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Research Report

Charging Service Elements for an Electric Vehicle Charging Service Provider

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***Abstract*—Electric vehicles are often seen as a key element in smart grids. Potentially, electric vehicles can be used for providing grid services, both for peak shaving and for ancillary services. To achieve this, an aggregator or charging service provider could control the charging of large electric vehicle fleets or, if sufficient information is available to the vehicle, the EV itself can control the charging and provide these services. In the literature, little attention is devoted to the charging services offered to the EV user. This paper outlines a set of building blocks for such end-user charging services. These building blocks can easily be transformed into objectives and constraints in a charging schedule optimization problem formulation. The focus of this paper is on describing the various potential service elements rather than on assembling actual products from these elements.**

I. INTRODUCTION

Traditional methods of generating and consuming electric energy have limitations when it comes to power systems with a large share of renewable energy sources, such as wind and solar power. A large share of these intermittent renewable energy sources creates uncertainty and fluctuations in an otherwise relatively predictable and stable power system. Integrating information and communication technologies is one of many factors that can assist in making the grid smarter and more flexible. In such smart grids, electric vehicles (EVs) can play an important role. If EVs are intelligently charged, they can become an asset to the grid rather than a mere traditional load [1].

There are two types of studies that aim at making the charging of EVs more intelligent [2]. The first is a decentralized concept in which the invidual EVs optimize their charging based on market information made available to them. Such a decentralized concept has been studied in [3]. The second approach is to have a centralized aggregator that offers charging services to its member EVs. In the literature, such centralized units are referred to as EV fleet operator, EV virtual power plant, or EV aggregator. Each of the methods, whether centralized or decentralized, has advantages and drawbacks. The decentralized approach assumes that the EV itself optimizes its charging behavior based on, for example, a price signal. The drawback of this approach is that the EV needs to collect and store trip history and that, if the EVs need to coordinate their charging, for example to include grid constraints, the need for communication is high. The centralized approach, on the other hand, assumes that the centralized unit optimizes the charging and that the resulting charging schedules are communicated to the EVs, transferring the charging schedule intelligence to a central location. In this paper, the centralized entity is referred to as charging service provider (CSP).

Figure 1 shows the two concepts of smart charging. The electricity retailer plays an important role because it receives meter readings, typically from the local distribution system operator responsible for the metering, of the meters in the EV supply equipment (EVSE), i.e., where the EV connects to the grid. Regardless of whether the decentralized or the centralized approach is the prevailing way of managing the charging of large EV fleets, the intelligence that optimizes the charging needs to take the end user into consideration. Figure 1 also shows where the charging planning is performed, which is also where end-user services need to be considered.

In the literature, the emphasis is mainly on the services that the EVs can provide to the electric energy system. If sufficient number of EVs are available, which several studies are projecting [4], they can potentially provide services to the grid, such as load shifting, balancing power, and frequency response [5], [6], [7]. A CSP can, for example, offer services to the power system because it is flexible in allocating the charging of the EVs. Even nontraditional stakeholders may be interested in managing the EV charging. The distribution system operator (DSO) can, for example, be interested in influencing the charging of large EV fleets. One reason is that it is benefitial for the DSO that expansions in capacity of the grid can be avoided when integrating large EV fleets.

What is not clearly understood is the actual service the EV user demands. This paper outlines various options to accomodate different services and service levels for the end user that can easily be included in an optimization problem formulation. In this study, the view of a centralized charging management is taken and it is assumed that the CSP can act on the power market, either alone or in cooperation with a retailer, and use the available electricity products and financial instruments to, for example, minimize the cost of charging the EVs.

The paper is structured as follows: Section II describes the basic functions of a centralized charging service provider. Section III outlines the various basic service elements that can be provided to the end user. Section IV shows how these charging service elements can be mapped to a charging optimization problem formulation. Finally, Section V concludes and discusses the service elements presented in this paper.

