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Demand side integration for electric transport vehicles

Johannes Schmidt[a], Lars-Peter Lauven[b], Norman Ihle[c], Lutz Kolbe[a]

[a]: Professur für Informationsmanagement, Georg-August-Universität Göttingen, Göttingen, Germany

[b]: Professur für Produktion und Logistik, Georg-August-Universität Göttingen, Göttingen, Germany

[c]: Department of Computer Science, University of Oldenburg, Oldenburg

The purpose of this study is to examine both the technical feasibility and the commercial viability of several demand-side integration (DSI) programs to utilize the charging flexibility of electric transport vehicles in a logistic facility. DSI is important for improving system reliability and assisting in integrating renewables into the energy system. A pre-assessment of several DSI programs is performed by considering effort for implementation, costs and economic potential. Afterward, the most promising programs are compared economically on the basis of optimization methods and economic analysis. The analysis is based on a comprehensive electric mobility project dealing with electric transport vehicles operating in container terminals.

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. Based on the analysis, other companies using electric transport vehicles have a foundation for identifying the most promising demand-side management program. While most research has focused on individually used electric vehicles, here commercial electric transport vehicles operating in closed systems were investigated as this area of application was found to be particularly suitable for participation in DSI programs.

1.1 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, 2013). 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., 2011; Andersson et al., 2010; Mullan et al., 2012) 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, 2005). 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 1.2, we discuss fundamentals of DSI and introduce our case study. Section 1.3 presents the approach for determining the most promising DSI programs, while the corresponding results are provided in Section 1.4. Section 1.5 examines the implications resulting from our findings, which leads us to the conclusions presented in Section 1.6.

1.2 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 1 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 1.

Table 1: Demand-side integration programs

DSI progam	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).

1.2.1 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., 2011). 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, 2005). EV users can thus reduce their total cost of EV utilization because of additional profits gained from participation in energy markets (Mullan et al., 2012).

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.

1.2.2 Case study: Battery electric heavy goods vehicles in 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 (BAGVs) 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 BAGVs. 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 BAGVs 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 BAGVs 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 BAGVs 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 BAGVs 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 1, which depicts a charging process for one battery on a selected day when using a plug-and-charge approach.

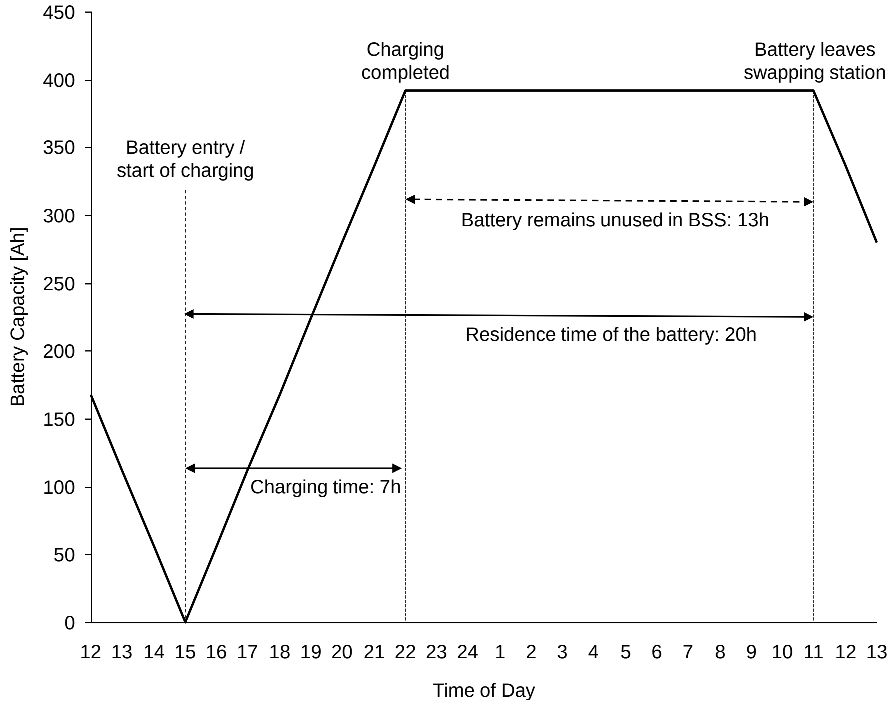

Figure 1: Depiction of a charging process on an illustrative day

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 state of charge (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.

