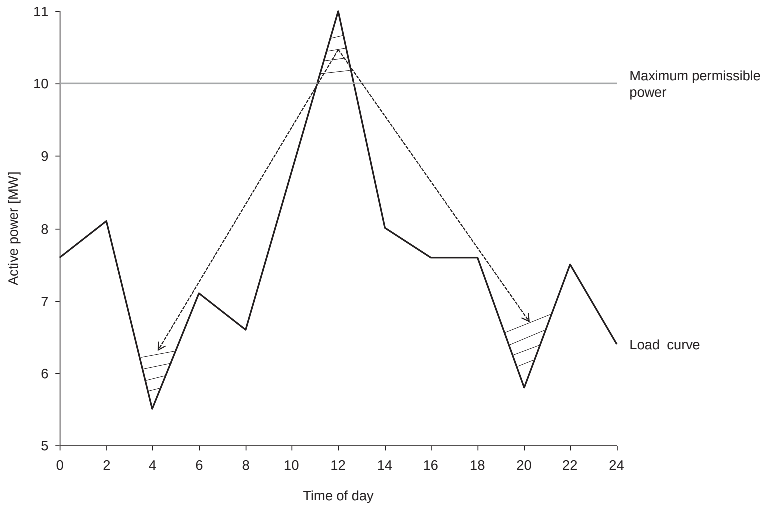

Figure B:15. Basic principle of the DSI program optimizing the company's load curve.

Companies operating a distributed generation system that uses renewable energy sources can use the charging flexibility for another potential DSI program, *optimizing the charging in regard to a decentralized energy source*. To do so, the batteries should primarily be charged in periods when power generation from renewables is high. Using self-generated electricity has several advantages: no grid or concession fees are due and several subsidies can be granted, e.g., in the form of reduced apportionments for the promotion of renewable electricity (Bardt et al., 2014). It is questionable, however, whether the high volatility of renewable energy is compatible with the energy planning that is required for smooth logistic operations. In principle, the B-AGVs can at least contribute to the integration of such distributed generation systems on company grounds. However, this requires forecasts about the electricity generation from renewables. The economic potential depends on the size and type of the distributed generation system and can therefore not be assessed precisely.

4.3.1.2 Balancing Group Management

One further DSI program is supporting *balancing group management* (Bilanzkreismanagement) in order to reduce balancing energy costs. In Germany, a balancing group manager must monitor the supply and demand of electricity and achieve a balance between forecasted and actually delivered electricity volumes in 15-minute intervals within a certain area (§4 StromNZV, Bundesregierung, 2014b). Discrepancies between the load forecast and actual electricity consumption must be compensated for by buying or selling the difference on the intra-day market. Any remaining differences are charged to the balancing group manager via balancing energy costs. According to this, the more accurately a balancing group manager can forecast (or adapt) electricity consumption, the lower the balancing energy costs (Schwab, 2012). While companies operating their own balancing group can benefit directly from reduced balancing energy costs, other electricity consumers can be rewarded for supplying a sound forecast of their energy consumption. The objective of this DSI program is therefore to achieve a high correlation between forecasted and actual energy consumption (see Figure B:16), which requires precise forecasting models. The B-AGVs play an important role for this DSI program as their charging processes can be shifted if the forecasted schedule is in risk of being jeopardized. The revenue potential depends on the individual power procurement contract and therefore cannot be determined precisely.

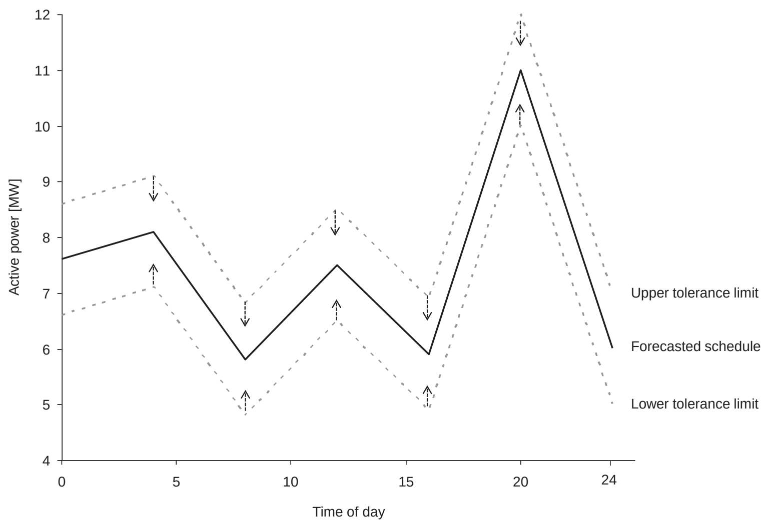

Figure B:16. Basic principle of the DSI program balancing group management.

4.3.1.3 Price-Based DSI

The third potential market for the use of the flexible load is *controlling the charging processes based on variable prices* for electricity. The overall goal of this DSI program is to charge the batteries during the hours with the lowest possible prices. Some rather simple examples of variable prices are different prices for daytime and nighttime or other time-of-use (TOU) prices. A more sophisticated approach is to procure the required power on the electricity spot market (e.g., the European Energy Exchange – EEX), where hourly prices are determined by day-ahead auctions. High volatility and price spikes on this market are based on fluctuation in both demand and supply (Zachmann, 2013). Information about forecasted power consumption and operation times of the B-AGVs is a necessary precondition for this DSI program because the required energy must be procured day-ahead. Based on this information, the load can be shifted in order to benefit from short-term price fluctuations on this electricity market. There are two ways that this DSI program can be realized: either the company using B-AGVs acts on the energy market itself or an intermediary procures the required energy on behalf of the company (EPEX Spot SE, 2014). The latter case is applicable to the container terminal in our case study. The utility company would offer market access, with a service fee, while the terminal procures power demand at the exchange market. This DSI program holds enormous economic potential but also bears uncertainty because of the high price volatility. As seen in Figure B:17, significant price volatility can be observed on the spot market.

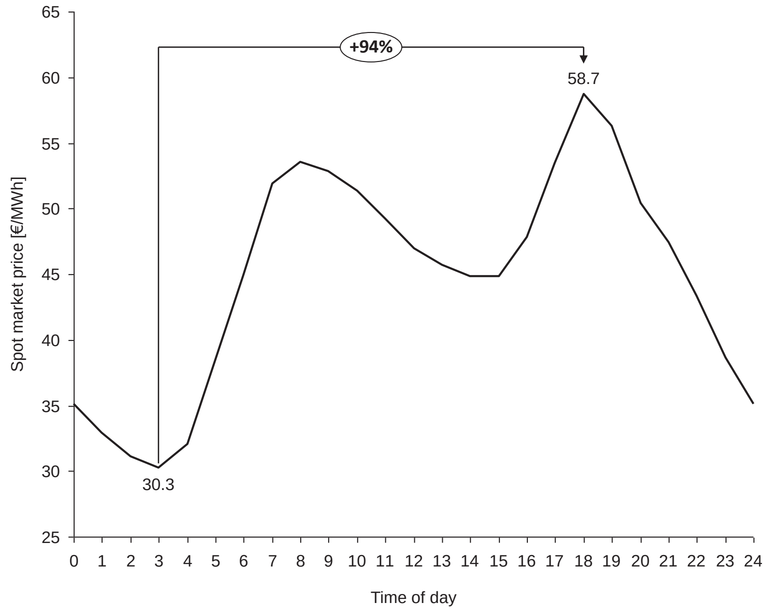

Figure B:17. 2012 average electricity spot prices per hour and resulting price spread in Germany.

4.3.1.4 Ancillary Services

The final application of a DSI program regarded in this study is *providing ancillary services*. This means that the company's ability to alter its load at a given point in time is offered to an external partner via specific markets. Offering such ancillary services to the corresponding transmission system operator (TSO) requires a so-called pre-qualification, which is intended to guarantee that the technical means are suitable for reliable participation in such programs (Regelleistung, 2014b). In principle, it is possible to provide primary control, secondary control, or minute reserve in Germany. While offering greater economic benefit, primary and secondary control reserve require a high-speed reaction to external signals and a planning horizon of about two weeks, neither of which is feasible for the investigated case study company. *Providing minute reserve* is less demanding, as a reaction is only necessary within 15 minutes and a planning horizon of less than 48 hours is sufficient (Hirth and Ziegenhagen, 2013). In the case of fleet operators, battery-charging processes can be initiated earlier or accelerated in order to increase power consumption (negative minute reserve) or can be postponed or decelerated in order to lower power consumption (positive minute reserve). From an economic point of view, offering negative minute reserve is the more attractive case because the incentives for this kind of minute reserve are usually greater (Andersson et al., 2010). However, this DSI program is difficult to implement for our pilot case company. In addition to suitable data exchange systems for communication with the external partner, operation standards of the technical units in question must comply with the requirements of the external partner or grid operator (VDN, 2007). Furthermore, trained staff must be available during the time frame in question to respond to any request for load reductions or increases. If the load reduction provided (in case of negative control reserve) does not exceed certain thresholds (e.g., minimum lot size of 5 MW for minute reserve), companies may be forced to pool their offers with others. Hence, profits from this DSI program might have to be shared with other pooling agents.

Another potential ancillary market is the capacity market, in which interruptible loads can be offered. Load reductions or interruptions are generally required when the grid operator believes that system reliability is in jeopardy. *Offering interruptible loads* is only feasible for electricity consumers who are connected to the high voltage grid. Furthermore, technical requirements according to the pre-qualification (e.g., regarding reaction time) are extremely high and interruptible loads are allocated in one-month contracts (Regelleistung, 2014c). As our pilot case company is not connected to the high voltage grid and the technical requirements cannot be fulfilled, this DSI program is not feasible.

4.3.2 Economic Assessment of DSI Programs

In the previous section, we introduced various DSI programs that can be applied at the container terminal. However, only two of them seem promising for short-term realization: *optimizing the company's load curve* and *controlling the charging process based on variable prices*. This is due to the small number of market actors involved and the minimal regulatory complexity faced. In addition, both programs can be implemented without large investments on the container terminal's side while offering high cost-saving potentials. In the following we will therefore assess the economic impacts of each program.

The economic assessment of the two DSI programs is based on simulated operating and charging times of the B-AGVs' battery systems for the reference year of 2013. For the economic assessment of the DSI program *controlled charging based on variable prices*, we perform an optimization of charging costs for the reference year based on spot market prices. In order to evaluate our results, we first calculate charging costs for the baseline scenario, uncontrolled charging with fixed prices for electricity $C_{uncontrolled}$. To do so, we multiply the simulated annual electricity demand of the B-AGVs $\mathrm{d_{BAGVs}}$ by the average price of electricity for industrial consumers $\mathrm{p_{industry}}$ of the reference year. Moreover, the charging efficiency η is considered. Thus, we deduce

$$C_{uncontrolled} = \frac{\mathrm{d_{BAGVs}}}{\eta}\mathrm{p_{industry}}. \qquad \text{(B.33)}$$

The subsequent optimization of charging costs is performed for the 2:1 equipment ratio (battery system to B-AGV) mentioned before. As described above, the average use time with one fully charged battery system is longer than the time required to fully charge a battery system. In the following, the optimization approach is illustrated for one battery system and charging process.

Let I be the number of 15-minute time slots i in which the battery is located in the swapping station (depending on the utilization rate of the terminal), and thus a subset of the set T of 15-minute intervals t in the year as a whole, and let M be the number of time slots necessary to fully charge the battery. Through the simulation model, both values can be predicted for a certain period. Therefore, charging costs C_{TF} for the time frame in which the battery is located in the swapping station can be optimized by shifting charging times to the M time slots in the time frame in which the electricity spot market prices per time slot $p_{spot}(i)$ are the lowest.

M is dependent on the current state of charge of the battery SOC_t (in kWh), the amount of energy required for the next utilization period (in kWh), and the charging power of each connector in the battery-swapping station W_{con} (in kW). It is required by the terminal operator that a battery must be fully charged when put back into use. Let S be the usable capacity of the storage device. We then derive the number of time slots necessary to fully charge a battery (four per hour) by dividing the discharged power ($S - SOC_t$) by the power of each connector in the swapping station W_{con}

$$M(SOC_t) = \frac{S - SOC_t}{W_{con}} 4. \tag{B.34}$$

It must be taken into account that the spot market/wholesale price for electricity only represents one part of the variable end price for industry consumers. In Germany, electricity prices consist of three components: the wholesale price for a certain amount of energy (on average approx. 50% of the variable end price for industry consumers), electricity taxes (approx. 10%), and additional fixed fees (approx. 40%) (BDEW, 2014). The only component that can be influenced by controlled charging concepts is the wholesale price; the other price components are fixed p_{fix}. In addition, we consider a certain service fee per kWh $p_{service}$ because an intermediary is required to act on the spot market on behalf of our pilot case company (see Section B.II.4.3.1.3). The variable end price for industrial consumers $\mathrm{p_v(i)}$ can thus be calculated with the following equation

$$\mathrm{p_v(i) = p_{spot}(i) + p_{fix} +}\ \mathrm{p}_{service}. \tag{B.35}$$

The decision of whether to charge in a certain hour of the time frame must be made on the basis of (day-ahead) EEX–spot market prices. In order to make this decision, we use the following binary variable

$$\mathrm{x(i)} = \begin{cases} \text{1 if the battery is charged in time slot i within the time frame} \\ \text{0 if the battery is not charged in time slot i within the time frame.} \end{cases} \tag{B.36}$$

Furthermore, the electricity demand d_t (in kWh) per time slot t of 15 minutes in which the battery is charged must be calculated. To do so, one must consider η as well as the charging power. Thus, we derive

$$d_t\big(x(i)\big) = \frac{W_{con}\ \frac{1}{4}h}{\eta}\ x(i). \tag{B.37}$$

The corresponding optimization problem for one time frame and battery resolves to

$$\min_{x(i)} C_{TF} \sum_{i=1}^{I} p_v(i) d_t x(i), \tag{B.38}$$

subject to

$$\sum_{i=1}^{I} x(i) = M\ \forall\ x(i) \in \{0,1\}; i \in \{1, \dots, I\}. \tag{B.39}$$

The annual charging costs from this DSI program are calculated by considering each time frame and battery of the reference year individually and summing up all charging costs.

The overall goal of the DSI program *optimizing the company's load curve* is to reduce grid usage fees for the pilot case company. In order to calculate the company's grid fees, the load $L(t)$ (in kW) metered in ¼-hour time intervals and the annual power consumption W (in kWh) must be known. Moreover, grid fees for large electricity consumers in Germany consist of a working price p_W (in €/kWh) and a demand price p_D (in €/kW). Both prices are charged by the grid operator responsible and depend on the voltage level of the consumer's connection point and the full-load hours. The equation for calculating the full-load H is given below

$$H_{Company} = \frac{\mathrm{d}_{\mathrm{company}}}{\max(L(t))}. \tag{B.40}$$

Finally, the grid utilization fees C_G can be calculated as follows

$$C_{G,Company} = \max\big(L(t)\big)\, p_d + \mathrm{d}_{\mathrm{company}}\, p_W. \tag{B.41}$$

In order to economically assess this DSI program, we first calculate grid usage fees for our pilot case company when charging the battery systems in an uncontrolled manner. This requires the consideration of W_{con}, the number of battery systems simultaneously charged in the swapping station n_{bss}, and the simulated annual electricity demand $\mathrm{d}_{\mathrm{BAGVs}}$. The full-load hours for the company including B-AGVs $H_{Company,BAGVs}$ can therefore be described by

$$H_{Company,BAGVs} = \frac{d_{company}+d_{BAGVs}}{max(L(t)+W_{con}\, n_{bss}(t))}. \tag{B.42}$$

Likewise, the calculation of grid usage fees for the company including B-AGVs $C_{G,Company,BAGVs}$ can be calculated as follows

$$C_{G,Company,BAGVs} = max\big(L(t)+W_{con}n_{bss}(t)\big)p_d + (\mathrm{d}_{\mathrm{company}} + \mathrm{d}_{\mathrm{BAGVs}})\, p_W. \tag{B.43}$$

In the second step, grid usage fees are calculated under the assumption of an optimized load curve. To this end, we shift all simulated charging processes of the reference year to the hours with the company-wide lowest demand for electricity of each time frame in which the battery is located in the swapping station until the next scheduled operation. This has two benefits: first, it becomes less likely that the charging processes cause an increase in peak load and, second, grid fees can be reduced significantly when achieving a certain full-load hour threshold (see Section B.II.4.3.1.1). The procedure for optimizing the companies load curve is similar to the first DSI program.

4.4 Results

All parameters and values necessary for the assessment of both DSI programs are presented in Table B-20.

Table B-20. Parameters used to economically assess the selected DSI programs in the reference year.

DSI program	Parameter	Value	Comments	Data source
Baseline scenario	d_{BAGVs}	0.93	Annual electricity demand of all B-AGVs [MWh]	Project data
	η	72	Charging efficiency [%]	Project data
	$p_{industry}$	15.02	Average electricity price for industrial customers [€/MWh]	BDEW [2014]
Controlled charging	p_{spot}	[-87.52 – 265.3]	Electricity spot market prices in the reference year [€/MWh]	EEX [2014]
	p_{fix}	72.70	Fixed electricity price components [€/MWh]	BDEW [2014]
	$p_{service}$	10	Service fee for spot market participation [€/MWh]	Own calculuation
Optimization of the company's load curve	L	11.24	Peak load of the company without B-AGVs [MW]	Project data
	$d_{company}$	70.16	Power consumption of the company without B-AGVs [MWh]	Project data
	p_W	0.0137	Working price [€/kWh]	Stromnetz HH [2013]
	p_d	20.55	Demand price [€/kW]	Stromnetz HH [2013]

The annual costs for charging the B-AGVs in an uncontrolled way at fixed prices can be calculated using Eq. (B.33) and the parameters listed in Table B-20 to be €194,343.

Our pilot case company can expect significant cost-saving potentials when procuring the energy required to charge the batteries on the spot market and implementing *controlled charging based on variable prices*. The result of the optimization for one charging process and one battery system on a certain day within the reference year (November 10th) is illustrated in Figure B:18; the depleted battery system enters the BSS at 1 a.m. and is needed again in operation at 5 p.m. As it is possible to fully charge the battery system in 6 hours (charging rate 48 kW), the charging process takes places during the 6 hours within the total residence time (16 hours) in which the spot market prices are the lowest.

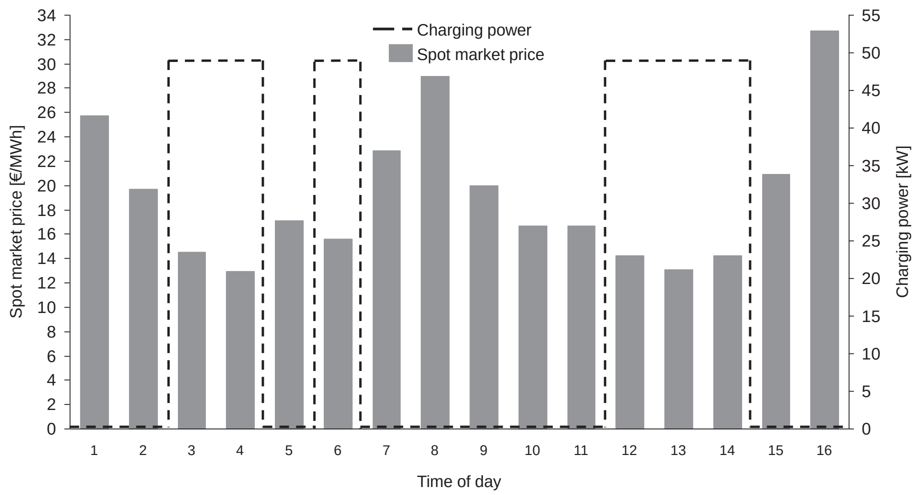

Figure B:18. Illustration of the optimization procedure for one battery system on a certain day.

The annual charging costs for this DSI program were calculated to be €129,164 using Eq. (B.38). For the calculation, we considered fixed electricity price components that must be added to the spot market prices as well as a service fee. Nevertheless, under the assumption of a 0.01 €/kWh fee, a cost-saving potential in the amount of €65,179 (33.5%) can be achieved compared to the baseline scenario.

For the economic assessment of the DSI program *optimizing the company's load curve*, we first calculated grid usage fees for our pilot case company without the additional load resulting from the charging processes of the B-AGVs using Eqs. (B.40) and (B.41). In the second step, (additional) grid fees were calculated for two further scenarios. In the first scenario, the B-AGVs are, again, charged in an uncontrolled manner. In the second, we calculated the grid fees when implementing the DSI program *optimizing the company's load curve*. The results are summarized in Table B-21.

Table B-21. Economic assessment of the DSI program optimizing the company's load curve.

