*EVS30 Symposium*
*Stuttgart, Germany, October 9 - 11, 2017*

# Implementation Schemes for Electrified Bus Fleets at Intra-Urban Depots with Optimized Energy Procurements in Virtual Power Plant Operations

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**Abstract**

For the purpose of utilizing electrified bus fleets in metropolitan areas and with regards to provide an active energy management at intra-urban depot, a profound understanding of the transactions between the market entities involved in the charging process is given. Sophisticated charging strategies with energy procurements in joint market operation are presented. Further, the operation procedures and characteristics of an intra-urban depot including the physical layout and utilization of appropriate charging infrastructure are investigated. For the purpose of joint market operations and provision of power system services, a Virtual Power Plant (VPP) is formulated and developed that integrates the capacities of the electrified bus fleet in the power plant portfolio. The proposed optimization model is verified in numerical analysis and the applicability of using the energy capacity of the electrified bus fleet in VPP operations is demonstrated.

## 1 Introduction

The rollout of mobility solution is accompanied by substantial challenges in the transport and energy sector. This includes, for example, the reduction of the total cost of ownership, provision of sufficient charging infrastructures, standardization and regulatory requirements [1,2]. For the purpose of providing an active energy management and sufficient energy supply, a variety of limiting factors has to be taken into account [3], such as the distance traveled, road topology (elevation) and driving behavior (desired speed, acceleration, prevailing traffic conditions, ambient temperature). The physical layout and utilization of appropriate charging infrastructure needs to be considered, as these factors can have a significant influence to enable similar operational deployments as of conventional vehicles with internal combustion engines. With focus on the operation of electrified bus fleets, this requires comprehensive analysis for the determination of network capacities and appropriate solutions for the power supply. Therefore, several optimization techniques for smart charging strategies can be adapted [4–7] to lower the overall energy cost and avoid grid congestion and peak loads caused by charging processes [8]. However, considering the charging load for the energy management and supply, it is necessary to determine the energy demands at a range of spatial and temporal scales. Compared to the existing research, the paper proposes a solution to integrate electrified bus fleets in VPP operations to obtain optimal charging schedules and make use of those additional mobile energy sources for energy market participation and provision of power system services. This is achieved thanks to novel VPP functions that exploit the potential of optimized redispatch solutions through the utilization of these storage capacities. First, section 2 introduces the framework condition for the operational planning and operation of electrified bus fleets. Timetable-based driving behaviors and comprehensive unit models are provided. Section 3 details possible operation procedures for charging processes applicable at intra-urban depots. Then, the charging strategies and the value of the proposed methodology for optimized energy procurements in VPP operations is substantiated in section 4 in numerical simulations. Feasible solutions for the balancing group management and provision of systems services through optimized redispatch measures are presented. Finally, section 5 contains the concluding remarks.

## 2 Framework Conditions and Operational Planning

Addressing the system complexity for the integration process of electrified bus fleets in liberalized energy markets, clear definitions of functional roles and responsibilities are essential. This may include Electric Vehicle Supplier/Aggregator (EVS/A) which collates the energy demand of a number of electric vehicles (EVs) and which is responsible for the maintenance planning, operating data acquisition and management. The EVS/A cooperates with the VPP operator to gain access and visibility across the energy market [9]. Therefore, appropriate charging strategies are negotiated and the commercial conditions defined in advance. Figure. 1 structures the framework conditions of the considered multilateral system.

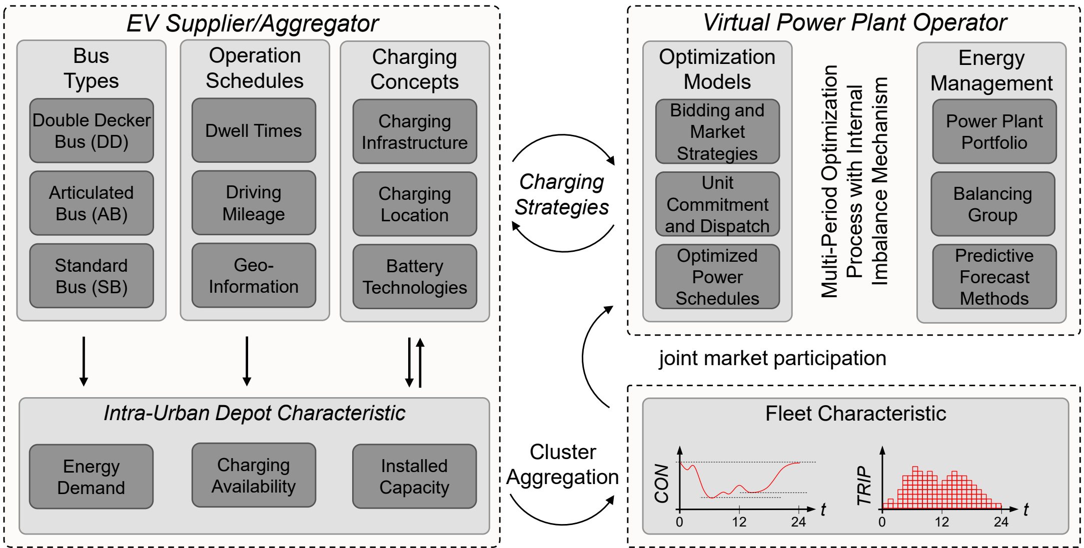



Figure 1: Framework conditions for the integration of electrified bus fleets in the operation scheme of EVS/A and VPP operator.

First, the energy demand for the operation of an electrified bus fleet is determined by the EVS/A. Let $H_{\mathrm{ev}} \in \{1, 2, \ldots, i, \ldots n^{\mathrm{ev}}\}$ denote the total number of considered vehicles. Then, timetable-based operation schedules and field-recorded diesel demands are analyzed and comprehensive unit models developed. Next, the basic characteristics for a layout of an intra-urban depot are investigated, considering the operation schedules and taking into account the spatial availability for charging processes. Internal operational processes, maintenance and service processes are analyzed as this reduces the charging availability. Finally, the required capacity for the charging infrastructure at the intra-urban depot is identified.

The findings reveal significant boundary conditions for the optimization problem of the VPP operator, which incorporates the electrified bus fleet in the energy management of the power plant portfolio.

