Bidirectional Charging Management – Field Trial and Measurement Concept for Assessment of Novel Charging Strategies

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***Abstract*—The transition of the energy system to lower emissions and higher shares of renewables inevitably causes an increasing demand for flexibility in order to match generation and consumption. Electric cars can contribute to this flexibility, in particular if they allow for bidirectional charging, which enables them for decentralized provision of battery storage. A research project with several partners from all relevant fields (automotive industry, grid operators, research) is set up that aims to define use cases for the operation of these batteries, which e.g. include ancillary services or self-sufficiency. These use cases are implemented, tested and evaluated in a field trial with a couple of dozen cars, which allows assessing the charge management strategies, the interoperability of developed solutions, the impact on electricity grids on different voltage levels and on the potential cost reduction for the end user as well as from a system perspective. Based on that, recommendations regarding integration of storage from electric vehicles in the energy system, specifically regarding necessary technological and regulatory development, are deduced.**

Keywords—charge management, e-mobility, bidirectional, field trial

I. Introduction

The ongoing transition of the energy system to renewable sources and reduced emissions of greenhouse gases requires contributions by all consumption sectors. Since the transport sector accounts for a substantial share of total emissions [1], measures for abatement of emissions are an important component for the future energy system. Switching to electric vehicles is one of these measures, but is not necessarily economically viable at the moment. The possibility of bidirectional charging, i.e. feeding energy back to the grid or to local consumers from the vehicles' batteries, enables additional use cases and therefore potential additional revenue streams. These applications will be collected, analyzed, implemented and evaluated in a new research project called BDL, which is introduced in this paper, with a focus on the research activities by FfE.

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II. Project Overview

The project BDL involves a variety of participants, tasks and goals. Therefore, a general overview is given in this chapter.

A. Motivation

Recent development in charging technology for electric vehicles (EVs), specifically battery electric vehicles, allow for flexible bidirectional charging and therefore, for utilizing the EV as a storage unit in the energy system. Discharging the EV's batteries and feeding the energy back to the grid or to on-site consumers can contribute to the profitability of the system. Several use cases are possible which utilize this technology. In order to reliably evaluate these, the project is set up to collect, classify and analyze use cases for bidirectional charging, identify promising ones, develop and implement these within field tests or in a lab environment, and eventually evaluate their performance and benefits based both on practical experience and on simulations.

B. Objectives

The overall objective of the project BDL is the development and testing of a holistic, user-oriented way of integration of EVs in the German energy system. Therefore, a strong collaboration of energy transition and e-mobility is investigated and demonstrated. The intelligent interaction of EVs, charging infrastructure and electricity grid contributes to cost-effective and low-emission electricity for EV users. The developed technology supports supply reliability and potentially reduces the necessity for cost-intensive grid expansion. A test fleet will point out customer benefits, industrial feasibility and economic viability of the technology.

This leads to the definition of three main goals for the project, which will be pursued in cooperation of all contributing project partners:

- Development of a working system for bidirectional charging, including vehicles, wallboxes and backend systems

- Contributions to the relevant standardization and regulation
- Establishment of valuable customer benefits through the bidirectional charging process

C. Field Trial

Selected use cases will be evaluated in a field trial with customers. Therefore, EVs and accompanying wallboxes are distributed to a group of pilot customers, which fulfill several criteria like evincing suitable usage patterns, suitability for installation of both a wallbox and a smart meter gateway and approval by the respective grid operator. Additionally, it is assumed that the majority of charging processes of these cars takes place at the installed bidirectional wallbox.

Participants are expected to lease the car and the wallbox, agree to installation of the necessary equipment, partake in surveys for user research and switch their electricity supplier. This field trial allows the analysis of identified use cases in a real-life environment, therefore, it leads to more reliable conclusions regarding the actual implementability, since it does not only consider idealized technical issues. As a result, the developed system can be adapted and revised to overcome the identified challenges and shortcomings.