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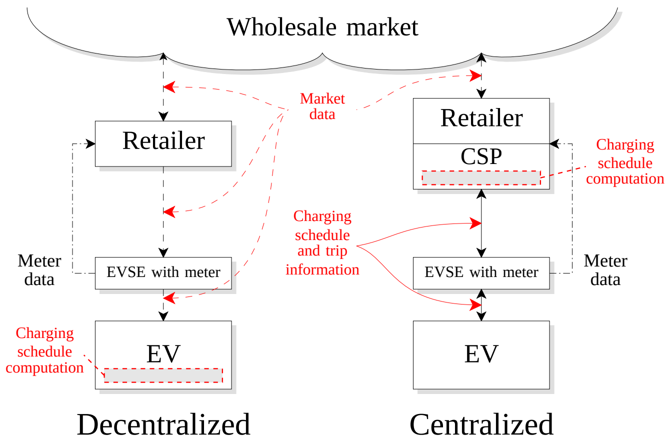

Figure 1. Overview of decentralized and centralized control of charging service. The retailer buys electricity on the wholesale market based on the demand forcast. Either the CSP or the EV computes a charging schedule based on usage patterns and other information.

II. Charging Service Provider

The role of the CSP is to manage the charging of multiple EVs and to leverage the flexibility in the time of charge to lower the total cost of charging. The CSP has a close relationship with the EV users, as well as with the retailer[1] that sells the electric energy to the CSP. The CSP can be structured into a set of basic modules. In this paper, the CSP has the following basic modules:

- *Communication*: To gather data from the various entities (EVs, users, retailer, distribution grid, and markets) an appropriate communication infrastructure must be deployed and managed. A more detailed description of the communication aspects can be found in [8].
- *Data storage*: Using the communication infrastructure the CSP gathers considerable amounts of data to perform its tasks. In particular, historical trip data is needed to predict future EV usage. In addition, end customer information as well as billing information need to be stored.
- *Trip forecasting*: The forecasting of the anticipated energy requirements for EV usage is essential to minimize driver interactions and to accurately acquire the necessary energy from the market/retailer. The CSP has to estimate how much energy has to be charged into an EV while it is connected to the power grid. The connection location also plays a role when handling potential grid congestions. This module evidently depends on the data-storage subsystems.
- *Optimization*: This module computes an optimal EV charging plan, taking into account energy production estimates, energy needs, the expected durations of charging periods, and potential grid constraints. Figure 2 shows a sketch of a typical charging plan. The charging power is given as a piecewise constant signal with a step size Δt. More information on the optimization of charging plans is presented in [9] and [10]. The charging plan is also dependent on the available communication and charging technologies, which is discussed in Section II-A.
- *Customer relationship and billing information*: This is a traditional IT infrastructure for maintaining information on customers, their billing information, as well as the metering of the EV-specific power consumption and feedback, if possible, to the grid. A user-facing portal with a graphical user interface needs to be provided to enable users to manage their charging preferences and personal data and to let the CSP interact with the customer when needed.

This paper aims at connecting the *Optimization* and the *Trip Forecasting* module with the *Customer relationship and billing information* by outlining the various potential charging services and their mapping into constraints and objectives in an optimization problem formulation.

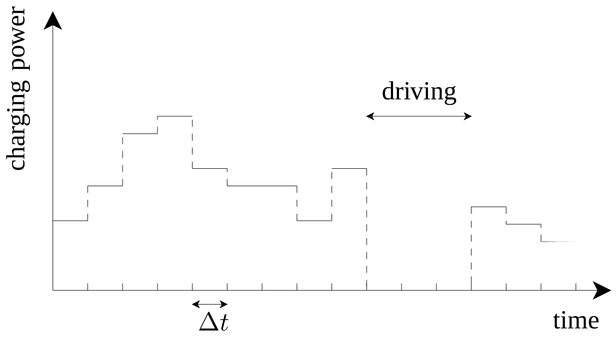

Figure 2. Charging power schedule to be followed by the charger in the EV. It is computed either by a CSP or by the vehicle itself.

A. Level of charging control

The control of the charging can be done in several ways. Depending on the technology available, in terms of both software and hardware, the level of control can be limited. Initially, no direct control of the charging of EVs is possible by an external service provider. This type of charging is a form of direct charging and it may have a severe impact on the distribution grid [11], [12]. Such an unasked-for quick charging is not a response to the user's needs but rather a result of the limited availability of control technologies.