### 2.1 Modeling Timetable-Based Driving Schedules

To capture the main characteristics of the electrified bus fleet, (1) is applied that assigns different vehicle models $H_{\text{mstor}}$ of mobile storage units, e.g. to represent standard (SB), articulated (AB), and double decker buses (DD).

$$H_{\text{ev}} \supseteq H_{\text{fleet}} \quad \text{, with} \quad \bigsqcup H_{\text{fleet}} = \{(mstor, i) \mid mstor \in H_{\text{mstor}}\ i \in H_{\text{fleet}}\}\,. \tag{1}$$

Each vehicle is matched with timetable-based driving schedules so that the required energy demand for the operation can be estimated and considered in the energy management algorithm of the VPP operator. For simplicity, every trip $trip_n^{\text{ev},m}$ is defined by the departure time at origin $t^{\text{D},O}$, arrival time at destination $t^{\text{A},D}$, and the mileages of driving $m^{OD}$. An example of which is given in Fig. 2. The schematically shown trips of an arbitrary electrified bus fleet define the operation schedule, e.g. for each day of the year.

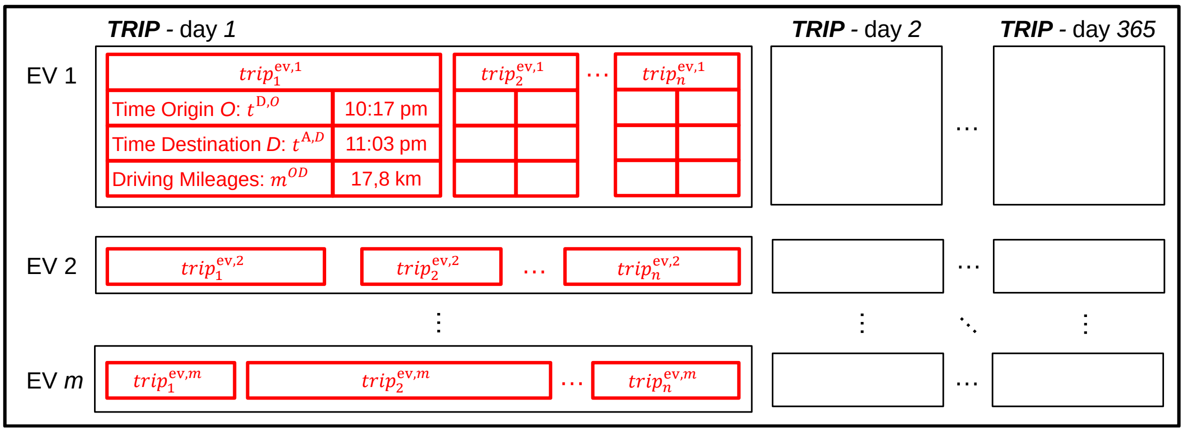



Figure 2: Schematic representation of an operation schedule specified by the departure time $t^{\text{D},O}$ at origin, arrival time $t^{\text{A},D}$ at destination and the mileages of driving $m^{OD}$.

For modeling the driving behavior and determine the required energy demand, operation schedules of specific bus routes of the Berlin metropolitan area are analyzed. Then, the event-oriented trips are converted to timetable-based driving profiles. The time increment $\Delta t$ of the operation schedules is set to 0.25 h which allows to follow typical accounting requirements for the participation in liberalized energy markets and operation of balancing groups, e.g. defined by the European imbalance price system and Association of European Transmission System Operators. Let $H_{\text{ts}} = \{k_{\text{ini}}, \ldots, k_{\text{fin}}\}$ denote the set of discrete time steps $k$, which specifies the planning horizon for the investigated operation processes. Under consideration of the given time increment, the mileages of driving are equally distributed among the corresponding time steps, using a stepwise approximation. The processing yields the discrete variables $k_{k,i}^{\text{D},O}$ and $k_{k,i}^{\text{A},D}$, defining the time-discrete departure and arrival time, while $m^{OD}$ specifies the mileages of driving. The $\boldsymbol{TRIP}$ matrix, as generally expressed by (2), contains the discrete variables.

$$\boldsymbol{TRIP} : H_{\text{ts}} \times H_{\text{fleet}} \to \mathbb{R}^3 \text{ with } \boldsymbol{trip}_{k,i} \mapsto \begin{pmatrix} k_{k,i}^{\text{D},O} \\ k_{k,i}^{\text{A},D} \\ m_{k,i}^{OD} \end{pmatrix} \tag{2}$$

Then, the estimates are aggregated on sub-hourly bases. The compact description of the operation schedule is forwarded by the EVS/A to the VPP operator. As the electrified buses are individually connected to charging infrastructures, the connection matrix $\boldsymbol{CON}$ gives the binary relation of spatial movement and temporal availability for charging/discharging processes. The logical relation is defined by

$$\{con_{k,i} = 1\} \oplus \{\boldsymbol{trip}_{k,i}(3) > 0\} \qquad \forall k \in H_{\text{ts}},\ i \in H_{\text{fleet}}. \tag{3}$$

The element $con_{k,i}$ is equal to 1 if the $i$-th vehicle is connected to the charging infrastructure in the $k$-th time step and 0 otherwise. Subsequent, the total energy demand can be calculated by (4), through the assignment of a specific energy demand for driving $E_{\text{d},k}^{mstor,\text{km}}$.

$$E_{\text{d},k}^{\text{fleet}} = E_{\text{d},k}^{mstor,\text{km}} \cdot \sum \boldsymbol{trip}_{k,i}(3) \qquad \forall mstor \in H_{\text{mstor}},\ \forall k \in H_{\text{ts}},\ \forall i \in H_{\text{fleet}} \tag{4}$$

The specific energy demand is a representative value for different electric vehicle models $H_{\text{mstor}}$. The assigned model attributes are detailed in the following sections.

## 2.2 Energy Equivalence and Bus Type Specific Models

Considering the influence of the ambient temperature and temporal utilization of the electrified buses as reported in [10], the energy demand for driving, auxiliary devices and recuperation has to be identified. This is achieved by using the efficiency method and calculating the energy equivalents as a function of the field-recorded diesel demands. The specific energy demand for driving is assumed to cover the required energy for the traction and energy conversion units. Additional factors, such as the driving behavior, weight loading, rolling resistance and ambient temperature are considered in different operation scenarios. First, the average diesel demand $E_{\text{tank}}^{\text{dBus}}$ per kilometer is calculated by (5), as function of the diesel demand of an entire fleet $V_{\text{d,diesel}}^{\text{fleet}}$, the lower calorific value of diesel $LCV$ and the total mileages of driving.

$$E_{\text{tank}}^{\text{dBus}} = \frac{V_{\text{d,diesel}}^{\text{fleet}} \cdot LCV}{\sum\sum \boldsymbol{trip}_{k,i}(3)} \qquad \forall k \in H_{\text{ts}}, \forall i \in H_{\text{fleet}} \tag{5}$$