	Company without B-AGVs	**Company with B-AGVs**	
		Uncontrolled charging	**Controlled charging**
Peak load [MW]	11.24	11.60	11.24
Annual power consumption [MWh]	70,165	71,537	71,537
Annual full-load hours [h]	6,243	6,170	6,365
Working price [€]	961,264	980,054	980,054
Demand price [€]	231,061	238,384	231,061
Annual grid fees [€]	**1,192,835**	**1,218,438**	**1,211,115**

Our pilot case company must be prepared to experience higher annual grid fees, even if the B-AGVs' battery systems are charged in a controlled manner. This is because of the increase in the company's annual power consumption. Nevertheless, the additional €7,300 in fees resulting from the peak-load increase when charging the batteries in an uncontrolled manner can be avoided when controlling the charging processes of the B-AGVs by shifting all charging processes of the reference year to the hours with the company-wide lowest demand for electricity (see Section B.II.4.3.2). For the year 2013, the company's peak load (without B-AGVs) occurred on November 5th at 10:30 p.m., when seven battery systems would be charged in the uncontrolled charging scenario. As illustrated in Figure B:19 this would have resulted in a peak-load increase of almost 350 kW.

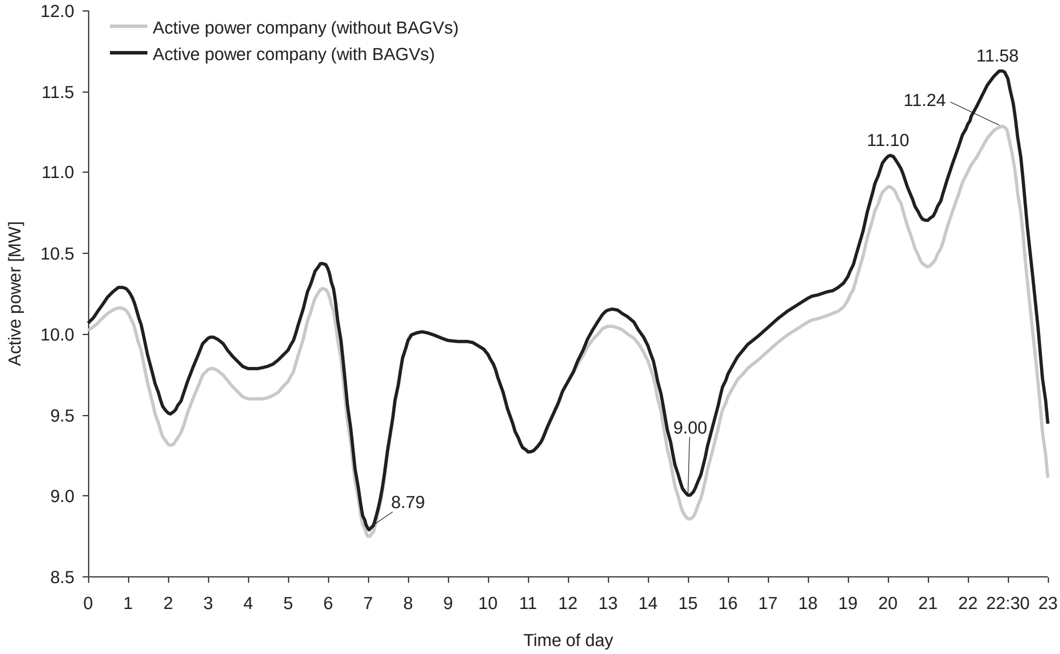

Figure B:19. Active power of the company on November 5th with and without additional load from the B-AGVs (uncontrolled battery charging).

The result of our optimization is illustrated in Figure B:20 for November 5th, when the company's peak load occurred. Even on this day the residence time of each battery system in the BSS was long enough for the charging processes to be interrupted and completed later. Moreover, one can see that the load is shifted away from the peak hours into hours in which the load is low (e.g., 7 a.m. or 3 p.m.).

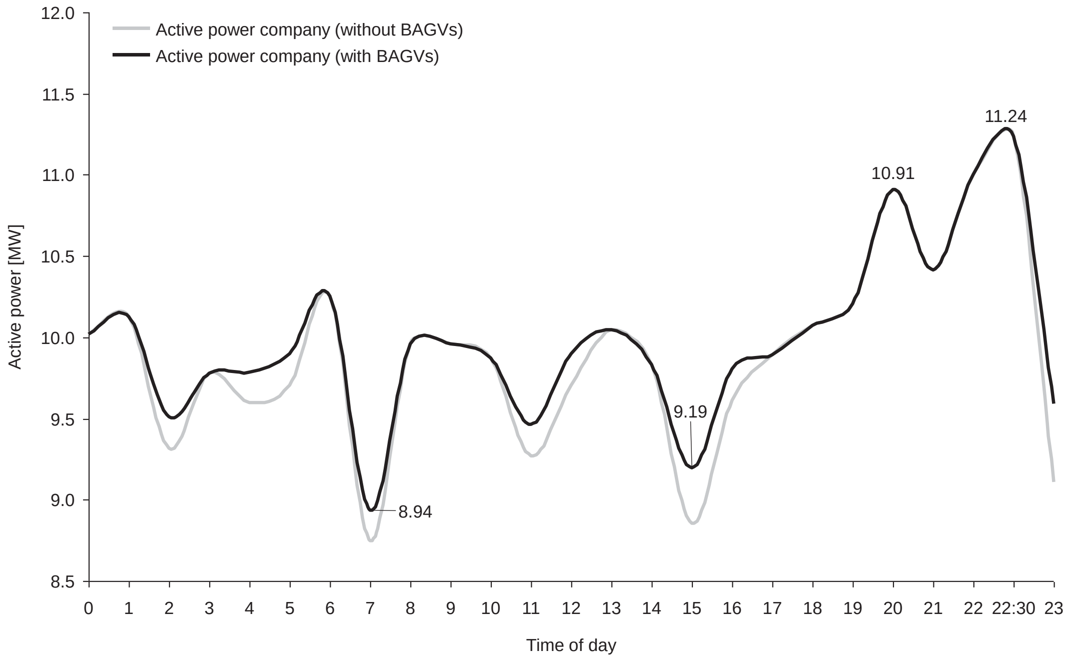

Figure B:20. Active power of the company on November 5th with and without additional load from the B-AGVs (controlled battery charging).

Although the annual full-load hours of the company increase, the threshold of 7,000 hours for obtaining an individual grid fee cannot be achieved. Achieving this would require more than 65 additional B-AGVs, assuming an increase in peak load can be prevented despite the greater number of B-AGVs. The theoretically achievable cost-saving potentials are considerable as up to 80% of annual grid fees (€968,892) could be saved.

4.5 Discussion

This study has demonstrated that the EV fleet of our pilot case company can be used for a broad range of DSI programs and is not limited to established DR programs for electric vehicles, such as smart charging and the vehicle-to-grid concept. An overview of all DSI programs investigated as well as an evaluation of the suitability for our pilot case company is presented in Table B-22. As explained in Section B.II.4.3.1, the assessment is based on three main sets of criteria: implementation effort, cost, and economic potential.

Table B-22. Overview of all investigated DSI programs.

DSI programs	Effort for implementation			Cost		Economic potential	Suitability for pilot case company
	Regulatory	Operational	Technical	Initial	Running		
Internal load management							
- Optimization of the company's load curve	Low	Medium	Low	Medium	Low	High	Yes
- Optimizing the mode of operation	Low	Medium	Medium	Medium	Medium	Low	Not yet; no decentralized power-generation systems in use
Balancing group management	Low	Low	Medium	Medium	Low	Low	Depends on balancing group manager
Price-based DSI	Low	Low	Low	Low	Low	High	Yes
Ancillary service							
I) Control reserve							
a) Primary	High	High	High	High	High	-	Regulatory requirements too high
b) Secondary	High	High	High	High	High	-	Regulatory requirements too high
c) Tertiary	High	Medium	Medium	High	Medium	Low	Partly; aggregator required
II) Interruptible loads	High	High	Medium	Medium	Medium	-	Regulatory requirements too high

It becomes obvious that several DSI programs cannot be realized under the prevailing conditions, mainly due to regulatory requirements. These include offering primary and secondary control reserve power as well as offering interruptible loads on capacity markets.

One DSI program that could become relevant in the future is using the flexible load to *provide negative minute reserve*. In particular, selling regulation down appears sensible as the batteries are only charged in case of activation and earning potentials from selling regulation down are greater than those from selling regulation up (Regelleistung, 2014d). This DSI program was not investigated in detail, because regulatory requirements (e.g., minimum bid size) cannot yet be met. Therefore, the flexible load of our pilot case company must be pooled with others providers, probably diminishing the economic benefits. Schmidt et al. (2014) also demonstrate that there is a limited economic potential of this DSI program, even if the company is able to act on the control reserve market itself. Nevertheless, this DSI program has the potential to become economically sustainable in the future, as the quantity demanded and thus the prices of negative control reserve power continue to increase in Germany, mainly due to the increasing share of renewable energies (Bundesnetzagentur and Bundeskartellamt, 2013).

The DSI program *optimizing the mode of operation in regard to a decentralized energy source* is not yet applicable and has not been assessed, but it may become relevant in the future if our pilot case company builds its own wind power system. The *balancing group management* DSI program seems particularly interesting for companies operating their own balancing group. Nevertheless, companies lacking such a balancing group can benefit from this DSI program if they are able to supply a good forecast of their energy consumption to their balancing group manager. The question of whether it can be beneficial to provide the company's energy demand forecast to the supplier must be investigated further, as the forecast would be available in all DSI programs discussed.

Based on our pre-assessment, the DSI programs *optimizing the company's load curve* and *controlling the charging process based on variable prices* were identified to be the most promising for utilizing charging flexibility. In this regard, both programs offer attractive saving potentials and are rather easy to implement.

Optimizing the company's load curve is part of a company-internal load management. Based on our results, we demonstrated that an increase of the company's peak load could be prevented for 10 B-AGVs when controlling the charging processes, which also leads to an economic benefit. If the share of EVs is increased further while simultaneously preventing an increase in peak load, companies could save up to 80% of their annual grid fees, resulting in high economic potentials of this DSI program. However, this DSI program is only suitable for companies that have already implemented further energy management measures, because the charging processes can only contribute to a balanced company-wide load curve to a certain degree. If the discrepancy between power supply and demand were to increase further, the German government might decrease the threshold of annual usage hours in order to motivate more companies to implement energy management measures.

For the *controlled charging based on variable prices* DSI program, an intermediary that offers access to the energy stock exchange is required. Within the frame of the project, this would probably be the company's electricity utility, which is likely to charge a fee for this service. Based on our economic assessment, we determined that energy procurement costs could be reduced considerably when controlling the charging processes based on spot market prices. In addition, this DSI program is beneficial for the security of energy supply because electricity prices will be particularly low if a large amount of renewable energy is available or electricity demand is low. Under current market conditions, this DSI program seems to be the most promising for our pilot case company. However, *optimizing the company's load curve* is very easy to realize and does not require any changes in the electricity procurement of the company, so it could be implemented first.

Our study contributes to energy economics in three major ways. First, we appear to be among the first to investigate a broad range of DSI programs for electric transport vehicles operating in closed transport systems. Second, we were able to identify several promising DSI programs for these vehicles by considering technical, regulatory, and economic aspects. Such an investigation is necessary both to help develop energy market design and advocate applications towards greater compliance/congruence. Third, we were able to show that the current energy market design in Germany is ill-suited for smaller providers of flexible loads. This calls for changes in the market design if owners of electric vehicles are to be encouraged to participate in DSI programs. In fact, even many larger electric fleet operators cannot sensibly implement potential DSI programs at this point in time. Therefore, further research should focus on how to develop a future market design and regulatory framework for the electricity sector that also allows smaller providers of flexible loads to participate.

Our results also provide valuable information for practitioners. In this regard, the characteristics of our pilot case company are likely to be similar to those of other transportation companies (e.g., in terms of transport requirements or operation times). Hence, the DSI programs and their respective results can be adapted by other companies in related fields of application, such as airports. Finally, our study can help policymakers by providing information about the deficits of the current energy market design for using flexible loads to balance energy generation and consumption. The need for such investigation has recently been highlighted by the publication of a Green Book “A Power Market for the Energy Reform", which is meant to promote the public debate about a new power market design (BMWi, 2014b). As flexible loads play a major role in this Green Book and the related discussions, it becomes apparent that new and relevant insights into aspects that must be considered in designing an adequate future market and regulatory framework are required.

4.6 Conclusion

In this paper, we evaluated several DSI programs for utilizing the load-shifting potential resulting from the charging flexibility of EVs. While most research has focused on individually used EVs, we focus on an electric transport vehicle fleet that operates within a container terminal. In order to ensure the practical relevance of our results, our analysis is based on a large-scale electric mobility project. Principally, we found that it is advantageous to implement DSI programs when using electric transport vehicles. This result is not restricted to our case study but might also be appropriate for similar ports or even other logistic facilities.

Nevertheless, our pre-assessment of potential DSI programs revealed that many of these programs are presently unsuitable for utilizing the flexible load-shifting potential. This finding is of particular importance because the technical implementation of most DSI programs is relatively simple for our pilot case company. The main reasons why many DSI programs are not feasible are the lack of standardized products from utilities regarding the respective program and extensive regulatory requirements. In this regard, most potential DSI markets in Germany have minimum requirements for tender periods, power gradients, or tender quantities. Moreover, most programs are required to join a pool and share profits with pooling agents, which diminishes the benefit for any EV user. Under current market conditions, two DSI programs were identified to be most promising for making use of the charging flexibility, namely *optimization of the company's load curve* and *controlled charging based on variable prices*. We introduced a formal model for the economic analysis of these programs, revealing that significant cost-saving potentials could be achieved when implementing *controlled charging based on variable prices*. To do so, however, an intermediary who procures the energy on the spot market on behalf of the company is required. In addition, we could show that charging flexibility can be used for internal purposes in order to prevent an increase of the company's peak load, which also leads to economic benefits, albeit significantly lower ones. These could increase in the future, as regulatory frameworks in Germany have recently changed in order to encourage companies to balance their load curves. Moreover, this DSI program would become more important if the share of electric transport vehicles were to increase. However, the following limitations should be considered. As the investigation is based on a case study, the results cannot be expected to be representative for all kinds of users. Furthermore, the evaluation of the regulatory complexity is based on today's energy market design in Germany, which is likely to change in the future. The DSI programs discussed as well as the model introduced should also be applicable in countries with similar regulatory frameworks, but the results, especially those of the pre-assessment, will vary depending on the specific framework. This is significant because electric transport vehicles are currently being introduced in ports throughout the world.

Essentially, it must be taken into account that many governments intend to significantly increase the share of renewable energies, which has an influence on most DSI programs. A larger share of renewables will lead to increasing discrepancies between power supply and demand, thus rendering DSI measures more urgent in order to create a balance while simultaneously increasing energy efficiency. Accordingly, it can be assumed that DSI regulatory frameworks will be adjusted in order to improve market success for EVs and other small actors. Finally, increasing discrepancies between power supply and demand will also have an influence on prices, potentially allowing DSI programs that are currently not competitive to become economically sustainable in the future.

5 Study 6: Using Electric Transport Vehicles within Closed Transport Systems – Assessing the Potential and Optimizing the Economic Viability

Table B-23. Fact sheet of study no. 6.

Title	Using Electric Transport Vehicles within Closed Transport Systems – Assessing the Potential and Optimizing the Economic Viability
Authors	Johannes Schmidt[a,*], Claas Meyer-Barlag[b], Matthias Eisel[a], Lutz M. Kolbe[a], Hans-Jürgen Appelrath[b] [a]Chair of Information Management, University of Göttingen, Platz der Göttinger Sieben 5, 37073 Göttingen, Germany [b]Department of Computer Science, University of Oldenburg, Escherweg 2, 26121 Oldenburg, Germany *Corresponding author. Tel.: +49 551 3921177. E-mail address: jschmida@uni-goettingen.de
Outlet	Research in Transportation Business & Management 2015, Submitted (under review), Completed Research Paper
Highlights	• The economic viability of electric mobility in closed transport systems is assessed. • The economic assessment is based on a large-scale project with a port operator. • Electric transport fleets are economically beneficial in closed transport systems. • The cost effectiveness can be further increased through several strategies.
Abstract	Many large container terminals make use of diesel-powered automated guided vehicles (AGVs) to transport containers between quay cranes and container storage, thereby ensuring a high degree of productivity. However, battery-powered AGVs (B-AGVs) appear to have several economic, environmental, and technical advantages compared to conventional transport fleets. In this study, we use data from a large-scale electric mobility project conducted in a container terminal using B-AGVs in combination with a battery-swapping station to assess the cost efficiency of this emerging transport technology. Our findings indicate that the use of B-AGVs is economically beneficial in closed transport systems while several strategies can be used to further increase their profitability. Most promising from an economic perspective is shifting charging processes to off-peak hours, yielding lower energy procurement costs. In this context, terminal operators can achieve savings in total expenditures of more than 10% compared to a diesel-powered transport fleet.
Keywords	Electric Transport Vehicles, Container Terminal, Economic Assessment, Simulation Model, Charging Strategies

5.1 Introduction

The global container trade has gained significantly in importance over the last decades. In this regard, the world container throughput grew from 76 million twenty-foot equivalent units in 1988 to 600 million twenty-foot equivalent units in 2013 (UNCTAD, 2013). In order to accommodate the increasing supply of containers, terminal operators should achieve a high level of productivity and container throughput, ideally at low costs. One means of achieving this is to provide an advanced level of automation in container terminals to increase efficiency, especially in high-wage countries (Xin et al., 2014). This strategy is pursued by many large container terminals (e.g., Singapore or Rotterdam), where automated guided vehicles (AGVs) transport containers between quay cranes and the container storage. The advantages of AGVs include labor cost savings, predictable and continuous operation, high reliability, and reduction of error rates of transport processes due to the high degree of automation (Gelareh et al., 2013; Liu et al., 2004). Currently, this kind of transport is almost exclusively executed by driverless, diesel-powered AGVs. However, battery-powered AGVs (B-AGVs) represent an emerging transport technology for this application context and appear to have decisive economic, technical, and ecological advantages in closed transport systems, such as container terminals.

In general, the use of electric transport vehicles (ETVs) offers economic potentials because their lower maintenance costs and electricity costs relative to fuel costs make them cheaper to operate than conventional ones (Lyon et al., 2012; Peterson and Michalek, 2013). Furthermore, commercial fleets operating in closed transport systems seem to be particularly suited for the implementation of controlled charging concepts due in part to the significantly better predictability of energy consumption and vehicle operating times compared to those of privately used vehicles (Schmidt et al. 2014; Guille and Gross, 2009; Tomić and Kempton, 2007). By significantly decreasing energy procurement costs, the application of controlled charging concepts can make a valuable contribution to ensuring that these vehicles become economically competitive. From an environmental point of view, replacing the internal combustion engine with an electric motor is regarded as crucial for future sustainable mobility because the transport sector alone accounts for about one-fifth of greenhouse gas emissions in the European Union (European Environment Agency, 2012). In this regard, many port authorities, such as Genoa or Hamburg, aim to improve energy efficiency and promote energy management on ports (Acciaro et al., 2012). Further favorable technical characteristics of ETVs include the possibility of reducing the company's local emissions and noise pollution. Therefore, fleet operators can also expect reputational benefits from adopting eco-friendly technologies (Orsato, 2009). Finally, the typical motion profile of vehicles in closed transport systems is driving short distances with many intermediate stops and frequent reacceleration. In such a profile, electric motors are more efficient than conventional engines in terms of energy consumption because of their higher power generation in low torque ranges (Lin et al., 2003).

Despite the promising potential for fleet operators and further stakeholders, the assessment of the commercial viability of B-AGVs operating in closed transport systems still seems to be an open research gap. It can be assumed that fleet operators would only be convinced to use an eco-friendly technology if it were economically comparable to its conventional counterpart. Within this study, we therefore examine whether ETVs are a viable alternative to diesel-powered transport vehicles in closed transport systems on the basis of a total cost of ownership (TCO) analysis. To do so, we analyze data gathered in a comprehensive field experiment conducted in one of the largest European ports using heavy-duty B-AGVs in combination with a battery-swapping station (BSS) to enable nearly continuous B-AGV operation. Because the use of a BSS requires the employment of more batteries than vehicles, one of this study's key goals is to determine a suitable battery-to-vehicle ratio on the basis of a simulation study. Moreover, the economic potential of controlled charging concepts is assessed using an optimization approach for energy procurement. The aim of our research is therefore to address the following research questions:

1) What are the total costs of ownership for an internal transport system using automated, battery-powered heavy-duty vehicles in combination with a battery-swapping station?
2) How can controlled charging processes reduce the total costs of ownership for the transport system?
3) Is it more cost efficient to reduce the number of batteries employed to a minimum or can the use of additional batteries provide economic benefits by creating a load-shifting potential to reduce energy procurement costs?

The remainder of this paper is organized as follows. In Section B.II.5.2, we present the state of the art of relevant topics from the fields of transportation science. In Section B.II.5.3, we present the material and methods used to perform a TCO analysis for a case study, assess the economic potential of controlled charging concepts, and determine a suitable battery-to-vehicle ratio; the corresponding results are provided in Section B.II.5.4. In Section B.II.5.5, we discuss the findings and limitations of our research endeavor, which lead us to the conclusions presented in Section B.II.5.6.