D. Consortium

The project consortium consists of project partners is led by a manufacturer of EVs with bidirectional charging functionality. Other partners include TSOs, DSOs, a manufacturer of charging wallboxes, a law firm for regulatory issues and several research institutes for user research and for scientific monitoring and evaluation.

E. Timeline

The project commenced in May 2019 and is scheduled for three years in total, therefore, final results are expected for April 2022. After an initial phase of development, the provision of vehicles to participating customers starts after about 15 months in 2020. After successful delivery and installation of the hardware, the actual pilot phase is planned for a duration of about one year.

III. Research Focuses

The activitites of FfE within the project BDL focus on four main research areas. These are explained and illustrated in the subsequent sections.

A. Use Cases and Business Models for Bidirectional Electric Vehicles

The experience aggregated in the research consortium evoked the call for a well-structured process of use case development at the very beginning of the project. As an entirely new technology is developed, it has been agreed upon a series of workshops with the goal of clarifying which use cases should be discussed in detail. To avoid any misunderstandings, the use case development is accompanied by the definition process regarding a consistent business model language.

1) Use Case Selection Process

In order to obtain a list of use cases, which are practicable from an engineering perspective, a selection process was conducted. A use cases is defined as a specific set of actions which yields a beneficial result for the stakeholders [2], i.e. the application of the technology for a specific purpose. The selection process must be collaborative to receive a consensual list of use cases, which have the potential to fulfill the research goals of each project partner.

A first use case workshop was conducted to collect use case ideas and proposals. This workshop involved a brainstorming session, where each participant – all of which represented various partners – was free to develop its own suggestions. Apart from a variety of ideas, the workshop helped to emphasise the necessity of agreeing upon use cases was emphasised as each work package is somehow related to the use case topic.

In a subsequent workshop, a proposed clustering and prioritising was presented and finally agreed upon. As Fig. 1 shows, the generally accepted use cases were clustered by customer group (private or public/commercial) and place of revenue creation. The prioritisation was conducted through a collaborative method, where each participant had a vote. At the end of the workshop, a ranking of relevant use cases was produced. Low-prioritised suggestions were discarded.

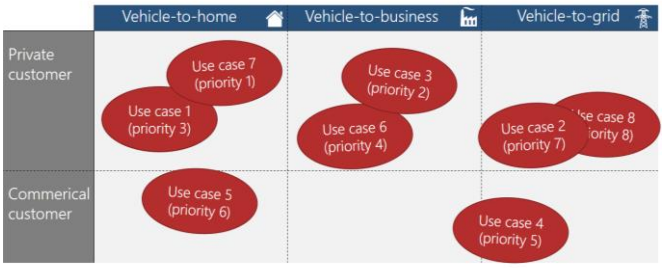

Fig. 1 Exemplary view of the clustering of use cases to be examined

2) Final Choice of Use Cases

As an outcome of the selection process, 13 different use cases are defined and ranked. A user story was developed for each case. The final choice of use cases and their clustering is presented in Table I. The three use cases, which will be tested through trials, are the ones with highest priority. Trials will be conducted through 50 fully-equipped electric vehicles.

TABLE I. Use Cases Analyzed in the Project

Use case name	Revenue creation	Customer group	Project aim
Time arbitrage (intraday)	Vehicle-to-grid	Private and commercial	Trial operation
Increased self-consumption	Vehicle-to-home	Private	Trial operation
Peak-shaving	Vehicle-to-business	Commercial	Trial operation
Primary control provision	Vehicle-to-grid	Private and commercial	Lab operation
Time arbitrage (day-ahead)	Vehicle-to-grid	Private and commercial	Lab operation
Local network service	Vehicle-to-grid	Private and commercial	Lab operation
Redispatch	Vehicle-to-grid	Private and commercial	Lab operation
Provision of reactive power	Vehicle-to-grid	Private and commercial	Lab operation
Tariff optimized charging	Vehicle-to-home	Private	Lab operation
“Real” green electricity (PPA)	Vehicle-to-business	Commercial	Lab operation
Fleet management	Vehicle-to-business	Commercial	Lab operation
Emergency power supply	Vehicle-to-home	Private and commercial	Simulation
“Real” green electricity (CO_2-optimized)	Vehicle-to-business	Commercial	Simulation

