Grid Integration in the Context of Public Transport Electrification

– Pre-Print –

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Abstract. The transition of the public transport sector towards a zero emission pathway is a key challenge to address the climate crisis and air quality issues. Bus networks are currently using mainly Diesel vehicles to fulfill the mobility needs of the population. The simple replacement of conventional busses with battery electric models is not feasible in most cases. In this paper, a methodology is presented to choose a technology (depot or opportunity charging, hydrogen/fuel cell) fitting the local circumstances. We find that the grid integration of the charging infrastructure is a main criterion when deciding for a strategy. The challenges and possibilities of grid connection for depot and opportunity charging are presented. Our results consequently show that battery storages and renewable energy power plants can be beneficial and cost effective in the context of energy systems for high power charging stations. In addition, options for synergies with other fleet operators are discussed and the grid integration process of distribution system operators (DSOs) with fleet operators is analyzed based on the legislative framework.

Keywords: Public transport, grid integration, energy system.

1 Introduction

In 2016, the German government passed their long-term plan to target climate protection. This “Klimaschutzplan 2050” sets the main goal to reduce greenhouse gas emissions by 55 % until 2030 compared to 1990 [1]. Fig. 1 shows the target values for each sector.

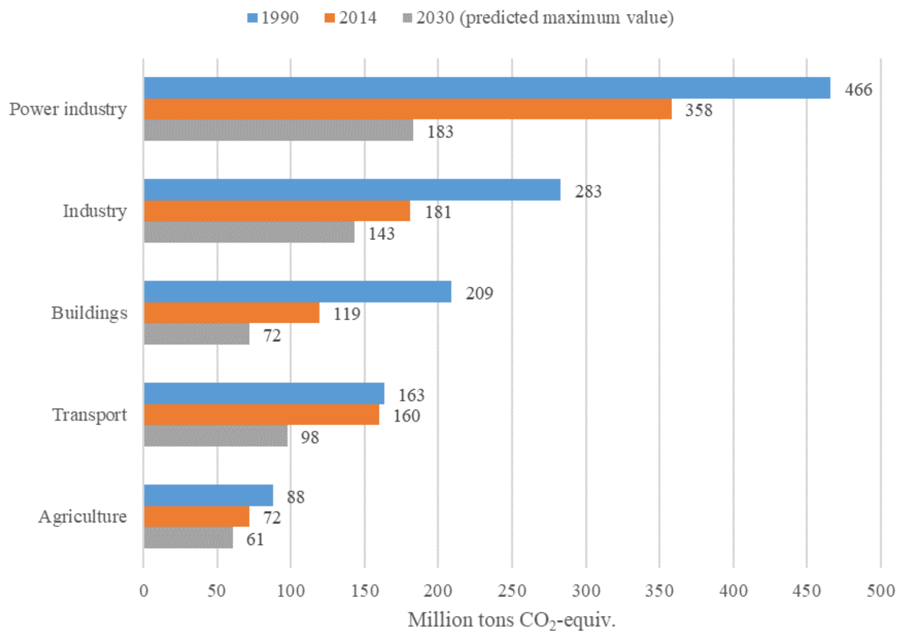

Fig. 1. Sector goals for 2030 stated in the Climate Protection Plan 2050 [1]

The transport sector is the only sector where the emissions of 2014 are nearly identical compared to 1990. The transformation of the transport sector is a key challenge to address the climate crisis and air quality issues. The European Union took action and released the Clean Vehicle Directive, setting quotas for the future purchases for vehicles owned and used by public institutions. This directive sets the required percentage of zero emission and clean vehicles for future purchases, starting August 2021. By transferring the directive into national law, transport operators are facing the challenge to include electric vehicles in their operations. For buses, 45% of all new purchases starting 02.08.2021 have to be clean vehicles (H_2, PHEV, BEV, Gas (CNG, LNG, Biomethan, LPG), Biofuels, Synthetic fuels), including 22.5% of them zero emission vehicles (no combustion engine, <1g CO_2/kWh) [2].

