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Toward User-Centered, Trustworthy, and Grid-Supportive E-Mobility Ecosystems: Comparing the BANULA Architecture Against Existing Concepts

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Abstract: Advances in electric vehicles and charging infrastructure technology have given the electrification of road traffic a positive momentum. Nowadays, it is becoming more and more evident that the related energy and financial processes of the current e-mobility ecosystem are reaching their limits. This leads to usability losses for end users as well as administrative and non-causation-based financial burdens on various energy system participants. In this article, use cases are inferred from the literature, the aforementioned challenges are discussed in more detail, and strategies for addressing them are presented. Furthermore, the information system architecture of the BANULA project, with its core elements of open communication standards, virtual balancing areas, and blockchain components, is explained. BANULA addresses the aforementioned challenges by holistically considering the needs of all participants. A special focus of the project is implementing and investigating the concept of virtual balancing areas. This concept has been available since 2020 but has not been implemented in the market yet. To the best of the authors' knowledge, BANULA is the first project that utilizes current legislation to transfer charging infrastructure to virtual balancing areas in conjunction with distributed ledger technology to support related processes. In the first step, the BANULA implementation prototype targets the German e-mobility ecosystem, but applicability to other states in the European Union is planned. Using an independent framework, the BANULA architecture and its prototypical implementation are evaluated. The authors show that the unique combination of virtual balancing areas and the related processes, enhanced through distributed ledger technology, has the potential to contribute to a user-centered, trustworthy, and grid-supportive e-mobility ecosystem.

Keywords: charging; infrastructure; mass market; data acquisition; virtual balancing area

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1. Introduction

Innovations in the field of battery and charging technology have led to increased acceptance and a continuously growing number of electric vehicles (EVs) in road traffic. The cost of lithium-ion batteries has decreased from USD 649 per kWh in 2013 to USD 152 per kWh in 2023 [1]. The global fleet of EVs has increased from 7.2 million in 2019 [2] to nearly 42 million in 2024 [3]. On the one hand, this presents a great opportunity to reduce greenhouse gas emissions. On the other hand, the increasing number of EVs poses challenges to current electric grids on technical, organizational, and process levels. Charging

EVs involves EV drivers and participants from the e-mobility, energy, and financial sectors. Many of today's challenges arise from the present role model and the related distribution of energy-economic responsibilities among the involved roles.

In the context of this article, the roles of the charge point operator (CPO), electric mobility service provider (EMSP), and roaming platform are the most important roles in the e-mobility sector.

CPOs are responsible for building, operating, and maintaining charging points (CPs) that are used by EV drivers to charge their EVs. In order to gain access to a CP, EV drivers require a charging contract with an EMSP. EMSPs offer charging contracts to end users, provide charging cards/apps, and invoice charging sessions.

Frequently, companies take the role of CPO and EMSP at the same time to provide charging services at their CPs to EV drivers. However, if EMSPs want to offer electric power through the charging infrastructure of other CPOs, bilateral contracts or contractual relationships via intermediary roaming platforms are mandatory to provide access to the CP for EV drivers.

From an electric grid perspective, the relevant roles include the distribution grid operator and the electricity supplier. Electricity suppliers sell energy to consumers like companies, households, or CPOs. Electricity suppliers have to project the electricity consumption of their customers for every 15-min interval throughout the day and are financially responsible for the balancing energy required to close the gap between the projections and the real measured energy consumption. Therefore, larger consumers like manufacturing plants have meters that measure the energy consumption for every 15-min interval throughout the day. For a long time, such meter infrastructure was too expensive for smaller consumers. Hence, simple meters have been and are still used to measure consumed energy. Usually, these meters are read only once a year for billing purposes. The shortcoming of this method is that it is not possible to project the energy consumption of an individual consumer, and, consequently, projection deviations cannot be allocated to each 15-min interval.

Distribution grid operators (DSOs) operate electric grids on high, medium, and low voltage levels and connect consumers, like production plants, households, and CPs, to the electric grid. Operating a grid also involves forecasting the energy consumption of all consumers who do not have a 15-min meter infrastructure and taking on the burden of being financially responsible for deviation compensation (balancing energy), regardless of the electricity supplier they use.