These three use cases represent the most promising group for bidirectional electric vehicles, where all customer groups and places of revenue creation are covered. Time arbitrage incorporates electricity trading at the intraday market during times of high price spreads. Increased self-consumption aims on using the electric vehicle as a mean to utilize as little electricity from the grid as possible. Peak shaving covers the reduction of peak loads so that lower grid connection fees need to be payed.

For the majority of use cases, the applicability will be tested in the laboratory at BMW. Most of these uses cases such as primary control provision, redispatch or provision of reactive power are relatively straightforward and thus manageable once the trial operations have been implemented. Others, such as the "real" green electricity use cases, must be tested in a lab environment, as their feasibility is not yet ensured.

The two use cases, which should be analysed only by simulation, represent special cases of high uncertainty in terms of practicability. For this reason, they are examined by various simulations with the objective of proving both their systemic usability and their economic value.

3) Further analysis through business model development

Special attention in the regard of use case analyses should be paid to revenue potential and commercially valid business models for the usage of bidirectional charging. Thus, after establishing the clustered use case ranking and their underlying user stories, the next step is the successive development of use case specific business models.

These business modes will incorporate general content such as a precise business proposition, environmental analysis and stakeholder management plan. More specific topics such as financial planning, staff assignment and risk analysis should also be included [3], [4]. The use case specific business models can be developed through a series of workshops. In a first workshop, a so-called value network consisting of three business model tools is employed to come to a common understanding of the important internal and external business factors. Core business tasks and responsibilities are defined, interfaces and boundaries are set and an accepted business idea is agreed on.

A second workshop subsequently aims on structuring and specifying the developed business model of the first workshop. Through a business model guideline, topics such as the product development, market analyses or financial plan are addressed. As a final outcome, the business model of each use case can be presented as a summarised business case. A crucial step to ensure a viable business case is the assessment of revenue potentials. As many of the use cases target previously terrain, neither empirical values nor best estimates exist in literature. Even if some analyses have been conducted for specific applications, these are subject to uncertainty.

Hence, parallel to the business model development, the revenue potential of each relevant use case is analyzed. First, basic knowledge in terms of market size, profit opportunities, competitors and regulatory is gathered through literature research. Second, a simulative model is developed which generated the potential revenue for each use case. In the model, use cases should be specified by input parameters, so that all discussed use cases can be evaluated by the same model and standards.

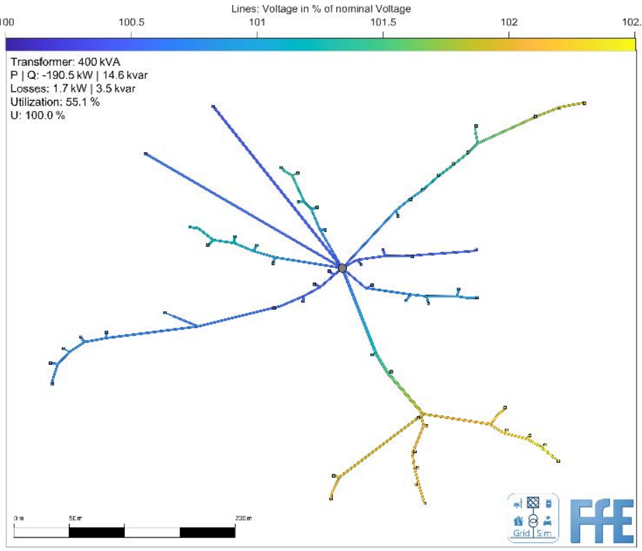

Fig. 2 Exemplary results in a typical low voltage grid

B. Simulation of Effects on the Distribution Grid

The described use cases and business models for bidirectional electric vehicles also have an influence on the distribution grid to which the EVs are in most cases connected via a DC wallbox. Therefore, the simulation model GridSim, a modular simulation tool for detailed 3-phase calculation of low-voltage distribution grids was developed at FfE. GridSim is a small-scale bottom-up energy system model with an integrated load flow calculation model. Within the energy system model, it is possible to define different control strategies for all components. [5], [6]; [7], [8]

