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A Novel Approach for the Grid-Serving Implementation of Charging Infrastructures and Their Techno-Economic Integration in the Existing Power Grid

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Abstract: The integration of electromobility with its required charging infrastructures into the existing power grid, which is demanded by politics and society, is an enormous challenge for electrical power grid operators. Especially considering further challenges, such as the electrification of heat supply systems and sector coupling, it is to be expected that the power grid's capacity will be strongly overstrained. On the other hand, grid expansion is an extremely expensive and time-consuming method of ensuring that the existing grid is not overloaded, and sufficient grid capacity is available. A suitable grid operations management approach can enable comprehensive and grid-serving control of flexibility, especially charging processes. This article presents a cluster-based and incentive-oriented grid operation management concept and describes the integration of the system into the current German regulatory framework. In addition, the structural integration of charging infrastructures for electromobility into a grid-oriented control system is presented. The suitability of grid charges and their dynamization for stimulating grid-oriented behavior is analyzed. Furthermore, the derivation of additional costs arising from the utilization-dependent thermal aging of grid assets and their imputed integration into the incentive system is described.

Keywords: e-mobility; power grid; charging stations; charging control; dynamic pricing; thermal aging

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1. Introduction

The increasing penetration of electric vehicles (EV) and the high number of charging points, with a growing demand for power, pose major challenges especially for distribution grid operators (DSO). The current government in Germany, for example, has set the goal of up to 15 million fully electric vehicles in the general vehicle fleet by 2030. Consequently, up to one million publicly accessible charging points are planned to be installed over the same period [1].

The existing power grid infrastructure can no longer meet these developments with their resulting high, erratic, and unpredictable load demand requirements. Especially in historically grown and densely built-up areas, maintaining security of power supply will become a huge challenge. Numerous studies carried out in various countries [2–5] show that, in particular with increasing penetration levels, voltage band violations, overloads of the local grid transformers, and cable systems often occur in study network areas. Thus, an increased need for grid expansion arises [6–10].

Although grid expansion is one way to upgrade the electrical grids to meet the new requirements, it is associated with very high costs and cannot keep up with the development of the integration of both renewable energy systems and charging stations. Therefore, methods must be developed that can postpone power grid expansion or prevent uneconomical or technologically unnecessary grid expansion.

Several studies illustrate that, by means of intelligent charging control, it is possible to reduce high grid load and to shift power requirements in times of high feed-in from local renewable energy plants [11]. This load shifting can be executed by remote control, although this is usually not desired by the users. In order to achieve the required flexibility of grid usage, in particular with charging processes, incentives must be created (in line with the regulatory framework) to motivate the consumer to participate. Incentives can arise, for example, from dynamic electricity prices as the user is motivated to postpone the purchase of services to low-cost periods [12,13]. At the same time, however, it is also important to consider the status of the power grid to avoid simultaneity effects that generate new load peaks [14]. Thus, the impact of price signals on the flexibilization of charging processes, on the one hand, and on the electrical power grid, on the other hand, has to be examined in detail.

Shifting charging power to the beginning of favorable time periods due to self-consumption optimization can lead to negative effects on the power grid load. Time-varying price tariffs can lead to aggregated load requirements which result in higher load on the power grid and voltage reductions compared to scenarios with static electricity prices [15,16]. Vanselow et al. [15] proposed to implement staggered price tariffs and to upgrade interconnection transformers to mitigate the technical disadvantages detected for grid operation when using time-variable tariffs. There is no explanation about the design of the price staggering strategy nor transparent dealing with the equal treatment of all power grid participants.

Flath and Gottwalt [12] presented different tariff models and evaluated them with regard to their effects on new load peaks due to price-driven simultaneities. The tariffs examined were standard rate designs, like flat, real-time, and time-of-use-pricing (TOU), as well as additional design elements, such as power surcharges, randomized group rates, and closed-loop adaptive real-time pricing. The regular pricing approaches, like real-time and TOU, show the expected occurrence of load synchronization effects. The presented modifications reduce synchronization effects but show weaknesses, such as penalizing individual increases in consumption in uncongested situations, complex transferability in terms of grouping and group pricing, as well as unreliable price signals for the customers and significant complexity of market communication for billing and transaction verification. The results show a positive effect especially on the synchronization effect of EV charging processes, but the price signals consist of market signals based on renewable generation. The costs of the power grid operation were not considered.

In [13], a direct and an indirect charging control was examined. The direct control of charging processes through disconnection is based on thermal cuts or voltage cuts. The indirect approach is based on a price-driven change of charging behavior by means of a TOU-tariff. A combination of both approaches was suggested by the authors. The weaknesses of this approach, that charging demand is not considered in the direct control mechanism, and the indirect control mechanism is only grid-serving within an adoption rate below 40%, are also not taken into account in the combination of approaches.

In addition to the fact of considering dynamic prices within the model, it is common in the literature to use optimization methods for scheduling the charging processes [12,15–19].

To solve the problem of new load peaks through TOU-pricing-based charging control, a multi-objective charging strategy was developed in [16]. It considers peak load values, charging bills, and travel rates. This approach follows the assumption that the electrical power grid benefits from the reduction of the peak load of large-scale EV charging stations. Furthermore, there is the need to know the future TOU-price structure so that the optimization process can schedule the charging processes to cheaper periods. Thus, prices cannot be linked to the real actual grid load.

In [17], different charging control approaches were compared depending on variable electricity prices including uncontrolled charging, charging with smart charging control, and vehicle-to-grid (V2G) charging. The optimization results show that the intelligent charging method far exceeds the other two methods in terms of savings for the owner, with the smart V2G method being more efficient than the uncoordinated method. Charging costs vary within the methods because of time-dependent price differences. Charging during off-peak periods is a lot cheaper than during peak times. The power losses in the transmission line are used to take the grid into account. Losses vary between the methods and the difference between them is regarded as a grid benefit [17]. Another approach of considering the status of the power grid within an optimization process is presented in [18]. The optimization process considers the benefits for the EV owners, the peak load of the transformer, the power loss, and the loss of the transformer's service life as part of the optimization process. This means that both the EV owner and the power grid are included in the optimization function. When comparing uncontrolled charging, charging according to TOU-prices, and controlled charging based on optimization, it becomes apparent that the highest peak loads occur with charging according to TOU-prices and the lowest costs can be achieved through optimization [18]. In [19], the grid condition, in the form of operating costs, is also taken into account in the optimization function.

Optimization procedures often lead to better results compared to unmanaged scenarios or to simply shifting load to favorable times. But to obtain an optimal solution, many facts and data need to be known, like electricity price, the occupation of the charging infrastructure, individual charging demand, and the load profile of the superimposed power grid. This leads to the risk of the calculated optimal solution differing from the real situation, even though uncertainties were considered.

Investigations in the field of charging control based on time-varying prices show that it is not automatically possible to achieve a grid-relieving effect. The impact of load shifting on the power grid depends strongly on the distribution of prices throughout the day and the extent to which the aggregated total load of vehicles contributes to new peak loads in the system at the beginning of more favorable periods. In addition, the lack of real-time data and future knowledge reduces the accuracy of optimal solutions.

To overcome the weaknesses of the presented approaches, a system is needed that uses the information of the power grid load in real-time to control the flexibility of EVs. To achieve this, a system was developed which enables a price-driven adaptation of charging behavior through a monetary interpretation of the actual grid load. This paper presents a suitable approach for the grid-serving integration of charging infrastructure. Firstly, the operational management system is presented, which allows grid usage to be flexibilized on the basis of the current grid load. In a second step, the relevant players involved and their roles in a charging process are clarified so that their requirements can be considered in the model. In addition, an overview of the real structure of electricity billing in Germany is given in order to show the possibilities of using and adapting existing structures to dynamize prices. In the third section, the overall simulation model is presented and the integration of public charging infrastructure into the grid-serving management system is shown. Furthermore, the modeling of the charging behavior, the economical evaluation of the load of the electrical power grid, and the charging control are described. Section 4 provides the results of the grid-serving charging control. Finally, Section 5 concludes the findings of this study.