1.3 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.

1.3.1 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 (BAGVs, batteries, and charging points within the BSS) must be equipped with metering and communication technologies, such as smart meters. As explained in Section 1.2.2, 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 BAGVs, 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.

Table 2: 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 forecasting 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

During the research project, six DSI programs were identified to be of potential interest. These programs can be grouped as shown in Table 2.

1.3.1.1 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 2.

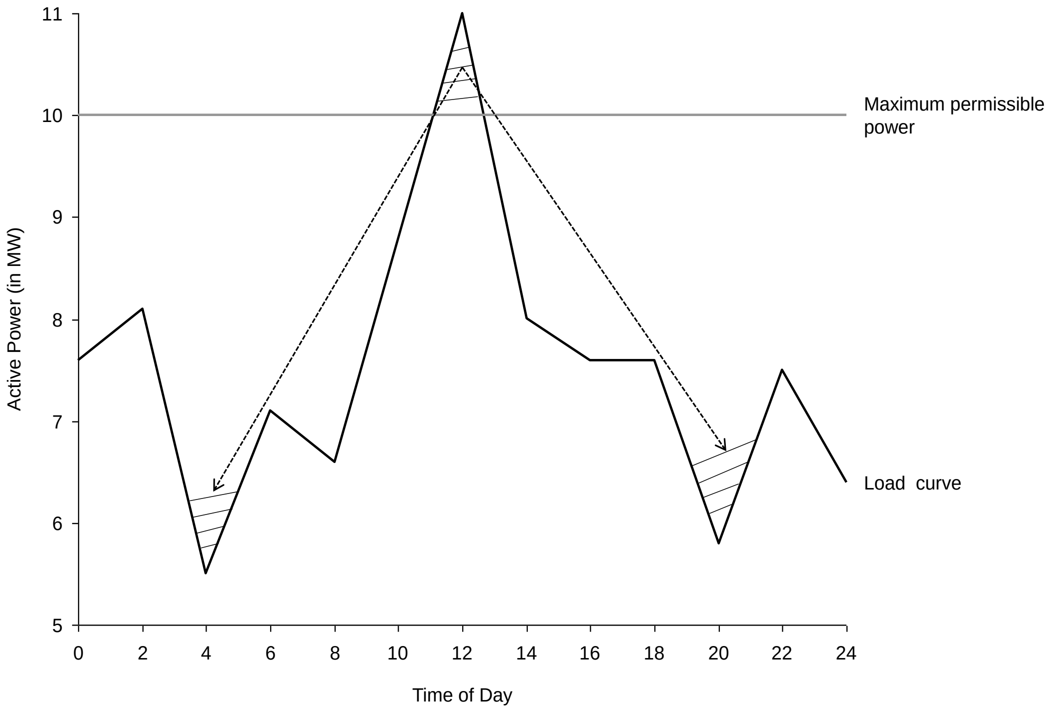

Figure 2: Basic principle of DSI program *optimizing the company's load curve*

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 (IW/EWI, 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 BAGVs 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.

1.3.1.2 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 3), which requires precise forecasting models. The BAGVs 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.