In addition to the European Directive, local governments developed their own strategies to tackle climate change. In Berlin, the Senate released the “Berliner Mobilitätsgesetz”, setting the frame for mobility standards in the coming years [3]. On that basis, the Berlin bus operator BVG has to operate their entire bus fleet of currently 1500 buses with zero emission vehicles by 2030. Within this framework, the BVG is testing articulated electric buses with opportunity charging on the line 200 in the scope of the funded project E-MetroBus[1]. Reiner Lemoine Institute (RLI) and the Technical University Berlin are partners in this project. The RLI is studying the potential of charging strategies to enable up to 100 % electrification of the bus network. The research is focused on the case study Berlin but findings will be applicable to other cities and areas as well.

2 Electrification strategies

The challenge for the BVG and other bus operators is that a simple replacement of conventional buses with battery electric models is not realizable in most cases. This is due to the limited range of internal battery storage and the costs of charging infrastructure in addition to the investment costs of new vehicles. The chosen technology for electrification (depot or opportunity charging, hydrogen/fuel cell) has to fit the local circumstances and adjustments in schedules as well as staff deployment. In the context of the research project, we developed a methodology to identify feasible technologies for individual bus networks. Fig. 2 shows the methodology as an iterative approach.

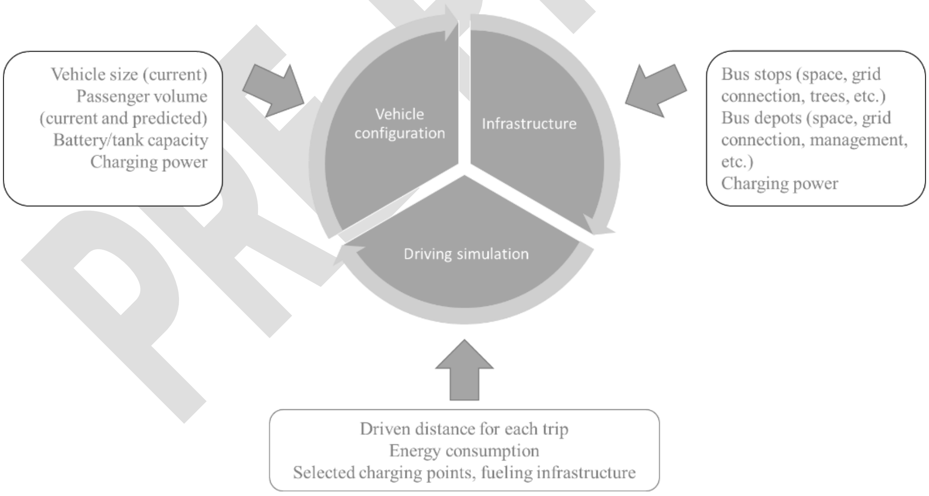

Fig. 2. Methodology of the process to identify suitable electrification strategies

First step is a detailed analysis of the given bus network, consisting of information about the schedule, vehicles and locations. The schedule analysis results in data of each line, representing the distance driven (in km), the break time at end of the line stations (in minutes) and the energy consumption (in kWh/km).

[1] https://e-metrobus.berlin/

Current vehicle sizes, passenger volumes (current and predicted) and specific line requirements (some bus types are not feasible for every line due to height or length restrictions at stations) are results of the vehicle analysis. The locations (bus depots and end of the line stations) are evaluated for their capability of installing charging infrastructure. This includes information of available grid connection levels and specific conditions such as existing vegetation etc.

The data from the three analysis restrict the possible technologies for the given bus network due to limits for vehicle configuration, infrastructure and energy consumption. The range of possibilities is input for the iterative process. Each run a technology is selected with a suitable vehicle configuration (battery capacity and consumption) and charging infrastructure is assumed on different stations and depots. The driving simulation of every line in the network shows the feasibility of the selected scenario. This process goes through all possible solutions. The result is the technology and configuration with the best fit for the entire network. Also a mix of different technologies is a feasible solution, e.g. depot charging for lines with lower daily driving distances and opportunity charging for the rest of the lines.

3 Grid integration – public transport

In a next step, the grid integration of the identified scenarios is analyzed. The requirements of grid connection levels differs between depot and opportunity charging.