2. Introduction of a Novel Grid-Serving Energy Management Approach with Integrated Charging Infrastructures—Consideration of Structural, Economic and Regulatory Responsibilities

2.1. A Grid-Serving Cluster-Based and Incentive-Oriented Grid Operation Management System

Current implementations for controlling charging processes (e.g., at employee parking spaces) only consider local control of power limited by the point of common coupling, which serves to optimize individual consumption behavior (self-consumption optimization). Information exchange to the higher-level electrical grid and its current status of load does not exist yet. Only by providing information about the load on upstream power grid nodes, a grid-friendly control of charging processes, which not only optimizes the single electricity procurement, can be carried out for the entire power grid according to individual economic benefits. In addition, due to the high number of charging stations required, there will be both a locally concentrated occurrence, e.g., in metropolitan areas, and also a widespread distribution of charging points, e.g., in suburban regions. This effect should also be considered by a management system.

To take these requirements into account in a grid-serving control system, a higher-level operations management system is required. It has to collect, manage, and document information about load on the power grid across voltage levels on the basis of measurements and calculations, and make it available to verified and approved actors, which enable a local and location-specific assignment of load states. Figure 1 schematically illustrates the possibility of implementing such a higher-level system. The Energy Cluster Service System (ECS), which was developed and investigated, is based on a grid structure-oriented division of the electrical grid area into clusters and motivates local energy balancing through grid-friendly behavior. It is constructed and configured by a software agent-based system of microcomputers (ECS server), reproducing the hierarchical clustered structure of the electrical power system. Each software agent program collects all necessary information within its cluster (e.g., actual load levels, voltages, etc.), derives the load dependent lifetime consumption of all relevant assets in the cluster and, finally, calculates the resulting depreciation and costs for a specific energy transport, depending on the actual investment costs and load levels of the equipment.

In this way, the ECS servers, which are located at a grid node in the electrical grid, act as measuring points and, at the same time, process the data and make it available to selected subordinate ECS servers. Each ECS server has a subordinate network within its area of responsibility (see Figure 1). This type of distribution or hierarchical division of the power grid into areas results in clustering. A special feature of the system is the structure of the information flow, which only takes place vertically from top to bottom. The information is not sent but can be read by selected subordinate ECS servers. For this system, the push principle is preferred to the pull system and is used since membership in a cluster is made by individual assignment.

The ECS servers provide a minimum amount of data with the valid apparent power and the applicable incentives. The assignment of individual ECS servers to each other, which is to be defined in the configuration, represents a closed system in which current communication standards are considered. The already integrated measuring systems, or the measuring systems that can be integrated into the system, only need to provide the power grid status parameters of current, voltage, and cos(φ), from which the power flows, as well as the loads on the infrastructures of the power grid and their evaluations can be determined. The minimal transmission and processing of information enables a real-time assessment of the current and local load of the power grid. The subordinate nodes, which form a subcluster of the superimposed cluster, and can be precisely allocated by assigning ID identifiers, read and process the information that they need to determine the load on the power grid. This makes it possible for the evaluation of the network conditions to be based not only on the local measured values but on the loads of superimposed network areas. The assessments of the power grid conditions are consistently cumulated from top to bottom, following the hierarchy of the power grid, resulting in an evaluation of the load on the power grid for each ECS server, which allows an actual holistic statement about the status of the power grid.

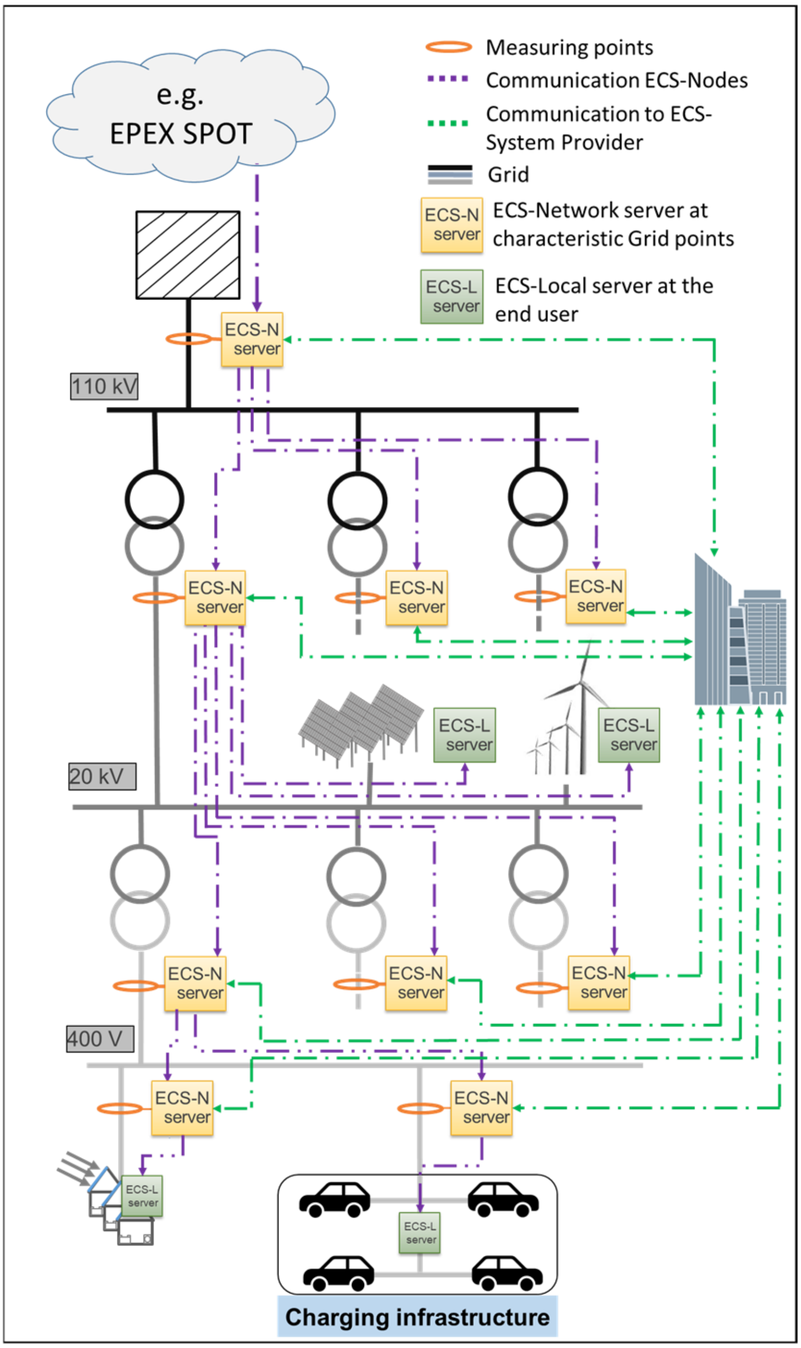

Figure 1. Functional diagram of the applied Energy Cluster Service System for a simplified network structure showing the clustering of the electricity grid, the structural distribution of the ECS-N and ECS-L servers, and the information flow within the system.

The necessity of cumulation can be illustrated by the following situation. A subordinate grid area is balanced and therefore there is no need for action locally. In higher, e.g., medium-voltage levels, there is a high load on the electrical grid due to the feed-in of renewable energies. This means that a locally increased consumption of subordinate grid participants would have a behavior that is conducive to the grid, i.e., an increase in consumption must be motivated in order to avoid, for example, feedback to higher voltage levels. In such a case, the charging capacities can be increased to their maximum, considering safety-relevant parameters. The incentives for assessing the status of the power grid and their creation are described in Section 3.