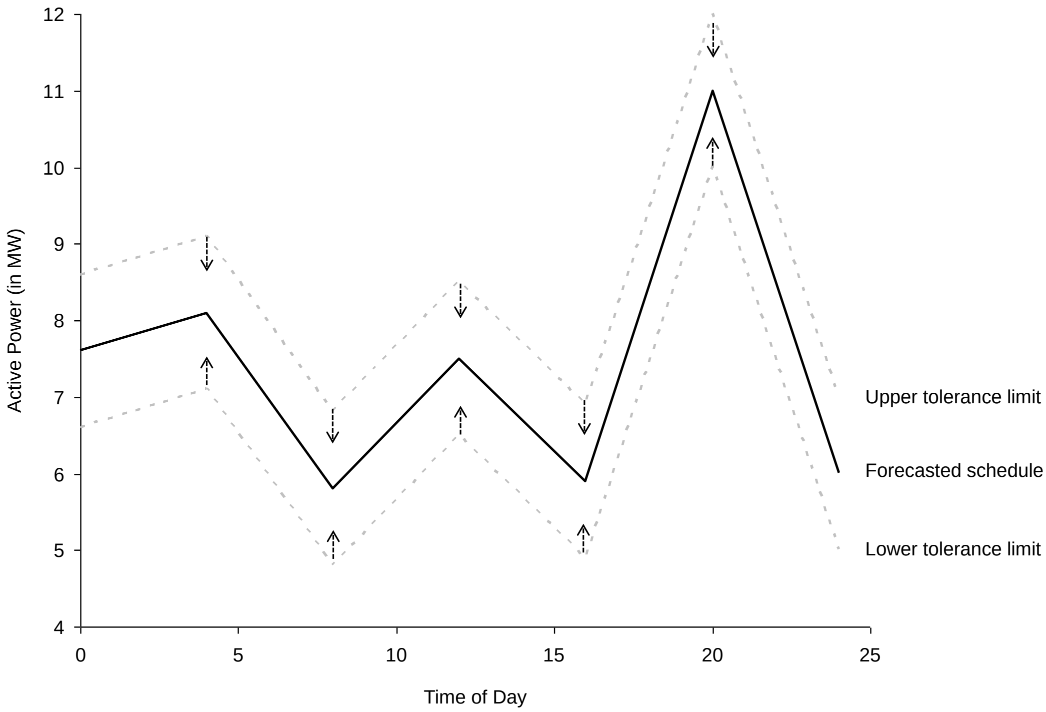

Figure 3: Basic principle of the DSI program *balancing group management*

1.3.1.3 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 BAGVs 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 BAGVs 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 4, significant price volatility can be observed on the spot market.

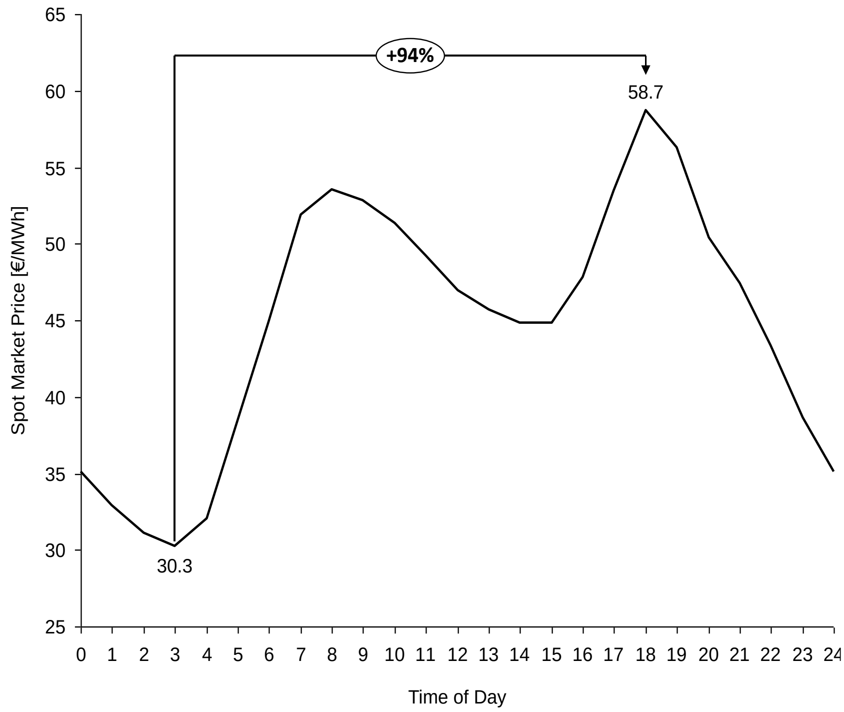

Figure 4: 2012 average electricity spot prices per hour and resulting price spread in Germany

1.3.1.4 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.net, 2014a). 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.net, 2014b). 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.