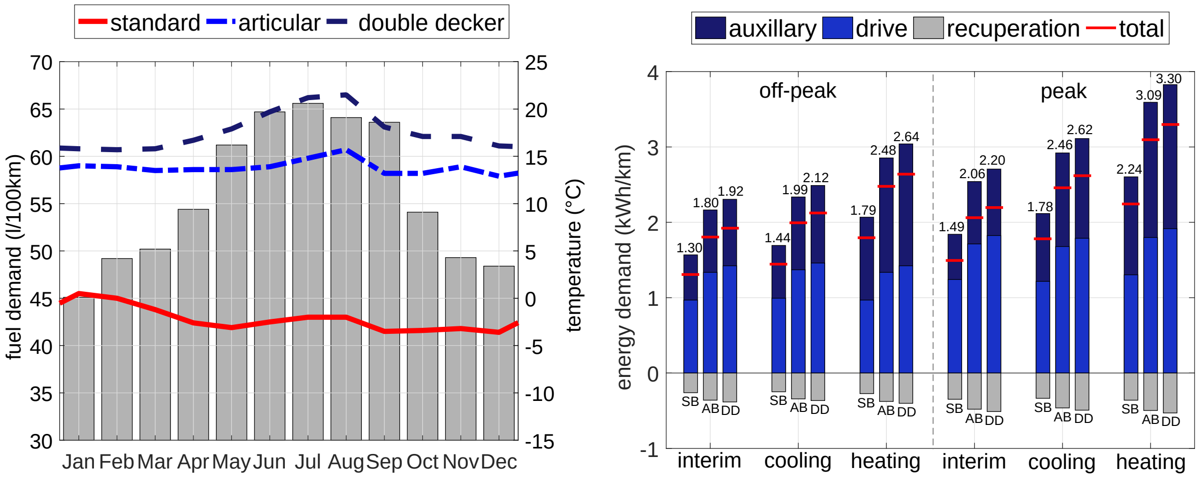
Assuming an annual mileages of driving $\sum\sum \boldsymbol{trip}_{k,i}(3) = 13 \cdot 10^6$ km and a total amount of $V_{\text{d,diesel}}^{\text{fleet}} = 6.5 \cdot 10^6$ l diesel with $LCV = 9.94$ kWh/l, the average diesel demand is $E_{\text{tank}}^{\text{dBus}} \approx 4.95$ kWh/km. Then, the energy demand for driving $E_{\text{d,drive}}^{\text{eBus}}$ is approximated by (6).

$$E_{\text{d,drive}}^{\text{eBus}} = E_{\text{d,drive}}^{\text{dBus}} = E_{\text{tank}}^{\text{dBus}} \cdot \eta_{\text{mot}}^{\text{tank}} \cdot \eta_{\text{drive}}^{\text{mot}} - E_{\text{d,idle}}^{\text{dBus}} \tag{6}$$

The diesel equivalent is multiplied with the tank-motor $\eta_{\text{mot}}^{\text{tank}}$ and motor-drive $\eta_{\text{drive}}^{\text{mot}}$ efficiency. The idling losses $E_{\text{d,idle}}^{\text{dBus}}$ are considered within the approximation. Finally, the energy demand served by the battery $E_{\text{d,bat}}^{\text{eBus}}$ for the traction process is estimated with (7), where $\eta_{\text{mot}}^{\text{bat}}$ and $\eta_{\text{mot}}^{\text{recu}}$ denote the battery-motor and recuperation-motor efficiency, respectively. The offset values correspond to the energy demand for driving, auxiliary components $E_{\text{d,aux}}^{\text{eBus}}$ and the energy $E_{\text{g,recu}}^{\text{eBus}}$ of the recuperation process.

$$E_{\text{d,bat}}^{\text{eBus,km}} = \frac{E_{\text{d,drive}}^{\text{eBus}}}{\eta_{\text{mot}}^{\text{bat}} \cdot \eta_{\text{drive}}^{\text{mot}}} + E_{\text{d,aux}}^{\text{eBus}} - E_{\text{g,recu}}^{\text{eBus}} \cdot \eta_{\text{mot}}^{\text{bat}} \cdot \eta_{\text{mot}}^{\text{recu}} \tag{7}$$

Possible values for auxiliary components are $E_{\text{d,aux}}^{\text{eBus}} \in \{0.6, 0.9, 1.3\}$ kWh/km [10] and for the energy of the recuperation process $E_{\text{g,recu}}^{\text{eBus}} = [20, 40]$ kWh/100km [11]. The chemical, mechanical and electrical efficiency values can be derived from the literature [12–14]. A linear regression model is initialized as a hypothesis concerning the relationship among the specific energy demand, use of auxiliary devices and the ambient temperature. The influence on the energy demand is reflected by using field-recorded demand curves as depicted in Fig. 3a. By applying (5)-(7), and substituting $V_{\mathrm{d,diesel}}^{\mathrm{fleet}}$ in (5) through the values given in Fig. 3a, Fig. 3b shows the obtained energy equivalents for the introduced set of electric vehicles models $H_{\mathrm{mstor}}$.




(a) dBus energy demand

(b) eBus energy demand

Figure 3: Fuel demand of (a) diesel buses (dBus) in accordance to the ambient temperature and (b) approximated energy demands of electrified buses (eBus) summarized for defined operating scenarios.

Table 1 defines the corresponding model attributes. Additionally, the table reports descriptive statistics for the analyzed operation schedules in terms of the weekly mileages of driving and daily energy demand. The assigned energy capacities of 175, 225, 250 kWh refer to the usable battery capacity of electrified buses used in pilot projects [15].

Table 1: Set of unit models $H_{\mathrm{mstor}}$ of electrified buses (eBus) specified by the energy capacity, annual mileages of driving, and specific energy demand.

| unit model | | energy capacity (kWh) | weekly mileage of driving *) (km) | specific energy demand **) (kWh/km) | daily energy demand (kWh) |
|---|---|---|---|---|---|
| standard | SB | 175 | 1,045/1,147/1,469 | 1.30/1.80/2.30 | 245-345 |
| articular | AB | 225 | 1,135/1,231/1,566 | 1.80/2.50/3.10 | 368-508 |
| double decker | DD | 250 | 1,118/1,231/1,500 | 1.90/2.60/3.30 | 385-517 |

*) values refer to lower 25th, median 50th and upper 75th percentile, outliers are excluded