The ECS servers can be divided into ECS-N servers (ECS-Network server) and ECS-L servers (ECS-Local server). The structural distribution of the ECS System is carried out by the ECS-N servers. The ECS-L servers are functionally identical but installed at the voluntarily participating grid actors (producers, consumers, prosumers), who can thus decide whether to behave in a grid-friendly way that is conducive to the grid. This decision is based on an assessment of the status of the power grid and their individual electricity purchase/generation model.

The hierarchical structure for implementing the ECS system and the similar design of the ECS servers enables a heterogeneous transferability to any electrical power grids. The process for analyzing the power grid, setting the ECS servers, evaluating the power grid status, and accumulating the incentives stays the same. Thus, the approach is directly and inherently scalable. The number of ECS servers needed is influenced by the structure and size of the electrical power grid. Furthermore, in comparison to, e.g., flexible markets [20], no additional marketplace is needed.

A system that allows grid-serving control offers both the opportunity to make optimal use of available capacities in the electrical grid and to avoid unnecessary power grid expansion. Due to the grid-oriented design of the charging infrastructure control, current and local power grid conditions are considered during the charging process. However, in addition to the technical implementation of the grid-serving operation of the charging infrastructure, the common and recognized methods for the operation of the charging infrastructure and the billing of charging processes, including all stakeholders involved, must also be taken into account.

2.2. Charging Processes and Responsibilities

To charge an electric car at a public charging station, many instances are passed through before the electricity from the charging station flows into the vehicle. The user of the EV usually concludes a contract with an e-mobility provider (EMP). The latter has a roaming contract with a roaming provider via a roaming platform or is directly linked to the owner and operator of a charging facility (charge point operator—CPO) in the form of an access contract. The access contracts regulate the EMP customer's access rights to CPO charging stations. The "owner" of the charging stations must settle the electricity purchased at his charging stations with his electricity supplier, including the power charges with the local grid operator. These costs are, in turn, settled between the operator or owner of the charging stations and the EMP, and thus indirectly with the end customer, i.e., the vehicle user [21]. The involved players and the contractual links are shown in Figure 2.

The charging process can be initiated by the electromobility user authenticating himself at the charging station, e.g., with his charging card, SMS, smartphone app, etc. Identification is carried out via the EMP. If successful, the EMP releases the charging process in the backend (where the commercial data processing for the billing of the charging process takes place). Subsequently, the backend of the CPO (where the technical functioning of the charging station is regulated) can release the charging infrastructure and the charging process starts [21].

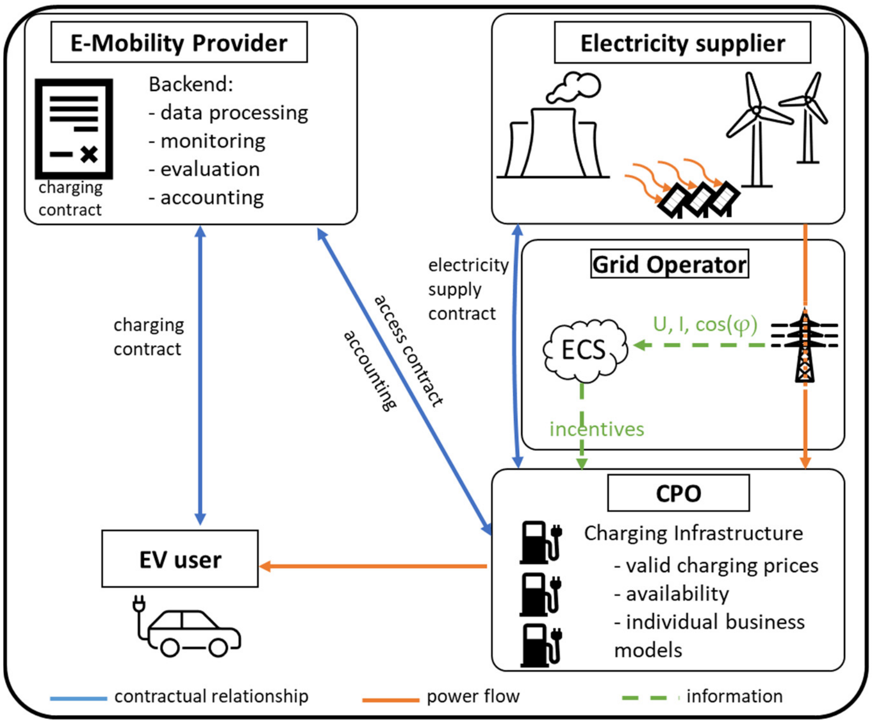

Figure 2. The charging process and contractual connection of e-mobility provider, electricity supplier, grid operator, CPO, and EV user.

In Germany, the price indication as well as the billing of charging processes only according to the delivered kilowatt hours (kWh) must be correct, comprehensible, and transparent. According to the legal opinion on the applicability of § 3 of the Price Indication Ordinance (in German: Preisangabenverordnung—PAngV), the different tariff models for charging processes include pure consumption-based billing models (according to kWh charged), a combination of kWh tariff and charges per charging process (e.g., through a start-up or basic charge), a combination of kWh tariff and charges in the sense of time-based tariffs (such as for parking tickets), a flat rate billing (comparable to a smartphone flat rate), or a free distribution of electricity, for example at supermarket parking lots [22].

If there are no flat rate settlements or free supply of electricity, § 4 of the Charging Station Ordinance (in German: Ladesäulenverordnung—LSV) nevertheless ensures simple and spontaneous charging (ad hoc charging) of the EV by the CPO. The charging infrastructure can be used both with (cashless payment process) and without (payment by means of cash) authentication [23].

2.3. The Current Structure of Electricity Billing in Germany

To show the implementation of the systematic of dynamic incentives into the electricity billing system, the regulatory framework of Germany is described in more detail in this section. Even if every country has its own regulatory framework, the system of implementation is transferable.

In Germany, electricity costs are made up of various components. A distinction is made between consumption-dependent and consumption-independent cost components. In addition to the price components for energy procurement, sales, and the electricity supplier's margin, there are also levies, taxes, and charges, as well as fees for the power grids and metering point operation [24]. The electricity price is the central control signal for the allocation of generation and consumption on the electricity market and reflects the shortages on the generation market [25]. The grid fee, on the other hand, reflects the costs of utilization of the power grid, as well as for the provision of system services and the coverage of losses occurring during electricity transmission. From the interaction of both scarcity signals, a grid-serving reaction of the producers and consumers should be encouraged [25]. Grid-serving behavior, however, should be reflected in grid charges and must be decoupled from the electricity market. Furthermore, grid charges offer a suitable lever for reducing electricity costs, as the share of grid fees is the second largest price component after energy procurement. Depending on the purchase case, grid charges account for around 19.8% (in 2023) of the total electricity costs for end consumers in Germany [24].

However, the current German regulation of the grid fee system and incentive regulation are more of an obstacle to the use of grid-friendly flexibility. The current regulatory framework offers flexible power grid users, producers, and consumers less incentives and opportunities to use the grid in line with demand and, at the same time, in a way that is compatible with the power grid [26]. It was assumed that the electrical grid costs derive from the contribution of grid users to the simultaneous annual peak load. However, grid situations in which an increase/decrease in peak load is not associated with a corresponding increase/decrease in grid costs are increasingly possible. This applies, for example, in cases in which the dimensioning of the power grid is determined not only by the load but by the feed-in of renewable energy [27]. German legal regulations on rewards for grid-serving behavior are already given by § 14a of the EnWG (Energy Industry Act—in German: Energiewirtschaftsgesetz). The Federal Network Agency may issue uniform national regulations in accordance with § 29 (1), according to which operators of electricity distribution grids and suppliers, end consumers, and connection recipients are obliged to conclude agreements on the grid-oriented control of controllable consumption devices or grid connections with controllable consumption devices (controllable grid connections) in return for reductions in grid charges in accordance with the specifications of the Federal Network Agency [28].