With appropriate technologies, the charging can be controlled in various degrees. The simplest control is to signal a delayed start time of the charging. The charging is continued until the battery is full. Using this limited control, it is only possible to meet the customer needs in the temporal domain. In other words, it is only possible to shift the time when the battery is full and not the final internal energy level of the battery after the charging period. The second level of control is to control the charging with both an on and an off signal. Using this approach, it is possible to individually serve the customers

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[1] This is only needed if the CSP itself is not a retailer. To become a retailer purely for EVs the CSP needs to aggregate a sufficient number of vehicles to meet the minimum bid sizes on the electricity markets.

both in the energy domain and in the temporal domain. The third level of charging control is to have fully variable charging power. The charging power can then vary between the start and the end of charging. This concept is more useful if the maximum charging power is high, because the battery lifetime can be prolonged by reducing the maximum charging power. It also offers the highest flexibility in terms of potential services for the end user.

B. Charging service units

The charging service that the EV user gets can be quantified in different units, such as energy, time, or distance. There is a risk that the end user does not get the energy needed to drive the intended trip. Depending on the service unit as well as the type of service, this risk varies in size and is either is with the CSP or with the end user. The simplest service unit is the amount of energy externally charged to the vehicle. The externally charged energy is measured at the meter level, and this unit offers a low risk to the CSP because the charging control is likely to directly influence this quantity. The service unit can also be the charged energy actually stored in the battery. With this unit the risk is slightly higher for the CSP: It has to estimate the losses during charging for each vehicle and charging period, and therefore incurs an additional risk. Apart from energy, the service unit can be specified in terms of available driving distance. In this case, the CSP also has to estimate the energy consumption per kilometer of each vehicle and each trip, including the charging losses. The service unit can also be the available driving time. This unit is similar to the available driving distance in the sense that the CSP has to estimate a quantity related to the driving behavior of the user, here the consumption per time unit. The CSP then has to estimate the energy consumption per time unit. CSPs can offer their services in one or more of these units. However, it is likely that the higher the risk the CSP is taking in the estimation of the energy needed to be charged, the more the service will cost.

III. CHARGING SERVICES

The majority of the customers of a CSP are the electric vehicle users. This section outlines a set of service elements that can easily be transformed into constraints and objective functions in an EV-charging optimization algorithm. This set can be divided into three types of services:

- Energy services: these services aim at supplying sufficient energy to the electric vehicle during normal operation. There are several levels of user interaction in these services. Sections III-A and III-B focus on these service types.
- Incidental services: these services specify the behavior when something unexpected occurs. These unexpected events can either originate from the end user or from the electricity grid, for example. Section III-C discusses a typical incidental service. Another, grid-related aspect is described in Section IV-B.
- Add-on services: these services are not required and can be added by the user on demand. In Section III-D, various potential add-on services are described.

A. User-defined charging levels

The simplest charging service concept is to let the EV user enter the amount of energy to be charged and the time when the charging should be completed. Hence, the specification is simply

- $E_{\min,k}$: the minimum energy needed to drive trip k
- t_k: the time of departure of trip k

where k is the index of the trip. This concept has the benefit that the user has the most knowledge about the future trips and can, therefore, specify the energy level required in the vehicle at certain times during the day. For example, some users would like to have at least the minimum energy level in battery in the morning and in the afternoon that is necessary to travel to and from the workplace. Two conceptual examples of such energy levels are shown in Fig. 3. Note that the figure shows the regions from where the energy-level specifications cannot be reached as red areas. Because the charging power is limited, either by the EVSE or by the EV itself, the battery energy level must be kept above these red areas.

A benefit with this type of service is the reduced risk for the CSP. The CSP is only required to charge the battery to a certain level. The risk that this energy level is not sufficient for intended trip is absorbed by the user. The drawback of this type of service is that the user needs to be involved regularly in the charging process. This can lead to an overly conservative specification by the user and to reduced user acceptance. The flexibility of the charging process can therefore be reduced unintentionally, and the CSP could have less flexibility in optimizing the charging.