The related processes are explained in more detail in Section 4.1. For now, it is important to know that electricity suppliers are only financially responsible for the required balancing power if their consumers have a 15-min sharp-meter infrastructure. If this is not the case, the costs and risks are shifted to the DSO.

In theory, the e-mobility ecosystem, with its roles of CPOs, EMSPs, and roaming platforms, has found appropriate solutions to provide EV drivers with wide access to CPs. Also, the electricity ecosystem has worked quite well for a long time. However, both systems have shortcomings, each on its own, and even more so when considering them together. Figure 1 is showing how the different roles from the e-mobility and electricity sector are currently related to each other and how they work together for EV charging. The shortcomings of this approach are illustrated by the following use cases (UCs).

Even though there are roaming platforms available, in today's e-mobility ecosystem, many EV drivers are forced to or feel the need to have charging contracts with multiple EMSPs [4]. This is because EMSPs do not have contracts with all CPOs to access the charging infrastructure. Consequently, EMSPs' charging services may not be available at every CP. This leads to a fragmented and inconvenient user experience, as described in [4].

The inconvenience is so great that there is a willingness among users to pay for unified access to the charging infrastructure (UC: unified access) [4].

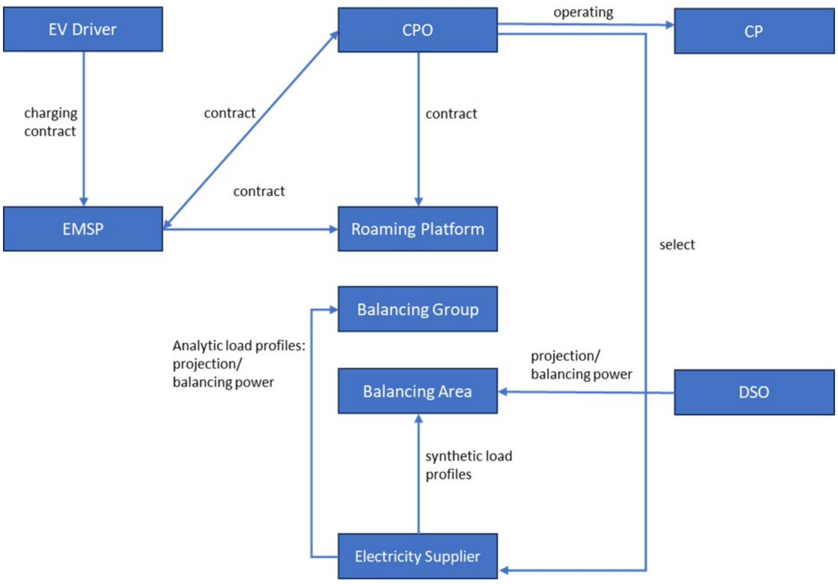

Figure 1. Parties in the e-mobility and electricity sectors that are involved in EV charging.

From a power grid perspective, in Germany, CPOs are responsible for the electricity supply at their CPs. Charging electricity is allocated on a balance to the CPO and its electricity supplier [5]. This means that drivers who have charging contracts with EMSPs can only charge their EVs using the electricity provided by their EMSP if the EMSP is also the CPO of the CP. In roaming operations, where the EMSP and CPO are different entities, the CPO procures the electricity and resells it to the EMSP with a markup that has to be paid by the end customer. In other words, roaming EMSPs bill their customers for the electricity that EMSPs buy from the CPOs providing the CP. In this case, EMSPs cannot make statements or advertise the origin of the billed electricity (e.g., green electricity, cooperative procurement, etc.). Hence, from an energy economics perspective, there must be a relationship between charging energy and its provider, the EMSP. In essence, the charged electricity needs to be allocated to the EMSP (UC: electricity allocation).