The focus is on assessing future challenges and options for distribution grids in the context of the energy transition and increasing number of flexibility options like EVs. GridSim helps to analyze the impacts of new technologies like distributed power resources, battery storage systems as well as high market penetration of heat pumps, PV systems and electrical vehicles. Critical grid conditions such as exceeding voltage tolerance ranges or cable and transformer overloads can be identified and evaluated. Fig. 2 shows a typical low voltage grid and the occurring voltages along the lines for one specific timestep during a simulation.

Within the scope of the project, the model is to be extended for different use cases of bidirectional charging. The goal is to integrate use cases, which are controlled outside the considered grid area, e.g. intraday optimization or systems services, as well as local grid reliefs. Likewise, use cases are to be integrated, whose purpose is the optimization of the own consumption of photovoltaic energy within a property, e.g. commercial enterprise or private building.

These use cases and the corresponding control strategies will be combined with scenarios of the expected share of bidirectional EVs and other components and then analyzed in terms of their impact on the distribution. The following research questions are addressed thereby:

- Which use cases are beneficial for the distribution grid and is it possible to integrate more renewables using bidirectional EVs charging strategies?
- Which share of bidirectional EV providing system services or are participating at wholesale markets is

compatible with the current distribution grid infrastructure?

- From the point of view of the distribution grid, what should be done to reasonably integrate bidirectional vehicles into the grid? What simultaneity factors [9] will arise for the different use cases? Will there be only more energy consumption resulting in higher utilization of the grid which is beneficial for the operating costs, or higher peak powers, which would lead to grid expansions, due to bidirectional charging?

The mentioned questions will be answered using data which is collected during the project and provided by the partners. It is planned to carry out case studies for the various use cases using real grid data as well as synthetic and typical grid data in order to obtain representative results and a deep understanding.

C. *Simulation of Effects on the Energy System*

By modelling the energy system with the linear optimization model ISAaR (Integrated simulation model for unit dispatch and expansion with regionalization), effects of applications of bidirectional charging on the energy system are investigated. These applications are modelled with corresponding constraints, price- and emission-related charging strategies and associated regionalization.

The energy system model ISAaR formulates a mathematic description of the energy system. It can perform a minimization of total system costs, emissions or grid congestions. A detailed description of the input data and the modelling is given in [10].

Therefore, this section deals only with adjustments made within this project. All use cases listed in section III.A. that have a relevant impact on the electricity market or the transmission network are modelled in ISAaR.