1.3.2 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 BAGVs' 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 BAGVs $\mathrm{d_{BAGVs}}$ 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

$$C_{uncontrolled} = \frac{\mathrm{d_{BAGVs}}}{\eta}\mathrm{p_{industry}}. \quad (1)$$

The subsequent optimization of charging costs is performed for the 2:1 equipment ratio (battery system to BAGV) 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}

$$M(SOC_t) = \frac{S - SOC_t}{W_{con}} 4. \quad (2)$$

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 1.3.1.3). The variable end price for industrial consumers $\mathrm{p_v(i)}$ can thus be calculated with the following equation

$$\mathrm{p_v(i)} = \mathrm{p_{spot}(i)} + \mathrm{p_{fix}} + \mathrm{p}_{service}. \quad (3)$$

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

$$\mathrm{x(i)} = \begin{cases} 1 \text{ if the battery is charged in time slot i within the time frame} \\ 0 \text{ if the battery is not charged in time slot i within the time frame.} \end{cases} \quad (4)$$

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

$$d_t\big(x(i)\big) = \frac{W_{con}\,\frac{1}{4}h}{\eta}\,x(i). \quad (5)$$

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

$$\min_{x(i)} C_{TF} \sum_{i=1}^{I} p_v(i) d_t x(i), \quad (6)$$

subject to

$$\sum_{i=1}^{I} x(i) = M \,\forall\, x(i) \in \{0,1\}; i \in \{1, \dots, I\}. \quad (7)$$

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

$$H_{Company} = \frac{\mathrm{d_{company}}}{\max\,(L(t))}. \quad (8)$$

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

$$C_{G,Company} = \max\,(L(t))\, p_d + \mathrm{d_{company}}\, p_{W.} \quad (9)$$

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 $\mathrm{d_{BAGVs}}$. The full-load hours for the company including BAGVs $H_{Company,BAGVs}$ can therefore be described by

$$H_{Company,BAGVs} = \frac{\mathrm{d}_{\mathrm{company}}+\mathrm{d}_{\mathrm{BAGVs}}}{\max\left(L(t)+W_{con}\, n_{bss}(t)\right)}. \tag{10}$$

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

$$C_{G,Company,BAGVs} = max\big(L(t)+W_{con}n_{bss}(t)\big)p_d + \left(\mathrm{d}_{\mathrm{company}} + \mathrm{d}_{\mathrm{BAGVs}}\right) p_W. \tag{11}$$

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 1.3.1.1). The procedure for optimizing the companies load curve is similar to the first DSI program.

1.4 Results

All parameters and values necessary for the assessment of both DSI programs are presented in Table 3.

Table 3: Parameters used to economically assess the selected DSI programs

DSI program	Parameter	Value	Comments	Data source
Baseline scenario	d_{BAGVs}	0.93	Annual electricity demand of all BAGVs [MWh]	Project data
	η	72	Charging efficiency [%]	Project data
	$p_{industry}$	15.02	Average electricity price for industrial customers [€/MWh]	BDEW (2014)
Controlled charging based on variable prices	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 calcluation
Optimization of the company's load curve	L	11.24	Peak load of the company without BAGVs [in MW]	Project data
	$d_{company}$	70.16	Power consumption of the company without BAGVs [in MWh]	Project data
	p_W	0.0137	Working price [in €/kWh]	Stromnetz HH (2013)
	p_d	20.55	Demand price [in €/kW]	Stromnetz HH (2013)

The annual costs for charging the BAGVs in an uncontrolled way at fixed prices can be calculated using Eq. (1) and the parameters listed in Table 3 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 5; 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.