3.1 Depot charging

Depot charging usually uses power chargers up to 150 kW. It is applied to charge a high number of buses at the same time and in a single location, which results in challenges for the grid. In a theoretical scenario that all buses use depot charging in Berlin, the power demand is concentrated on less than ten locations throughout the city. Each depot serves up to 200 buses, which require charging. The result is a very high simultaneity of charging events that leads to high power peaks for the grid. The advantage of depot charging from a grid operator point of view is that the charging time of the buses (usually overnight) is two to eight hours in most cases. Long standing times are a great possibility to integrate grid-serving charging management. This flexibility offers chances for the grid operator to shift charging events of buses from time slots with high grid loads to more grid serving periods. The bus operator has the possibility to expand the charging time to the full standing time with the benefit of lowering the required maximum power level for the charging event. Both options require good planning and intelligent digital solutions to manage the process but are beneficial in comparison to an uncoordinated charging strategy. Uncoordinated means that buses are connected to the charger immediately after entering the depot and then charged with the maximum available power until a full charge is reached. The charging strategy that is used at a bus depot mainly influences the impact on the grid.

3.2 Opportunity charging

In contrast, opportunity charging has other requirements and possibilities for grid integration. The charging stations are distributed over several locations (end of the line stations) throughout the bus network and mainly use high power chargers (HPC). In the context of the project E-MetroBus, the HPC are equipped with 450 kW and the buses have only a few minutes of charging time. Results of the analysis of the entire BVG network show that a complete conversion of all lines to opportunity charging at end of the line stations requires 80% of the stations to be equipped with HPC. For the grid operator this results in 357 HPC locations with high power peaks in short time periods with basically no flexibility to change charging times or power. One way to reduce the impact on the grid is the implementation of stationary battery storages at the stations to buffer the high peaks and enable lower grid connection levels.

The HPC can be integrated into the electric grid on different levels. Fig. 3 shows the six grid connection types that are used for the energy systems analysis in the project. The numbering of the types describe increasing power outputs from type I, a regular house connection with an output of 30 kVA, to type VI, a high voltage connection that typically supplies loads of 20 MVA and above. Table 1 shows a detailed description of the different grid connection levels.

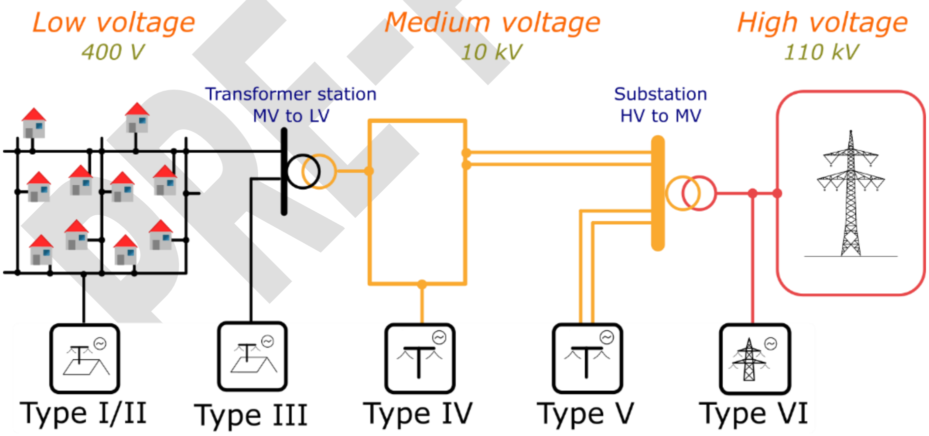

Fig. 3. Grid connection types for high power chargers

Table 1. Grid connection types with voltage levels and maximum power output (data based on interviews with grid operators)

Grid connection type	Description	Voltage Level	Maximum power output in kVA
I	House connection	Low voltage (LV)	30

II	Low voltage grid	Low voltage (LV)	100
III	Transformer station	Low voltage (LV)	200 - 540
IV	Medium voltage grid	Medium voltage (MV)	1000 - 3000
V	Substation	Medium voltage (MV)	5000 - 12000
VI	High voltage grid	High voltage (HV)	above

While connection types in lower voltage levels are usually faster to implement and have lower initial costs, the electricity costs are higher due to increased grid charges. In higher voltage levels, the customer also has to operate the transformers needed for low voltage supply behind the grid connection point, which increases complexity, required space and operating costs of the local energy system. A challenge in the planning of grid connections is that the maximum power output depends on the degree of capacity utilization of the feeder system. It can therefore vary within one connection type depending on the exact location of the planned connection and over time. This information normally is only available to the grid operator. The analysis of the charging infrastructure for buses therefore takes the advantages and disadvantages of different grid connection types into account. An adapted charging strategy or the incorporation of an energy storage system can for example facilitate the choice of a different connection type for a specific problem.