B. Prediction-based charging levels

As indicated in the preceeding section, the performance of a CSP is likely to be linked to the level of manual inputs required by the user. A CSP that can accurately predict the travel behavior of all its subscribers during normal operation can manage the charging without requiring the user to specify the energy levels. In this type of service, the CSP collects travel information from each of the EVs and uses this data to build statistical models for predicting the future trips. In such a service, the energy level specifications, $E_{\min,k}$ and t_k, are predicted values. Conceptual examples of such predicted energy levels are shown in Fig. 4.

The concept of predicting the energy needed to be charged can of course be combined with user-defined levels. The predicted energy levels can, for example, have a minimum level supplied by the user that should always be charged. This would guarantee that at the predicted time of departure there is always a certain energy level in the battery no matter how short the predicted trip is.

If the user is not involved in the charging process and the CSP predicts the trips, then the risk of not having charged enough energy to the vehicle is absorbed by the CSP. However,

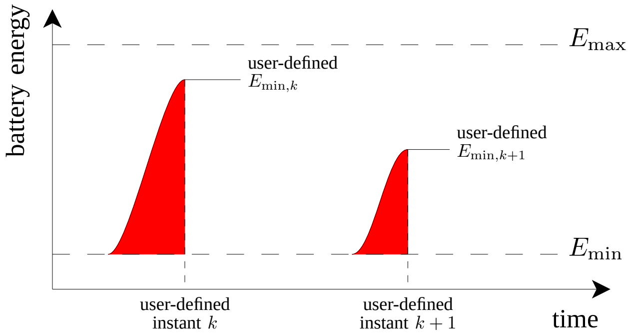

Figure 3. User-defined charging specification of the required charging energy $E_{\min,k}$ before t_k for the specifications k and $k+1$.

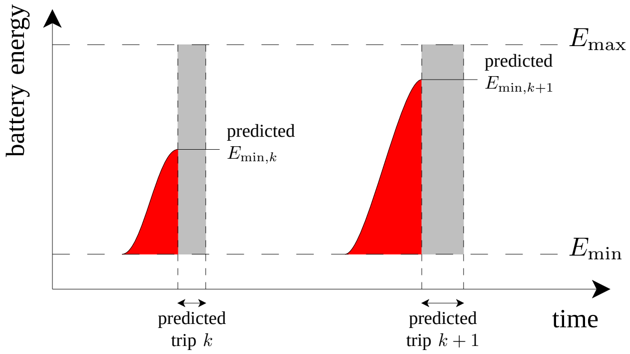

Figure 4. Prediction-based charging specification of the required charging energy $E_{\min,k}$ before the time of departure t_k for specification k and $k+1$.

the CSP needs to be conservative in the charging, i.e. generally charge a higher amount, because if the vehicle is repeatedly charged insufficiently before an intended trip, the user may change the service provider.

C. Quick charge

For all types of charging services, the user must be able to override the initial charging plan and indicate that the battery should be charged as quickly as possible. This service is an incidental service and is only invoked if something unexpected occurs. If quick charge is invoked, the EV is charged with full power until the battery is fully charged or the vehicle is disconnected. To switch on emergency charging, the user could use any mobile device connected to the CSP portal. This option is likely to have a negative effect on the scheduled commitments of the CSP to the market or the retailer. Thus, only a reduced number of such possibilities may be available to the end user. Also, an additional fee for using this option could compensate the negative effects on the schedule commitments and reduce the number of such events.

D. Additional services

In addition to the charging level services and the quick charge service, the CSP can offer a variety of other services. For example, the CSP can ensure that the power used to charge the vehicle has a certain percentage of green energy. The CSP buys the green electricity from its retailer or enters bilateral agreements with other entities in the electricity market. To do this, a labeling framework has to be in place for green energy [13].

The CSP can also provide services to guide a driver to an available charging spot. This service could also direct the driver depending on the energy needed because drivers with a high energy need will need a charging spot with high charging power, and ideally no competing users should be connected to the same area in the electricity grid. However, this type of service requires direct communication with the driver during a trip.