5.2 Related Work

Much research has been conducted on the general topic of AGV routing and scheduling in container terminals. For example, Liu et al. (2004) use a multi-attribute decision-making (MADM) method to assess the performance of two terminals and determine the optimal number of deployed AGVs for each one. Their simulation results show that a substantial increase in the terminal's throughput can be gained through the deployment of AGVs. Gelareh et al. (2013) propose a mixed-integer program for scheduling a fleet of AGVs to minimize the makespan of operation for transporting. However, all of these studies consider diesel-powered AGV fleets, while we focus on a B-AGV fleet used in combination with a BSS. Furthermore, it is not the focus of our paper to investigate routing and scheduling problems but rather to analyze and improve the economic viability of this new transportation technology.

Some TCO analyses (e.g., Kihm and Trommer, 2014; Plötz et al., 2014; Sharma et al., 2012) have been performed to assess the profitability of privately owned electric vehicles (EVs). These studies have demonstrated that the economic viability of EVs is constrained, mainly because of their significantly higher acquisition costs compared to conventional vehicles. However, there is no study assessing the profitability of B-AGVs in closed transport systems.

Another research focus of this study is to evaluate the influence of controlled charging processes on the TCO for the transport system. There do exist some studies that analyze the problem of operating a BSS with intelligent charging concepts. In this regard, Yang et al. (2014) and Sarker et al. (2013) propose an optimization model for a BSS to acquire additional revenues by responding actively to price fluctuations in the electricity market. However, the authors focus on individual traffic, which is not the case in our study. Further, Schmidt et al. (2014) assess the economic potential of applying controlled charging concepts for a B-AGV fleet used with a BSS in a container terminal. Their results indicate that controlled charging concepts provide substantial economic cost-saving potentials. However, their study lacks real data and the influence of the resulting cost-saving potentials on the TCO is not evaluated.

Finally, there are studies regarding the optimization of BSS operations, which is also part of this study. Although some literature investigates location needs for area-wide coverage of BSSs for EVs or the exchange station capacity (i.e., number of batteries deployed) needed for this purpose (e.g., Mak et al., 2013; Xiao et al., 2012; Wang, 2011b), all of these studies lack stochastic elements and focus on individual traffic. In our case, we have different preconditions: a closed transport area with a given number of electric transport vehicles and battery systems.

While the literature provides insights into TCO for EVs, AGV scheduling and routing problems as well as the economic impacts resulting from the implementation of various charging strategies on B-AGV fleets, little is known about the economic potential of ETVs operating in container terminals with a BSS.

5.3 Material and Method

5.3.1 Description of the Project Setting

In order to investigate the commercial viability of ETVs in closed transport systems, we use data from a comprehensive electric mobility project (called BESIC) with one of the largest port operators in Europe. The HHLA Container Terminal Altenwerder was the first to test a prototype of a fully electric AGV (HHLA, 2011). Within the project, 10 of the terminal’s 80 diesel-powered AGVs were substituted by B-AGVs in order to perform fleet tests under actual terminal conditions and to economically and technically compare both means of transport. Based on practice experience the new technology was proven to work reliably and have similar performance characteristics to diesel-powered AGVs.

The B-AGVs (payload ≈ 70 tons) were equipped with lead–acid batteries, as these have already been used in several heavy-duty ETVs (e.g., forklifts) and are therefore standardized to a greater extent than lithium–ion batteries. Furthermore, lead–acid batteries of this size are significantly cheaper than similar state-of-the-art lithium–ion batteries and are sufficient to meet the defined transport requirements; the battery systems are designed to guarantee a minimum operation time of at least 12 hours.

One important aspect that was considered for the use of B-AGVs in this context is that the vehicles usually operate more than 5,000 hours per year – sometimes even 24 hours a day. Therefore, a BSS was implemented on company grounds. The use of a BSS is particularly suited for this application context because depleted batteries can be exchanged for full ones within a few minutes, allowing the transport vehicles to be operational around the clock, as normally required by terminal operators. If a battery's state of charge drops below a certain level, the B-AGVs are automatically called to the BSS and the depleted battery is exchanged for a fully charged one. However, the construction of a BSS requires significant investments. Furthermore, enough spare batteries must be procured so that the stock of charged batteries is sufficient to replace the depleted ones. In the first part of the project, two battery systems per vehicle were procured, resulting in a total of 20 batteries with a useful capacity of 289 kWh each. The batteries can be fully charged within 6 hours in the BSS.

At the 2:1 battery-to-vehicle ratio, the batteries often remain idle in the BSS after completing their charging processes when using a plug-and-charge approach (batteries begin charging immediately after being connected to the grid). This can be seen in Figure B:21, in which all battery charging and idle times in the BSS are illustrated for one week. Within the frame of the project, it should then also be investigated how these idle times can be used to optimize energy procurement or whether it is possible to decrease the 2:1 battery-to-vehicle ratio without having a negative effect on system productivity. Both approaches can be used to reduce the TCO of the transport systems and will be assessed in this paper.

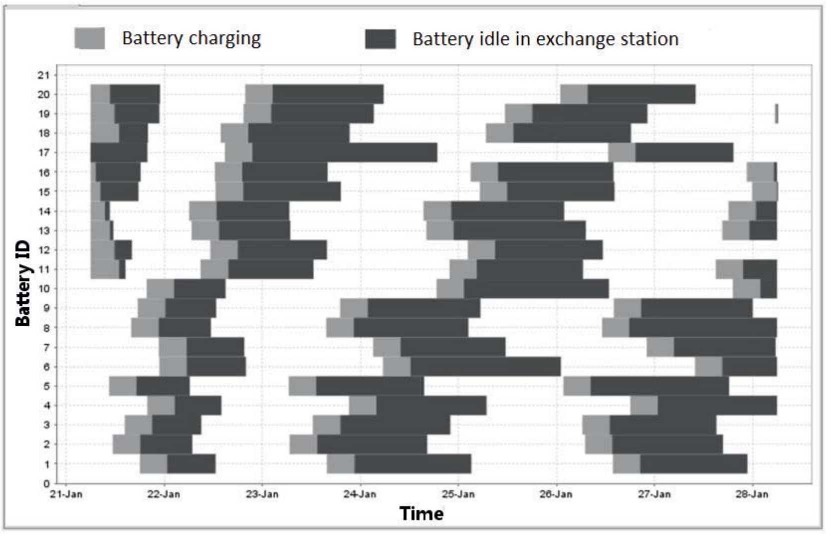

Figure B:21. Battery charging and idle times in the BSS for one week.

5.3.2 Simulation-Based Analysis of Container Transports

Within the frame of the project, a simulation model forecasting the logistic processes and the related electricity demand at the container terminal was developed (Grundmeier et al., 2014). Because transport systems are often highly dynamic and depend on many different influence factors, it is often impossible to model these systems completely mathematically. Based on this model, it is possible to implement controlled charging concepts (see Section B.II.5.3.4) and determine a minimum battery-to-vehicle ratio (see Section B.II.5.3.5).

In order to forecast electricity demand from the B-AGVs, the simulation model uses the "sailing list" as an input parameter. Among other data, it includes the estimated time of arrival of container vessels and the number of planned loading and unloading operations. Hence, the number of necessary container transports from and to each vessel can be determined.

By replicating the algorithms for transport order assignment and vehicle routing from the source transport system, the execution time and duration for each order can be forecasted. Because the exact assessment of a vehicle's energy consumption requires a representation for every vehicle movement, a model of the path network was implemented. In this model, we consider quay cranes as container sources and block storages as sinks for import processes (and vice versa for export processes). During the simulation, each transport order is broken down into the longest possible vehicle movements that are assured to not be influenced by other AGVs and then executed by moving vehicles through the transport grid. Both the duration as well as the battery usage can be calculated and logged to a relatively precise degree for conflict-free movements. By modeling vehicle motion in such explicit detail, estimation of the energy consumption can be made as exact as possible (Ihle et al., 2014). The main benefits gained by this approach are twofold: First, a forecast of the energy requirements for each vehicle can be made, allowing energy procurement to be planned in advance, and second, it enables an in-depth analysis of the influence of different strategies for order assignment, routing, and recharging.

As the simulation platform was designed with the main purpose of assessing the performance of B-AGVs during various terminal-capacity scenarios, the simulation model includes all conventional parts of a container terminal's logistic system (e.g., quay cranes and transport vehicles) as well as the charging infrastructure of the ETVs (see Figure B:22). The BSS was modeled in great detail to monitor the degree of capacity utilization as well as the energy required for all recharge processes during simulation. This allows for an evaluation of controlled charging approaches.

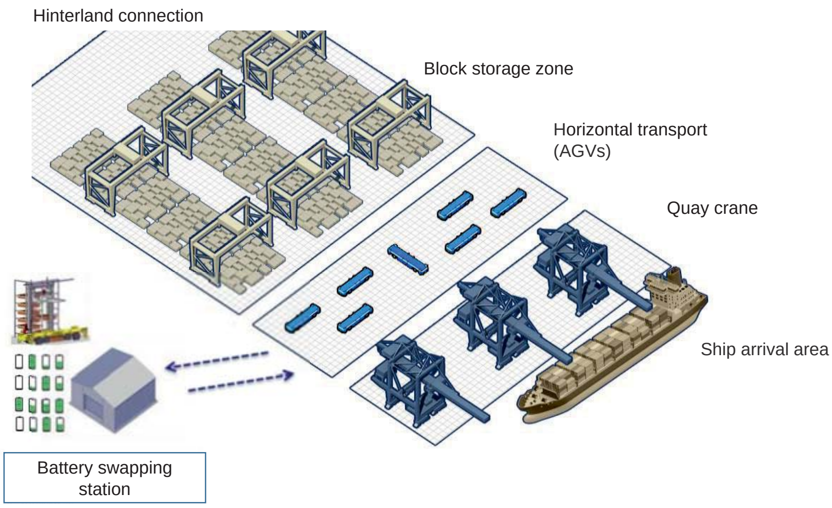

Figure B:22. Components of the simulation model.

The model was parameterized and verified with measured data and knowledge from the actual system. In this context, the model parameter can be divided into three different types: fixed values that can be directly represented in the model (e.g., transport grid layout, locations of battery-swapping stations, quay crane lines); values that depend on data outside the modeled scope, which are represented as stochastic values (e.g., battery aging, exact container loading and unloading times, container retrieval times in block storage); and process flows, which are modeled using embedded algorithms (e.g., berth planning, quay-crane scheduling, vehicle selection, and routing). During simulation runs, typical key performance indicators (KPIs) such as transport durations, average times without battery exchange, and duration of battery stays in the BSS are recorded. These KPIs are also logged in the source system, allowing for a comparison with results from a simulation based on historic input data and thus validating the simulation model.

5.3.3 Total Cost of Ownership Analysis

To assess the profitability of ETVs in this application context, we compare electrically and diesel-powered transport vehicles on the basis of a TCO analysis. According to Ellram (1993), a TCO analysis “implies that all costs associated with the acquisition, use, and maintenance of an item are to be considered in evaluating that item and not just the purchase price.” In order to ensure a realistic assessment, we used data gathered within the BESIC project (see Section B.II.5.3.1). Accordingly, the TCO analysis is performed both for a fleet of 10 ETVs as well as for one of 10 diesel-powered transport vehicles. Both transport fleets comprise different assets. While a conventional transport vehicle fleet consists of vehicles (AGVs) and a petrol station, the B-AGV fleet’s assets include the BSS as well as the vehicles and batteries. An important characteristic of using a BSS is the need to have more batteries available (spare batteries) than the number of B-AGVs in use. Currently, two batteries for each B-AGV are used; thus, the 2:1 equipment ratio (battery to B-AGV) serves as the *base case*. Furthermore, we consider a planning period of 15 years, starting from the reference year 2012, when the ETVs and BSS were procured.

To estimate the TCO of each fleet, we calculate and compare the corresponding net present costs (NPCs). Each future cost is in the form of cash flows. Hence, the NPCs are calculated from total annual costs starting at the initial period in which all assets are purchased and ending with the last year of the period considered T. The annual TCO consist of capital expenditures C^{capex} for a transport fleet and the corresponding operating expenditures C^{opex}. Furthermore, a discount factor $(1+i)^{-t}$ is used to modify future annual costs C_t, where t is the time in years since the initial period. The NPCs of the TCO of a transport fleet including all required assets C_{TCO} is the sum of the products of yearly cash flows and the corresponding discount factor

$$C_{TCO} = \sum_{t=0}^{T} \left(C_t^{capex} (1+i)^{-t} + C_t^{opex} (1+i)^{-t} \right). \tag{B.44}$$

All cost components and assets of both transport fleets considered in the TCO model are illustrated in Figure B:23.

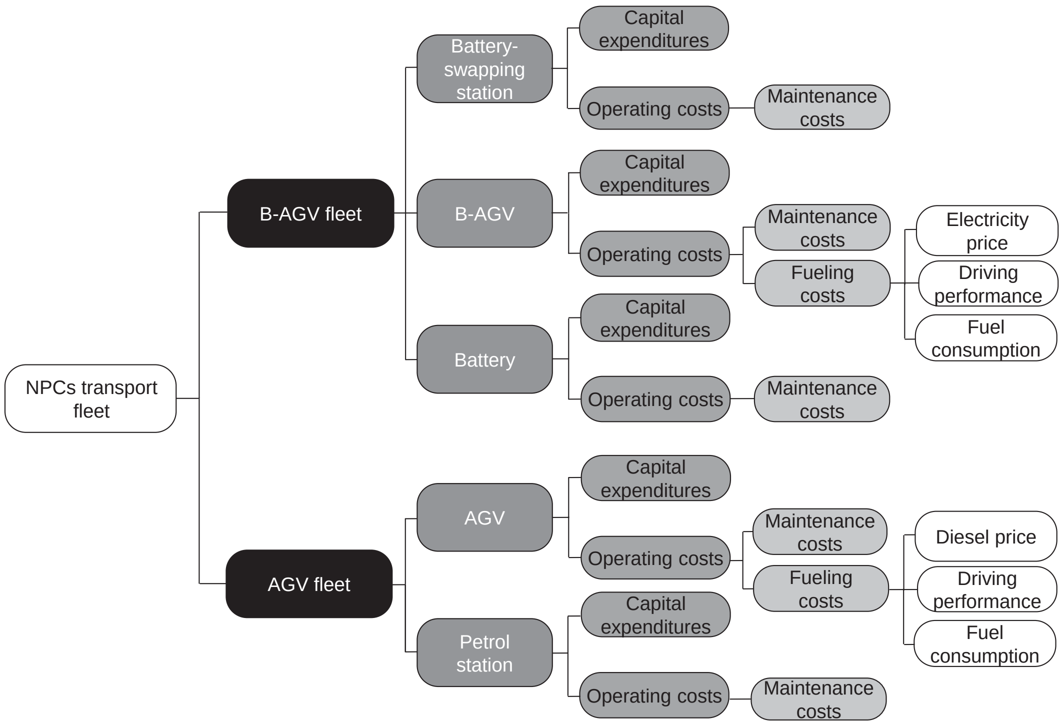

Figure B:23. Elements considered in the TCO model.

Annual capital expenditures are calculated by multiplying the list prices p of an asset with the required number of assets n in this year. Note that, assets with a shorter lifetime than the planning period (e.g., batteries) must be replaced to retain operational readiness for the transport fleet. Furthermore, incidental acquisition costs, such as construction costs for the BSS, must be included in the list price. Annual capital expenditures C_{BAGV}^{capex} for a fleet with n_{BAGV} B-AGVs, n_{Bat} batteries and n_{BSS} battery-swapping stations can hence be calculated by

$$C_{BAGV}^{capex} = n_{BAGV} \cdot p_{BAGV} + n_{Bat} \cdot p_{Bat} + n_{BSS} \cdot p_{BSS}. \qquad \text{(B.45)}$$

In this study, the salvage value of an asset is assumed to be zero because a company usually uses a transport fleet until the end of its life, leaving it with no resale value. Furthermore, we neglect the disposal costs of the assets because, by law, the vehicle manufacturer must take back vehicles and batteries free of charge in Germany.

The operational costs include maintenance costs for the BSS, petrol station, batteries, and vehicles as well as fueling costs, which depend on the driving performance, fuel price (diesel or electricity), and the fuel consumption of each type of engine. As the profitability of a fleet strongly depends on the development of electricity and oil prices, three different scenarios are considered (see Figure B:24). For the forecast in oil price development, we use data from the U.S. Energy Information Administration (2014) (low oil price, reference oil price, and high oil price cases). Referring to the electricity prices, most studies assume a further increase in prices in Germany as a result of the development of renewable energy, among other factors (e.g., European Commission, 2014a; Gerbert et al., 2013). We consider three electricity price scenarios (very low, moderate, and significant electricity price increases) from Nitsch et al.

(2012). The respective forecasted price increase rates are added to the average diesel and electricity prices for industry customers in 2012 (initial period).

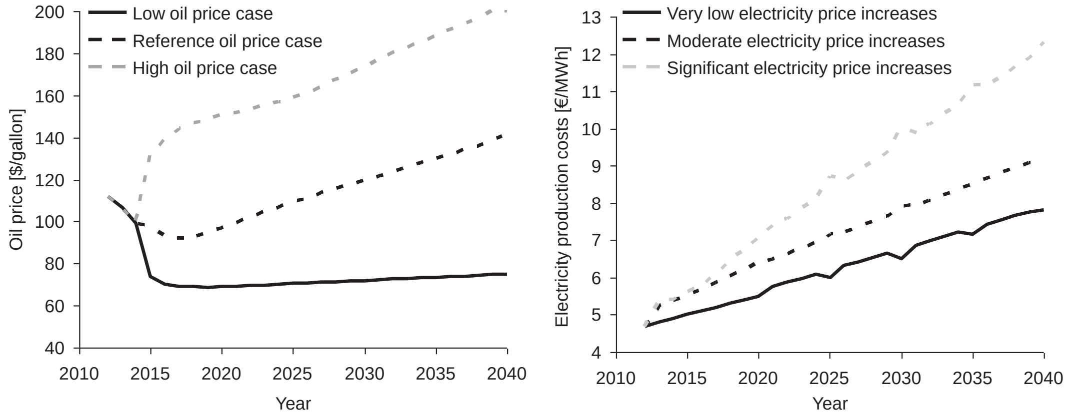

Figure B:24. Forecasted development of oil prices and electricity production costs in Germany.

Maintenance costs of the assets include regularly planned maintenance (monthly or yearly maintenance measures), unplanned maintenance (responding to faults), and repair costs. For the B-AGV fleet, it must be taken into account that the batteries require separate maintenance measures. Unlike privately used vehicles, there are no circulation taxes for either transport fleet. The annual operating expenditures C_{BAGV}^{opex} for a B-AGV fleet can thus be calculated by

$$C_{BAGV}^{opex} = n_{BAGV} \cdot \left(p_{el} d_{hour} T_{op} + C_{BAGV}^{om}\right) + n_{Bat} \cdot C_{Bat}^{om} + n_{BSS} \cdot C_{BSS}^{om}. \tag{B.46}$$

To calculate the cost for electric driving (fueling costs), we multiply the driving performance T_{op} (annual hours of operation) of a B-AGV with the electric consumption per hour d_{hour} and the electricity price for the fleet operator p_{el}. Furthermore, the operations and maintenance costs per year C^{om} for the B-AGV fleet must be calculated by multiplying the number of assets with the annual operations and maintenance costs per asset. The procedure for calculating operating expenditures C_{AGV}^{opex} for the AGV fleet is similar.

5.3.4 Optimization of Charging Cost

Using the B-AGV fleet offers the opportunity to reduce energy procurement costs by implementing controlled charging strategies. To date, the most promising charging concept is controlled charging based on spot market prices, because of its attractive saving potential and relatively simple implementation compared to other charging concepts, such as offering control reserve on regulation markets (Schmidt et al., 2014; Tirez et al., 2010).

In order to evaluate the economic potential of controlled charging concepts, we first calculate annual procurement costs c_{pnc} when charging the B-AGV fleet in an uncontrolled manner (plug-and-charge concept) with fixed prices for electricity. For the calculation, we only consider the average wholesale price for electricity offered by the fleet operator's energy supplier, because it is the only component that can be influenced by controlled charging concepts; the other price components (e.g., grid fees or electricity taxes) – which amount to 40% of the retail price for industry customers – are fixed (BDEW, 2014). Considering the wholesale price thus allows for an economic comparison with a controlled charging approach on spot market prices. Let d_{fleet} be the annual electricity demand of the B-AGV fleet and $\bar{p}_{el,ws}$ be the average electricity (wholesale) price for the fleet operator. Furthermore, the charging efficiency η must be considered by adjusting the demand parameter. Thus, we deduce

$$c_{pnc} = \frac{\bar{p}_{el,ws} \cdot d_{fleet}}{\eta}. \tag{B.47}$$

The main goal of controlled charging concepts is to reduce energy procurement costs by charging the batteries during the hours with the lowest possible prices. To apply this charging concept, the company itself can procure the required power on the electricity spot market, where hourly (wholesale) prices are determined by day-ahead auctions (Fanone et al., 2013). To assess the economic potential of this charging concept, we perform an optimization of charging costs for the reference year 2013 and evaluate the effect on the TCO, referred to as the *controlled charging case*.