The RLI uses the open-source simulation tool SMOOTH[2] to identify the required grid connection levels for electrified stations or depots. Each considered station is modelled and simulated with this tool. The model includes the charging demand of the buses at the station, the grid connection, a photovoltaic (PV) power plant and a stationary battery storage. The potential for PV power generation is analyzed within the project for all BVG stations in Berlin with available roof area. The results of the energy system simulation for one exemplary station is described below.

Energy system simulation

In the analyzed scenario for one exemplary station, the HPC charging power is set to 450 kW and the buses are assumed to charge during their entire standing time at the stations at the end of the line. Fig. 4 shows the generated power load curve of the station considering the given assumptions.

2 https://github.com/rl-institut/smooth

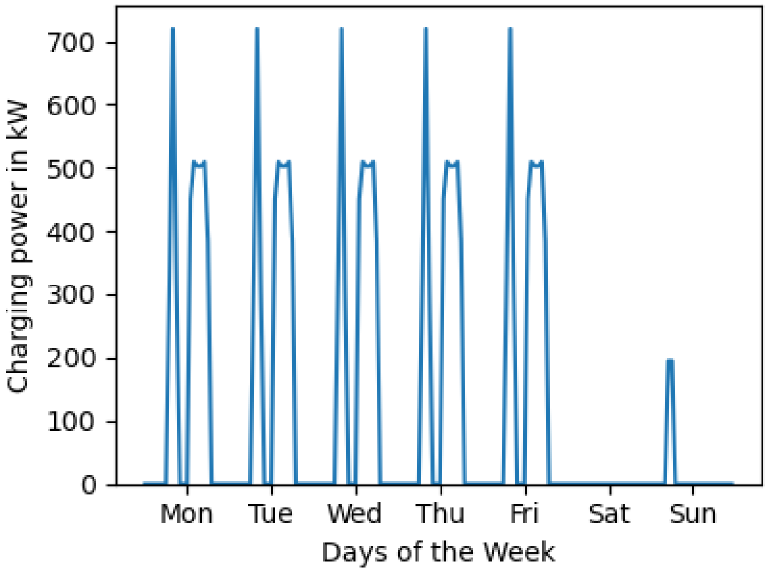

Fig. 4. Power load curve of one exemplary end of the line station in Berlin, charging power 450 kW, buses are assumed to charge during their entire standing time

Several energy systems are capable to meet these demands. Table 2 shows the assumptions for the simulation and optimization of the energy system. With these assumptions, five different energy systems (ES I - ES V) were modelled, optimized and analyzed regarding their technical and financial fitness. Fig. 5 shows the different energy systems.

Table 2. Assumption for the energy system simulation and optimization for one exemplary station

Distance to MV (10 kV) grid	300 m
Available capacity for MV grid connection	> 900 kW
Distance to LV (400 V) transformer station	100 m
Available capacity for LV grid connection	540 kW
PV power plant potential	69 kWp

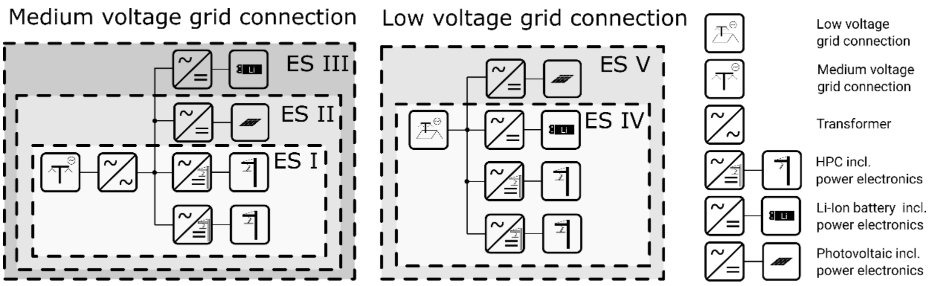

Fig. 5. Overview of the modelled energy systems for HPC grid integration

Energy system I (ES I) acts as a reference energy system and represents the current situation of HPC integration into the electrical grid. A transformer station is connected to the medium voltage (MV) electrical grid with voltage of 10 kV and supplies two HPC stations with 400 V and 450 kW each. The energy system model includes cost models for the relevant components and services and calculates the individual and total annuities. The total annuities of ES I result in 323,852 € considering the investment and operational costs of all components excluding costs for the buses.