Due to the growing number of EVs, the need for balancing energy, i.e., the difference between predicted and actual charging energy, has significantly increased in recent years, as discussed by Enzenhöfer [6]. Figure 2 shows the increasing amount of required delta energy in one of Germany's control areas. Currently, CPOs are responsible for procuring electricity and predicting the charging loads, while EMSPs, respective of their customers, use the charging energy. This creates a responsibility gap between the party projecting and procuring the electricity (CPO) and the party consuming the electricity and causing the deviation between projected and real electricity usage (EMSP). Consequently, the costs of forecast deviations are borne by the CPO. Moreover, since most CPs do not have a 15-min sharp meter, the costs have to be borne by the CPO's distribution system operator (DSO), rather than the party using the electricity that is causing the deviation, the latter being the EMSP. From the authors' perspective, the responsibility for projecting, procuring, and billing electricity should be consolidated into one entity, with all rights and obligations (UC: responsibility).

Studies like [7] have highlighted that clearing houses and roaming platforms have strong market power that can be abused. The German Federal Cartel Office also concluded in [8,9] that CPOs frequently act as regional monopolists. Hence, another use case is fair competition among all parties involved (UC: competition).

Due to the growing number of decentralized components, like EVs, battery storage, and renewable energy sources, congestion management has become increasingly important in today's electric grids [10]. As highlighted in [11], using EVs as flexible assets could become an important strategy to support congestion management. However, the current data fragmentation in electric grid-related applications [12], particularly in e-mobility and energy data structures, hampers coordination between transmission system operators (TSOs) and DSOs [13]. Overcoming data fragmentation between the electricity and e-mobility ecosystems is, therefore, essential (UC: data availability).

EVs have the potential to provide services to stabilize and support the grid, such as balancing power. In the future, these services will be provided by numerous small and anonymous entities, rather than TSOs' large power plants, as they are currently. Building trust with small and distributed flexibilities on a large scale is, therefore, necessary (UC: trust).

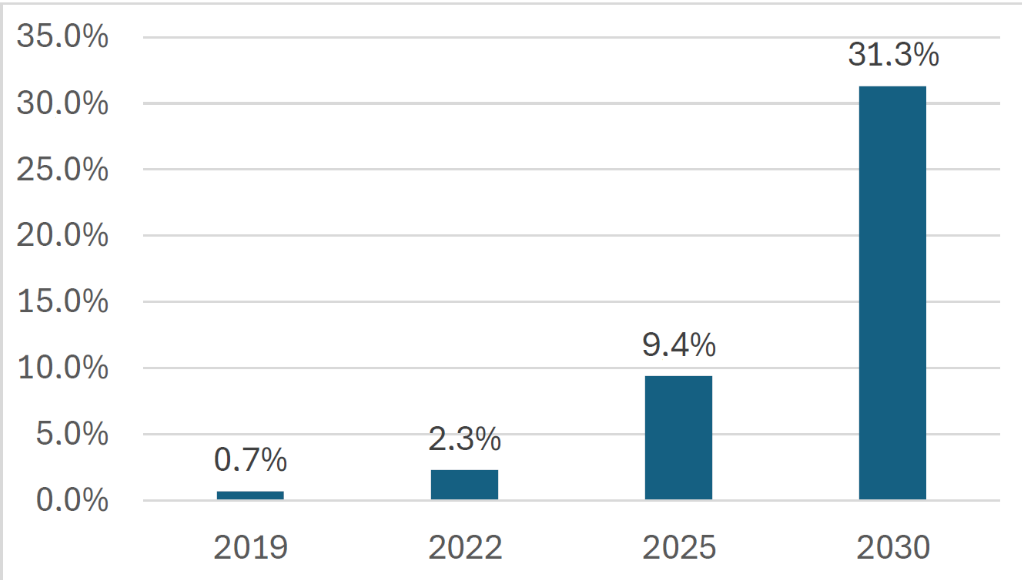

Figure 2. Ratio of model-based delta energy vs. the amount of delta energy in 2019 due to increased EV charging in the control area of the German TSO, Transnet BW, based on data from [6].

This paper is structured as follows. Section 1 provides a general insight into the role models in the e-mobility and electricity sectors. Also, six use cases are defined, which are used in Section 4 for validation. Section 2 gives some background knowledge on the BANULA project, its origin, its organization, and its scientific contributions. This section also shows how the concepts of the BANULA project have been addressed in other scientific contributions. In Section 4.1, we give a general introduction to electricity systems and their organization in balancing areas and balancing groups. Building on this information, we explain the approach of virtual balancing areas and highlight the organizational and technical concepts of the BANULA project. In Section 5, the BANULA architecture is evaluated using the framework defined by Hoess et al. [14].