The optimization approach is based on simulated operating and charging times of the battery systems and is illustrated for one battery system and charging process. In the first step, the minimum number of time slices to fully charge a battery system must be calculated. The terminal operator requires that each battery system must be fully charged when put back in use. The little flexibility gained by releasing the batteries earlier does not compensate for the reduced transport capabilities, as each battery exchange means that the B-AGV is unavailable for container transport needs for about 10 to 15 minutes.

Let $T = \{t_1, \dots, t_n\}$ be the set of one-minute time slices with $t_i \in T \; \forall \, i \in \mathbb{N}$ and $|T|$ as the number of time-slices in the observation period. Moreover, k_b is defined as a battery system with $k_b \in K = \{k_1, \dots, k_m\} \; \forall \, b \in \mathbb{N}$ as the set of all battery systems deployed in the transport system. The state of charge of a given battery and time-slice is defined as $soc(k_b, t_i)$. Because the batteries deployed in this transport system are type-wise homogenous, we assume the maximum battery capacity for all systems cap, the charging power w, and the charging efficiency η to be constant values. By using these input values, the number of time-slices required to fully recharge a battery $r(k_b, t_i)$ can be denoted as

$$r(k_b, t_i) = \alpha \cdot \frac{cap - soc(k_b, t_i)}{w \cdot \eta}, \tag{B.48}$$

with $\alpha = \frac{60}{hour}$. As a battery can only be charged when located in the BSS, the binary variable $s(k_b, t_i)$ is used to account for this fact

$$s(k_b, t_i) = \begin{cases} 1 \; if \; battery \; k_b \; is \; located \; in \; the \; BSS \; in \; time \; slice \; t_i \\ 0 \; if \; battery \; k_b \; is \; not \; located \; in \; the \; BSS \; in \; time \; slice \; t_{i.} \end{cases} \tag{B.49}$$

A single stationary use su of a battery system k_b (a battery is located in the BSS) is defined as a vector of time slices where

$$su(k_b, t_i) = (t_s, t_{s+1}, \dots, t_e), \tag{B.50}$$

with $s \leq i \leq e$. Furthermore, we assume that the following holds

$$s(k_b, t_{s-1}) = 0, \tag{B.51}$$

$$s(k_b, t_{e+1}) = 0, \tag{B.52}$$

$$s(k_b, t_i) = 1 \; \forall \; t_i \in [t_s, t_e]. \tag{B.53}$$

The set of all stationary uses for all battery systems

$$SU = \{su(k_b, t_i) \;|1 \le b \le |K|, 1 \le i \le |T|\}, \tag{B.54}$$

can be derived from results of the simulation and can therefore be used as an input value for the optimization problem. The subset of SU that contains only the stationary uses for one specific battery is notated as

$$\forall k_b \in K: SU_{k_b} = \{su(k_b, t_i) \mid 1 \le i \le |T|\} \;\subseteq SU. \tag{B.55}$$

As stated in Section B.II.5.3.1, the number of time slices $|su(k_b, t_i)|$ a battery is located in the BSS is normally significantly larger than the number of time slices $r(k_b, t_i)$ required to recharge the battery system. To optimize energy procurement costs per charging process, we shift all time slices in which a battery system is charged to the time slots in which electricity spot market prices are the lowest. The variable $h_{t_i,k_b} \in \{0,1\}$ is therefore introduced as the decision variable denoting whether battery k_b is charged at time slice t_i.

The energy procurement costs per charging process can be calculated by multiplying the electricity demand in the time slot the battery system is charged (adjusted by η) with the electricity spot market price $p_{spot}(t_i)$ that applies during this time slice. The corresponding optimization problem for minimizing energy procurement costs for the whole fleet in the reference year resolves into

$$\min_{h_{t_i,k_b}} \sum_{k_b \in K} \sum_{t_i \in T} \frac{\eta w}{\alpha} \cdot \; p_{spot}(t_i) \cdot h_{t_i,k_b} \,, \tag{B.56}$$

subject to

$$h_{t_i,k_b} \le s(k_b, t_i) \; \forall \; k_b \in K, t_i \in T, \tag{B.57}$$

$$\sum_{i=s}^{e} h_{t_i,k_b} = r(k_b, t_s) \; \forall \; k_b \in K, t_i \in T. \tag{B.58}$$

in which the second constraint states that each battery system must be fully charged at the end of each charging period.

5.3.5 Determining a Minimum Battery-to-Vehicle Ratio

The minimization of electricity procurement costs (see Section B.II.5.3.4) is one approach to reducing the TCO of the transport system. Another method is minimizing the number of spare battery-systems deployed and their charging infrastructure, thereby reducing spare battery holding costs. By cutting the battery-to-vehicle ratio to a minimum, however, the charging flexibility and thus the load shifting potential tends to be close to zero, rendering it nearly impossible to implement controlled charging approaches. Both concepts must therefore be considered separately to make valid statements about the profitability of ETVs for this application context.

To decrease the number of battery systems deployed, it is useful to start with a mathematical model to calculate the theoretical minimum required to fulfill all transport orders. We define n_{BAGV} as the number of B-AGVs and n_{Bat} as the number of deployed battery systems, with Δ_{ct} as the number of one-minute time slices necessary to fully charge a completely empty battery system. Because batteries are normally not completely depleted when returned to the BSS, we define a usable capacity c_u as a percentage of the battery with $0 \leq c_u \leq 1$.

Nevertheless, due to the high dynamic in the system, the average charge remaining will be close to $1 - c_u$ when observed over the complete course of the scenario. Assuming a simplified recharge model with a linear increase of the soc for a battery system over Δ_{ct}, the average time to recharge a battery system returned to the BSS is $c_u \Delta_{ct}$. Furthermore, by defining Δ_{wt} as the average number of time slices a vehicle can operate with a fully charged battery system before needing to return to the BSS (including battery exchange times), a theoretical minimum for n_{Bat} can be calculated as

$$n_{Bat} = \left\lceil \frac{n_{BAGV}}{\Delta_{wt}} \cdot c_u \Delta_{ct} \right\rceil + n_{BAGV}, \tag{B.59}$$

with the term $\frac{n_{BAGV}}{\Delta_{wt}}$ representing the battery exchanges per time slice.

It must be noted that the number of batteries calculated is the bare minimum required. B-AGVs are to arrive at the BSS at evenly distributed intervals. However, as battery discharge is not strictly linear, B-AGVs almost never arrive on an exact schedule. It is possible to remedy this with a control approach, ordering vehicles to exchange a battery prematurely or lighten the number of transport orders fulfilled by vehicles with a battery status that is lower than expected. However, this would negatively influence transport productivity, as battery exchanges can take up 30 minutes with travel time to and from the BSS. We therefore neglect such a control approach at this time.

In order to determine a minimum battery-to-vehicle ratio with a sufficient number of spare batteries to ensure that B-AGVs can obtain full batteries almost without waiting, a simulation study is conducted based on the simulation model described in Section B.II.5.3.2. We first select a sailing list with a high density of container traffic, requiring B-AGVs to operate at maximum capacity over a period of weeks. Multiple simulation runs are conducted while gradually reducing the number of additional batteries. B-AGVs that arrive at the swapping station and cannot be provided with a fully recharged battery are parked in waiting positions. These waiting times are logged and evaluated, allowing the minimum feasible battery-to-vehicle ratio to be determined.

5.4 Results

In this section, we present our results for the TCO analysis of a B-AGV and AGV fleet by 2026, considering various cases for the B-AGV fleet. All TCO results are illustrated for the reference oil and electricity price scenarios because both scenarios represent the expected price development. We assume a constant battery price within the planning period because lead–acid batteries are considered to be technically and economically mature (Lacey et al., 2013). Furthermore, a discount rate of 5% is used, which is a typical discount rate for logistic companies in Germany (Geginat et al., 2006). Finally, the B-AGV fleet costs are expressed in relation to the AGV fleet costs as specific prices for certain assets must not be published due to the confidentiality agreement that was part of the research project.

5.4.1 Base Case

The *base case* is represented by the 2:1 battery-to-vehicle ratio as well as uncontrolled charging of the B-AGVs' batteries with fixed electricity prices. All parameters and values necessary to perform a total cost of ownership analysis for both a conventional and a battery-electric transport fleet consisting of 10 vehicles each are summarized in Table B-24.

Table B-24. Parameters used to calculate annual costs of both fleets considered.

Parameter/ Asset	Cost component	Value	Lifetime (years)	Data source
BSS	Acquisition costs [€]	Under confidentiality agreement	15	Project data
	Maintenance costs [% of initial investment cost per year]	3–4		Project data
Petrol station	Acquisition costs [€]	Under confidentiality agreement	15	Project data
	Maintenance costs [% of initial investment cost per year]	3–4		Project data
Battery	Acquisition costs [€]	34,320	5	Project data
	Maintenance costs [% of initial investment cost per year]	2–3		Project data
AGV	Acquisition costs [€]	Under confidentiality agreement	15	Project data
	Maintenance costs [% of initial investment cost per year]	4–5		Project data
B-AGV	Acquisition costs [€]	Under confidentiality agreement	15	Project data
	Maintenance costs [% of initial investment cost per year]	3–4		Project data
General	Discount rate [%]	5		Geginat et al. [2006]
	Annual operating hours [h/a]	5,800		Project data
	Average fuel consumption for an AGV [l/h]	8		Project data
	Average power consumption for a B-AGV including charging losses [kWh]	21.5		Project data
	Average diesel price for 2012 (industry) [€/l]	1.16		Destatis [2014]
	Average electricity price for 2012 (industry) [€/kWh]	0.14		BDEW [2014]

The cumulative expenditures of the fleets by 2026 (normalized to the NPCs of the AGV fleet for the initial period) are illustrated in Figure B:25. Moreover, the transportation fleets' NPCs at the end of the planning period are presented as percentage values (normalized to the NPCs of the AGV fleet for the last period); we distinguish between capital expenditures (investment of the assets), fueling costs (electricity or diesel), and maintenance costs.

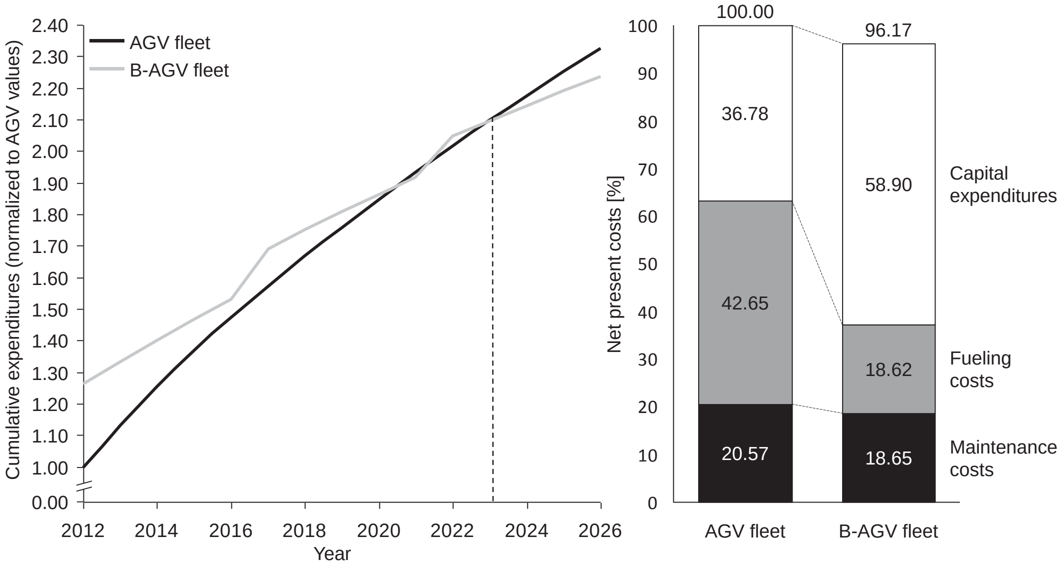

Figure B:25. TCO results for the base case.

The results reveal that the NPCs of the B-AGV fleet is approximately 4% lower than that of the AGV fleet over the 15-year planning period. This lower average TCO indicates that the B-AGV fleet is a more cost-efficient solution. When considering the cumulative expenditures of each fleet, one can see that the B-AGV fleet becomes cost competitive from 2023 onwards. This is because the use of EVs is accompanied by a progressive reduction in running costs that eventually exceeds the additional investment. In this regard, the lifetime electricity procurement costs are substantially lower than those for diesel procurement (by approx. 40%). A favorable factor for the profitability of the B-AGV fleet is the oil price development; the expected increase in oil prices at the end of the planning period is greater than that of electricity prices (see Section B.II.5.3.3). Finally, the maintenance costs of the B-AGV fleet are lower than those of the AGV fleet. However, the capital expenditures for the B-AGV fleet are significantly higher than those for the conventional transport fleet, mainly due to the BSS being more expensive than a petrol station and the necessity of procuring (additional) batteries. Furthermore, batteries must be replaced twice during the whole planning period, exhibited in the sharp increase of lifecycle costs in the years 2017 and 2022 in the left side of the figure.

5.4.2 Controlled Charging Case

Within this case, we present the results of the optimization of energy procurement and evaluate its influence on the B-AGV fleet's TCO. In order to evaluate the results and assess the achievable cost-saving potentials, we compare the annual charging costs for this charging concept with those when charging the B-AGV fleet in an uncontrolled manner. As explained in Section B.II.5.3.4, we consider the average wholesale price, which amounts to 0.05 €/kWh, to ensure comparability between this charging concept and uncontrolled charging with fixed electricity prices. In this regard, the wholesale price for the fleet operator is the only component of the final retail price that can be influenced by smart charging. The parameters necessary for assessing each charging concept are presented in Table B-25 for the B-AGV fleet.

Table B-25. Parameters used to economically assess each charging concept in the reference year.

Charging strategy	Parameter	Value	Comments	Data source
Plug-and-charge	p_{el}	0.05	Average electricity wholesale price for the industry sector [€/kWh]	Bundesnetzagentur and Bundeskartellamt [2013]
	d_{Fleet}	1,122,300	Annual electricity demand of the B-AGV fleet [kWh]	Project data
	η	0.90	Charging efficiency	Project data
Controlled charging	cap	289	Maximum battery capacity [kWh]	Project data
	w	48	Charging power [kW]	Project data
	$p_{spot}(t_i)$	[-87.52 – 265.3]	Electricity spot market prices in the reference year [€/MWh]	EEX [2014]

The annual costs when charging the fleet in an uncontrolled manner with fixed electricity (wholesale) prices can be calculated using Eq. (B.47) and the parameters listed in Table B-25 to be €62,973. Energy procurement costs for charging the battery systems of the B-AGV fleet can be reduced considerably for the fleet operator by using controlled charging concepts. The annual charging costs were calculated to be €33,243 using Eq. (B.56). This results in cost savings of 47.21% in comparison to the simple plug-and-charge approach. We use the percentage savings in electricity procurement costs compared to the plug-and-charge concept as the basis for a reduction of electricity procurement costs within the planning period (Section B.II.5.3.4). In Figure B:26, we present the overall costs through 2026 of the AGV and B-AGV fleets using controlled charging concepts.

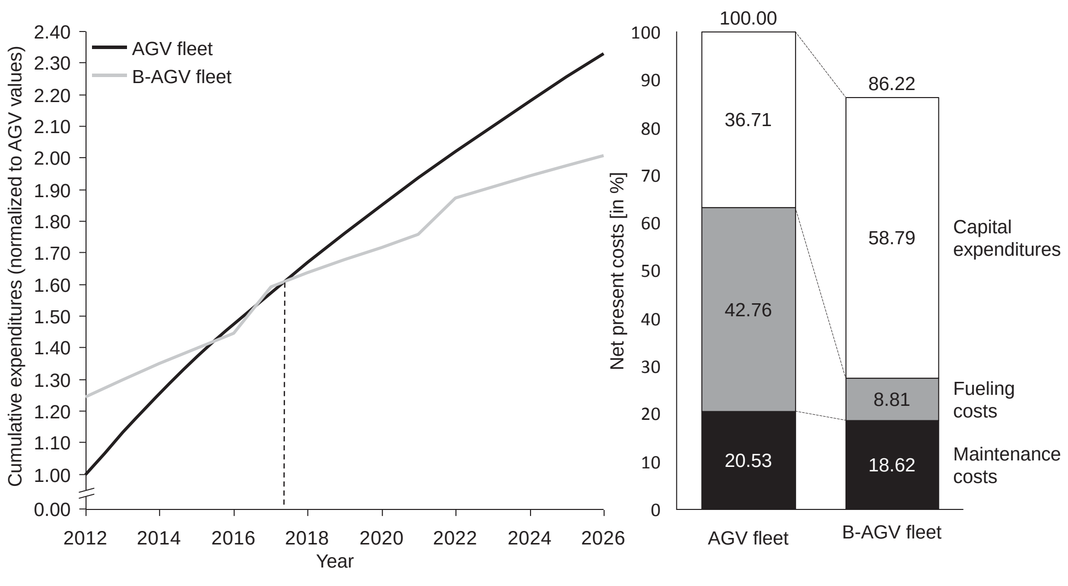

Figure B:26. TCO results for the controlled charging case.

Overall, the B-AGV fleet is more cost efficient than the AGV fleet, seen in the almost 14% lower NPCs. Through the application of controlled charging concepts, it now takes just five years until the B-AGV fleet is a more cost-efficient solution than the AGV fleet. Afterwards, the higher investment costs of the B-AGV fleet can be compensated for by its significantly lower fueling and maintenance costs compared to the AGV fleet.

5.4.3 Minimum Battery-to-Vehicle Ratio Case

Within this case, we present the results of the determination of a minimum battery-to-vehicle ratio and evaluate its influence on the B-AGV fleet's TCO. To fulfill all daily logistic tasks, a B-AGV must provide reliable operational transport capability, working efficiently with the BSS, even if the terminal is at maximum capacity for days at a time. Accordingly, input values of the simulation model (see Section B.II.5.3.2) were specified to simulate maximum terminal utilization while gradually increasing the number of additional battery systems. For each simulation run, the transport capability and the average waiting time for a B-AGV to receive a fully recharged battery system were measured for a fleet of 10 B-AGVs (see Figure B:27).

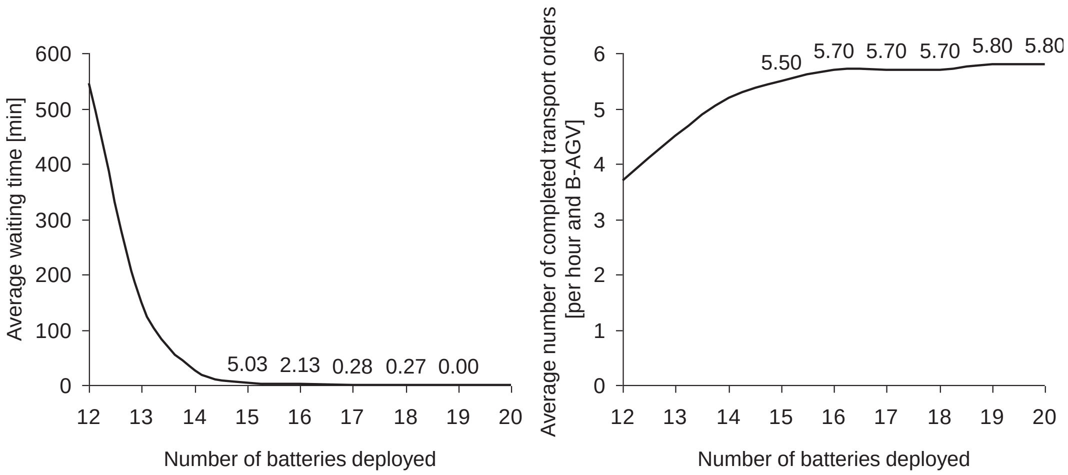

Figure B:27. Results of the simulation model.

Practical applications within the research project have shown that heavy-duty lead–acid battery systems (with 400 Ah and higher) can only feasibly recharge with rates up to 1/6 C. Accordingly, a complete recharging cycle takes six hours during the simulation runs. Based on data gathered from a field test, we found that vehicles require a battery change roughly every 11.5 hours, taking into consideration the time loss during battery exchange with on average slightly more than 20% of battery capacity remaining, which is congruent with the data collected during simulation runs. This results in an average of approximately 0.87 vehicles arriving at the BSS every hour. Using Eq. (B.59), the minimum number of batteries required is 15. Although the recharging requirements for 10 vehicles can theoretically be fulfilled with just five additional battery systems, B-AGVs do not always arrive on an exact schedule. The simulation results illustrated in Figure B:27 demonstrate that the transport performance sinks drastically with four or fewer spare batteries due to high average waiting times. As seen in the left side of the illustration, having 15 batteries for the 10 vehicles deployed means that a B-AGV is unavailable for container transport needs for longer than five minutes on average.

Because the B-AGVs compete with conventional diesel-powered AGVs, which only need refueling once a week, the terminal operator set an acceptable threshold of two minutes waiting time on average. This means that at least 17 battery systems are required. However, the average number of orders completed by a fleet of 10 vehicles is unaffected when decreasing the number of spare batteries from seven to six; the fleet would be able to execute 57 orders per hour on average either way. As productivity does not increase by a noteworthy margin with more batteries, the minimum battery-to-vehicle ratio for this case is derived to be 16:10.