**) indicates low / average / high values of the calculated energy demands.

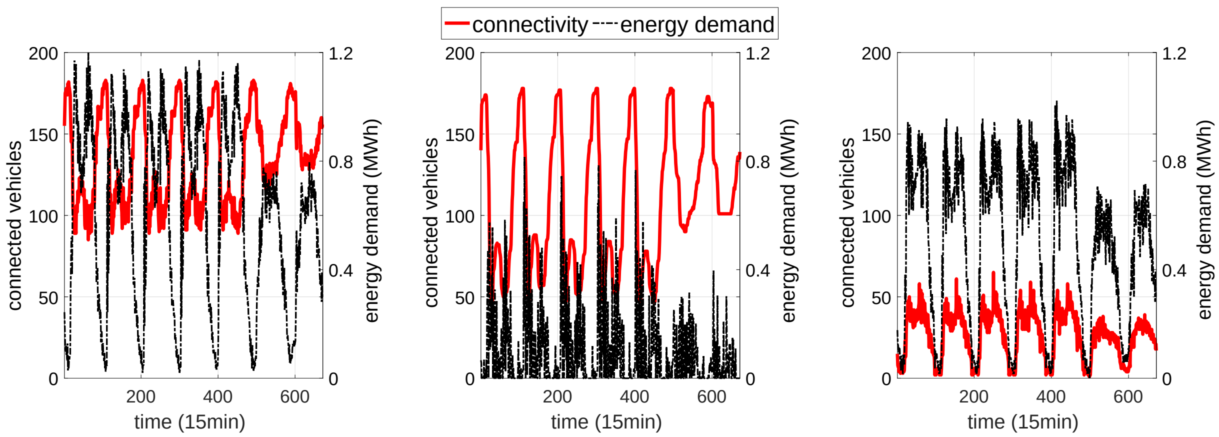
For simplification, four distinct operating scenarios according to [10] are considered. The scenarios represent different changing conditions while varying the ambient temperature, peak and off-peak hours. The peak and off-peak hours derive from the time sequences of the timetabled operation and routing schedules. Figure 3b shows the lower, upper and total values (red line) of the specific energy demand by using (7). In peak hours, for example, there is a higher energy demand as a result of the assumed passenger load and traffic volumes. In heating and cooling mode, the energy demand rises due to the additional operation of auxiliary devices. This includes the operation of cooling and heating units, auxiliary pumps, air compressor and battery cooling.

## 2.3 Charging Concepts and Strategies

With particular focus on the operation of electrified bus fleets several charging concepts are proposed, including depot charging, opportunity charging, in motion charging and battery swapping concepts [16]. In the following elaborations, the depot charging concept combined with opportunity charging is further investigated. While depot charging envisages that the vehicle is charged/discharged during the dwell times in the intra-urban depot, opportunity charging takes place on the route, e.g. at terminal stations, by using automated charging systems (pantograph or induction system). For the determination of the planned energy demand served by 1st-base depot charging and 2nd-base opportunity charging at termini, the total energy demand $E_{\mathrm{d}}^{fleet}$ is separated as follows.

$$\begin{aligned} E_{\mathrm{d}}^{fleet} &= E_{\mathrm{d}}^{fleet,\mathrm{1st}} + E_{\mathrm{d}}^{fleet,\mathrm{2nd}} \\ &= \underbrace{\boldsymbol{CON}^{\mathrm{1st}} \cdot P_{\mathrm{r}}^{\mathrm{1st}} \cdot \eta^{mod} \cdot \Delta t^{mod,\mathrm{1st}}}_{\text{1st-base charging}} + \underbrace{\boldsymbol{CON}^{\mathrm{2nd}} \cdot P_{\mathrm{r}}^{\mathrm{2nd}} \cdot \eta^{mod} \cdot \Delta t^{mod,\mathrm{2nd}}}_{\text{2nd-base charging}}. \end{aligned} \tag{8}$$

The corresponding amount of connected vehicles is given by $\boldsymbol{CON}^{\mathrm{1st}}$ for 1st-base and $\boldsymbol{CON}^{\mathrm{2nd}}$ for 2nd-base charging. The temporal availability for the charging/discharging processes is denoted by $\Delta t^{mod,\mathrm{1st}}$ and $\Delta t^{mod,\mathrm{2nd}}$, respectively. To represent different charging infrastructures and charging modes, the charging/discharging efficiency $\eta^{mod}$ is taken into account. In the simulation, for simplification, the value is assumed to be equal and set constant. The charging power $P_{\mathrm{r}}^{\mathrm{1st}}$ denotes the contracted charging capacities at the intra-urban depot within variable charging rates. Due to the limiting charging time at termini, the charging capacity $P_{\mathrm{r}}^{\mathrm{2nd}}$ is assumed to be fix and not part of the optimization process. This is comparable with non-controlled charging processes with maximum charging power. As an example, Fig. 4a shows the total energy demand, which is separated into the parts for 1st-base and 2nd-base charging locations in Fig. 4b and Fig. 4c, respectively.




(a) total (b) 1st-base (c) 2nd-base

Figure 4: Energy demand of an (a) arbitrary electric fleet separated by energy demand occurring at (b) 1-st base charging at depot and (c) 2nd-base charging at termini.

The connectivity of the aggregated profiles is indicated by the red solid lines while the black dashed lines denote the corresponding energy demands. The elaborations indicate that different charging concepts and strategies as a function of the expected level of connected vehicles and the total energy demand are required.

# 3 Operation Procedures and Depot Characteristics

Depending on the charging strategy, operation procedures and charging processes may differ. Therefore, charging/discharging possibilities are identified by analyzing the operation processes at an intra-urban depot. An example of which is given in Fig. 5 that schematically shows an activity diagram of the operation processes. Generally, these activities are coordinated by the EVS/A which uses a depot control center for automatization purposes and for interaction with the VPP operator. The activities are further differentiated by the employee responsibilities for bus driver, service and workshop staff.