The German resolutions BK6-22-300 and BK8-22/010-A specify the integration and use of controllable consumption devices and the structure of the reduction of the grid charges in accordance with § 14a of the EnWG. The Federal Network Agency proposes three fee models for the adjustment of grid fees in return for the grid-oriented control of consumption devices. Module 1 proposes a nationwide regulation for the creation of an individual grid operator flat rate. This flat rate reduction in grid charges results from the compensation of the additional costs for a smart metering system and a control box, as well as a grid operator-specific stability bonus, which in turn results from an assumed consumption of 3750 kWh/a, the corresponding working price per kWh of the local grid operator, and a stability factor of 0.2. No separate metering point needs to be installed for the controllable devices, and it is not possible for the grid charges to fall below €0 (repayment from the grid operator to the end consumer) [29].

Module 2 describes the percentage reduction of the energy price. This requires a separate metering point for controllable devices. According to the current status, a nationwide reduction of the grid fee per kWh by 60% is assumed [29].

Module 3 is a complementary incentive module to module 1. Here grid operators are forced to offer time-variable grid fees as an adaptation to the flat rate reduction in grid charges. Three variable price-levels for the grid charges are defined by the grid operator (low-load tariff (NT), standard tariff (ST), and high-load tariff (HT)). Some of the individual tariff levels must comply with time limits and the prices are limited in their amount [29].

The current billing system between the end consumer, energy supplier, and grid operator is to be retained for all three models [29].

It has already been shown, in a discussion paper by the Federal Network Agency on flexibility in the electricity supply system, that a dynamization of grid charges makes sense. A grid fee structure, which includes the costs of the load on the power grid, should lead to an efficient pricing of infrastructure. So, the shortages of the power grid can be reflected by the grid fees [27]. In their study, the German Energy Agency (Netzflexstudie) also concluded that a further development of the grid fee system is an essential element to incentivize the grid-serving use of flexibility [26]. As the adoption of the grid fee system regarding dynamic/time-variable and grid-serving acting components is recommended by various institutions and experts as a potential measure for using flexibility potential, the economic advantage of reducing electricity costs for grid-serving control of charging processes is also based on dynamic grid fees. Besides the suitability due to the above mentioned points, the grid operator achieves considerable cost savings compared to conventional electricity grid planning by taking grid-supporting flexibility use into account in the planning. According to a study by E-Bridge, the additional investment required in the distribution grid for the integration of new storage systems, loads, and feed-ins can be reduced by up to 55% by 2035 if flexibility is taken into account in its planning [30]. In addition, redispatch costs in the transmission grid can be reduced by up to €150 million per year from 2023 by using grid-supporting flexibility [31]. Furthermore, a study conducted by Agora describes that controlled charging at the low- and medium-voltage level for a future scenario for the year 2030 with an electromobility share of 15 million vehicles can reduce investment costs in these two voltage levels by up to 50% compared to uncontrolled charging [32].

These cost savings can partially be passed on to the provider of grid-serving behavior in the form of dynamic grid charges.

In addition to the legal efforts of dynamization of grid fees, energy suppliers are also obliged by § 41 of the EnWG to offer dynamic tariffs to their customers from 2025 onwards. These developments will have effects on the future usage of the power grid. Corresponding price signals can lead to simultaneities that are desirable from an energy technology perspective and for the utilization of renewable electricity, but they can also cause high local loads on the power grid and therefore grid congestion. This development also reinforces the need for a dynamic electricity price component, which considers the load of the power grid. The above-mentioned Energy Cluster Service System shows an implementation option, pushing forward the required flexibilization based on dynamic grid charges. In contrast to the three proposed modules, this cluster-based and incentive-oriented approach is oriented on the existing holistic load of the power grid. The monetary incentives are to be seen as a passive control instrument which, in the sense of the market principle, reflect the scarcity (limitedness) of the resource power grid (grid capacity) and can serve as an instrument of economic management and balancing of interests.

3. Development of the Hardware-in-the-Loop (HIL) Simulation Environment—Integration of a Grid-Serving Control System in the Current Operation and Billing System

3.1. The Two-Layer Simulation Model

A two-layer simulation model was developed to meet the requirements of mapping the effects of the grid-serving control mechanisms of charging infrastructures in large central parking facilities on the utilization of the superimposed distribution grids. This approach allows us to model power grids with integrated charging infrastructures to analyze and evaluate grid conditions, as well as charging strategies for different scenarios. Furthermore, the decoupling of the layers enables the implementation into a hardware-in-the-loop demonstrator based on real-time measurement data acquired in the operational electricity grid. Figure 3 shows the principal structure of the two-layer simulation model.