The corresponding TCO results for an AGV fleet including petrol station and a B-AGV fleet with 16 batteries and a BSS (*minimum battery-to-vehicle ratio case*) are illustrated in Figure B:28.

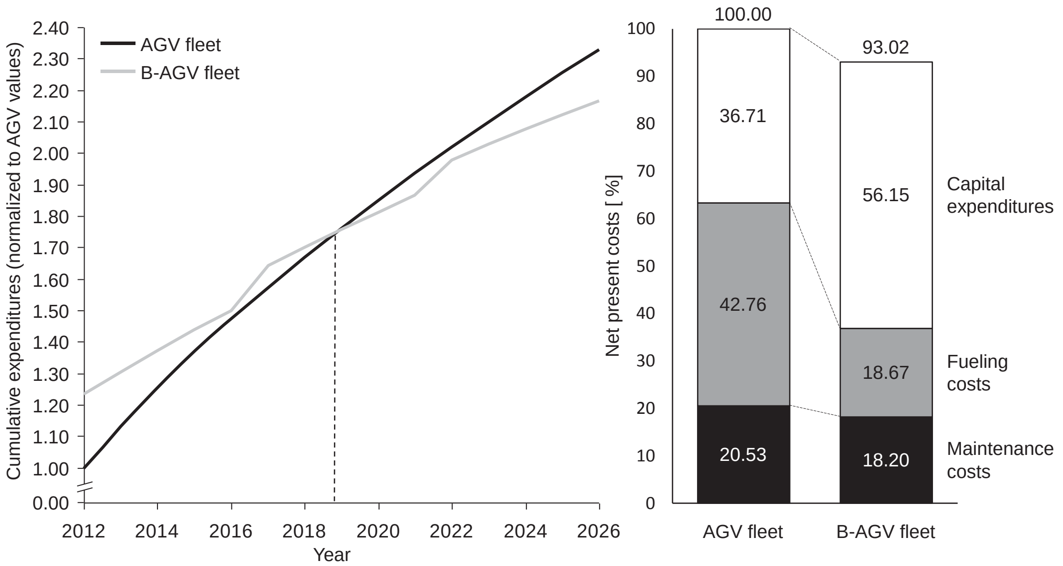

Figure B:28. TCO results for the minimum battery-to-vehicle ratio case.

In this case, it takes less than seven years before the B-AGV fleet is a more cost-efficient solution than the AGV fleet. The NPCs of the B-AGV fleet at the end of the planning period is approximately 7% lower than that of the AGV feet.

5.5 Discussion

We considered three different TCO cases for a 10-vehicle B-AGV fleet and compared the results with the TCO for a comparable conventional transport fleet:

1) *Base case*: 2:1 battery-to-vehicle ratio with uncontrolled charging of the B-AGVs' batteries and fixed electricity prices;
2) *Controlled charging case*: 2:1 battery-to-vehicle ratio with controlled charging of the batteries by shifting charging processes to the hours with the lowest spot market prices; and
3) *Minimum battery-to-vehicle ratio case*: 16:10 battery-to-vehicle ratio and uncontrolled charging of the B-AGVs' batteries with fixed electricity prices.

For all cases, the fleets' NPCs for the reference oil and electricity price scenarios are illustrated in Figure B:29.

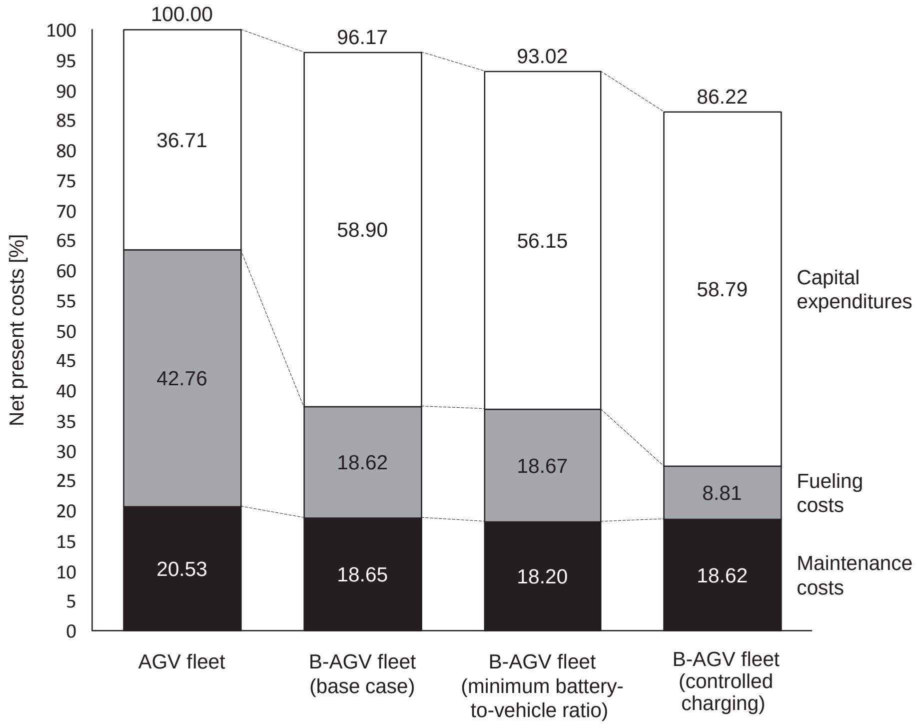

Figure B:29. NPCs for all considered TCO cases.

The results indicate that, even in the *base case*, the B-AGV fleet is more profitable than the AGV fleet when considering a period of 15 years. This is due to the lower costs of maintenance (fewer moving parts relative to conventional gasoline engines; no oil changes required) and fueling (energy procurement) for the B-AGV fleet. Moreover, an expected increase in petrol prices (from 2017 onwards) – which is projected to be higher than the predicted increase in electricity prices – will augment the already prevailing operating cost differences and thus lead to a long-term cost advantage for the B-AGV fleet. This is of particular importance as B-AGVs' capital costs are much higher than those of AGVs, mainly due to the expensive battery-swapping station and the additional batteries that must be procured. Nevertheless, the reduced maintenance and energy costs can offset the higher initial acquisition costs.

Compared to the *base case*, using a *minimum battery-to-vehicle ratio* results in lower capital and maintenance costs because fewer spare batteries must be procured and maintained. Thus, the cost-efficiency of the B-AGV could be further improved while its performance remains comparable.

Among the B-AGV fleet TCO cases evaluated, *controlled charging* with a greater number of spare batteries than necessary to fulfill all daily logistic tasks seems to be most promising from an economic perspective, as the net present costs of the B-AGV fleet are the lowest. This case is more profitable than the *base case* because it allows energy procurement costs to be reduced while other cost components remain unchanged. In contrast, in the *minimum battery-to-vehicle ratio case* the investment and maintenance costs of the B-AGV fleet are higher because more spare batteries must be procured. However, having more batteries provides charging flexibility that can be exploited by shifting charging processes to the hours with the lowest prices for electricity. As a result, energy procurement costs and consequently operational costs can be reduced by up to 50%. This significant difference can be explained by the price volatilities that prevail on the spot market. Even negative prices (e.g., -83.25 €/MWh on March 24th, from 3 p.m. to 4 p.m.) could be observed and exploited in the reference year, thus charging the batteries at practically no cost in some hours of the reference year. Based on our results, it becomes clear that the greater charging flexibility can compensate for the higher acquisition costs of procuring additional spare batteries. The German government's intention to increase the share of renewable energies to at least 80% of total energy production by 2050 (BMWi and BMU, 2010) will influence this charging concept in two ways. First, price spreads are expected to increase due to the development of intermittent renewable energy resources (Genoese et al., 2010). Second, the increased participation of renewables in the market will lead to a reduction in wholesale power prices. Wholesale prices declined from an average of over 70 €/MWh in 2008 to less than 50 €/MWh in 2012 (Ketterer, 2014). Hence, it is possible to generate even higher profits when charging EVs in a controlled manner. Along with economic benefits, the implementation of controlled charging concepts also brings energetic benefits, as charging in off-peak hours makes a valuable contribution to balancing electricity supply and demand (Shao et al., 2011).

Finally, our investigation also revealed that changes in energy prices (fuel or electricity) have a significant influence on the profitability of both fleets. This can be seen in Table B-26 in the fleets' NPCs for all oil and electricity price scenarios (see Section B.II.5.3.3).

Table B-26. Net present costs of the fleets for all oil and electricity price forecast scenarios (normalized to the NPCs of the AGV fleet for the reference oil price scenario).

Fleet	Fueling cost scenario	TCO case	NPCs
	Low oil price	-	0.91
AGV	Reference oil price	-	1
	High oil price	-	1.16
	Very low electricity price increase	Base	0.95
B-AGV	Moderate electricity price increase	Base	0.96
	Significant electricity price increase	Base	1
	Very low electricity price increase	Controlled charging	0.86
B-AGV	Moderate electricity price increase	Controlled charging	0.86
	Significant electricity price increase	Controlled charging	0.91
	Very low electricity price increase	Minimum battery-to-vehicle ratio	0.92
B-AGV	Moderate electricity price increase	Minimum battery-to-vehicle ratio	0.93
	Significant electricity price increase	Minimum battery-to-vehicle ratio	0.97

In general, using ETVs could become even more cost efficient in the future as environmental legislation becomes more restrictive. As heavy-duty vehicles (HDVs), such as AGVs, produce about a quarter of the total CO_2 emissions from road transport in the EU, several possible actions for reducing emissions from freight transport are currently being discussed. One action under consideration is setting mandatory limits on average CO_2 emissions from newly registered HDVs, as is already done for cars and vans. Manufacturers not reaching the target

CO_2 emissions level must then pay an emissions premium for each car registered (European Commission, 2014b). Such a mandate would make conventional heavy-duty vehicles more expensive if the target CO_2 level is not reached, thus playing an important role in motivating industry to deliver eco-friendly HDVs, such as B-AGVs, eventually resulting in both higher operational costs for conventionally propelled vehicles and lower prices for E(T)Vs due to economies of scale. Furthermore, the approach of differentiation of infrastructure charges by port authorities can be used in future to promote technology changes, reduce emissions or encourage more environmental performance, also resulting in higher operational costs for conventionally propelled vehicles (Wilmsmeier, 2012).

However, the following limitations should be considered when interpreting the results. All findings are based on a case study conducted in a German port. Therefore, it is advisable to modify some parameters before transferring the results to other countries, as electricity and diesel prices differ significantly by country. For example, the average electricity price for the industry sector in France is roughly 33% lower than the electricity price in Germany (Statista, 2014b). In addition, we assume that controlled charging concepts can be implemented without any effort for transport companies. In reality, however, the transport company would require an intermediary to procure the energy on the spot market on behalf of the company because of regulatory requirements on the spot market, such as minimum order sizes or the need for certified and authorized energy dealers (Tirez et al., 2010).

5.6 Conclusion and Further Research

In this study, we assess the commercial viability of electric transport fleets operating in closed transport systems. In order to ensure the practical relevance of our results, we use data from a large-scale electric mobility project conducted in a container terminal using heavy-duty electric transport vehicles in combination with a fully automated battery-swapping station. For the terminal operator, one critical feature to consider in the planning process for swapping-station operations are the spare battery inventory requirements.

Principally, we found that electric mobility is economically beneficial in closed transport system because the charging and maintenance costs of an ETV fleet are significantly lower than – and can even compensate for – the higher investment costs of procuring charging infrastructure and spare batteries. Moreover, we developed two strategies that can be used to further increase the cost efficiency of an ETV fleet. As the ratio of batteries to vehicles has a significant impact on the profitability of an EV fleet, we determined a minimum battery-to-vehicle ratio sufficient for the daily logistic tasks to be fulfilled under any terminal conditions on the basis of a simulation study. Through this strategy, the costs of holding spare batteries can be reduced without restricting the ETV fleet's performance. Furthermore, we found that it is possible to exploit charging flexibilities by shifting charging processes to off-peak hours, yielding lower energy procurement costs. To implement controlled charging processes, however, it is necessary to procure more spare batteries than the minimum required to ensure the fulfillment of daily logistic tasks within the terminal. From an economic perspective, the concept of controlled charging with additional spare batteries is the most promising, as energy procurement costs can be reduced significantly. Compared to the total expenditures for an appropriate AGV fleet, cost savings of almost 14% can be achieved in the best-case scenario.

Essentially, we could show that container terminals using ETVs can already gain a competitive advantage by reducing overall fleet costs while simultaneously reducing noise emissions and local toxic concentrations. Furthermore, we demonstrated that fleet operators can expect significant further cost savings when applying controlled charging concepts for their EV fleets. These findings could pave the way for the application of ETVs in many related areas. Thus, fleet operators may become a key force influencing the market development of electric vehicles. A larger share of ETVs in use would support most governments' objectives of achieving a sustainable transport system. In this regard, heavy-duty transport vehicles are responsible for approximately 6% of total EU greenhouse gas emissions (Luz et al., 2014).

Our study contributes to the research field of transportation science in two major ways. We appear to be the first to assess the impacts of B-AGVs used with a battery-swapping station on a transportation system's performance in terms of economics. This is important as the increasing pressure of competition between container terminals and environmental regulations on noise and air pollution pose new and intricate problems for terminal-operating companies (Rijsenbrij and Wieschemann, 2011; Saurí and Martin, 2011). Second, we adapted research methodologies from the fields of operations research and informatics to improve the profitability of B-AGVs. Based on our results, we derived several general recommendations for how to best make use of B-AGVs in transportation systems, as the basic characteristics of our pilot case company are likely to be comparable to those of other transportation companies (e.g., in terms of transport requirements or operation hours).

A useful extension of this work is to investigate the profitability of electric mobility in closed transport systems in further areas of application, for example, at airports or cargo transport centers. Furthermore, the determination of an optimal battery-to-vehicle ratio requires further investigation. In this regard, we only considered cases with a minimum stock of spare batteries and a large stock of spare batteries. However, it is also important to investigate how to determine an optimal equipment scenario for using EVs in combination with a battery-swapping station while considering both acquisition and maintenance costs for the batteries as well as energy procurement costs. In addition, container terminals deciding to procure electric transport vehicles would not replace the conventional transport fleet all at once, as there are still AGVs not ready to retire. Hence, two-stage stochastic optimization models could be used in further research projects to establish an optimal investment plan that determines when and how many B-AGVs to procure.

III. Recommendations for Actions for Policymakers – Study 7: Shaping the Future Energy Market

Insights from the previous studies revealed significant energetic and economic potentials of applying DSI programs for E(T)Vs for both the energy industry and EV and ETV fleet operators). Nevertheless, the fifth study (Section B.II.4) found that even for large ETV fleet operators, DSI applications are hardly realizable under prevailing conditions, mainly due to regulatory requirements. Against this background, the seventh and last study of this thesis investigates how regulatory requirements must be modified to provide smaller providers of flexible loads, such as EV or ETV fleet operators, the opportunity to utilize their load-shifting potential on energy markets. Therefore, valuable information can be given to policymakers regarding how to design an adequate future energy market and regulatory framework that also allows smaller providers of flexible loads to participate. Consequently, the final research question of this thesis can be answered.

Table B-27. Fact sheet of study no. 7.

Title	Shaping the Future Energy Market – Making Energy Demand more Flexible
Authors	Johannes Schmidt*, Lutz M. Kolbe Chair of Information Management, University of Göttingen, Platz der Göttinger Sieben 5, 37073 Göttingen, Germany *Corresponding author. Tel.: +49 551 3921177. E-mail address: jschmida@wiwi.uni-goettingen.de
Outlet	Erasmus Energy Forum 2015, Published, Completed Research Paper
Abstract	Demand response (DR) has experienced only moderate expansion in Germany, mainly due to regulatory requirements. Given the rapid expansion of renewable energies, however, it is important that in the future smaller, flexible consumers will also be able to participate in DR and respond to the intermittent supply of energy. In this paper, we conduct a case study with a fleet operator that applied DR programs for its electric vehicle fleet. The results are then used to derive recommendations on how to redesign the energy market in order to utilize flexibility options on the demand side to a greater extent. Our findings indicate that there are several parameters that policymakers can influence to lower the entry barriers to energy markets.
Keywords	Energy Market Design, Demand Response, Electric Transport Vehicles, Container Terminal, Case Study

III.1 Introduction

The German Federal Government aims to increase the share of renewable energies to at least 35% by 2020 and 80% by 2050 (BMWi and BMU, 2010). However, the integration of intermittent renewable energy resources poses new and intricate problems for utilities and grid operators because of the expected increasing discrepancies between power supply and demand (Ketterer, 2014). One possibility for balancing power supply and demand while simultaneously increasing energy efficiency is provided by the concept of demand response (DR), which refers to the consumer’s ability to alter his or her energy consumption pattern in response to time-dependent electricity prices or incentive payments (U.S. DOE, 2006).

Electric vehicles (EVs) are well-suited for the application of DR because they remain idle for the greater part of the day (Kempton and Tomić, 2005a). Furthermore, the wide dissemination of EVs in the market would result in a significant load, potentially threatening the security of power networks (Schmidt and Busse, 2013). To avoid the possibility of power outages, EV users should engage in smart charging, which involves aligning charging times with low electricity prices and an unstressed grid (Valentine et al., 2011). In addition, EVs batteries can also provide utility services such as frequency control, known as the vehicle-to-grid (V2G) concept. When there is a surplus of energy in the grid, EVs can provide regulation down by charging their batteries and, vice versa, EVs can provide regulation up by supplying power to the grid when it is lacking (Mullan et al., 2011). Though these areas of application are quite indisputable, there are several key impediments to the expansion of DR for: insufficient IT infrastructure, unsuitable market structure, considerable regulatory requirements, and user acceptance problems (Geleen et al., 2013; Strbac, 2008).

Schmidt et al. (2014) identify commercial electric transport vehicles (ETVs) operating in closed transport systems as particularly suitable for a broad implementation of DR. However, even for larger commercial ETV fleet operators, DR applications are hardly realizable under the prevailing conditions, mainly due to regulatory requirements. Because regulatory requirements were designed for an energy system based on centralized large-scale energy generation in which controllable power stations follow electricity demand, the current energy market design in Germany seems ill-suited for smaller providers of flexible loads (Connect, 2014). To ensure power supply security in the future, despite the increased share of wind and solar energy in the mix, smaller, flexible consumers should also be able to respond to the intermittent supply of energy. It therefore seems inevitable that the current market design and regulatory framework for the power sector be restructured (BMWi, 2014b).

This paper contributes to the current energy management discourse. Using a case study, we describe what a particularly proactive fleet operator has been developing to apply DR programs for its ETV fleet and explain the regulatory barriers to participating in DR. Based on these elements, we derive recommendations for redesigning the energy market to encourage smaller providers of flexible loads to participate in DR programs.

III.2 Methodology

The case study method is suitable for studying a current phenomenon in depth and in a timely manner, especially when boundaries are vague and context may play an important role (Yin, 2009). Furthermore, data-collection methods in case study research provide rich data and can be effective tools for analyzing complex constructs (Stake, 1995). Therefore, we determined that an explanatory case study methodology is the most appropriate for deriving recommendations on how to redesign the energy market to make demand more flexible.

We followed the process model of Yin (2009), who structures the methodology of case studies into four distinct stages, starting with its design. We use a single-case design, which is appropriate for revelatory cases (see Section B.III.4) (Benbasat et al., 1987). The unit of analysis is a sociotechnical system, as we consider a project in which a fleet operator applies DR programs to its ETV fleet. To conduct the case study, multiple data-collection methods were combined to enhance data credibility and increase validity by comparing the generated results (Patton, 1990). First, we analyzed and evaluated archival records and internal documents, such as technical reports, feasibility studies, process descriptions, profitability analyses, interim and final reports, as well as minutes of meetings. Additionally, we used focused, semi-structured, telephone interviews with two representatives of our case company to acquire more extensive material. Finally, several field visits were conducted during our case study to observe how the socio-technological system was working and understand the technology and any potential problems being encountered (Paré, 2004). As part of the third step, all sources of information were categorized, analyzed, and consolidated. Finally, the case study report was written.

III.3 Case Study Research Design

The focal firm HHLA is the largest container terminal operator in Europe; port logistics is their core business. With the “on course” initiative, HHLA has initiated several sustainability programs, one of which is to develop and use eco-friendly driving systems. HHLA has been a pioneer in using fully electrified automated guided vehicle (B-AGV) for the transportation of containers between quay cranes and the container storage. Currently, 10 of the terminal’s 80 conventional diesel-powered AGVs have been substituted by B-AGVs. To allow the B-AGVs to be operational around the clock, a fully automated battery-swapping station was installed.

Within the frame of the BESIC research project, HHLA examined how to apply DR programs for its ETV fleet. The company was the first to assess the possibility of coordinating charging times with operating requirements and the occurrence of peak loads. In addition to energetic benefits, significant cost savings are expected to arise from adjusting the time of energy use, thus taking advantage of lower prices that prevail in certain periods. To create the technical conditions for applying DR programs, HHLA procured energy management systems, metering and ICT systems, or load control devices. The core element was a battery administration system developed to automatically calculate the optimal charging times.