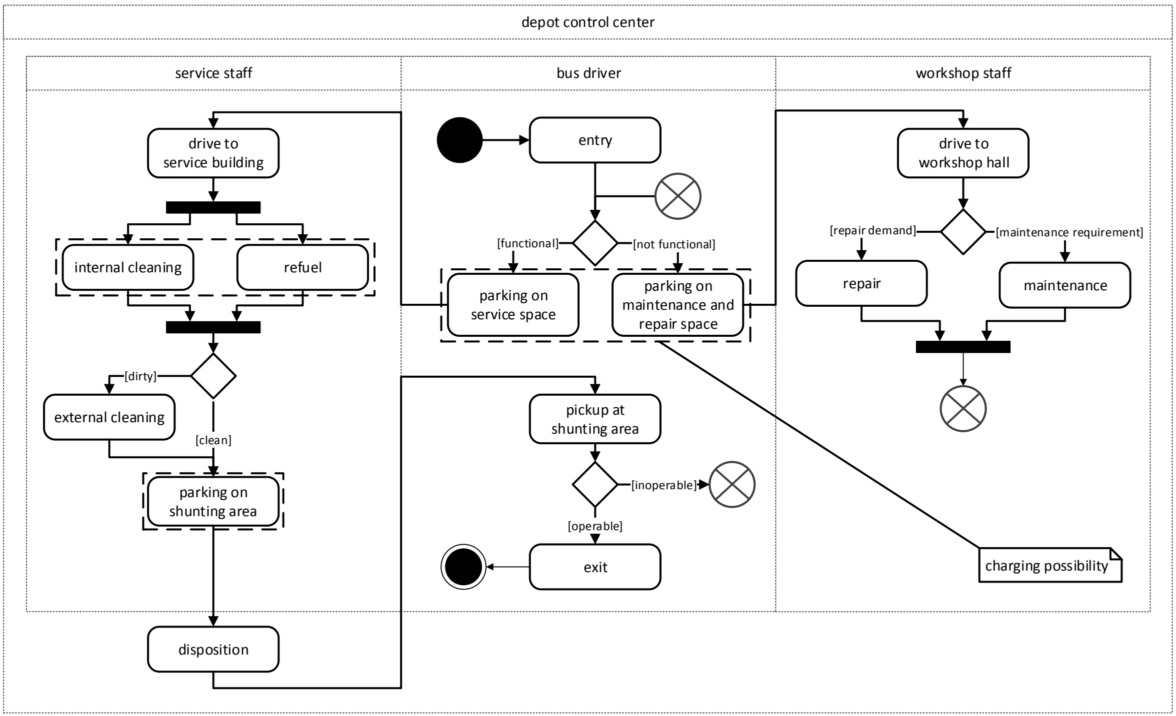
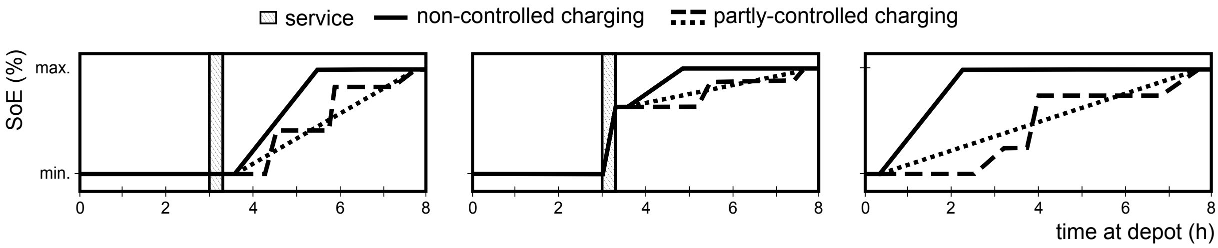



Figure 5: Operation processes coordinated by the EVS/A and highlighted charging possibilities at an intra-urban depot.

Throughout the processes, three charging possibilities are identified where generally sufficient time and space are available. These are highlighted with dashed rectangles and further discussed in the following. First, after entering the intra-urban depot, the buses are checked for functional capability and then parked on different waiting areas. Afterwards the service and workshop staff, usually an external service provider, picks up the buses for a required repair, maintenance or cleaning and refueling. Each bus is required to pass through the daily service process which lasts about 10-15 min. The remaining operation processes are flexible in time and thus also the associated charging possibilities. Since the repair or maintenance path is characterized by unplanned faults of single buses, additional charging possibilities are not explicitly considered here. The second last operation process denotes the parking on a shunting area with sufficient time for charging/discharging processes. After the disposition, the buses are ready for the next operation and can leave the intra-urban depot.

## 3.1 Analysis of Operation Processes and Schedules

At the time of possible charging processes, Fig. 6 schematically introduces different charging scenarios which are further investigated. Scenario 1 maintains the processes at the intra-urban depot as described before. Charging is only possible after the service, when the buses are parked on the shunting area. Thus it appears, that the time a bus is waiting for service reduces the possible charging time. Scenario 2 is an extension of the previous scenario. It is assumed that fast charging during the service is possible. This is comparable with conventional refuel processes when considering vehicles with internal combustion engines. Scenario 3 provides for an adjustment of the operation processes. Since usually buses are cleaned daily only from the inside, this process can take place outside the service hall. Thus, a wait on the service space will be unnecessary and a bus can be parked directly on the shunting area after arrival and can be charged.




(a) scenario 1 (b) scenario 2 (c) scenario 3

Figure 6: Charging process considering the introduced charging scenarios.

Each charging process of the presented scenarios can basically be designed individually. For all scenarios, a distinction is made between non-controlled and partly-controlled charging. Non-controlled charging represents the simplest implementation. Once the bus is connected to the charging infrastructure, the charging process immediately starts with the maximum possible charging power and lasts until the vehicle gets disconnected or the battery is fully charged. However, partly-controlled charging uses the entire dwell time at the intra-urban depot and applies lower but also constant charging power. In accordance to the considered scenarios, there are differences when considering the connectivity of the electrified bus fleet which is shown in Fig. 7.

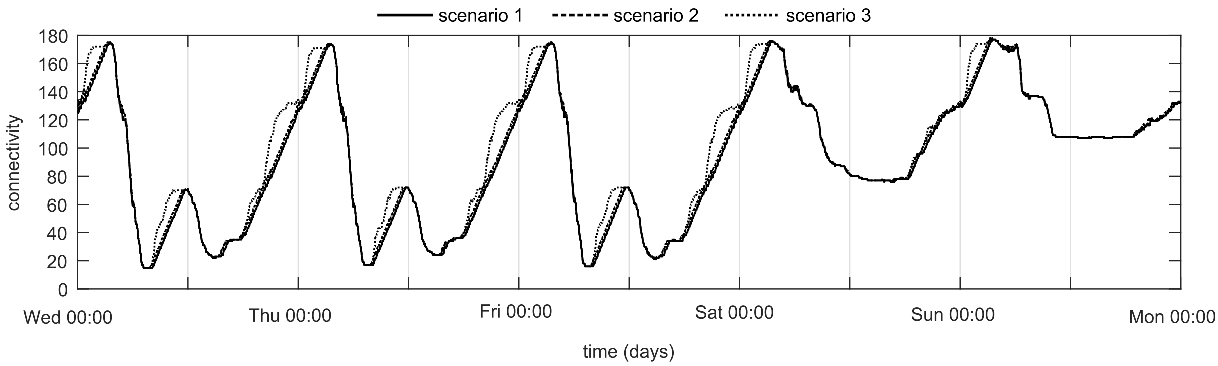



Figure 7: Connectivity of buses on selected weekdays and weekend.