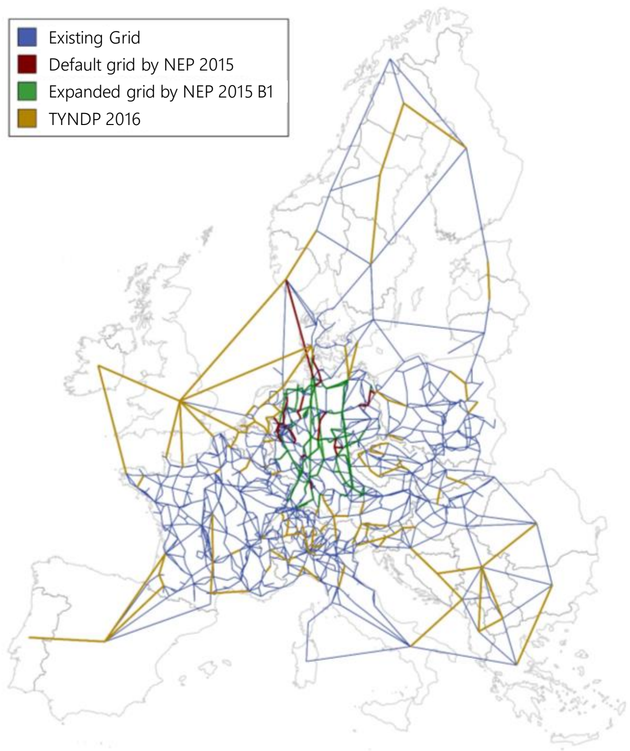

Fig. 3 Transmission grid infrastructure in ISAaR

1) *Input Data*

The mapping of the transmission network in ISAaR is largely based on OSM data [11] and its processing [12], [13]. To map the future transmission network, data from the German and European network expansion plans (NEP [14] in Germany and TYNDP [15] for Europe) are integrated. Fig. 3 illustrates the latest modelled transmission grid infrastructure in ISAaR that will be updated by current data. The greater the distance between a country and Germany, the higher is the aggregation level of the transmission nodes and lines as shown in Fig. 3.

In a second step, the scenario framework for Germany and other European countries evaluated in exchange with the project partners is defined. Investigations of use cases focus on the energy system in Germany. For this, it is necessary to determine the penetration rates of these applications and the parameterization of these (e.g. charging capacities, battery sizes and usage concepts).

Further relevant demand-side data must be obtained. For use cases relevant for business customers, this includes e.g. industrial load profiles as well as employee numbers and employee distributions for simulating the potential of peak shaving in industry.

2) *Methodology*

The energy system model ISAaR is extended by additional elements that have a similar behavior to a storage system:

- Vehicle-to-grid elements by modelling the participation at different markets and offering transmission grid services
- Vehicle-to-home elements by addition of a detailed modelling of household consumers and flexibility options (e.g. heat pumps)
- Vehicle-to-business elements by taking into account industrial or commercial consumption, modelling of peak load dependent grid fees and reduction possibilities

Furthermore, ISAaR models price- and emission-dependent bidirectional charging strategies of bidirectional charging applications for evaluating the impact on the energy system.

In order to evaluate the transmission-grid relevant effect of these applications, they are included in the redispatch cascade. Instead of conventional power plants they can offer redispatch and therefore contribute to a reduction of grid congestions.

3) *Investigations*

Simulations of ISAaR focus on the impact of the described use cases on the electricity market and the transmission grid. Investigations on the grid are carried out regarding various non-transmission-network-relevant charging strategies and charging strategies integrating the offering of transmission grid services.

Since many simulation runs are necessary for the analysis of the different use cases, a uniform processing of the results in a database is essential for an effective scenario comparison. This includes the processing of the resulting data and the extraction from the solution vector of the optimization. Based on the uniform processed data, iterative model calibration processes, scenario comparisons, visualizations and interpretation of the results can be performed based on that.

Simulating the integration of the defined use cases with the energy system model ISAaR results in a quantitative evaluation of a possible positive effects of the bidirectional charging technology on the energy system. Dependent on the applied use case, these applications can have a relevant impact on the energy system.

D. Data Acquisition and Data Analysis

For comprehensive analysis and evaluation of the field trial, a unified data acquisition infrastructure is set up in the project. This provides transparent access for all stakeholders and allows providing a central system for assessment and report creation.

1) Measurement Concept

The project distinguishes between a measurement concept for pilot operation in the field trial and for an actual realization. Since the measurement concept for actual realization depends strongly on the outcome of the pilot operation and therefore is not yet fully foreseeable, we will focus on the measurement concept for pilot operation. The measurement concept for pilot operation consists of two application areas: private and commercial customers. Fig. 4 shows the arrangement of measuring equipment (ME) and the flow of electricity and data for private customers during pilot operation. Red lines indicate power flow, while data flow is represented by black lines. A total of eight measuring devices is installed, of which two are calibrated, which is indicated by a red circle. Five different fields can be identified: customer, household, service provider, electricity market roles and project data server, whereby service provider and electricity market roles are simplified.