Following the analysis of the project setting, one can derive recommendations for redesigning the energy market in order to encourage smaller, flexible consumers to participate in DR. The procedure is illustrated Figure B:30.

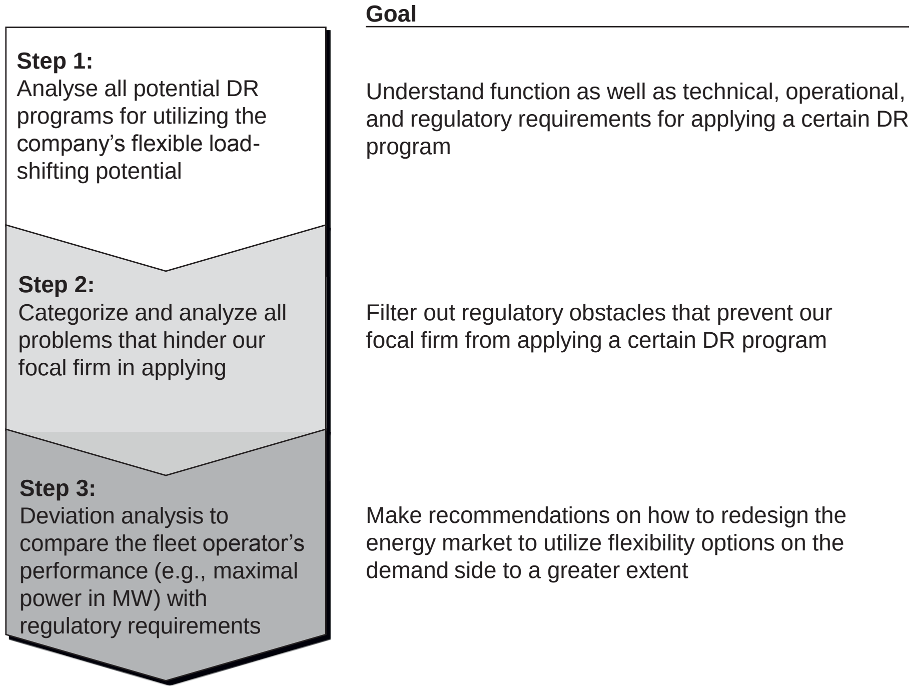

Figure B:30. Procedure for deriving recommendations on how to redesign the energy market to make demand more flexible.

Based on the deviation analysis, it is possible to analyze how regulatory requirements must be changed to provide our focal firm the opportunity to utilize their load-shifting potential. This information can be applied as a guideline for policymakers to increase flexibility on the energy market.

III.4 Main Result and Discussion

Our focal firm identified three superordinate DR programs to be of potential interest, each of which requires acting on different energy markets. Smart charging is usually realized by acting on the spot market; the company can procure power for charging the fleet on the day-ahead spot market and charge the batteries during the hours with the lowest possible prices. The V2G concept can be realized by acting on the ancillary energy market and thus helping to balance energy supply and demand. Finally, it is possible to offer interruptible loads on the capacity market via bilateral agreements with the grid operator.

During the planning phase, it became apparent that our focal firm would not be able to apply the DR programs by itself, mainly due to extensive regulatory requirements. Hence, an external partner would be needed to procure the required energy on behalf of the company (smart charging) or pool the flexible load with other providers. An overview of all regulatory barriers preventing our focal firm from participating in DR is provided in Table B-28.

Table B-28. Key parameters for helping smaller providers of flexible loads apply DR programs.

Market	Key parameter	Description
Spot / Ancillary / Capacity market	Market time frame	Tendering period for the procurement of energy (time period between market closure and delivery)
	Auction design	Pay-as-bid vs. uniform pricing
	Minimum order size	Smallest capacity an actor is allowed to offer on a potential energy market
	Pooling	Possible within a control area or not
Ancillary / Capacity market	Reaction time	Time an operator has to deliver contracted power after activation
	Contract time	Period during which an actor guarantees power
	Security level	Actors must prove that they can deliver power according to a predefined level
	Penalty payments	Actors are subject to a penalty if they fail to deliver the contracted power
	Tender procedure	Separate or joint bid invitations for negative and positive control reserve
	Pre-qualification	Proof of technical competence necessary to provide different types of balancing power for guaranteeing supply reliability

To offer smaller providers of flexible loads – such as our focal firm – the opportunity to utilize their load-shifting potential, some key regulatory requirements in the relevant energy markets must be modified. The most important recommendations that were derived from our case study are presented below.

In all energy markets, the minimum bid size should be decreased. The total load-shifting potential of our pilot case company amounts to 480 kW. Because the minimum bid size in energy markets is 1 MW (primary control and spot market), our pilot case company needs an external partner to act on the energy market on behalf of the company. Lowering the minimum bid size would hence facilitate fleet operators' access to energy markets.

Furthermore, the tender period should be shortened in control and capacity markets. Because transport systems are often highly dynamic, it is impossible to predict the power consumption of batteries over an extended period (approx. 40 hours for our fleet operator). Therefore, the only way to currently implement the V2G concept for our pilot case company is offering minute reserve, as it is tendered daily, while primary and secondary control reserve are tendered weekly. However, tendering control reserve daily would allow the participation of smaller actors on control markets. Furthermore, the contract time would need to be decreased. In this regard, our fleet operator requires that participation in DR programs not compromise the execution of daily logistic tasks. As the contract time for primary and secondary control is one week – and for interruptible loads even one month – our pilot case company cannot act on these markets. Hence, reducing the contract time to one hour would be sensible, as it would provide smaller actors the opportunity to utilize their flexible demand. Another important aspect is the reduction of the required security level; smaller actors cannot guarantee the 100% availability that is required on some control markets. For our case study, it is almost impossible for the fleet operator to always forecast the ETVs' energy consumption accurately because transport systems are influenced by many different factors.

Finally, the pricing signal for flexibility on the spot market can could be further strengthened further by extending short-term trading. In this regard, trading closed closer to delivery time facilitates energy and capacity planning for fleet operators.

An overview of all proposals for making DR more attractive for smaller providers of flexible loads is given in Figure B:31.

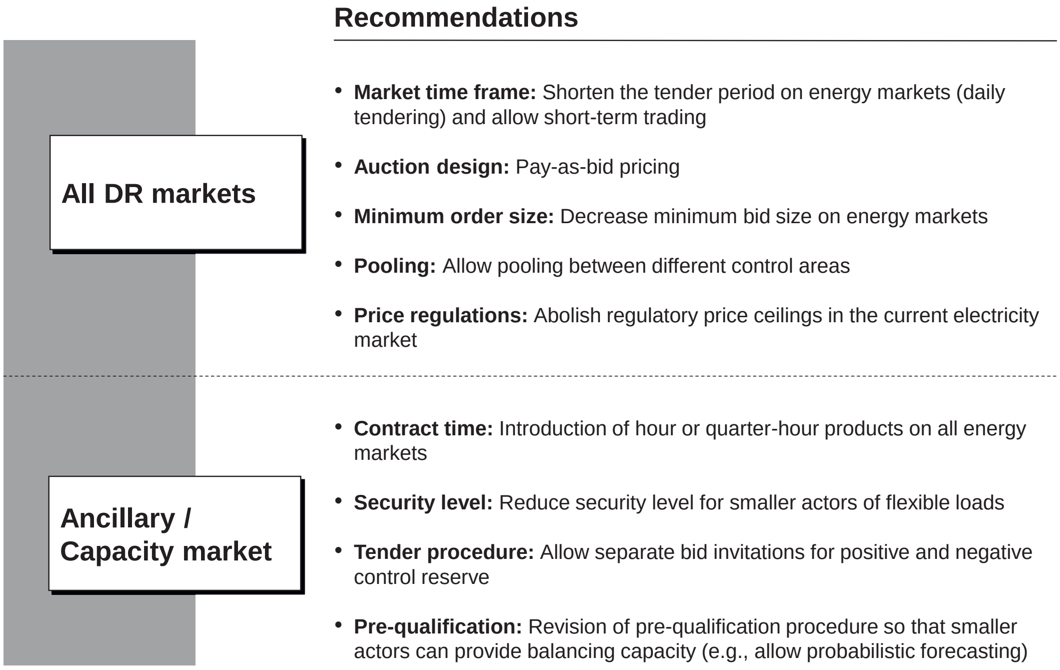

Figure B:31. Recommendations for a future energy market design.

III.5 Conclusion and Future Outlook

This study made nine recommendations for enabling smaller providers of flexible loads to participate in DR programs. In principle, it seems sensible to reduce regulatory requirements in order to facilitate access to energy markets; however, this is not always possible. Therefore, one might consider creating a secondary market for the provision of balancing capacity with more lenient requirements. Another measure suitable for utilizing flexible loads to a higher degree is making electricity price components (e.g., EEG surcharge or grid fees) more dynamic, thus increasing incentives for demand adjustments. This would provide actors more opportunities for utilizing their flexible load-shifting potential.

The main limitation of this study is its focus on a single fleet operator that applies DR programs for its fleet, which does not allow for generalization to other small providers of flexible loads with different characteristics. Therefore, there is a need for further case studies. This paper, however, highlights important issues to be considered when restructuring the power supply system, as currently demanded by policymakers, utilities, and grid operators (BMWi, 2014b).

C. Contributions

The cumulative thesis at hand had two overarching goals. First, it aimed to quantify the financial impacts of applying DSI programs for EVs and (heavy-duty) ETVs for both fleet operators and energy suppliers. While previous research has focused on individually used EVs or EV fleets for applying DSI programs, at the center of this thesis are fleet operators using heavy-duty electric transport vehicles. Second, the thesis aims to offer policymakers and fleet operators suggestions on how to integrate flexible loads, such as ETVs, into existing energy markets. To achieve these goals, four research questions were derived within the frame of this cumulative dissertation.

This first section in this part (C.I) recapitulates the findings from each study conducted in order to answer the core research questions presented in Section A.I.2. Afterwards, the implications for practice and energy economic research are presented in Section C.II. This thesis then presents a final conclusion in Section C.III, also revealing the limitations of this research endeavor and highlighting further research opportunities.

I. Findings and Results

This chapter summarizes the results of each publication and gives answers to each research question posed in Section A.I.2. As explained in Section A.I.3, this thesis offers both an energy supply-side (energy industry) and a demand-side perspective (energy user) on DSI programs for EVs, with a focus on fleet operators using heavy-duty electric transport vehicles. Furthermore, recommendations for policymakers on how to redesign the energy market in order to utilize flexibility options on the demand side to a greater extent are derived. Therefore, the findings are presented within three subsections: supply-side assessment of DSI programs for EVs, demand-side assessment of DSI programs for electric (transport) vehicles, and recommendations for policymakers. In the last step, these findings are combined and integrated into a final framework that represents the overall findings of this thesis.

I.1 Findings Regarding the Supply Side of the Energy Sector

The aim of the first chapter ("Supply-Side Assessment") in this thesis' main Part B was to estimate the financial benefits of applying DSI programs for EVs for the supply-side of the energy system, represented by the energy industry. DSI programs for EVs can create significant cost-saving potentials for the energy industry, as these enable charging processes to be shifted to off-peak hours, thus reducing the need for increases in power plant capacities. The title, related core research question, and main contribution of the study in this part are highlighted in Table C-1.

Table C-1. Title, research question, and main contribution of Study B.I.

Findings of Study B.I	
Title of study	The Value of IS to Ensure the Security of Energy Supply
Research question	RQ 1: What is the economic value of applying DSI programs for EVs for the energy industry?
Main contribution	Recommendations were given for the energy industry regarding whether investments in DSI programs for EVs are a suitable alternative to an expansion of power plant capacities

In light of this research question, it was found that uncontrolled charging processes may lead to significant additional costs for the energy industry due to the considerable required increase of power plant capacity by 2030. The most intriguing finding of this study was that significant cost-saving potentials – up to 8 billion Euros – can be achieved for the energy industry by applying DSI programs for EVs, mainly as a result of improved integration of the additional demand into the existing load pattern. Hence, the first research question of this thesis could be answered by providing information about the economic value of applying DSI programs for EVs from the perspective of the energy supply side.

I.2 Findings Regarding the Demand Side of the Energy Sector

The focus of this thesis lied on quantifying the economic potential of applying DSI programs for the demand side, represented by E(T)V users. To this end, two central research questions were answered in the second chapter (“Demand-Side Assessment”) of Part B.

The first research question of this chapter focused on “normal” EVs within an existing business relationship as these vehicles seem to be good candidates for initial DSI applications, such as smart charging or the vehicle-to-grid concept (Section A.II.2). The analysis was based on a business case with a car-sharing operator in Germany that uses EVs. Beside the title of the study, the core research question and main contributions are highlighted in Table C-2.

Table C-2. Title, research question, and main contribution of Study B.II.1.

Findings of Study B.II.1	
Title of study	Applying Demand Response Programs for Electric Vehicle Fleets
Research question	RQ 2: How does an information system need to be designed to apply smart charging and the V2G concept for EV fleets? What is the economic potential resulting from the application of a suitable DSI program?
Main contributions	(1) An IS design was developed, enabling fleet operators to apply established DSI programs for an EV fleet that operates outside the premises (2) The cost-saving potentials of applying a suitable DSI program were calculated using real-world data

As part of the comprehensive IS artifact designed for this study, a prediction model was established to forecast the vehicles’ usage times and energy consumption. To assess the economic potential of applying DSI programs for an EV fleet, data from the car-sharing operator were evaluated using an optimization approach. The main finding of this study was that fleet operators can expect significant cost savings when applying DSI programs for their EV fleet. Compared to a simple plug-and-charge approach with fixed prices for electricity, cost savings of at least 42% can be achieved when applying a suitable DSI program. However, it was also found that there are several complications obstructing the realization of DSI programs in this application context, most notably the difficulty of precisely predicting future trips and the resulting charging flexibility for EVs that operate outside the premises and the high number of EVs required to act independently on energy markets. In this regard, it was assumed that the fleet operator itself can act on the energy (spot) market which, however, is not possible under current energy market conditions.

In contrast to RQ 2, which focused on EV fleets, RQ 3 focused on battery heavy-duty electric transport vehicles (B-AGVs) operating in closed logistic systems, representing the main body of this thesis. Four related studies (Studies 3–6) were conducted to provide answers on how to both apply DSI programs for this application context as well as estimate the economic value of applying the most promising DSI program for an ETV fleet. To do so, data from a large-scale electric mobility project conducted in a container terminal that uses B-AGVs were analyzed (A.II.3). The main findings of each study, the connections among these studies, and the integrated findings of all studies are illustrated in Figure C:1.

Research Question 3: How can DSI programs be applied for a fleet operator using ETVs? What is the economic value for a fleet operator?

Study 3

Research Question 3a
How can smart charging and the V2G concept be adjusted and transferred to the environment of closed transport systems? What is the economic value for a fleet operator?

Main findings
- Commercial ETV fleets using a battery-swapping station are particularly well suited for applying DSI programs
- The V2G concept is much more complex for the fleet operator to implement than smart charging
- Both DSI programs offer substantial cost savings compared to a plug-and-charge strategy

Limitations
- Use of static and fictitious operation times of the ETVs
- Focus on two DSI programs
- Effect of applying these DSI programs on the ETVs' TCO not evaluated

Study 4

Research Question 3b
How can electricity demand and the resulting load-shifting potential from ETVs operating in closed transport systems be forecasted in order to apply DSI programs?

Main Findings
- Simulation-based forecasting is suitable for forecasting the logistic processes and the related electricity demand at the container terminal
- Precise forecasts about the electricity demand from the B-AGVs can be made on the basis of the simulation model developed

Study 5

Research Question 3c
Which kinds of DSI programs are applicable for ETV fleets in general? What is the economic potential resulting from technically feasible DSI programs for a fleet operator?

Main findings
- The ETV fleet of the pilot case company can be used for a broad range of DSI programs
- Many DSI programs cannot be realized under the prevailing conditions, mainly due to regulatory requirements
- There is a significant potential for cost saving (>30%) when applying the most promising DSI program

Study 6

Research Question 3d
What is the TCO of an ETV fleet? How can DSI programs reduce the TCO for the closed transport system?

Main findings
- The ETV fleet of the port operator is more profitable than a comparable diesel-power fleet
- The TCO of the ETV fleet can be reduced considerably – up to 10% – when applying a suitable DSI program (smart charging)
- Smart charging is more profitable than reducing the number of spare batteries to a minimum

Main contributions
1) Estimation of financial profits when applying DSI programs for an ETV fleet
2) Assessment of the economic viability of electric mobility in closed transport systems

Figure C:1. Integrated findings of applying DSI programs for ETV fleets.

The third study (Section B.II.2) provided information about how to transfer two well-researched DSI programs (smart charging and the V2G concept) to the environment of closed transport systems. It was found that the efforts required to implement the V2G concept are significantly greater than those necessary for the smart charging concept, as V2G leads to considerable constraints in charging flexibility. Using fictitious and static operation times of the B-AGVs, this study found that both DSI programs bear substantial cost-saving potentials compared to uncontrolled charging with fixed electricity prices. Due to this economic potential of applying DSI programs for the ETV fleet, this work was extended and improved in the subsequent studies.

The fourth study (Section B.II.3) contributed to applying DSI programs under actual conditions. In this regard, the fleet operator must forecast the electricity demand of the B-AGVs for a certain period in order to apply DSI programs in practice. The major finding of this study was that simulation-based forecasting seems to be more accurate for predicting the B-AGVs' energy demand than mathematical forecasting based on historical energy demand data. Based on the simulation model developed, precise projections can be made. Thus, an essential step towards the actual implementation of DSI programs has been taken.

The fifth study (Section B.II.4) found that the load-shifting potential of the B-AGV fleet can also be used for a broad range of DSI programs and is not limited to the two established DSI programs for EVs investigated in Section B.II.2. The major contribution of this study was identifying the most promising DSI program for the fleet operator through analyzing technical, operational, and regulatory requirements in detail. Under current market conditions, the DSI programs smart charging and optimizing the company's load curve were found to be most promising for the pilot case company. Using driving profiles based on the simulation model developed (Section B.II.3), a cost-saving potential of up to 30% compared to the case of no DSI program application was calculated.

The last study of this chapter (Section B.II.5) made three major contributions. It first demonstrated that the B-AGV fleet can be (under the assumptions made) more profitable than a comparable diesel-powered AGV fleet. Second, the study revealed that the total cost of ownership of the B-AGV fleet can be reduced considerably when applying the most promising DSI program, identified in the previous study. Finally, this study determined a suitable battery-to-vehicle ratio. As explained in Section A.II.3.3, the use of a battery-swapping station requires the employment of more batteries than vehicles. The results indicate that it is more cost efficient to create a certain load-shifting potential by procuring additional spare batteries than to reduce the number of batteries employed to a minimum, which would render it nearly impossible to apply DSI programs.

To sum up, the central research question of this part could be answered. The studies B.II.2 and B.II.3 provide answers on how to apply DSI programs for an ETV fleet operator under current energy market conditions. Finally, on the basis of the studies B.II.4 and B.II.5, detailed information about the extent of DSI's economic value for the fleet operator could be provided.

I.3 Findings Regarding Policymakers

Insights from the previous studies revealed significant energetic and economic potentials of applying DSI programs for E(T)Vs for both the energy industry and fleet operators. However, to apply DSI programs for "normal" electric vehicles, it is necessary to aggregate thousands of independent and dispersed EVs, likely diminishing the economic benefits. Therefore, the focus of this thesis – expressed in Research Question 3 – lies on heavy-duty electric transport vehicles because they have several favorable characteristics for applying DSI programs under current conditions, most notably the possibility of aggregating numerous vehicle batteries – each with considerable storage capacity – on company grounds.

Nevertheless, the fifth study in this thesis (Section B.II.4) found that even for large ETV fleet operators, DSI applications are hardly realizable under prevailing conditions, mainly due to regulatory requirements. The current energy market design in Germany therefore seems ill-suited for smaller providers of flexible loads, such as ETV fleet operators. The seventh and last study of this thesis contributed to the current energy management discourse, using a case study with a fleet operator that applied DSI programs for its heavy-duty ETV fleet. This study investigated how to redesign the energy market to encourage smaller providers of flexible loads to participate in DSI programs. The title, related core research question, and main contribution of the study in this part are highlighted in Table C-3.

Table C-3. Title, research question, and main contribution of Study B.III.

Findings of Study B.III	
Title of study	Shaping the Future Energy Market – Making Energy Demand more Flexible
Research question	RQ4: How could the German energy market be redesigned in order to better utilize flexibility options on the demand side?
Main contribution	Several recommendations for policymakers were given for enabling smaller providers of flexible loads to participate in DSI

Evaluating data from the case study, it was possible to analyze how regulations must be changed to provide smaller, flexible consumers the opportunity to utilize their load-shifting potential to a greater extent. In principle, it seems sensible to reduce certain regulatory requirements on DSI markets (e.g., spot, ancillary, or capacity markets). For example, the minimum order size – defined as the smallest capacity an actor is allowed to offer to a potential energy market – should be decreased to facilitate fleet operators' access to DSI markets. Based on this and further recommendations, the fourth and final research question of this thesis could be answered.