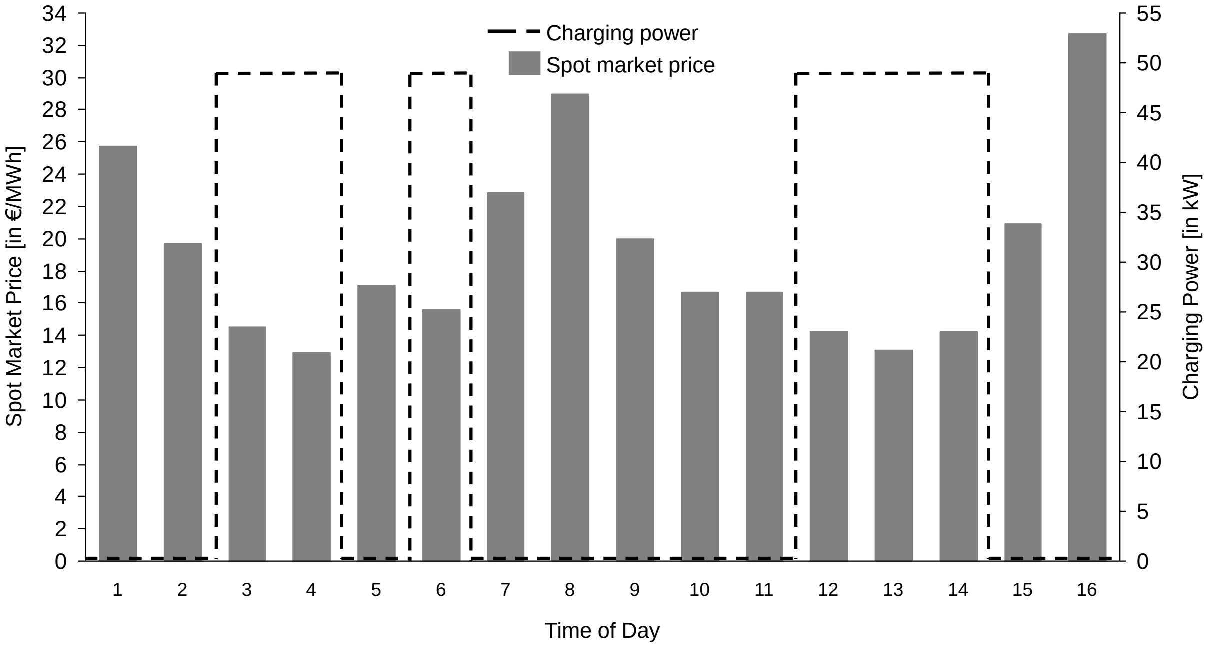

Figure 5: Illustration of the optimization procedure for one battery system on an arbitrary day

The annual charging costs for this DSI program were calculated to be €129,164 using Eq. (5). 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 BAGVs using Eqs. (7) and (8). In the second step, (additional) grid fees were calculated for two further scenarios. In the first scenario, the BAGVs 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 4.

Our pilot case company must be prepared to experience higher annual grid fees, even if the BAGVs' 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 BAGVs by shifting all charging processes of the reference year to the hours with the company-wide lowest demand for electricity (see Section 1.3.2). For the year 2013, the company's peak load (without BAGVs) 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 6, this would have resulted in a peak-load increase of almost 350 kW.

Table 4: Economic assessment of *optimizing the company's load curve*

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

The result of our optimization is illustrated in Figure 7 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.).

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 BAGVs, assuming an increase in peak load can be prevented despite the greater number of BAGVs. The theoretically achievable cost-saving potentials are considerable as up to 80% of annual grid fees (€968,892) could be saved.

1.5 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 5. As explained in Section 1.3.1, the assessment is based on three main sets of criteria: implementation effort, cost, and economic potential.
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.

Table 5: 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

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.net, 2014c). 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 other 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 can 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 BAGVs 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, 2014). 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.

1.6 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 the 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 considered 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.

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