IV. MAPPING SERVICES TO AN OPTIMIZATION PROBLEM

The preceeding section described the various types of services a CSP can offer an EV user. In this section, the focus is on how to map the various charging services to constraints and objectives in an optimization problem aimed at deriving charging schedules, as shown in Fig. 2. This section first shows how a service margin can be added to the service specification, and then how to differentiate between customers in case of a critical event.

A. Service margins

The minimum energy-level specification, especially the levels predicted by the CSP, can be lower than the actual energy needed for certain trips on some days.

There are several sources of such errors, and they can occur both in the energy specification and in the temporal specification. One reason can be that the trip destination, predicted by either the user or the CSP, is wrong. Moreover, even with a correct destination prediction the energy level can be wrong, because of errors in predicting the consumption and the time of departure. To accomodate for these prediction errors, a concept of shifting the energy-level specification can be added to the specification of the charging services. It is a form of charging service margin. Assume that the usable energy capacity of the battery is

$$\Delta E = E_{\text{max}}^{\text{op}} - E_{\text{min}}^{\text{op}}, \tag{1}$$

where $E_{\text{max}}^{\text{op}}$ is the maximum operational energy level in the battery and $E_{\text{min}}^{\text{op}}$ is the minimum operational energy level. Given an energy-margin coefficient $\alpha_{\text{energy}} \in [0,\ 1]$, the energy shift $\Delta E_{\text{mar},k}$ for the k-th specification is

$$\Delta E_{\text{mar},k} = \alpha_{\text{energy}}(\Delta E - E_{\text{min},k}), \tag{2}$$

and, given a time-margin coefficient $\alpha_{\text{time}} \in [0,\ 1]$, the shift in time $\Delta t_{\text{mar},k}$ for the same specification is

$$\Delta t_{\text{mar},k} = \alpha_{\text{time}} \left(t_{\text{min}}(\Delta E_{\text{mar}}, E_{\text{min},k}) - t_k \right), \tag{3}$$

where $t_{\text{min}}(\cdot)$ is the earliest time the specified energy level $\Delta E_{\text{mar}} + E_{\text{min},k}$ can be reached. However, in general, $t_{\text{min}}(\cdot)$ is also a function of the time of connection, which has to be predicted by the CSP or specified by the user. Thus, in the case of predicted charging levels, $t_{\text{min}}(\cdot)$ depends on the predicted time of arrival after the previous trip, $k-1$. In the case of user-defined charging levels, $t_{\text{min}}(\cdot)$ can be estimated by the average consumption together with the energy level of

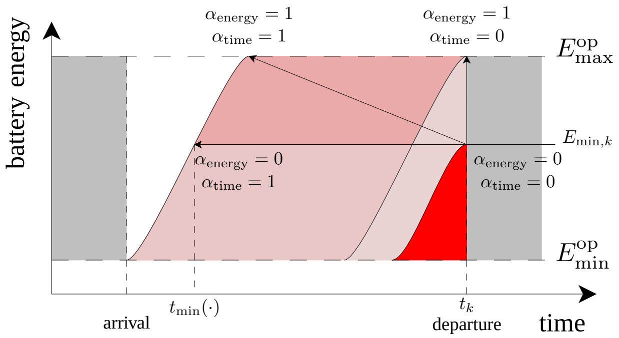

Figure 5. Service margin for the energy-level specification $\{E_{\text{min},k},\ t_k\}$ using the energy-margin coefficient α_{energy} and the time-margin coefficient α_{time}.

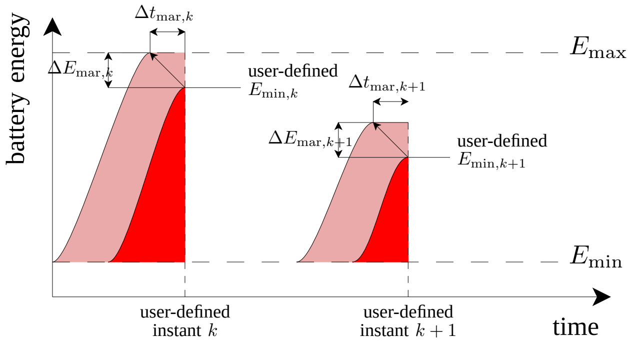

Figure 6. Shifting of the user-defined service level specification based on the energy-marging coefficient α_{energy} and the time-margin coefficient α_{time}.