As can be seen in Fig. 7, there are several peaks in the connectivity profile, e.g. after midnight due to the main operating pause of the fleet and small peaks at noon. The latter is a result of returned buses which are additionally used for the rush hour in the morning. Compared to the weekdays, the connectivity of the buses rises on the weekend, especially during the day, as the overall utilization of the electrified bus fleet is lower. The lowest connectivity can be observed in scenario 1, since the idle time before the service reduces the possible charging time. The connectivity of scenario 2 is comparable to scenario 1, as only the service time is additionally used. The highest connectivity is given in the scenario 3, because no congestion queue appears during the cumulated return of the buses to the intra-urban depot. At the weekend there is a marginal difference, because on the one hand fewer buses are in operation during the day and on the other hand, the time of the end of operation is stretched.

### 3.2 Charging Infrastructure and Process

For the design of the charging infrastructure and the determination of possible charging profiles, a total number of 193 buses is considered and the charging process as introduced with scenarios 1-3 are further investigated. The analysis uses the unit model attributes specified in Table 1. The service process, as shown in Fig. 5, is applied and assumed to be processed by using the FirstInFirstOut method. The amount of required charging points results the maximum connected vehicles according to Fig. 7 to serve the energy demand calculated by (8) at the intra-urban depot. As can be seen, only 178 buses are simultaneously connected. For the given time period of 24 hours, the charging capacity of each charging point is determined. Scenario 1 uses charging points with $P_{\mathrm{r}}^{\mathrm{1st}} = 125$ kW each. In scenario 2 charging points with $P_{\mathrm{r}}^{\mathrm{1st}} = 75$ kW as well as 4 additional charging points with $P_{\mathrm{r}}^{\mathrm{1st}} = 300$ kW are applied. The number of the additional charging points is derived from the maximum available service points. The charging power of each charging point in scenario 3 is $P_{\mathrm{r}}^{\mathrm{1st}} = 75$ kW. A higher charging power per charging point is necessary in scenario 1 since the potential charging time is lower compared to scenario 3. By utilizing fast charging in scenario 2, part of the required energy can be already supplied during the service. Hence, the charging power of the remaining charging points can be equally assumed to scenario 3. Figure 8 provides the results obtained by using these conditions for the charging processes.

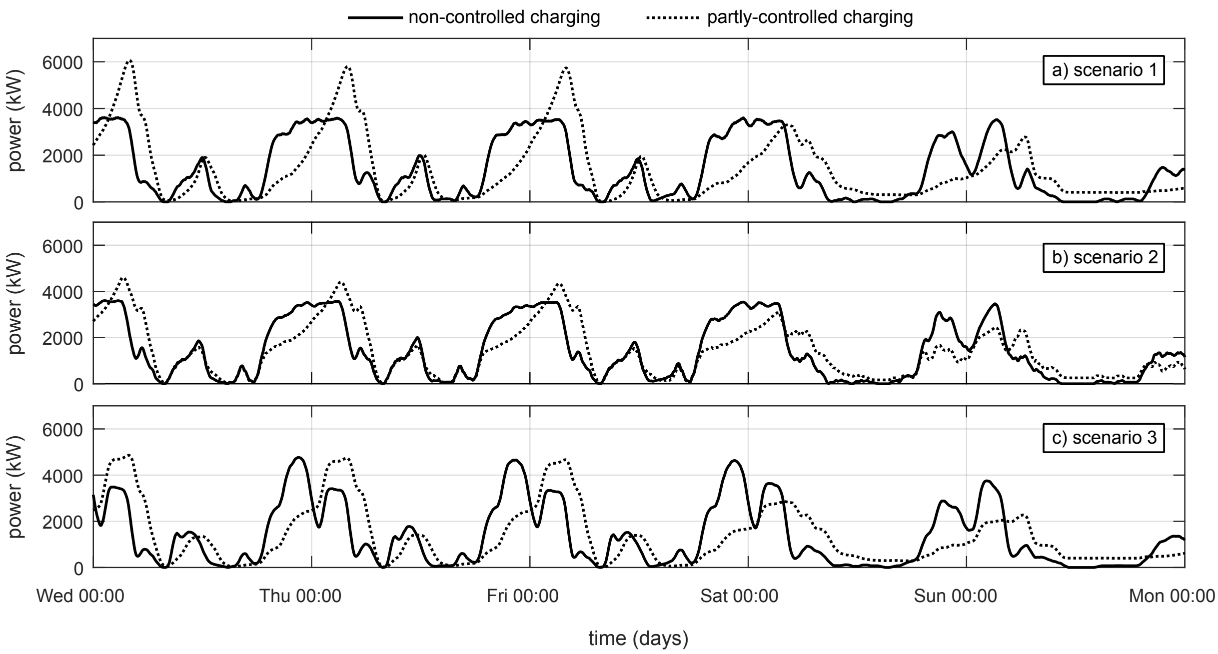



Figure 8: Charging profile obtained by applying non-controlled and partly-controlled charging.

The charging profiles of the first two scenarios show marginal deviations for the non-controlled charging. Through the successive operation sequence in the service an approximately even charging power can be obtained, e.g. on workdays in the evening and night hours. As can be seen in all three scenarios, partly-controlled charging does not necessarily reduce the charging loads and overall peak loads. The energy demand is mainly moved into the night hours. Only on weekends partly-controlled charging leads to a more even distribution of the charging power. To provide more sophisticated charging strategies, the use of an active charging management system is proposed that also consider the concept of smart charging and vehicle-to-grid services [17, 18]. A solution of which is given by the offered services of the VPP operator. Possible enhancements are discussed in more detail in the following section.

# 4 Optimized Energy Procurements in VPP Operations

The VPP operator integrates the electrified bus fleet within the operational planning of the power plant portfolio. Beside interoperable integration of information and communication technology [19], reliable and secured online measurements as well as current market and forecast data are considered with distinct forecast horizons $fh \in \{24\text{h}, 1\text{h}, 0.25\text{h}\}$. The classification of the forecast horizons is derived from the trading period and clearing sequence of joint market operations in day-ahead and intraday markets. Through the breakdown of generation and load schedules higher flexibilities in market tradings can be achieved [20]. Further, the VPP operator integrates shorter dispatch intervals to eliminate market framework barriers for the participation of renewable energy sources. It is shown how the VPP operator determines optimized charging schedules within a multi-period optimization process. This VPP service is provided to the EVS/A which buys the electricity and responds to requests for the adjustment of charging patterns. Based on the intra-urban depot characteristic discussed in the previous chapter, Table 2 specifies the composition of the electrified bus fleet and gives additional information of the power plant portfolio. Let $H_{\text{typ}}$ be the set of unit types, consisting of wind power plant (wind ), photovoltaic power plant (pv), combined heat and power plant (chp), electric vehicles (ev), and industrial load units (ind).