Table II. describes the characteristics of the various measuring equipment. MEs 1–7 are installed on the premises, whereas ME 8 is set up at the transformer station. The meters differ mainly regarding their temporal resolution and, as stated before, regarding their calibration status. The comprehensive coverage of relevant measurement points with appropriate metering equipment allows both extensive analyses of the field trial and reliable representation of the considered use cases within the simulation environment.

2) Central Data Acquisition and Processing

Measurement data is collected at various different locations and by several stakeholders. In order to enable all partners to access and evaluate these data, a central system for preparation, processing and storage is set up. This is of particular importance for the research institutes since a comprehensive view of all processes is crucial for scientific monitoring of the developed technology. Therefore, standardized interfaces between the data backends of all relevant participants are to be defined. This allows automated and direct access to the measurement data. After collection of the input data on the central data server also depicted in Fig. 4, several preparation and processing steps are necessary to ensure consistent and reliable data quality.

- Correction and unification of time stamps
- Detection and interpolation of data gaps
- Identification and correction of measurement errors
- Harmonization of data format and units

Besides these measures, automated feedback to the respective operators of measurement points in the event of missing data or potentially defective equipment is implemented. This whole data fusion process is scheduled to be executed at least once a day in order to continuously provide up-to-date data and to ensure quick reaction to occurring problems.