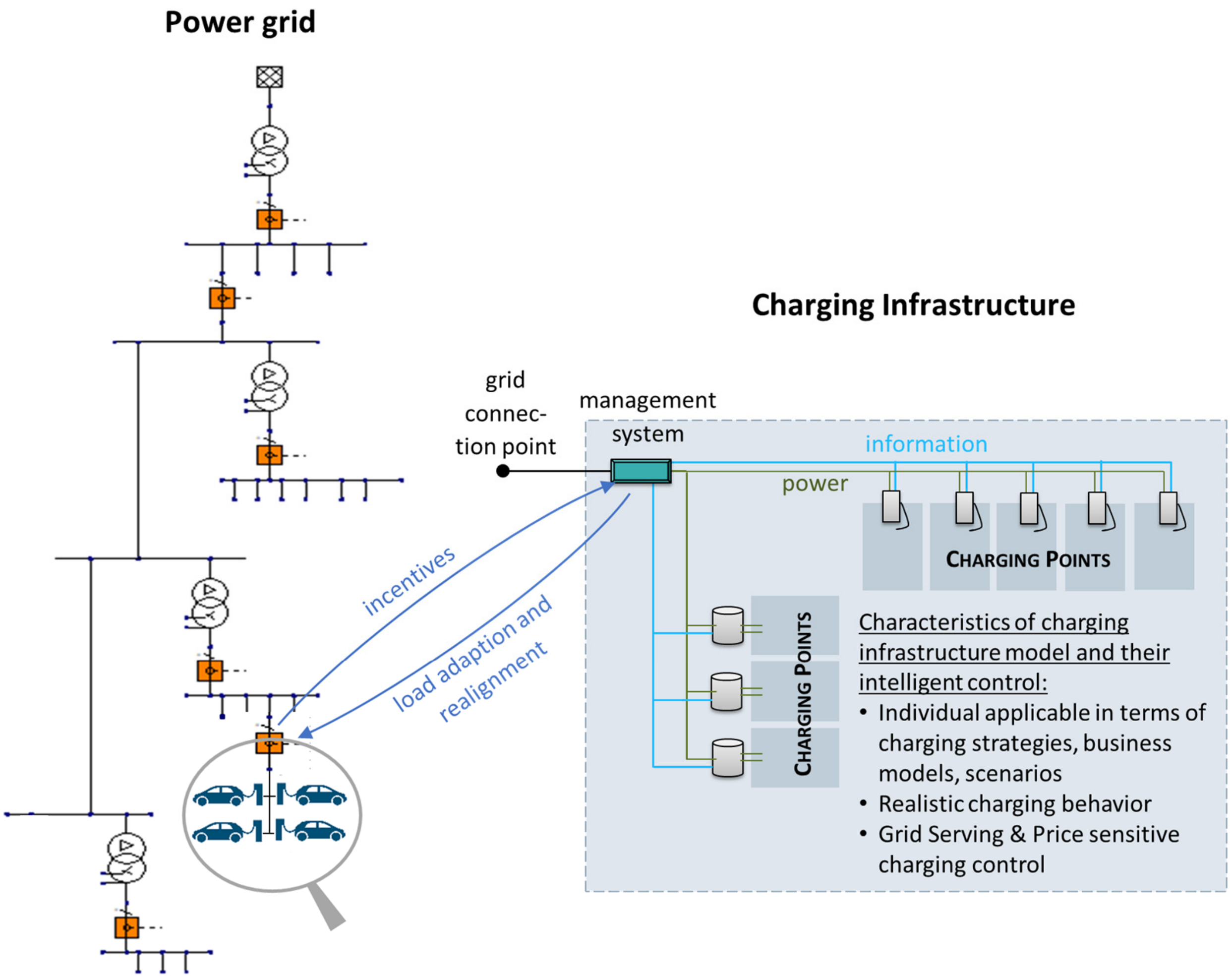

Figure 3. Principal structure of the two-layer simulation model. (**Left**) Real time acquisition of the cluster loads, calculation of load dependent lifetime consumptions and the resulting depreciation of cluster assets. Derivation of accumulated transmission costs by the ECS-system. (**Right**) Socio-technical agent-based charging infrastructure model with intelligent incentive-based grid-serving charging control.

State-space based load flow layer:

On the left side in Figure 3 there is an extract from the grid model taken from a real distribution grid. The developed state–space load flow simulation is implemented applying an analytically solvable system model. This systematic mathematical approach leads to a system of matrices in their minimal form so that the calculations of the physical and load-related processes resulting from the grid structure and the loads, feeders, and prosumers can be carried out in minimal simulation times. Further information about the fundamentals of state–space-based load flow calculation is given in [33–35]. At specific grid nodes, represented by the orange boxes in Figure 3, ECS servers are located with their economic evaluation of the actual grid condition based on aging models.

Socio-technical charging infrastructure layer:

The right side of Figure 3 represents a single charging infrastructure that can be implemented at certain nodes within the power grid model. The focus is on large-scale inner-city parking facilities. To meet the requirements of modeling a realistic mobility and charging behavior, a stochastic and microscopic socio-technical charging infrastructure model was developed. This setting provides the possibility of easily adapting the model in terms of changing technical or behavioral data. Moreover, different charging strategies and business models can be implemented.

Hardware-in-the-loop real-time demonstrator:

The decoupled structure of the model allows for implementation into a hardware-in-the-loop real-time demonstrator. The ECS servers, represented as orange boxes in Figure 3, are implemented into the existing power grid of the participating DSO. These ECS servers consist of a measuring device, if not present at the specific power grid node, a microcomputer, which processes the data in terms of load evaluation and determination of local and accumulated economic incentives, and data communication technology. They were implemented into the real grid at strategic locations, mainly in transformer and distribution stations, to record the power flows within the real test network region. At the same locations, virtual twins of the ECS servers were implemented in the simulation environment.

The charging points to be controlled are only in the virtual simulation framework, but a common battery system in laboratory is included in the whole hardware-in-the-loop design to see the delay times of communication and the reaction of a real system. This developed decoupled structure enables the validation of the cluster-based and incentive-oriented approach under real conditions without controlling within critical grid infrastructure directly. Figure 4 presents a flowchart that shows the schematic of the overall program structure.

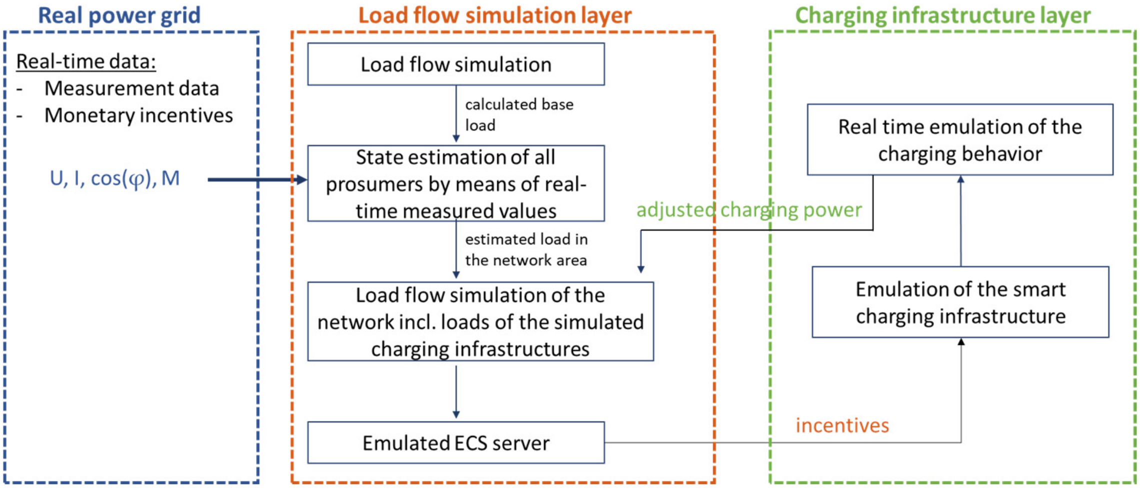

Figure 4. Schematic of the implementation of real-time data from the ECS servers (**left**), in the load flow simulation (**middle**), and the incentive-based charging control including repatriation of adjusted charging power to the load flow simulation (**right**).

The implementation of real-time data in a load flow simulation requires a state estimation to combine the real network status with the simulated load flow values. To match the measurement data, factors have to be derived in the simulated systems, so that the network areas which were not measured can be calculated correctly. A detailed description of the HIL and the state estimation can be found in [36].

3.2. Implementation of the Charging Infrastructure into the Power Grid and the ECS System

Information about the status of the power grid is contained in the servers of the ECS system. By connecting the charging infrastructure to the ECS system, charging processes can also be controlled in line with the grid, provided that the user's primary intention is to park and not to charge the vehicle immediately.

Thus, at times of high load on the power grid through feed-in, the charging power can be increased while considering vehicle-specific (e.g., state of charge) and user-specific (e.g., demand) parameters/information. In return, the charging power is reduced at times of high load through consumption. To adequately display the price and demand-driven charging behavior, a model is required that takes all aspects into account. Time-dependent characteristics, such as battery behavior in winter and summer, as well as the weather-dependent electricity demand for the power grid, must be considered. Furthermore, the control system must also be integrated into the current operating mode and billing method of charging infrastructures. To this end, the market roles and areas of responsibility of the individual players and the necessary contractual links must be defined. In the following discussion, the focus is on publicly accessible parking areas. Private charging points are not considered. All the players involved, except for the electricity supplier, the flow of information and electricity, and the integration into the electrical grid, are shown in Figure 5.