Table 2: Composition of the power plant portfolio, specified by the included number of vehicles, daily energy demand $E_{\text{d}}^{fleet,1\text{st}}$ for 1st-base charging assessments, and rated energy capacity $E_{\text{r}}^{fleet}$ of the electrified bus fleet.

| fleet composition | | | | $E_{\text{d}}^{fleet,1\text{st}}$ | $E_{\text{r}}^{fleet}$ |
|---|---|---|---|---|---|
| total | SB | AB | DD | (MWh) | |
| 193 | 53 | 103 | 37 | 10.59 | 41.53 |
| installed capacities of generation, load and storage units (MW) | | | | | |
| total | wind | pv | chp | ev | ind |
| 25 | 6 | 2.5 | 1 | 14.5 | 1 |

First, the economic efficiency and determination of optimized charging profiles is investigated. Then, the potentials for offering optimized redispatch measures are assessed as part of extreme condition tests.

## 4.1 Implementation Model and Mathematical Formulation

The introduced unit models given in Table 1 are assigned with the analyzed timetable-based driving schedules and transferred into boundary and constraint conditions in the optimization model of the VPP operator. The boundary conditions are reflected by means of $\boldsymbol{TRIP}$ and $\boldsymbol{CON}$ matrices handed over from the EVS/A for the prediction of optimized power schedules. The optimization problem combines the optimization variables given by the power dispatch $P_k^{typ}$ of all units and unit types considered in the power plant portfolio as well as the contracted market biddings $\tilde{P}_{\text{k}}^{em}$. The VPP operator applies charging strategies that aims to minimize the variable cost and the relative gross profit in EUR/kWh. The cost optimized objective function is given by

$$\min \sum -\Big( (-P_{\text{d},k}^{typ} \cdot \varpi_{\text{vc}}^{typ} - P_{\text{g},k}^{typ} \cdot \varpi_{\text{vc}}^{typ}) - (\tilde{P}_{k,fh}^{em} \cdot \varpi_{k,fh}^{em}) \Big) \cdot \Delta t \quad \forall \, typ \in H_{\text{typ}} \tag{9}$$

which is subjected to the operating ranges $P_{\text{g,min}}^{typ} \leq P_{\text{g},k}^{typ} \leq P_{\text{g,max}}^{typ}$ and $P_{\text{d,min}}^{typ} \leq P_{\text{d},k}^{typ} \leq P_{\text{d,max}}^{typ}$ for power generation and demand, respectively. In case of mobile storage units, the constraint formulation is

$$y_k^{stor} \cdot P_{\text{d,max}}^{stor} \leq P_k^{stor} \leq (1 - y_k^{stor}) \cdot P_{\text{g,max}}^{stor} \tag{10}$$

The binary variables $y_k^{typ}$ specify the operation mode of the distinct units. The available energy capacity values derive from (11) as a function of the assigned rated energy capacity of the define unit models in Table 1.

$$E_{k+1}^{mstor} = \begin{cases} E_k^{mstor} - P_{\mathrm{d},k}^{mstor} \cdot \eta^{\mathrm{mod}} \cdot \Delta t, & \text{charging mode} \\ E_k^{mstor} - P_{\mathrm{g},k}^{mstor} \cdot \frac{1}{\eta^{\mathrm{mod}}} \cdot \Delta t, & \text{discharging mode} \end{cases} \tag{11}$$

The dispatched power is bounded by the state of energy limits $SoE_{\mathrm{min}}^{mstor} \leq SoE_{k+1}^{mstor} \leq SoE_{\mathrm{max}}^{mstor}$, with $SoE_{k+1}^{mstor} = \frac{100\% \cdot E_{k+1}^{mstor}}{E_{\mathrm{r}}^{mstor}}$. The power balance $P_{\mathrm{g},k}^{\mathrm{VPP}} = P_{\mathrm{d},k}^{\mathrm{VPP}}$ is calculated in each time step $k$. The terms are specified as follows

$$P_{\mathrm{g},k}^{\mathrm{VPP}} = P_{\mathrm{g},k}^{\mathrm{pv}} + P_{\mathrm{g},k}^{\mathrm{wind}} + P_{\mathrm{g},k}^{\mathrm{chp}} + (1 - y_k^{\mathrm{fleet}}) \cdot P_{\mathrm{g},k}^{\mathrm{fleet}} + P_{\mathrm{IM},k}^{em} \tag{12}$$

$$P_{\mathrm{d},k}^{\mathrm{VPP}} = P_{\mathrm{d},k}^{\mathrm{ind}} + y_k^{\mathrm{fleet}} \cdot P_{\mathrm{d},k}^{\mathrm{fleet}} + P_{\mathrm{EX},k}^{em}. \tag{13}$$

where $P_{\mathrm{g},k}^{\mathrm{VPP}}$ denotes the total power generation and $P_{\mathrm{d},k}^{\mathrm{VPP}}$ the total demand of the power plant portfolio.

### 4.2 Computational Study and Dispatch Results

The mixed-integer linear programming problem is solved by using a branch-and-cut method with simplex algorithm, offered by the MATLAB extension of ILOG CPLEX optimization solver. Figure 9 provides the obtained real-time schedules of the power plant portfolio separated by unit types for each time step.

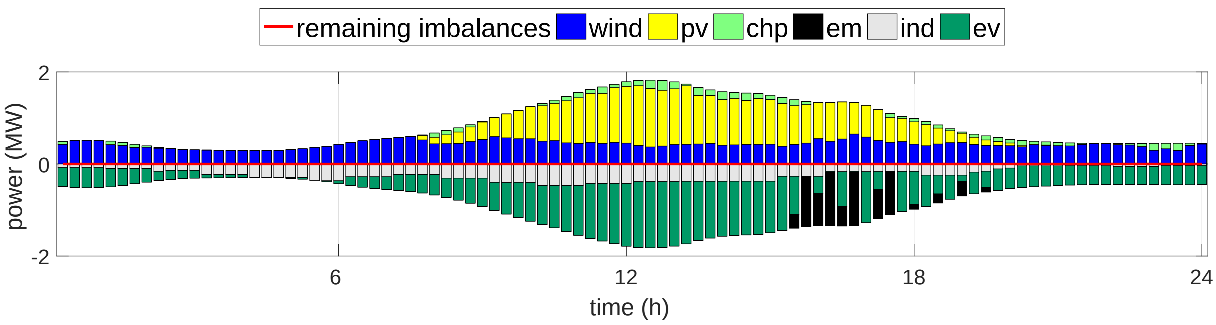



Figure 9: Optimized dispatch of the power plant portfolio separated by unit types.