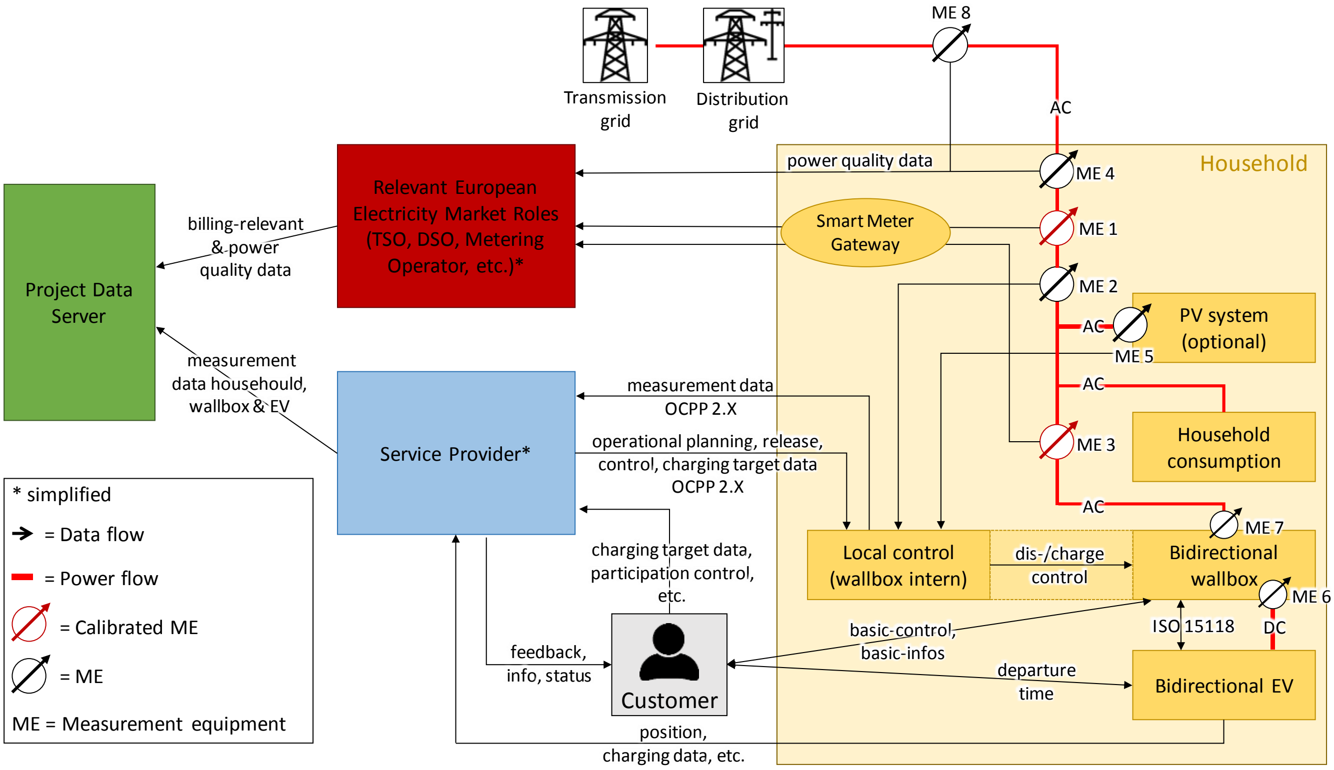

Fig. 4 Measurement concept pilot operation – private customers

TABLE II. CHARACTERISTICS OF THE MEASUREMENT EQUIPMENT

ME	Description	Temporal resolution	Calibr.
ME1	Calibrated bidirectional house meter measuring the amount of electricity consumption and supplied energy. Transmission of billing relevant data via Smart Meter Gateway to the relevant market role.	15 min	Yes
ME2	Bidirectional house meter measuring electrical power in high temporal resolution for local control. Transmission of data via wallbox to service provider using OCPP 2.X.	1 s	No
ME3	Calibrated bidirectional house meter measuring the amount of electricity consumption and supplied energy. Transmission of billing relevant data via Smart Meter Gateway to the relevant market role.	15 min	Yes
ME4	Power quality meter measuring voltage quality at the house connection. Transmission of data to the relevant market role.	At least 1 min	No
ME5	PV system meter measuring electrical power in high temporal resolution. Transmission of data via wallbox to service provider using OCPP 2.X.	1 s	No
ME6	Wallbox intern meter measuring electrical power in high temporal resolution at DC side. Transmission of data to the service provider using OCPP 2.X.	1 s	No
ME7	Wallbox intern meter measuring electrical power in high temporal resolution at AC side. Transmission of data to the service provider using OCPP 2.X.	1 s	No
ME8	Power quality meter measuring voltage quality at the transformer station. Transmission of data to the relevant market role.	At least 1 min	No

3) Data Analysis and Evaluation

Collected data can be divided into the following main categories: forecast, time, electrical measured values, user behavior, and communication. These categories can be further partitioned into subcategories to which measured values are eventually assigned. Time is e.g. subdivided into time duration and point of time. Measured values like dis-/charge duration or plug-in duration are mapped to time duration, while time of plugging in/unplugging or time of tariff change is allocated to point of time.

For every use case a list of possible evaluations is prepared. Afterwards, all measurement values necessary for the evaluations from these five categories are identified and essential evalutations for each use case are determined in cooperation with all stakeholders in the project. Moreover, evaluations concerning more use cases are defined. Since only use cases intended for customer implementation are tested during pilot operation, evaluations in this phase focus on these three.

After deduction of the required evaluations, the actual calculation and plotting routines are implemented on the central data server, processing and analyzing the collected and prepared data described in the previous section. For easy and accessible usage by all project partners, an interactive web-based dashboard for presentation, monitoring and exporting is set up. With this infrastructure, the considered use cases can be analyzed in detail and refined if necessary.

IV. SUMMARY

The described four activities of FfE within the research project BDL contribute substantially to the overall project results. On the one hand, simulations of the interactions and feedback effects of bidirectional charging strategies on both the distribution grid level and the transmission grid level are essential for the assessment of risks and benefits for the energy system. On the other hand, identification, classification and selection of potential use cases for implementation in the field trial or in the lab environment as well as central data collection, processing, evaluation and provision help in finding useful, beneficial, realizable and economically viable applications of bidirectional charging technology for the energy industry.

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