Integration of photovoltaic systems

On the pathway to a climate neutral city, Berlin aims at a 25 % share of photovoltaic (PV) electricity of the total energy consumption in 2050 [4]. Identifying locations and financially viable scenarios to include PV into the local energy systems is therefore crucial in reaching these goals. In ES II a PV system with a rated power of 69 kWp is added to the configuration of ES I under the assumption, that a suited nearby BVG owned rooftop is available and the generated electricity can be used for own-consumption ("Eigenversorgung") according to § 61b EEG [5], so that the renewable energy levy ("EEG Umlage") is reduced to 40 %. The excess electric energy is fed into the electric grid with a fixed price of 5 ct/kWh. As the simulation reflects one week in summer, the results are not equally valid for the whole year. Under these assumptions, the total annuities of ES II result in a reduction of 10,247 € compared to the costs of ES I. Table 3 shows the results of all simulated energy systems. Substituting grid electricity with locally sourced solar power at an own-consumption share of 48.5 % resulted in a cost mitigation in electricity costs of 13,389 €. To further increase the own-consumption share, a stationary Li-Ion battery with a capacity of 90 kWh is introduced into the system in ES III. With this, the own-consumption share increases to 77 %. The price reduction in electricity costs does not compensate for the investment costs for the stationary battery, which leads to an increased system annuity of 322,265 € for ES III.

Table 3. Total annuities of the five simulated energy systems

	ES I	ES II	ES III	ES IV	ES V
Electricity costs	191,503 €	178,114 €	173,139 €	195,416 €	171,414 €
Grid connection	63,667 €	63,667 €	63,667 €	39,787 €	39,786 €
Li-Ion battery	-	-	9,861 €	21,930 €	21,930 €
PV system	-	5,175 €	5,175 €	-	5,175 €
EEG levy	-	2,114 €	3,356 €	-	3,771 €
HPC	68,682 €	68,682 €	68,682 €	68,682 €	68,682 €
Feed-in compensation	-	- 4,147 €	- 1,615 €	-	- 1,087 €
Sum total	323,852 €	313,605 €	322,265 €	325,815 €	309,671 €
Self-supply PV-share	-	48.5 %	77.0 %	-	86.5 %

For the analyzed system with a MV grid connection, the integration of a local PV system leads to a cost reduction. Introducing a stationary battery increases the own-consumption share as well as the total annuities of the system.

Integration of different grid connection levels

ES I, ES II and ES III are all connected to a MV grid of type IV (see Table 1 and Fig. 3). To investigate the possible cost mitigation of a low voltage (LV) grid connection of 400 V, energy system ES VI is simulated with a type III grid connection with a maximum capacity of 540 kW. A stationary battery with a capacity of 240 kWh enables the system to deliver charge demand peaks above 540 kW. The grid connection costs are reduced in this configuration by 23,880 € per year compared to the previous scenarios. Owing to increased electricity prices due to increased grid charges in the LV grid, and the investment and operational costs of the stationary battery, the total annual costs of ES IV lie 1,963 € above the comparable system ES I with a MV grid connection (see Table 3). Reducing the grid connection from MV to LV grid level by introducing a stationary battery is hence not profitable for this system.

In ES V, the possibilities to reduce electricity costs by incorporating a PV system and including a stationary battery in order to reduce the grid connection to LV and at the same time increase the own-consumption share of the PV system are analyzed. The total annuity reflects the synergetic use of the battery storage. It is reduced by 14,181 € compared to the MV grid connection without PV in ES I and by 3,934 € compared to the MV system with PV in ES II.

For this analyzed station, energy system V is the most cost effective system, as the electricity costs are reduced due to a high own-consumption share of PV power of 86.5 % and the lower grid connection costs. Fig. 6 shows the power curves in and out of the individual components of ES V for the simulated time of one week.