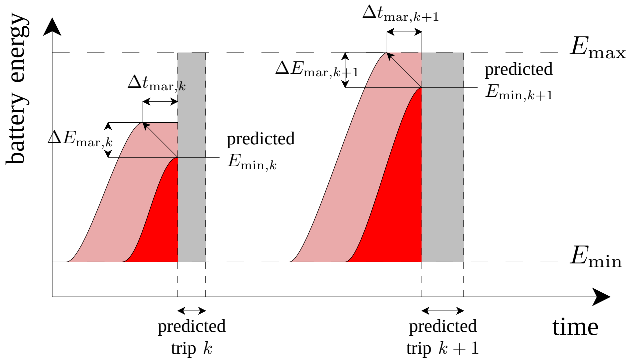

Figure 7. Shifting of the prediction-based service level specification based on the energy marging coefficient α_{energy} and the time margin coefficient α_{time}.

the previous specification at $k-1$. By using the energy and time marging coefficients, it is possible to shift from a direct charging $\alpha_{\text{energy}} = 1$ and $\alpha_{\text{time}} = 1$ to the user-defined or predicted levels $\alpha_{\text{energy}} = 0$ and $\alpha_{\text{time}} = 0$. Figure 5 shows how a charging specification $\{E_{\text{min},k},\ t_k\}$, is shifted using the margin coefficients.

The charging service margins actually change the energy requirements for the EVs in the optimization module of the CSP. The charging constraint for a single EV becomes

$$\sum_{t=t_{\text{arr},k-1}}^{t_k-\Delta t_{\text{mar},k}} \Delta t P_{b,t} \geq E_{\text{min},k} + \Delta E_{\text{mar},k}, \tag{4}$$

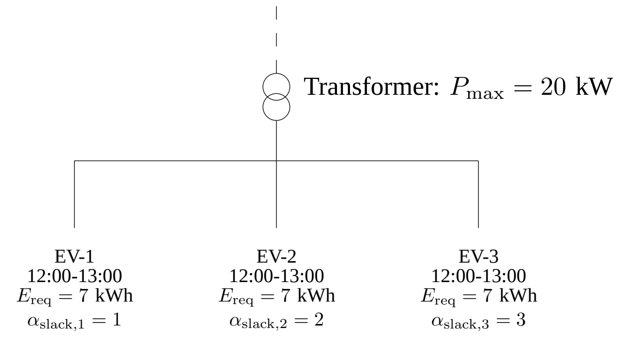

Figure 8. Critical grid situation in which the total requested energy of all EVs exceeds the capacity in the grid. Using the slack variable coefficient $\alpha_{\text{slack},i}$, the EVs are differentiated and a priority is established to distribute the available capacity.

where $t_{\text{arr},k-1}$ is the time of arrival of trip $k-1$ and $P_{b,t}$ is the charging power at time t. This shift in the charging specification is shown in Fig. 6 for user-defined energy levels and in Fig. 7 for energy levels predicted by the CSP.

Using the coefficients α_{energy} and α_{time}, it is possible to specify several levels of service margins. For example, if both coefficients are set to 1 the vehicle will be charged, similarly to nonmanaged vehicles, as quickly as possible until the maximum energy level is reached. Hence, there is no flexibility for the CSP to influence the charging. This service is likely to be the most expensive option. The service cost decreases with decreasing coefficients.

B. Customer differentiation

Even though the minimum energy level, either the predicted level or the level set by the user, has to be met, there might be times when this energy level cannot be reached. For example, when several EVs are parked and connected in close proximity of each other, the electricity grid might not be strong enough to deliver the required energy to all vehicles. In this case, users can have the possibility of getting priority over others by paying a premium to the CSP. To reflect this in the optimization of the fleet charging, a slack variable can be introduced in the minimum energy level constraint. The slack variable is included in the objective function with different coefficients that reflects the priority of the users.