I.4 Aggregated Findings and Results

Although each chapter of this thesis' main Part B provides a different perspective on DSI programs for E(T)Vs – supply side (Chapter I), demand side (Chapter II), and policymaker (Chapter III) – all chapters contribute to achieving the two overarching objectives of this thesis (see Sections A.I.2 and A.I.3):

1) Reduce uncertainty regarding the extent of DSI's economic value; and
2) Gain relevant insights on how to integrate flexible loads into existing energy markets.

The first overall objective of this thesis was set because DSI has experienced only moderate expansion in Germany, due in part to a limited understanding of the benefits of such DSI solutions as well as an uncertainty regarding the extent of DSI’s economic value (Goebel et al., 2014; Bradley, 2013; Strüker and van Dinther, 2012; Strbac, 2008). Furthermore, Aghaei and Alizadeh (2013) find that the economic potential of demand response or demand-side integration in deregulated markets has been insufficiently examined. Almost all studies of this thesis (Studies 1–6) followed this call, as these contribute to reducing uncertainty regarding the extent of DSI’s economic value. More precisely, these studies provide new insights about the economic potential of DSI programs for energy suppliers (RQ 1: Study 1), EV fleet operators (RQ 2: Study 2), and, in particular, ETV fleet operators (RQ 3: Studies 3–6). Hence, the first goal of this thesis could be achieved by reducing uncertainty regarding the extent of DSI’s economic value.

The second overarching objective of this thesis arose from the question of how distributed energy resources, such as flexible loads, can be integrated into existing energy markets – unanswered mainly because DSI is still in its infancy (Goebel et al., 2014). This is particularly true for EVs, which represent a valuable resource for DSI programs (Jochem et al., 2013). To gain insights into how to integrate EVs into the future energy system, operational requirements for applying DSI programs for E(T)Vs were given particular consideration throughout the whole thesis. In the course of this investigation, it was found that the fleet operator must forecast electricity demand and the charging flexibility from the EVs for a certain period in order to apply DSI programs in practice (RQ 2: Study 2 / RQ 3: Study 3). To this end, a prediction (RQ 2: Study 2) and a simulation model (RQ 3: Study 4) that can be used to predict the E(T)Vs’ energy consumption were established. Furthermore, DSI systems were viewed in this thesis from a technical perspective, mainly by investigating the technical requirements for applying DSI programs in practice (RQ 3: Studies 3 and 5). Finally, the energy market design and regulatory frameworks for applying DSI programs were considered in detail to ensure the effective implementation of potential DSI programs for the case study (RQ 3: Studies 3 and 5). Here, it was found that most DSI programs cannot be realized under the prevailing energy market conditions. Based on this analysis, the last study of this thesis (RQ 4: Study 7) described how regulatory requirements must be changed in order to encourage smaller providers of flexible loads to participate in DSI programs. By combining all findings, this thesis reveals important insights on how to integrate E(T)Vs into future energy markets.

Summarized in Figure C:2., it can clearly be seen that the main findings of each study included in this cumulative dissertation contribute to achieving the overall objectives of this thesis.

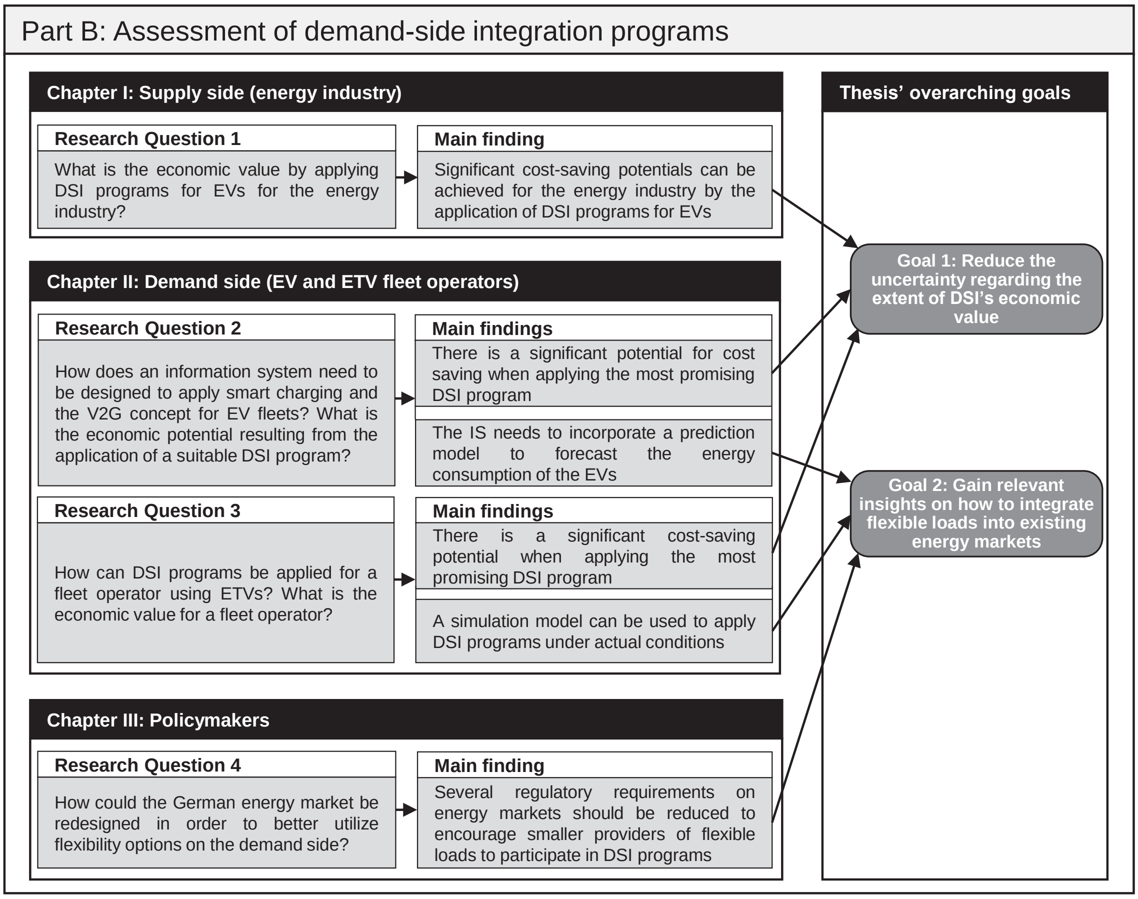

Figure C:2. Integrated findings of all studies included in Part B.

II. Implications for Theory and Practice

Based on the findings described in the previous chapter, this chapter discusses a number of major contributions of the thesis for the relevant stakeholders which include decision makers in the transport sector and in the energy industry, policymakers, and energy economics researchers (see Section A.I.5). In principle, the practical relevance of this thesis' results is likely ensured because most analyses are based on an ongoing electric mobility project in northern Germany (see Section A.II.3).

II.1 Managerial Implications

As this thesis offered both energy supply-side and demand-side perspectives on DSI programs, several managerial implications can be derived for two groups of practitioners. The first group are decision makers in the transport sector (energy demand side), with a focus on heavy-duty electric vehicle fleet operators. As the characteristics of the fleet operator from the electric mobility project are likely to be similar to those of other transportation companies, the respective implications can presumably be adapted by other companies in related fields of application, such as airport and railway operators as well as larger private transport companies. In total, four major implications can be identified for this group of practitioners.

The first implication refers to the composition of an operator's transport fleet. Due to the emerging saving potential identified when using ETVs, it seems advantageous to gradually replace the entire diesel-powered transport fleet of the port operator with ETVs. Increasing economic efficiency is particularly important for European port operators because of the growing cost pressure, mainly from Asian competitors; the results of Section B.II.5 indicate that using ETVs in combination with a battery-swapping station on company grounds is a suitable measure for achieving this. Besides economic benefits, ETVs are also associated with environmental benefits, as it is possible to reduce local emissions. This has a special significance for the fleet operator from the electric mobility project. With the "on course" initiative, the company has launched several sustainability programs with the overall objective of reducing CO_2 emissions per container handle by at least 30% by 2020. Nevertheless, it can be assumed that fleet operators would only be convinced to use an eco-friendly transport technology if it were economically comparable to its conventional counterpart. As this thesis found that an ETV fleet may even be economically beneficial in closed transport systems, ETVs should represent an important component in a company's environmental strategy.

Second, the findings of Sections B.II.2 and B.II.4 imply that the cost efficiency of ETVs can be further increased considerably by the application of DSI programs. It therefore seems reasonable for fleet operators to apply DSI programs for their ETV fleets. As DSI programs are also associated with energetic benefits, fleet operators adopting DSI solutions can also expect benefits.

Third, fleet operators intending to apply DSI programs for their ETV transport fleets should focus on two DSI programs for utilizing charging flexibility under current energy market conditions: optimizing the company's load curve and controlling the charging processes based on variable prices for electricity. From an economic point of view, controlled charging based on variable prices for electricity seems to be the most promising option for fleet operators. However, as optimizing the company's load curve is considerably easier to implement, this DSI programs could be implemented first. Hence, depending on the fleet operator's preferences, one of the two DSI programs could be applied for an ETV fleet.

The final implication for heavy-duty fleet operators refers to the practical application of DSI programs for a transport fleet. Fleet operators intending to apply DSI programs should be aware that applying even the simplest DSI program requires substantial financial and operational efforts. As revealed in Section B.II.4, the charging status of the batteries must be monitored constantly and a battery administration system is required to derive the optimal decision to shift demand at a given time. Further investments are needed for load control devices, metering and communication systems, and DSI information systems. Finally, companies must be able to predict the electricity demand of the ETV fleet for a certain period.

Based on the results of this thesis, it is also possible to derive two major implications for decision makers in the energy industry (energy supply side). First, decision makers in the energy industry are guided in assessing the energetic potential of an emerging flexible load in the energy landscape: ETVs applying DSI. Until now, the energy industry has focused on energy-intensive industries (aluminum, chemistry, or cement) as primary target groups for DSI programs. Furthermore, many practice projects are currently implemented by energy suppliers to investigate the possibilities of DSI programs for EVs (e.g., *Shared E-Fleet* or *iZeus* [IKT für Elektromobilität]; *Demand Response* or *Tanken im Smart Grid* [Schafenster Elektromobilität]). One application context for applying DSI programs that has been largely ignored by energy suppliers is heavy-duty electric transport vehicles operating in closed transport systems. The results of Chapter II in Part B, however, reveal that commercial ETV fleets using a battery-swapping station are clearly more suitable for applying DSI programs under current energy market conditions. Hence, in the first step towards a broad implementation of DSI programs in the field of electric mobility, it seems advisable for energy suppliers to focus on this application context. Besides the specific application context of automated guided container vehicles operating in ports, several further fields of application can be developed by energy suppliers, as mentioned above.

The last conclusion for practitioners refers to the extent of DSI's economic value for energy suppliers. The findings of Section B.I indicate that infrastructure investments in additional peaking power plant capacities can be deferred from using DSI to shift peak demand. The arising implication is that energy suppliers should focus on measures to realize DSI programs for EVs instead of power plant capacity extensions. Preventing an extension of power plant capacities could be even more important in the future against the background of the increasing integration of renewable energy resources into the market. As many renewable energy sources have short-run marginal costs close to zero, they displace electricity generated from conventional power plants with relatively high variable costs from the merit order. This results in a reduced utilization rate of conventional power plants and thus fewer hours in which these are running in order to cover their costs (Sensfuß et al., 2008). Even many new and highly efficient peaking power plants (e.g., gas-fired power plants) have become uneconomical as a result of the low utilization factor (Poser et al., 2014). To remain competitive, energy suppliers should therefore avoid any non-necessary capacity extensions of peaking power plants that are running for only few hours a year. As highlighted in this thesis, applying DSI programs for EVs is a suitable way of achieving this.

An overview of all implications for decision makers in the transport and energy sectors is given in Table C-4.

Table C-4. Major managerial implications.

Group	Implication	Explanation
Transport sector	(1) Fleet operators in the application context of closed transport systems should gradually replace their diesel-powered transport vehicles with ETVs	The results indicate that an ETV fleet is more profitable than a conventional fleet
	(2) ETVs should represent an important component in a company's environmental strategy	Environmental benefits result from the possibility of reducing emissions
	(3) Fleet operators using ETVs should apply DSI programs for their fleets	Significant potential for cost savings from adopting DSI solutions were identified
	(4) Fleet operators intending to apply DSI programs should focus on two DSI programs under current energy market condition: optimizing the company's load curve and smart charging	The findings reveal low regulatory requirements but high economic potential of these DSI programs
	(5) Decision makers should be aware that applying even the simplest DSI program requires substantial financial and operational efforts	Several investments must be made to enable DSI programs
Energy sector	(1) The energy industry should focus on the application context of closed transport systems as a first step towards a broad implementation of DSI programs in the field of electric mobility	Several favorable characteristics for applying DSI programs in this area of application were identified
	(2) Industry should focus on measures to realize DSI programs for EVs instead of power plant capacity extensions	The findings reveal significant cost-cutting potential for energy suppliers when applying DSI programs for EVs

II.2 Policy Implications

The German government has defined ambitious energy- and climate-related targets in order to create the German “Energiewende” (clean energy transition). These targets include increasing the share of renewable energies up to 80% by 2050 and reducing CO_2 emissions in the transport sector by at least 80% by 2050 compared to the 2008 level (BMWi and BMU, 2010). This thesis includes valuable information for policymakers that could contribute to reaching both goals.

First, the thesis presents policymakers with a way to efficiently reduce CO_2 emissions in the transport sector. In general, there is consensus that replacing the internal combustion engine with an electric motor is a suitable measure for reducing GHG emissions as the share of renewable electricity generation increases. Therefore, the German government has set the ambitious plan of putting one million electric vehicles on the road by 2020 (NPE, 2012). However, as their economic viability is constrained, the market penetration of EVs is still very low; only 29,000 EVs were registered in Germany in 2014 (KBA, 2015). Furthermore, the government’s efforts in supporting electric mobility projects or creating various incentive systems to promote EV sales have not brought the success expected. The results of this thesis suggest that policymakers should have a stronger focus on the use of EVs in niche applications of the commercial transport, such as heavy-duty vehicles (HDVs), as these represent particularly promising applications of electric mobility. For policymakers, fostering electric mobility in niche applications thus seems to hold promise; few government subsidies – especially in supporting electric mobility projects – would be necessary to make it profitable and thus reach market maturity. This could promote the market penetration of ETVs and would support the government’s objective of achieving a sustainable transport system. From an environmental point of view, the substitution of conventional transport vehicles for EVs is an important and often underestimated factor in achieving climate protection objectives. As heavy-duty transport vehicles are responsible for approximately 6% of total EU greenhouse gas emissions (Luz et al., 2014), replacing conventional trucks, such as forklifts, aircraft tractors, or container transport vehicles with EVs offers a huge potential for reducing GHG emissions in the transport sector.

Besides promoting electric mobility projects, policymakers can foster electric mobility in these niche applications by placing caps on average CO_2 emissions from newly registered heavy-duty vehicles, as is already done for cars and vans (European Commission, 2014b). For each registered car that surpasses the maximum CO_2 level, manufacturers must then pay an emissions premium. Conventional heavy-duty vehicles not meeting the emissions target would thus be more expensive, motivating industry to deliver eco-friendly HDVs and eventually leading to both increased operational costs for conventionally powered vehicles and reduced E(T)Vs prices due to economies of scale.

On the basis of the results of this thesis, it is also possible to derive recommendations on how to promote the development of renewable energies. As described in Section B.II.4, the current energy market design in Germany is ill-suited for smaller providers of flexible loads, such as EVs, EV fleets, or ETV fleets. This thesis therefore helps policymakers by providing information about the shortfalls of the current energy market design for using flexible loads. Furthermore, Section B.III suggested a broad range of recommendations on how to redesign the energy market in order to utilize flexible options on the demand side to a greater extent. The Green Book “A Power Market for the Energy Reform" highlights the need for such an investigation in its attempt to promote public debate about a redesigned power market (BMWi, 2014b). The prominence of flexible loads in this Green Book and the related discussions underlines the importance of developing new insights into aspects relevant to designing an adequate future market and regulatory framework. As found in Section B.III, it seems sensible to adapt regulatory requirements on energy markets in order to facilitate access to energy markets.

An overview of all major implications for policymakers is given in Table C-5.

Table C-5. Major policy implications.

Implication	Explanation
Pay more attention to niche applications in the field of electric mobility to foster environmental and energy goals	Niche applications are great examples of promising applications of electric mobility in commercial traffic
Set mandatory limits on average CO_2 emissions from newly registered heavy-duty vehicles	Positive economic effects on ETVs are expected
Reduce regulatory requirements on energy markets in order to facilitate access to energy markets	This would allow further penetration of intermittent of renewable sources / the cost efficiency of E(T)Vs could be improved

II.3 Implications for Energy Economic Research

Apart from its contributions to practice, which were discussed in the previous two sections, this thesis contributes to the research stream of energy economics in multiple ways. First of all, this thesis contains precise information about the economic value of applying DSI programs from the perspective of the energy supply side. As explained in Section A.II, most studies assessing the potential of applying DSI for EVs for energy suppliers have focused on technical effects while neglecting the economic impacts. This research gap was narrowed in Section B.I, which provides energy researchers with precise information regarding the extent of DSI's economic value for the energy supply side. Access to such information has significant implications for future energy researchers focusing on energy supply-side activities. The technical and energetic effects of applying DSI programs for EVs from the energy supplier's point of view have already been assessed; it could be shown that energy suppliers profit considerably from the application of DSI programs for EVs. One of the major challenges for energy researchers is then to determine how to convince users to participate in DSI programs, as there are several complications obstructing the realization of DSI programs for private customers (see Section A.II.2). A suitable approach could be to develop innovative and customer-oriented business models. An appropriate business model can increase the market attractiveness of a technology (e.g., DSI), improve the full value capture of an innovation, and lead to a competitive advantage (Chesbrough, 2010). For energy suppliers, it is particularly important to integrate customers in the business model development process; customer preferences have generally been ignored by most energy providers, due to their established market position (Valocchi et al., 2014). For example, it must be investigated whether the required DSI technology, such as intelligent charging stations, ICT technology, or smart grids, should be offered as a product bundle to reduce the customer's effort necessary in purchase decisions. To sum up, considering customer preferences appear to be a promising area for further research, as these play a crucial role in the future success of DSI.

In Chapter II of Part B, researchers in the field of energy economics can find detailed information about the energetic and economic potentials of applying DSI programs for a completely new actor on the demand side: fleet operators using (heavy-duty) ETVs in closed transport systems. Analyzing previous publications in this research field, it was found that most related studies have focused on individually (privately) used EVs (e.g., Mullan et al., 2011; Wang et al., 2011a; Andersson et al., 2010) or EV fleets (e.g., De Los Rios et al., 2012; Han et al., 2010; Tomić and Kempton, 2007) for the application of DSI programs. The results of this thesis, however, reveal that commercial ETV fleets using a battery-swapping station are clearly a more suitable application for DSI programs under current energy market conditions. In the future, researchers could therefore focus on how to apply DSI in related fields of applications, such as airports. To conclude, the thesis provides a good starting point for future research.

A further contribution for researchers could be achieved by advancing methodological knowledge in the field of energy economics research. This thesis adapted research methodologies from the field of operations research – in particular optimization models – to estimate DSI's economic potential under realistic conditions. This is significant because all related publications assessing the potential of DSI neglect energy market design – for example, in terms of effort required to act on energy markets – and are thus based on dubious assumptions. As revealed in this thesis, however, the actual profits generated by the application of DSI programs (e.g., V2G or smart charging) depend directly on the energy market's design. Adapting these thoughts, researchers in the field of DSI should build upon the models developed in this thesis and integrate energy market characteristics in their economic models, allowing them to assess the economic potential of DSI programs for EVs or ETVs under more realistic conditions. Besides improving existing models, several new techno-economic approaches were developed in this thesis to estimate the financial profits of DSI programs that had not yet been considered (e.g., optimizing the company's load curve). These techno-economic approaches can be used by other researchers and adapted to the researchers' specific application contexts. In principle, the models can also be used to assess the economic potential of applying DSI programs for a single EV or a fleet of EVs.

This thesis also introduces a methodological approach to applying DSI in practice. Surprisingly, all previous studies investigating the potential of DSI programs for EVs overlook the need to know the electricity demand of these vehicles in advance. In line with these thoughts, this thesis introduced a novel approach to apply DSI programs for ETV fleets without restricting mobility needs. For closed transport systems, simulation-based forecasting was found to be suitable for forecasting the electricity demand and resulting charging flexibility of the ETVs, mainly because transport systems are often highly dynamic and depend on many different influence factors. Therefore, it is often impossible to model these systems completely mathematically. Researchers assessing the potential of DSI programs in related fields of application should hence focus on simulation-based analysis rather than mathematical approaches.

A final contribution to energy economics research from the perspective of the demand side is provided by paving the way for a myriad of future studies. To date, most research has focused on two kinds of DSI programs for EVs: smart charging and the V2G concept. However, as shown in this thesis, providers of flexible load can participate in a broad range of DSI programs and are not limited to these established DSI programs; four further suitable DSI programs were identified in Section B.II.4. For closed transport systems, some programs were identified as very promising for utilizing charging flexibility due to attractive potentials for saving and relatively simple implementation. The major implication that arises is that energy researchers should also assess the potential of these DSI applications for both closed transport systems as well as for EVs that operate outside the premises.