2. Materials and Methods

In 2020, the German Federal Grid Agency (Bundesnetzagentur) published a concept [15] that seemed appropriate for addressing several problems related to the increasing number of EVs and the related rising loads and processing on the electric grid. The concept was further complemented by [16]. As shown in Section 3, this concept has not been adopted by the market. However, several future members of the BANULA project found that the approaches described in [15,16] were well suited to address the problems currently discussed by experts in the electricity and e-mobility sectors. Possible reasons for the non-implementation of the concept include network effects arising from the simultaneous participation of network operators, EMSPs, CPOs, and other participants in the electricity and e-mobility sectors.

Hence, a group of eight partners established a consortium and applied for funding to support the BANULA project. In the consortium, all market participants involved in EV charging are represented, including transmission grid operators, distribution grid operators, electricity suppliers, EMSPs, roaming platforms, and research institutions. The aim of the BANULA project is twofold. First, the ideas described in [15,16] should be implemented to evaluate the feasibility of the concept within the current legal and regulatory framework.

The second aim of the project is to develop a solution to address challenges that are currently pending in the electricity and e-mobility ecosystems. Therefore, the concepts described in [15,16] should be complemented by further technologies to find a holistic solution.

In regular expert workshops, BANULA project members discussed the problems and related requirements of current electricity and e-mobility ecosystems. In total, six shortcomings were identified, and all of them were confirmed by an extensive literature review.

Several contributions have been published by BANULA project members. A first article to indicate the necessity of addressing the growing amount of balancing power and how it should be managed by the BANULA concept was pupublished by Enzenhöfer [6]. Other important scientific articles closely related to the project include [5,17,18]. These articles focus more on the different roles of the market participants in the BANULA ecosystem. In [18], the first consideration of market participants, along with their adversarial or supportive intentions toward the BANULA ecosystem, was discussed. The article also examined the circumstances under which blockchain (BC) technology might best fit the requirements for the large-scale implementation of the BANULA architecture.

This article extends the authors' work presented in [19] and focuses on the technological aspects of the BANULA implementation and its potential applications. The architecture and a discussion of how the requirements are satisfied by the architectural design can be found in Section 4.

3. Related Works

Albrecht et al. stated in 2018 that there are only very few markets with ready BC applications. The authors investigated the question of "How and by which factors is the implementation of blockchain technologies in energy sector use cases affected?" [20]. A very important aspect of the work by Albrecht et al. was the distinction between different BC technologies and the business areas to which they apply.

Considering the concept of virtual balancing areas (VBAs), two prototypes were developed to test the concept in Germany. In 2022, a prototype was developed within the Rebeam project [21,22]. A group of four companies developed a prototype to test VBA processes in Germany, which has been ongoing since 2023 [23]. Unlike the BANULA implementation, in [23] there was no BC used, which restricted the possibility of business cases. Refs. [21,23,24] remain in prototype status, and none of them have had a significant impact on the German e-mobility ecosystem. Also, none of them were accompanied by scientific investigations or discussions, as is done with the presented BANULA architecture. Aside from these prototypes and the BANULA project, there are no known VBA-related projects.

The evaluation framework used in this paper is based on the work presented by Hoess et al. [14]. However, there are some major differences between their work and the presented BANULA architecture. While [14] remains theoretical, within the BANULA project, a concrete architecture has been developed that will be realized in a prototype during the project's runtime. Beyond this, an operational deployment of the BANULA system is planned after the completion of the research project.

Ferreira et al. [25] proposed and developed an EV prototype system enhanced with Self-Sovereign Identity (SSI) for identity management in a decentralized system, aiming to eliminate the need for charging cards and address interoperability. BC technologies are applied to support the identity management process of users charging their vehicles and to record energy transactions. With regard to the use of SSI, Ref. [25] seems to be more advanced than the BANULA implementation in its current state. However, Ref. [25] requires proprietary hardware for execution and focuses primarily on the relationships between EV owners, EMSPs, CPOs, and CPs. The BANULA approach goes beyond this and considers processes and roles in the broader electricity environment. Both systems utilize off-chain cloud-based storage for efficient BC transactions.