An illustrative example of a critical event is shown in Fig. 8. It shows three EVs each demanding 7 kWh to be charged in the same hour. If the charging could be shifted outside this hour it would no longer be critical. Hence, because all three EVs require 7 kW for the entire hour and the maximum transformer power is 20 kW, in this example, the CSP will have to prioritize between the EVs. This is done by introducing a slack variable and a slack variable coefficient $\alpha_{\text{slack},i}$ in the objective function. The overall optimization of the charging schedules $P_{b,i,t}$ $\forall$ t for all vehicles i is concatenated with the slack variable and coefficient.

$$\underset{P_{b,i,t},\ldots,s_{i,k}\ \forall\ i,k,t}{\text{minimize}} \quad \ldots + \sum_{i,k} \alpha_{\text{slack},i} s_{i,k} \tag{5a}$$

$$\text{subject to}$$

$$\vdots$$

$$\sum_{t=t_{\text{arr},i,k-1}}^{t_{i,k}-\Delta t_{\text{mar},i,k}} \Delta t P_{b,i,t} \ \geq \ E_{\text{min},i,k} + \Delta E_{\text{mar},i,k} - s_{i,k} \tag{5b}$$

$$s_{i,k} \ \geq \ 0 \ \forall \ i \tag{5c}$$

$$P_{b,i,t} \ \geq \ 0 \ \forall \ i, t. \tag{5d}$$

Note that the slack variable $s_{i,k}$ for vehicle i is the amount of energy that is needed to reach the predetermined charging level, including the energy margin $\Delta E_{\text{mar},i,k}$.

The coefficients for the slack variables actually order all the EVs and, in case of a critical event, prioritizes the charging to EVs with a high coefficient. It is not practical to have as many service levels as EVs, so a grouping of levels is necessary. To solve the ordering of the EVs within a group, a randomly assigned coefficient can be used. For example, if there are three service level groups, i.e., low, mid, and high, the coefficients for the EVs only need to guarantee that

$$\alpha_{\text{slack},i}^{\text{low}} < \alpha_{\text{slack},i}^{\text{mid}} < \alpha_{\text{slack},i}^{\text{high}}. \tag{6}$$

The individual coefficients within a group can be ordered using a uniform random distribution that is updated periodically. The grouping is therefore kept, and the prioritization within a group will be fair in the long run.

V. DISCUSSION

This paper presented charging service elements that can be easily mapped to an optimization problem in which charging schedules are computed. The EVs are assumed to only allow control of the charging power, but not of the discharging. However, the services described in this paper are likely to be similar even if discharging is allowed. The service framework is applicable to both the centralized and the decentralized approach of EV charging control.

Even though there will be different services offered by different CSPs, it is likely that they will include at least some of the elements described in this paper. Different subsets of the elements will be used depending on whether the provider offers a high-end service, green-energy service, or a low-price service.

The cost of subscribing to any of the services described in this paper must be lower than the cost of charging at full power whenever the vehicle is connected to the charging infrastructure, i.e., of the direct charging described in Section II-A. Several types of contractual setups can be envisioned. For example, a monthly fixed contract can provide certainty for the end user, whereas a pay-per-charge type of contract can offer freedom of choice in each charging period. A pay-per-charge concept is similar to the traditional gas stations. In a longer-term contractual setup, however, the CSP can collect travel information and therefore better predict the future trips. With a better prediction, the CSP can have a tighter marging in its optimization module and therefore leverage this to lower the charging costs. The pay-per-charge scheme, on the other hand, inevitably introduces uncertanty because new EVs can appear that have not been predicted. Another option for the CSP is to differentiate the service specification for weekdays and weekends. Also, daytime and nighttime can be used to separate different specifications. The coefficients for the energy levels and the slack variables then have different values depending on the time of day and the day of the week.

Charging schedule optimization can potentially also include stochastic elements in the prediction of the future travel behavior. Stochastic and robust optimization techniques need to be further investigated, in particular the scalability of such approaches. Also, an operational CSP is likely to combine all or some of the service elements into various products. This topic is left to future CSPs because it is a key business aspects of the service provider.

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