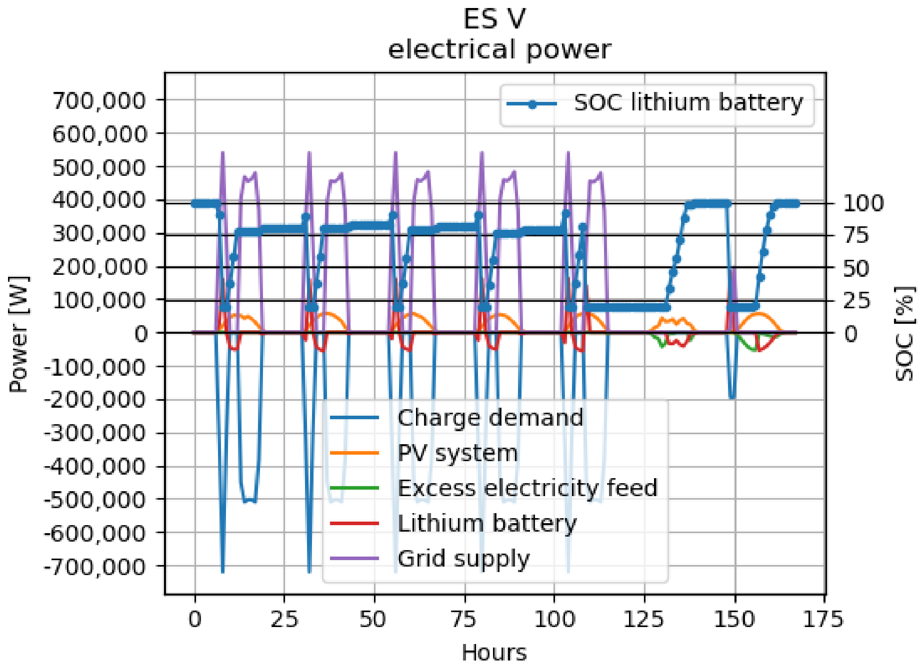

Fig. 6. Power curves of all simulated components of energy system V (ES V) over one week in hourly time steps

The analysis shows that opportunity charging leads to high power peaks and required suitable grid connection points. A grid friendly solution is the implementation of PV power plants and stationary batteries to reduce costs and allow lower grid connection levels.

4 Grid integration – other sectors

The consideration of the power grid has hardly been a priority for fleet operators. However, with the progress of fleet electrification and the coming ramp-up of electric mobility, intelligent integration of the charging infrastructure into the power grid is becoming increasingly important. Especially when larger vehicle fleets are charged overnight, this offers a high potential for flexibility, as both long standing times and high charging capacities come together. From the grid operator's point of view, two reasons are interesting. Firstly, electric fleets offer a very stable demand for electricity, as the daily mileage and driving times usually hardly vary. This means that it is usually clear in advance, in which period how much load can be shifted. This is especially true for bus companies, but also in the logistics sector, for example. On the other hand, this offers a high potential for load shifting through a single location. This is usually easier to manage than many small locations. The RLI is also investigating how this potential can be used in the logistics sector in the Netz_eLOG[3] project funded by the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU).

The increased use of load-side flexibilities is also gaining in importance due to new regulations. In order to avoid grid bottlenecks and thus ensure a stable and reliable supply, Redispatch measures (adjustment of planned electricity production) are implemented. As part of the amendment to the Grid Expansion Acceleration Act (NABEG 2.0), distribution system operators (DSOs) will be increasingly involved in the Redispatch process in the future. The conceptual design for this is being developed in the Redispatch 2.0[4] projects of BDEW and Connect+[5]. These developments make a grid-serving control of the charging processes of electric fleets relevant in the future, also from the perspective of congestion management. In order to keep the scope of possible Redispatch calls low, DSOs can integrate large electric vehicle fleets into their forecasting processes in the future. Fig. 7 shows a possible process.