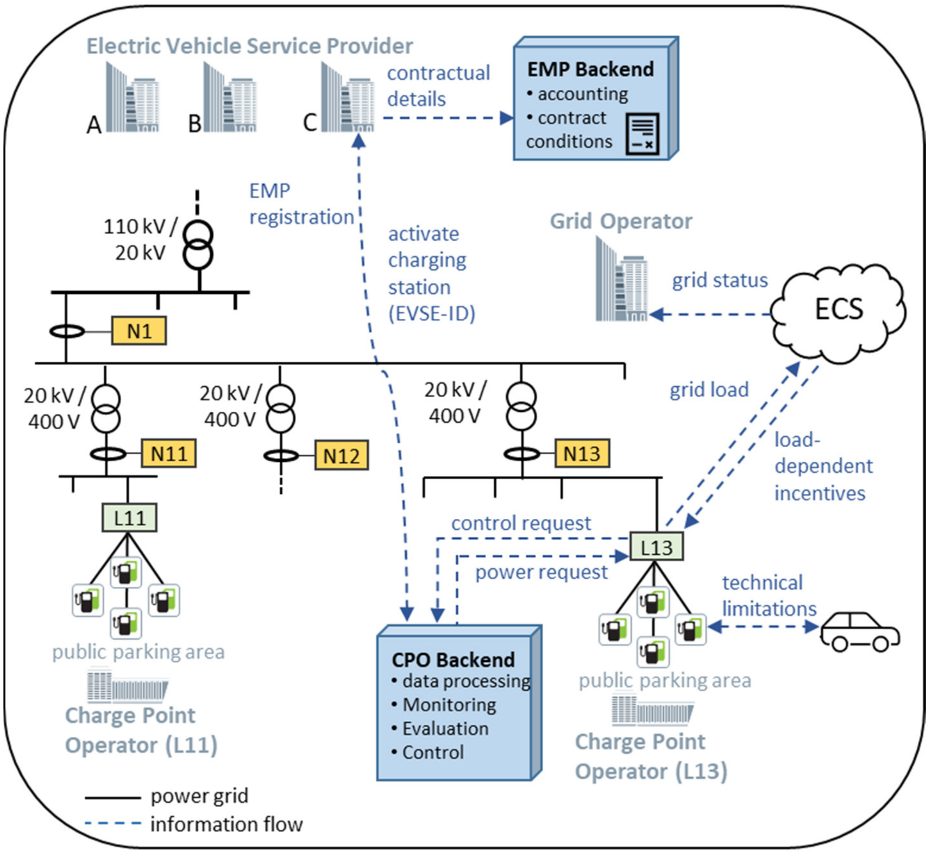

Figure 5. Schematic representation of the integration of the charging infrastructure into the power grid. Exemplary implementation of the ECS system with its basic information and communication structures.

The above-mentioned procedure before the charging process starts (from vehicle starts to charge) is not changing. After authentication, the EMP and the CPO check the identity and activate the charging station. A grid-serving control has no influence on this process because the goal here is to reduce charging power in a grid-friendly way and not to lock the charging station. Especially in the publicly accessible area and upon the provision of a consideration (e.g., monetary compensation), the users of charging stations must agree to a grid-serving control at every single charging process, as the needs of the users must not be disregarded.

To integrate the control systematics in the ECS system, first the role of the operator of the ECS system has to be defined. The local grid operator would be suitable for this, as power grid relief and careful operation of the power grid resources are predominantly in their area of interest. Furthermore, the structural design of the system allows the measurement of the status parameters of the power grid and grid utilization even at a low-voltage level, where there is only little knowledge or a small database of actual power grid utilization due to the lack of measuring equipment. The extended metrological recording of power grid status parameters is also of great interest to the grid operator due to its defined tasks (e.g., security of supply). It is not necessary to collect the data down to the ECS-L server level, so that the data protection of individual network players is also considered and safeguarded. Information about an upcoming charging process at a specific charging station can be passed on to the ECS system (through the corresponding ECS-L server) via the CPO backend. The localization of the charging station takes place after the identification of the user through their individual EVSEID (electric vehicle supply equipment ID). Furthermore, the amendment to the Low Voltage Connection Regulations makes it mandatory to register charging devices installed in the low-voltage grid in Germany with the responsible grid operator [37]. This ensures a clear assignment. The ECS-L server registers the information about a pending charging process (charging station is in its cluster), whereby a prediction of the resulting load on the electrical grid can be made before the charging process starts. For the prediction, the maximal power of the charging station is used. This creates the basis for carrying out grid-serving charging control. It is necessary to mention that a grid-serving control is only useful if the parking duration is long enough. Parking processes, e.g., at gas stations, service stations, or public parking lots, which purely serve to charge the vehicle as quickly as possible, are not suitable for grid-serving charging control. To be able to access the flexibilities (it is not about direct control, but rather about influencing through incentives), contractual agreements must be made in which the compensation for the grid-serving use is defined.

3.3. Design of the Charging Infrastructure Model

For examining the impact of electromobility on the electrical power grid, it is important to model the charging behavior in a realistic way. Until now, studies have mainly focused on the general mobility behavior of people. It remains unclear how charging behavior will develop. The reason, therefore, is that electromobility drivers are still a minor group and the expansion of the public charging infrastructure is progressing slowly. A common approach in science is to model the mobility behavior of electric vehicles by means of a microscopic stochastic approach based on data collected from trips made by vehicles with a combustion engine [38]. Depending on the objective of a study, assumptions of the charging behavior are different, e.g., only charging at home, always charging while parking, or charging only when limits were undercut [39–42].

To reach the requirements to show the impact of a cluster-based and incentive-oriented charging control system of big public charging hubs on the existing power grid, the common proceeding can only partly be applied in this study. This model also uses a microscopic stochastic approach to be able to individualize every arriving car. The difference is that only the characterized charging spots and the power grid is of interest and not the mobility behavior outside the parking facilities.

The stochastic correlations for the parameters time of arrival, parking duration, and charging demand derived from trip lengths are based on the Mobility in Germany dataset [43], which is a huge dataset with six sub-datasets which represent German mobility behavior. To consider the different vehicle types with their differing battery sizes, the arriving cars are distributed according to the sales figures for all EVs in 2023. Furthermore, four user types were defined with differing access to charging infrastructure (at home or at work). For the initial state of charge of the arriving cars, and depending on the user type, a Weibull distribution was chosen with different characteristic values. The initial state of charge for the type ‘no access to charging infrastructure besides public charging hubs’ are statistically the lowest ones. The probability of the plug-in behavior of the single arriving car depends on a sigmoid function based on the initial state of charge, as in [44]. Figure 6 shows the exemplary realization of the distributions of the initial state of charge for the four user groups on the left side, and the plug-in probability on the right side.

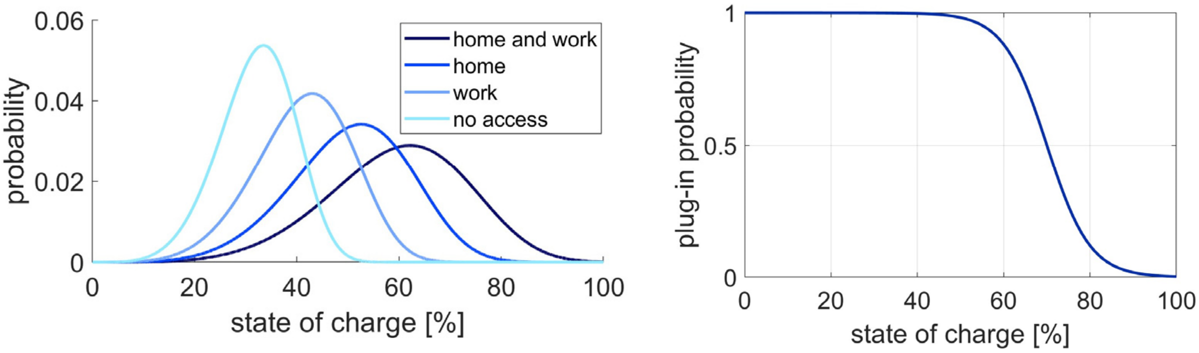

Figure 6. Exemplary probability distribution for initial state of charge (**left**) and plug-in probability (**right**).

3.4. Description of the Dynamization of the Grid Charges Based on Physical Aging Effects

As mentioned in Section 2.3, monetary incentives are an appropriate means for the flexibilization of charging processes. Therefore, a methodology to incentivize the flexibilization based on the actual grid load has to be developed. The following approach shows the dependency of the accelerated aging behavior under a higher thermal load of power grid assets. An economic evaluation of the grid load can be mathematically determined based on the monetary impacts of the chemical and physical aging processes without the need of installing a trading market. The cluster-based procedure enables a local resolution of the load on the power grid.