The charging power is adjusted for each time step in the multi-period optimization processes in day-ahead and intraday market operation. As a result, the additional constraints given by the temporal availability and energy demand profiles of electrified bus fleets are fully reflected in the optimization model. Optimal charging solutions are determined on basis of the examined timetable-based driving profiles. Additionally, a reduction of the peak loads is achieved compared to application of partly-controlled charging. Further, the power provided by renewable energy sources can be optimally utilized for charging processes.

In the next step, the potential for the provision of systems services is further investigated in extreme condition test. Therefore, several positive and negative control reserve requests of the system operator are investigated with 0.5 MWh (case 1), 1 MWh (case 2) and 2 MWh (case 3). The VPP operator reacts with optimized redispatch measures and calculates an alternative charging schedule. Figure 10 shows the dispatch pattern with and without considering the reserve power requests. In Fig. 10a-Fig. 10c positive control reserve requests are tested, while analogously introducing negative control reserve requests in Fig. 10d-Fig. 10f.

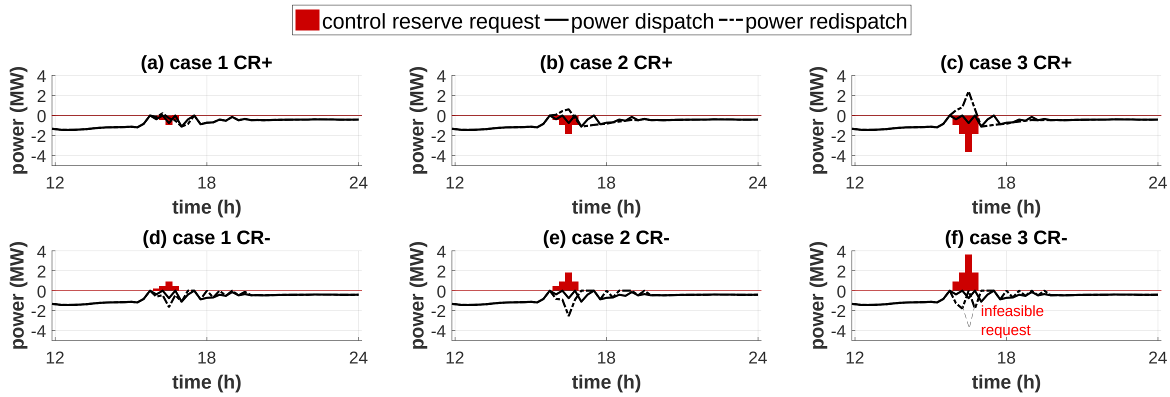
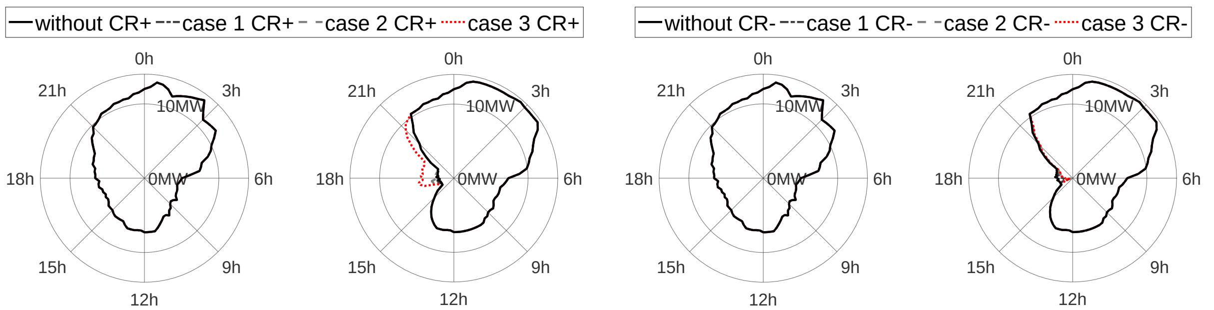


Figure 10: Response on positive and negative reserve power requests and performed redispatch measures.

The results show, that every positive control reserve request can be fulfilled through utilization of available reserve capacity provided by the electrified bus fleet available at the intra-urban depot. While this also applies for the first scenarios of negative control reserve requests, the peak request within the 2 MWh scenarios, as highlighted in Fig. 10f, cannot be fulfilled due to insufficient available reserve capacity. Thus, the request of the system operator is denied. In Fig. 11a and Fig. 11c the available positive and Fig. 11b and Fig. 11d the negative reserve of the electrified bus fleet including the possible responses are illustrated.



(a) positive (b) negative (c) positive (d) negative

Figure 11: Available (a), (c) positive and (b), (d) negative reserve capacity of the electrified bus fleet including the response on (a)-(b) positive and (c)-(d) negative reserve power requests.

As can be seen in the results of the 2 MWh negative control reserve requests in Fig. 11d, the available negative reserve capacity is completely reduced to zero. The available positive control reserve requests remains the same for every applied control reserve request. This effect is due to the intended charging strategy keeping the electrified bus fleet at high state of energy ranges, ensuring a high readiness for use of the electrified bus fleet. The simulation results prove that the proposed optimization model can properly follow the requests of the power system operator and provide a possible solution for coordinated redispatch measures while fulfilling the contract position with the EVS/A.

# 5 Conclusion

The paper addresses the specific challenges and opportunities presented by the electrification of bus fleets and presents comprehensive simulation frameworks for multilateral systems operated by different market entities involved in the charging process. By the identification of possible charging/discharging possibilities in the operation procedure at an intra-urban depot, the impact on the overall load profile caused by charging processes of the electrified bus fleet is specified. More sophisticated charging strategies are developed and substantiated in numerical simulations. It is shown that the mobility needs of EVS/A can be fulfilled through the provision of optimized energy procurements of the VPP operator. The optimized charging strategies allow reducing the peak loads at the intra-urban depot while utilizing renewable energy sources for charging processes. Further, the investigations show that electrified bus fleets are capable to provide control reserve capacity for system services through the application of optimized redispatch measures offered by the VPP operator.

## Acknowledgments

This work was supported in part by the Federal Ministry of Education and Research of the Federal Republic of Germany (BMBF) through Research Campus Mobility2Grid - Sustainable Development of Energy and Mobility by Coupling Intelligent Grids and Electromobility (MOBILITY2GRID) funding.

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