[3] https://netz-elog.de/
[4] https://www.bdew.de/energie/redispatch-20/
[5] https://netz-connectplus.de/home/projekt/

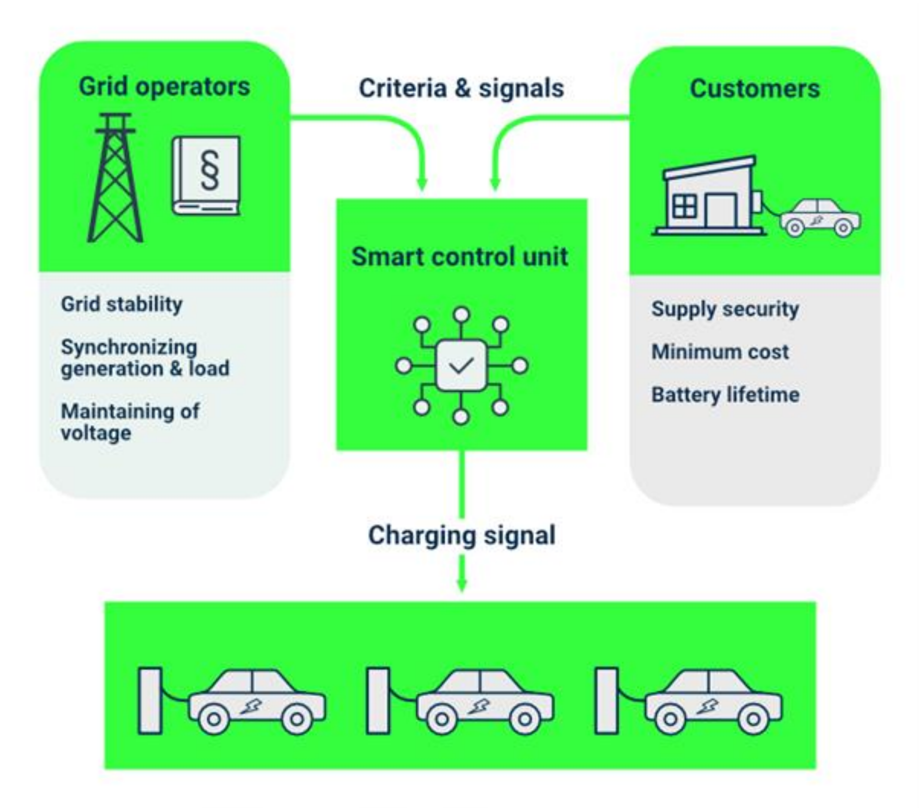

Fig. 7. Grid integration process of distribution system operators (DSOs) and fleet operators

In the Netz_eLOG project, German logistic leader DHL is charging its fleet overnight. The location lies in an area, where there is already high feed-in of wind power. Due to insufficient offtake in the grid area, the local DSO currently uses feedback energy into the transmission grid or Redispatch calls (e.g. regulating wind turbines). With intelligent charging strategies that combine both the fleet operators and the DSOs criteria, the energy demand of the electric logistics fleet can be used to lower these Redispatch calls.

In order to encourage grid-serving charging, there are already economic incentives such as §14a EnWG [6] or §19 StromNEV [7]. By using these paragraphs, grid operators grant connection users a low grid fee, in return for which they commit to grid-serving behavior. For this purpose, §19 StromNEV works with high-load time windows. However, these time windows are static and cannot be adjusted on a daily basis. They therefore do not fit into the renewable energy system with volatile feed-in. In the course of the ramp-up of electric mobility and other flexible consumers such as heat pumps, dynamic approaches such as time-variable grid charges should be considered.

5 Summary

In the public transport sector, the electrification of bus fleets plays a major role to achieve climate protection goals and improve air quality. Bus operators are facing the challenge to transform the bus network and fleet due to new legislative decisions. They need to find strategies to include electric vehicles into their daily operation. The proposed methodology is a possible way to find a technology that is feasible for the network. Grid integration is one key factor in this decision process:

- Opportunity charging results in several individual charging stations across the network with high power chargers. The grid connection has to be sufficient to cover the resulting power peaks.
- Depot charging works with lower charging powers but the charging stations are concentrated in a single location. The result is the requirement of a very high level of grid connection to make simultaneous charging of all buses possible.

Both charging technologies also offer chances to make a grid-friendly integration possible. Stationary batteries and PV power plants for energy systems on stations for opportunity charging buffer power peaks and enable lower grid connection levels. In the planning of new charging stations in the grid a close collaboration of grid and bus operator is beneficial to find the most cost effective location and even make synergies with other fleet operators possible.

At bus depots, intelligent charging strategies increase the flexibility to shift charging strategies to more cost effective slots. This includes grid-friendly charging behavior to avoid high load times in the grid (e.g. 18:00 – 20:00). Grid operators need to motivate this behavior by introducing financial incentives.

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