The components contained in the energy system are subject to continuous aging. These are irreversible changes in the physical and chemical characteristics of the materials used. The local electrical, thermal, and mechanical loads on the assets play a decisive role. During operation, for example, a permanent or short-term increase in the operating current leads to increased thermal stress. This can cause an accelerated aging of assets and therefore reduce service life [45], as the electricity flowing through the components can be influenced by the operational management of the vehicle. In the following discussion, a methodology to enable an economic interpretation of the current load of the power grid components is presented. This economic interpretation can then be used as a basis for grid-serving behavior. The approach of dynamizing grid charges within the ECS system is based on thermal aging models, as they reflect the load factors that determine the service life of our electrical grids best.

3.4.1. Thermal Aging

In science, the Arrhenius equation is often used to approximate quantitative temperature-dependent physical and chemical processes and their influence on accelerated thermal aging. For oil-impregnated transformers, information on the service life expectancy and the relative service life consumption of the insulation can be found in DIN IEC 60076-7 [46] and in the “IEEE Guide for Loading Mineral-Oil-Immersed Transformers”. “The correlation between lifetime and temperature of the considered medium is described by the thermal aging reaction rate k, given by the Arrhenius law” [47]:

$$k = A \cdot e^{\frac{B}{T}} \tag{1}$$

with

$$B = \frac{-E_a}{R} \tag{2}$$

The aging process for the insulation of the transformers can be determined as follows:

$$Per\ Unit\ Life = A{\cdot}e^{\left(\frac{B}{T}\right)} = 9.8{\cdot}10^{-18}\ {\cdot}e^{\frac{15{,}000}{\Theta_H+273}} = L(T) \tag{3}$$

Parameter	Description
A	Component specific constant
B	Component specific constant
T	Absolute temperature
T	Absolute temperature
E_a	Activating energy
R	Gas constant
Θ_H	Hot spot temperature of the winding [°C]
$L(T)$	Lifetime by occurring absolute temperature

Here an aging acceleration factor (F_{AA}) can be determined as follows:

$$F_{AA} = e^{\left(\frac{B}{T_{ref}} - \frac{B}{T}\right)} \tag{4}$$

In [48], the Arrhenius approach is also used for the service life estimation of XLPE-cables. Another approach determining an aging factor is based on the experimental findings of Montsinger. The aging rate according to Montsinger is determined as follows:

$$A = 2^{\left(\frac{\Theta_H - \Theta_{ref}}{\Delta T}\right)} \tag{5}$$

Θ_{ref} represents a reference temperature. According to [47], the Montsinger rule can also be used as an adaptation of the Arrhenius law for transformers for the determination of aging behavior for paper insulated lead covered cables (PILC). The life expectancy at the occurred absolute temperature T can also be expressed as follows [47]:

$$L(T) = L\left(T_{ref}\right) \cdot {F_{AA}}^{-1} \tag{6}$$

The influence of temperature on the service life of PILC cables for different reference data and aging models has already been investigated in [47].

3.4.2. Economic Interpretation of the Load on the Power Grid

Since thermal load influences the service life of technical assets, it also influences their economic impairment. The economic valuation of technical assets over its useful life is based on depreciation. The calculation of these imputed depreciation is determined in § 6 of the Electrical Grid Fee Ordinance (in German: Stromnetzentgeltverordnung—StromNEV). In this way, the financial outlay for the purchase is spread over the years planned for the service life. By balancing the acquisition costs, the time dependent depreciation due to the wear and tear of aging can be considered. That is the reason why amortization is used for the economic assessment of accelerated aging through the increased load of power grid assets within the ECS methodology. The amortization costs of power grid assets are included in the grid charges. The fundamental calculation of amortization is as follows:

$$Amortization = \frac{investment\ costs}{useful\ life\ in\ years} \tag{7}$$

The lifetime and the resulting annual amortization costs are continuously calculated for all assets, for the current load on the power grid, and for the grid load considering an additional kilowatt:

$$M = \frac{Amortization_{+1000\mathrm{W}} - Amortization}{8760\ \mathrm{h/a}} \tag{8}$$

The delta in the amortization costs shows the annual additional costs through the additional load of one kilowatt. These costs can then be converted to a transmission of that power over one hour (8760 h/a) and expressed as an economic value (M). Due to the exponential influence of the flowing current and thus the power, the additional kilowatt (-hour) has a greater impact on the lifetime and the costs under high load periods compared to times with a lower load. The cost difference can then be used as an incentive and be added to the electricity price whereby the load on the power grid is implemented in the electricity billing price.

3.5. Incentive-Based Charging Control

Charging control depends on a price-sensitive reaction of the charge point operator based on the monetary incentive and considering the charging demand of the individual EV. Optimization processes, as described in Section 1, are not feasible to the described approach of the ECS system. The incentives derive from the current grid status. These incentives are therefore not known in advance, so it is not possible to apply an optimized charging scheduling. A charging control that reacts to the dynamic incentives and considers the charging requirements was developed. The limitations within the control system can be defined by the charge point operator themselves. Figure 7 presents a flowchart showing the structural process within the program.

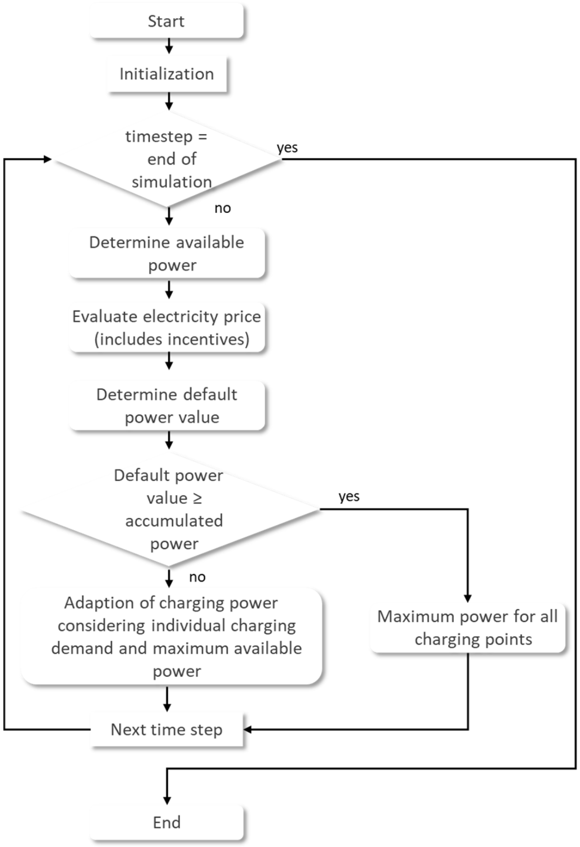

Figure 7. Structural flow chart program section for the incentive-based charging control.

In the initialization process, the setting of the charging infrastructure, as well as the parametrization of the single vehicles, following the distributions described in Section 3.3, takes place. Within the simulation time there is a continuous adaption of the default power value for the charging points depending on the available power at the grid connection point and the evaluation of the electricity price. This power value is compared to the uncontrolled charging power of all occupied charging points. When the default power value is higher than the uncontrolled demand, every car is charged with maximum power. If the default power value is smaller than the aggregated demand, the power at the individual charging points is reduced based on charging demand and parking time.

4. Simulation and Results

The test network is a section of a real inner-city subsystem of the participating DSO with a high charging requirement in the future. It consists of over 500 nodes and has a high, medium, and low voltage section. The structure of the test network is shown in Figure 8.