Fluhr and Lutz [26] developed a morphology for use-case types of EV integration into the power grid and instantiated two use-case types. They took a holistic approach and defined four requirements for an information system architecture. Al-Saif et al. [27] presented a literature review on BC applications in EV electricity trading. They defined seven challenges and six opportunities for the use of BC technology in energy trading. From our perspective, these requirements are directly related to blockchain technology and are too technical and narrow a focus for our purposes. Since the BANULA project aims to integrate its concepts, processes, and technologies into the real EV and energy markets, we used an evaluation framework with a broader focus, as proposed in [14].

Although the presented requirements and opportunities have a rather technical focus, Al-Saif et al. [27] pointed out that the implementation of BC technology in the energy sector can be influenced by various technological, social, and organizational challenges. Furthermore, they elaborated on the possibilities of smart contracts in EV applications.

In [28], principles for a 21st-century grid were discussed. According to Bronski et al., a modern grid should be decentralized, recursive, and exhibit private transparency. They emphasized that grids should not only be distributed but also decentralized at both the technical and organizational levels.

4. The BANULA Approach in the Context of the Current Electricity Ecosystem

The BANULA project [29] holistically addresses the problems illustrated in the use cases defined in Section 1. Instead of starting from scratch, the project builds on the existing German legislative and regulatory framework defined in [15,16]. The goal is to evaluate the practical feasibility and economic viability under the current framework conditions. On this basis, weaknesses can be identified, and improvements can be suggested.

4.1. The Current Electricity Ecosystem

To keep the physical grid in balance, monetize the related efforts, and enable trade, electric grids are organized into balancing areas and balancing groups. Physical grid sections are organized into balancing areas, with each balancing area having a metrological separation from neighboring grid sections and one responsible DSO. Within a balancing area, only one load profile method (either synthetic or analytical) is used.

To supply electricity in a grid section, market participants like electricity suppliers or traders require a balancing group within the relevant balancing area. A balancing group is more or less an energy account or table that shows, for each 15-min interval throughout each day, which producers are supplying energy and which users are using it. Every party responsible for a balancing group is required to provide a 15-min projection of its customers' energy consumption and a schedule indicating from which producers the energy is coming one day in advance. The deviation between projected and actual measured consumption is known as the balancing energy. The party responsible for the balancing group is invoiced by the balancing group coordinator, usually the TSO. In the case of synthetic load profiles, the DSO is responsible for paying the balance of energy.

Figure 3 is showing the organisation of electricity grids with the concepts of balancing areas and balancing groups. Due to the harmonization of the European energy systems and markets, these ideas and concepts are more or less the same all over Europe.

In the context of e-mobility, CPs are always linked to the balancing group of the CPO's supplier. If synthetic load profiles are used, the burden of the balancing energy falls on the DSO rather than the CPO. The significant expansion of charging infrastructure and its inadequate representation in synthetic load profiles are placing an increasing burden on DSOs (UC: responsibility).