Finally, this thesis provide a good foundation for energy researchers that focus on energy policy measures. The findings of Section B.II.4 call for changes in the energy market design. Therefore, future research should focus on how to develop a future market design that also allows smaller providers of flexible loads, such as ETV fleet operators, to participate. Although first investigations were conducted in Section B.III, they must be extended in the future.

An overview of the major implications for researchers that focus on the energy supply side, the energy demand side, or policy measures is given in Table C-6.

Table C-6. Major implications for energy economics research.

Research focus	Implication	Explanation
Energy supply side	(1) There is a need to develop innovative and customer-oriented business models	Users must be convinced to participate in DSI programs, as energy suppliers profit considerably from the application of DSI programs
	(2) Customers must be integrated into the business model development process	To date, energy providers have generally ignored customer preferences
Energy demand side	(1) Researchers should focus on how to apply DSI in further fields of applications that use ETVs	Commercial ETV fleets are particularly suitable for applying DSI programs
	(2) Energy market characteristics should be integrated into economic models used to assess the potential of DSI programs	The actual profits generated through the application of DSI programs depend directly on the energy market's design
	(3) Researchers should focus on simulation-based analysis to forecast the energy consumption of ETVs	Simulation-based forecasting was found to be suitable for forecasting the energy consumption of ETVs
	(4) The economic potential of all DSI programs identified in this thesis should be assessed for further fields of application	Some DSI programs were identified to be very promising for utilizing charging flexibility
Policy measures	Researches should focus on how to develop a future market design that also allows smaller providers of flexible loads to participate	The current energy market design was found to be ill-suited for smaller providers of flexible loads

III. Conclusion and Further Research Opportunities

The cumulative thesis at hand had two overarching goals. First, it aimed to quantify the financial impacts of applying DSI programs for EVs and (heavy-duty) ETVs for two groups: fleet operators and energy suppliers. While previous research has focused on individually used EVs or EV fleets for applying DSI programs, this thesis centers on fleet operators using heavy-duty electric transport vehicles. Second, the thesis aims to offer policymakers suggestions on how to integrate flexible loads, such as ETVs, into existing energy markets. To achieve these goals, four research questions were derived and then answered in seven studies in Chapters I, II, and III of this thesis' main Part B. Each chapter provided a different perspective on DSI programs for E(T)Vs; energy supply side, energy demand side (EV and ETV fleet operators), and policymakers.

The **first chapter** of Part B offered a supply-side perspective on DSI programs for EVs in general and answered RQ 1, regarding whether and to what extent energy suppliers can benefit economically from applying DSI programs for EVs. The results of the study in this part highlight the significant cost-saving potentials that can be achieved for the energy industry by applying DSI programs, mainly due to the possibility of shifting charging processes to off-peak hours, which reduces the need for increases in power plant capacities. The infrastructure costs avoided – reflecting DSI's economic value from the perspective of the energy supply side – will probably be reflected in electricity prices for all energy users. Furthermore, the financial profits revealed for energy suppliers could convince decision makers in the energy industry to fund EV users who participate in DSI programs. Both aspects could have a positive effect on EV adoption.

Subsequent, the **second chapter** of Part B provided a demand-side perspective on DSI programs. The first study in this chapter focused on estimating the financial profits of applying DSI programs for EV fleets using real-world data from a car-sharing operator. In doing so, the second research question of this thesis could be answered. The main finding of this study is that fleet operators can expect significant cost savings when applying DSI programs for their EV fleet. Applying DSI programs for EVs can thus make a valuable contribution to ensuring that these vehicles become economically competitive. This finding is significant because it addresses one of the main barriers to EV adoption, i.e., their significantly higher purchasing prices in comparison to those of conventional vehicles. However, it was also found that there are several complications obstructing the realization of DSI programs for EV fleets, such as the need to pool thousands of EVs to act on DSI energy markets due to the small size of EV batteries.

Against this background, this cumulative dissertation was primarily concerned with assessing the potential of applying DSI programs for a promising, innovative transport technology: heavy-duty electric transport vehicles operating in closed transport systems. The insights gleaned from this part contribute to answering RQ 3, which asks about how DSI programs can be applied for a fleet operator using ETVs and the economic value for a fleet operator. To ensure the practical relevance of the results, data from a comprehensive electric mobility project with one of the largest terminal operators in Europe that uses heavy-duty electric transport were analyzed in four related studies. Although it could be shown that commercial ETV fleets have several favorable characteristics for applying DSI programs, it was found that many possible DSI programs cannot be realized under prevailing conditions – even for the large ETV fleet operator – mainly due to regulatory requirements. The most intriguing finding of this thesis is the significant potential for cost saving (>30%) when applying the most promising DSI program. Finally, it could be demonstrated that the operator's ETV fleet is more profitable than a comparable diesel-power fleet, and the cost-efficiency of the ETV fleet can be reduced even further by applying DSI programs. Essentially, it could be shown that fleet operators using ETVs and applying DSI programs can gain a competitive advantage by reducing overall fleet costs while simultaneously reducing local emissions, thus ensuring the long-term profitability of the company. Therefore, the results of this chapter pave the way for the application of ETVs in many related areas, such as airports, railways, or cargo transport centers. A larger share of ETVs in use would support most governments' objectives of achieving a sustainable transport system by reducing CO_2 emissions from heavy-duty vehicles. Furthermore, the results have the potential to convince further fleet operators to adopt DSI solutions, which is crucial for the economically efficient and technically secure operation of a power system with a high share of intermittent generation sources.

Finally, the last **Chapter III** of Part B provided a governance perspective on DSI programs. Given the rapid expansion of renewable energies, it will be important for smaller, flexible consumers to participate in DSI and respond to the intermittent supply of energy in the future. This chapter aimed to determine how to integrate flexible loads (e.g., ETVs) into existing energy markets, taking into account the regulatory frameworks and energy market design in Germany; insights from this chapter contribute to answering Research Question 4. Based on a case study with an ETV fleet's operator, concrete measures could be derived on how to adjust regulatory frameworks to improve market success for smaller providers of flexible loads. In addition to energetic benefits for the entire energy system, this could have positive impacts on the market penetration of E(T)Vs, as users can reduce their energy bills by participating in DSI.

Overall, the results of the thesis contribute to reducing uncertainty regarding the extent of DSI's economic value for EV – and in particular ETV – fleet operators as well as energy suppliers. This is necessary because numerous studies have found that little is known about the economic potential of DR or DSI in liberalized markets (e.g., Goebel et al., 2014; Aghaei and Alizadeh 2013; Strüker and van Dinther, 2012). Furthermore, policymakers could be given concrete recommendations for enabling smaller providers of flexible loads to participate in DSI programs, which is important for ensuring power supply security in the future despite the expansion of renewable energy sources.

III.1 Limitations

Although this thesis adds several new and relevant insights regarding the potential of applying DSI programs for several actors in the field of electric mobility, the following limitations should be considered by researchers and practitioners when interpreting the results. In general, when reflecting upon the results of all publications, it should be noted that the evaluations are based on today's (2012–2014) energy market design, which is likely to change. Most modifications that are currently under discussion by policymakers, such as strengthening market price signals for producers and consumers or reforming emissions trading systems (BMWi, 2015), will have a direct or indirect influence on the profitability of DSI programs. Furthermore, it must be taken into account that many governments intend to significantly increase the share of renewable energies, which also has an influence on most DSI programs. For example, price volatilities on spot market are likely to increase, which will affect price-based DSI programs. Consequently, the results of this thesis must be adapted in response to changes in the energy market design or energy mix in the future. In the following, the main limitations of each Chapter I, II, and III of this thesis' main Part B are discussed.

The results of the assessment of DSI's economic potential from the perspective of the energy supply side (Chapter I) are based upon specific assumptions concerning the charging behavior of EV users. In this regard, simplistic driving profiles were used and a fixed time of day or latest end of charging was assumed to evaluate whether investments in smart EV charging technologies are a suitable alternative to an expansion of power plant capacities. Furthermore, the operational costs of DSI programs for energy suppliers were disregarded in the economic assessment. Therefore, further research should consider these constraints and employ actual driving patterns in their models in order to perform a stochastic simulation to determine the probable time of battery charge. Furthermore, DSI's operational costs for energy suppliers should be taken into account, thus more precisely quantifying the financial impacts of applying DSI programs for EVs from the perspective of the energy supply side.

The evaluation of the economic potential of DSI programs for heavy-duty ETV operators (Chapter II) are based on a comprehensive case study with a single fleet operator in Germany. Therefore, the results cannot be expected to be representative for all kinds of users. However, as the characteristics of the pilot case company are likely to be similar to those of other transportation companies (e.g., in terms of transport requirements or operation times), the analysis allows for at least a rough estimation of DSI's economic value for other fleet operators. The DSI programs discussed, as well as the techno-economic models developed to quantify DSI programs in economic terms, should also be applicable in countries with similar regulatory frameworks, but the results will vary depending on the specific framework. This is significant because electric transport vehicles are currently being introduced worldwide. Therefore, it is advisable to modify some parameters before transferring the results to other countries. From a methodological point of view, the simulation model that was established to predict ETV energy consumption is dependent on the quality of input data and the assumptions made. For the specific application context of container terminals, the simulation model shows promising results. However, future research is necessary to determine whether simulation-based analysis is also suitable for predicting the energy consumption of ETVs in related fields of application.

Finally, the investigation on how to redesign the energy market in order to utilize flexibility options on the demand side to a greater extent (Chapter III) was conducted based on a single pilot case study with a fleet operator. The main limitation of this approach is that it does not allow for generalization to other small providers of flexible loads with different characteristics. Therefore, the results should be evaluated in a multiple-case study in the future.

III.2 Further Research Opportunities

This thesis focused on the application area of closed transport systems for the utilization of DSI programs. A broad range of feasible DSI programs could be identified for commercial heavy-duty electric transport vehicles operating in closed transport systems. Furthermore, based on the techno-economic approaches developed, suitable DSI programs were quantified in economic terms and their influence on the TCO of an ETV fleet could be assessed. This section presents avenues for further research that result both from the remaining open questions regarding DSI programs for ETVs as well as from emerging fields of research.

There are still some open questions regarding the use of ETVs in combination with DSI programs in container terminals that can be addressed by further research. In this thesis, all analyses were based upon data from a specific electric mobility project. In doing so, the practical relevance of the results is likely ensured. However, most parameters, such as the battery type, vehicle type, charging infrastructure, or fleet size, were determined in advance as a result of the specific project setting. Therefore, further studies can concentrate on determining the optimum conditions for electric mobility and DSI programs for this application context. In this regard, several parameters of the project setting can be modified:

1) **Battery type deployed:** Currently, the ETVs of the fleet operator are equipped with lead–acid batteries; a possible alternative is using lithium–ion batteries. Although much more expensive, the energy consumption of the ETV fleet can be reduced by employing lithium–ion batteries, mainly because of their greater charging efficiency. Furthermore, lithium–ion batteries have a longer lifetime than comparable lead–acid batteries. Besides the type of battery, determining the optimal battery size or depth of discharge deserves a more detailed analysis. To answer these questions, detailed techno-economic analyses must be conducted in the future.
2) **Charging infrastructure:** Charging sites on company grounds represent a possible alternative or supplement to the currently deployed, expensive battery-swapping station. Besides economic calculations, further investigation is needed to determine whether the long charging processes would negatively affect the logistic processes of the fleet operator.
3) **Fleet size and composition:** The fleet size and composition optimal for the fleet operator must be determined in the future. In this regard, the fleet operator could employ a mix of two types of transport technologies: conventional and electric HDVs, as both vehicle types have specific advantages regarding costs or operational requirements. Two-stage stochastic optimization could be used to determine the investment plan for both vehicle types, answering both when and how many ETVs to procure.

As attested, there is a large scope for possible changes to the current setting. Further studies should therefore concentrate on determining the optimal parameters for electric mobility in closed transport systems. To this end, further techno-economic analyses must be conducted in collaboration with fleet operators. This thesis thus represents a good starting point for further investigations in the field of DSI for heavy-duty electric transport vehicles.

Furthermore, the results provide four potential pathways for further research in the field of demand-side management. The first area that displays fruitful avenues for further research is to transfer the thesis' results to other fields of application. Based on the electric mobility project, this thesis demonstrates the particular suitability of heavy-duty ETVs for applying DSI programs under current conditions. Furthermore, it could be shown that the ETV fleet of the port operator may be more profitable than a comparable diesel-powered HDV fleet. A particularly promising related application context seems to be airports: Like ports, several types of heavy-duty vehicles, such as aircraft tractors or freight tractors, are employed in different functions. Furthermore, airports and container terminals have considerable similarities in terms of logistic requirements. Given the potential of electric mobility in closed transport systems, further studies should be conducted to assess the potential of using ETVs in these and other fields of application and to estimate the financial profits of applying DSI programs.

A second emerging and promising research field that arises from this thesis' results pertains analyzing the energetic and environmental effects of electric mobility in closed transport systems. First, the environmental benefits of replacing conventional transport vehicles by ETVs can be quantified in further studies. In particular, further research should concentrate on estimating the CO_2-reduction potential that results from substituting conventional HDVs by ETVs; the possibility of reducing emissions is an important factor for convincing further fleet operators to employ electric mobility. Second, the environmental and energetic effects of applying DSI programs deserve a more detailed analysis. This thesis identifies a broad range of innovative DSI programs for ETVs that can also be applied for any kind of flexible load. As discussed, most of these DSI programs are also associated with environmental benefits. Price-based DSI programs, for example, indirectly promote the development of renewable energies because electricity prices are particularly low when a large amount of renewable energy is available. For the research field of demand-side management, it appears useful to quantify these effects in detail. This is also important because fleet operators adopting DSI solutions can also hope for reputational benefits from indirectly promoting renewables.

The third emerging field of research with promising prospects considers the interaction of all flexible loads in an energy system. This thesis concentrates on two types of flexible loads: EV and ETV fleets. For an integrated assessment of EVs and ETVs and their demand-side integration capabilities, further research must also consider their interaction with other flexible loads, such as specific household applications (washing machine or refrigerator) or shiftable industry processes. In particular, coordination strategies (when to activate a certain kind of flexible load) must be developed to fully exploit the potential of flexible loads in an energy system. To this end, the ability of E(T)Vs to curtail or increase load when needed must be quantified in terms of activation time or security level and compared with other flexible loads. Based on the results, it is possible to determine when to optimally activate a certain kind of flexible load in an energy system.

Finally, this thesis opens the door for a broad range of further studies on the development of a future energy market design and regulatory framework for the electricity sector that also allows for the participation of smaller providers of flexible loads. It was found that the current energy market design in Germany is ill-suited for smaller, flexible consumers, such as E(T)V fleet operators. This calls for changes in the market design in order to ensure power supply security in the future, despite the increased share of wind and solar in the mix. Initial suggestions were made on how to adjust regulatory frameworks. However, any modification (e.g., reducing requirements for acting on DSI energy markets) would also affect other fields of the energy sector, mainly because the energy market is characterized by several interdependencies. In the future, energy researchers should also expand on the possible unexpected negative effects associated with each of the recommendations made. Based on these analyses, it is possible to provide more reliable suggestions on how to redesign the energy market in order to utilize flexibility options on the demand side to a greater extent.

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Appendix

Appendix A. Overview of the authors' contribution in the studies included in this thesis.

No	Section	Title	Author	Authors' contribution
1	B.I	The Value of IS to Ensure the Security of Energy Supply	**Johannes Schmidt**	70
			Sebastian Busse	30
2	B.II.1	Applying Demand Response Programs for Electric Vehicle Fleets	**Johannes Schmidt**	60
			Björn Hildebrandt	20
			Matthias Eisel	15
			Lutz M. Kolbe	5
3	B.II.2	Assessing the Potential of Different Charging Strategies for Electric Vehicle Fleets in Closed Transport Systems	**Johannes Schmidt**	55
			Matthias Eisel	40
			Lutz M. Kolbe	5
4	B.II.3	Simulation of Power Demand in a Maritime Container Terminal using an Event-Driven Data Acquisition Module	Serge Runge	50
			Norman Ihle	25
			Hans-Jürgen Appelrath	5
			Johannes Schmidt	15
			Lutz M. Kolbe	5
5	B.II.4	Demand Side Integration for Electric Transport Vehicles	**Johannes Schmidt**	50
			Lars Lauven	30
			Norman Ihle	15
			Lutz M. Kolbe	5
6	B.II.5	Using Electric Transport Vehicles within Closed Transport Systems – Assessing the Potential and Optimizing the Economic Viability	**Johannes Schmidt**	55
			Claas Meyer-Barlag	25
			Matthias Eisel	15
			Lutz M. Kolbe	3
			Hans-Jürgen Appelrath	2
7	B.III	Shaping the Future Energy Market – Making Energy Demand more Flexible	**Johannes Schmidt**	90
			Lutz M. Kolbe	10

Appendix B. Overview of author's published and forthcoming double blind reviewed articles as of August 2015.

Authors	Publication	Ranking
Peer-reviewed Journals		
Schmidt, J.; Meyer-Barlag, C.; Eisel, M.; Kolbe, L. M.; Appelrath, H. J.	Using Electric Transport Vehicles within Closed Transport Systems – Assessing the Potential and Optimizing the Economic Viability, Research in Transportation Business & Management, 2015. (submitted; under review)	n.a.
Schmidt, J.; Lauven, L.; Ihle, N.; Kolbe, L. M.	Demand Side Integration for Electric Transport Vehicles, International Journal of Energy Sector Management, 2015. (forthcoming)	B
Schmidt, J.; Eisel, M.; Kolbe, L. M.	Assessing the Potential of Different Charging Strategies for Electric Vehicle Fleets in Closed Transport Systems, Energy Policy, Vol. 74, 2014.	B
Peer-reviewed Conferences		
Schmidt, J.; Hildebrandt, B.; Eisel, M.; Kolbe, L. M.	Applying Demand Response Programs for Electric Vehicle Fleets, Proceedings of the 2st Americas Conference on Information Systems (AMCIS) 2015, Puerto Rico, 2015.	D
Trang, S.; Busse, S.; **Schmidt, J**.; Falk, T.; Marrone, M.; Kolbe, L. M.	The Danger of Replacing Human Interaction in IS-driven Collaborative Consumption Services, Proceedings of the 23rd European Conference on Information Systems (ECIS) 2015, Muenster, 2015.	B
Eisel, M.; **Schmidt, J**.; Nastjuk, I.; Ebermann, C.; Kolbe, L. M.	Can Information Systems Reduce Stress? The Impact of Information Systems on Perceived Stress and Attitude, Proceedings of the 35th International Conference on Information Systems (ICIS) 2014, Auckland, 2014.	A
Eisel, M.; **Schmidt, J**.; Kolbe, L. M.	Finding Suitable Locations for Charging Stations – Implementation of Customers' Preferences in an Allocation Problem, Proceedings of the International Electric Vehicle Conference (IEVC 2014), Florence, 2014.	n.a.
Eisel, M.; **Schmidt, J**.	The Value of IS for Increasing the Acceptance of Electric Vehicles – The Case of Range Anxiety, Proceedings of the Multikonferenz Wirtschaftsinformatik 2014, Paderborn, 2014.	D
Schmidt, J.; Busse, S.	The Value of IS to Ensure the Security of Energy Supply – The Case of Electric Vehicle Charging, Proceedings of the 19th Americas Conference on Information Systems (AMCIS) 2013, Chicago, 2013.	D
Other Related Publications		
Schmidt, J.; Kolbe, L. M.	Shaping the Future Energy Market – Making Energy Demand more Flexible, Energy Informatics & Management (Science Day of Erasmus Energy Forum 2015), Rotterdam, 2015.	n.a.
Runge, S.; Ihle, N.; Appelrath, H. J.; **Schmidt, J**.; Kolbe, L. M.	Simulation of power demand in a maritime container terminal using an event-driven data acquisition module, International Conference on Logistics and Maritime Systems (LOGMS 2014), Rotterdam, 2014.	n.a.

The study ranking was assessed according to VHB Jourqual 3.

Curriculum Vitae

Personal Details

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Date of Birth	03 May 1986
Place of Birth	Wolfenbüttel, Germany
Nationality	German

Academic Career

Since 11/2012 — *Research Associate*, Chair of Information Management University of Göttingen, Germany

- Sub-project manager for a flagship e-mobility project in the harbor of Hamburg

10/2010 – 08/2012 — *Student Assistant,* Chair of Production and Logistics, University of Göttingen, Germany

10/2010 – 10/2012 — *Master of Science (M.Sc.) in Management*, University of Göttingen, Germany

- Focus on energy economics, mathematical optimization, logistics, and information management

04/2007 – 03/2010 — *Bachelor of Science (B.Sc.) in Business Administration,* University of Göttingen, Germany

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08/2011 – 12/2011 — *Internship*, Seat S.A. (Spain), Audit Department, Barcelona, Spain

03/2010 – 09/2010 — *Internship*, Volkswagen (Shanghai), Production Launch, Shanghai, China

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