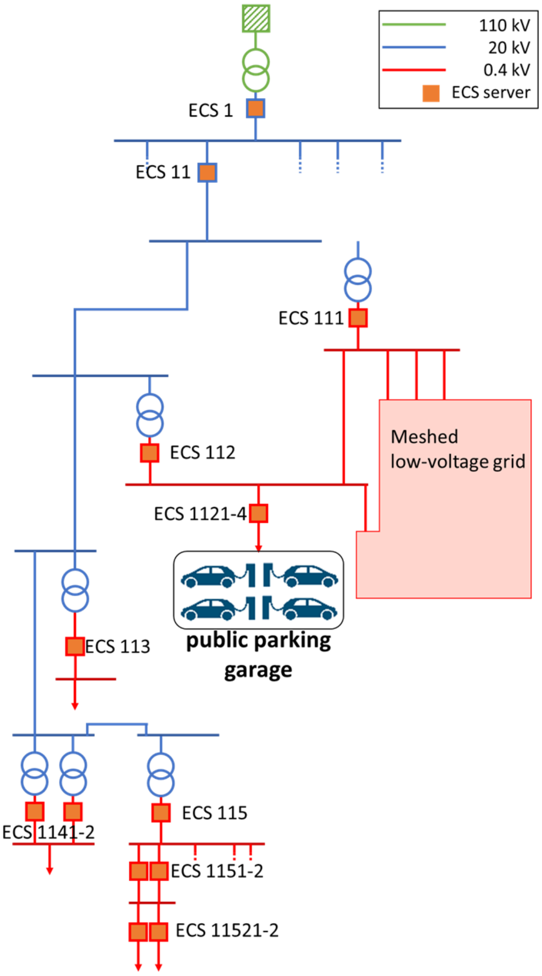

Figure 8. Structure of the test network with integrated ECS servers and an exemplary public parking garage with charging infrastructure.

To show the functionality of the developed charging control algorithm based on monetary incentives, the results are based on a consistent set of simulation and load settings. The charging infrastructure is implemented at the charging garage and has the usage characteristics of the employee's parking with a two-shift operation and an average parking time of 6.75 h. The mobility behavior is based on the stochastic derivations from [43] and the initial SOCs and the charging behavior result, as described in Section 3.3. The parking garage has 500 parking lots and 70 charging points with 11 kW each. Figure 9 shows the functionality of the charging control algorithm.

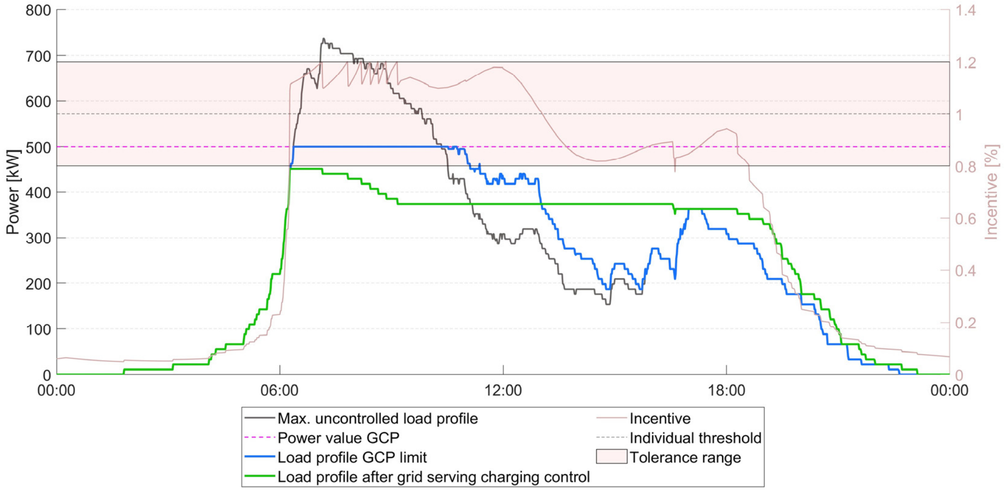

Figure 9. Simulated load profiles of the uncontrolled and controlled charging processes and incentives derivated by the ECS system.

The black curve shows the absolute uncontrolled profile through charging infrastructure. The parking garage is linked to a 630 kVA transformer. It can be seen that such a power demand cannot be provided by the existing power grid infrastructure without grid expansion. The blue graph shows a simple control which is only sensitive to the maximum available power specified by the grid connection point (GCP). The green graph shows the more intelligent grid-serving charging control. The orange graph shows the incentives as a percentage related to the individual threshold value and the tolerance range (red area) given by the charge point operator. If the incentive exceeds the upper threshold value, the control mechanism reacts and reduces the charging power. If the incentive stays within the tolerance range, the available charging power stays the same. It can also be seen that the grid-serving charging control considers the charging demand as the green graph exceeds the blue one between 1 pm and 5 pm, as well as during the evening hours.

This grid-serving load shifting to times of lower power grid load has a significant impact on the operation of the power grid assets. Considering the thermal degradation of the transformer involved, the calculated service life can be extended by a factor of 1.6 compared to the uncontrolled scenario. The calculated service lives of the cable systems supplying the parking garage can be extended by a factor of 2.9. This grid-serving operation with the achieved lifetime savings of central grid assets result in a more cost-efficient operation and gives the power grid operators more time to cope with the necessary grid expansion.

5. Conclusions and Summary

The expected high number of EVs on German roads and the charging infrastructure required for them not only represents a challenge for the electrical grids but offers great potential for the success of the energy transition, if integrated correctly. To guarantee a safe and economical supply of electricity, grid flexibility becomes increasingly important in times of high volatile feed-ins through wind and PV plants. As mentioned above, the charging processes of EVs have high power requirements from the electrical grid which obliges them to contribute to a safe and stable grid operation in the future. This can be achieved through a grid-serving control of the charging process. The resulting flexibility potential can help to locally use the volatile and partially unplannable feed-in of renewables or to decrease load on the power grid in times of low feed-in through a reduction of charging power. The holistic electrical energy system-serving behavior can be encouraged by the coordination of controllable charging processes through a superordinate incentive-oriented operation system. The savings resulting from the use of grid flexibility can partially be reallocated to the provider of flexible power by minimal adjustment of the existing structure of billing electricity. Due to the participation of different stakeholders, the charging control can be designed differently and so can the limit values for the adoption of power at the charging points. Furthermore, the amount of energy transmitted into the electrical vehicles can vary between the control designs. This setting of a two-layer simulation model with a socio-technical and microscopic charging infrastructure model allows for the investigation of different scenarios and business models through a flexible adoption of input parameter and control settings. The presented grid-serving charging control approach enables a significant reduction of the load on the power grid assets resulting in a more cost-efficient operation of the electrical power grid. The results show that simultaneity effects can be avoided and that future knowledge about prices or charging demand is not needed. The expansion of the electrical power grid can be reduced to a minimum through the efficient use of grid capacity as well as through a consideration of flexibility while planning power grids. The cost-reducing effect is transparent and comprehensible for all participants when using the described ECS system. The hierarchical and homogeneous structure enables a transferability to any electrical power grids.

The presented approach of a cluster-based and load-oriented operation of power networks is currently part of a real hardware-in-the-loop demonstrator. It is based on real-time measurement data from the grid and a virtual simulation environment with implemented charging infrastructure to investigate, evaluate, and validate their grid-serving charging control as well as the impact on the grid assets. The discussed method of a grid-serving implementation of charging infrastructure will be further investigated. Details on modeling the charging demand, implementing the ECS system into a state-space based load flow simulation, and results in the field of charging control and their grid-serving effect on the power grid assets will be part of future contributions. Furthermore, the model is to be adapted to new data in the field of charging demand and price driven-charging behavior when these are published.

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