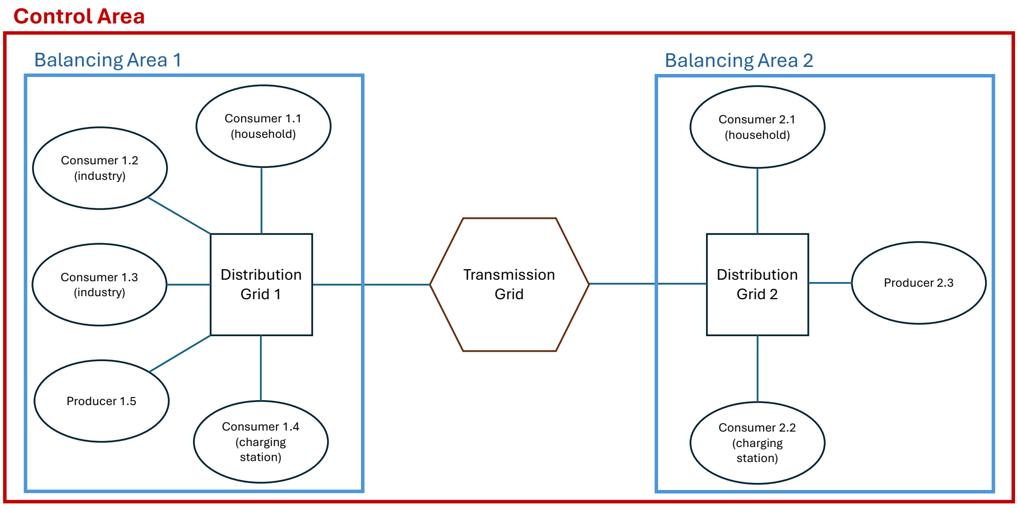

Figure 3. Organizational aspects of the current electricity ecosystem with its concepts of balancing groups and balancing areas. Charging stations are treated as regular consumers.

4.2. BANULA in Terms of the Energy Sector

The BANULA concept [29] is based on the current regulations of the Federal Network Agency BK6-20-160, Annex 6, regarding [15] (English: "network access rules for enabling an accurate energy quantity allocation for electromobility") and the related model specified in the associated BDEW application guide [16]. Referring to this legal and regulatory framework, the introductory use cases in BANULA are addressed by three key elements:

- Grouping all charging stations into VBAs;
- Adapting the role and process model to the e-mobility ecosystem;
- Providing a platform for secure and real-time data exchange between market participants.

In a VBA, CPs within a control area are organized and balanced in a separate grid area with a dedicated grid operator. A suitable measurement infrastructure separates the VBA from the connected neighboring distribution grids. Balancing energy must be managed within VBAs to prevent DSOs from procuring the amounts of balancing energy generated by charging processes (UC: responsibility). Utilizing the concept of VBAs has implications for the roles of CP, CPO, and EMSP.

In the adapted role model, CPs are no longer seen as energy consumers, as it is today; instead, they show characteristics of grid infrastructure components that transmit the charging energy to consumers. In this case, a consumer groups all charging transactions that can be related to a specific charging contract, regardless of where the charging takes place. For CPOs, this means that they no longer bill the charging energy. Instead, they take the role of an infrastructure provider and can charge an infrastructure fee to EMSPs that use the CPOs' charging infrastructure to sell the charging energy.

Access to CPs must be non-discriminatory for all EMSPs. This ensures competition among EMSPs (UC: competition), and for EV drivers, it means the availability of contractually ensured charging conditions at any CP (UC: unified access).

The adjusted role model states that participating EMSPs need a balancing group in the VBA. Once a charging process is started at any CP, the EMSP is identified, and the amount of energy consumed is attributed to the balancing group of the respective EMSP or its supplier. This means that a real change of supplier occurs at the CPs (UC: electricity allocation) and ensures that EV drivers always obtain charging energy directly from their EMSP rather than from the resold energy of the CPO (UC: electricity allocation). Therefore, the EMSP is responsible for projecting and procuring the charging electricity, as well as for procuring the balancing energy. Furthermore, there is the hypothesis that EMSPs have the most suited data for projecting charging electricity, so that consequently the need for balancing power will decrease.

Figure 4 illustrates the organisational aspects of the electricity system in context of the BANULA approach. Table 1 shows the most important aspects of and differences between today's e-mobility and electric ecosystems and how they are redefined by VBAs and the BANULA concepts. A discussion containing more detailed role-specific advantages and disadvantages can be found in Stetter et al. [17,18].

The next section describes the data and process management.

Table 1. Roles and responsibilities within the e-mobility and electric ecosystems: today and in virtual balancing areas.

Role	Today	Virtual Balancing Area
CPO	Responsible for operating/maintaining their CPs; responsible for energy supply. Business model: sells energy.	Responsible for operating/maintaining their CPs. Business model: infrastructure fees.
EMSP	Issues user contracts	Issues user contracts; provides charging electricity; responsible for projecting charging electricity; financially responsible for deviations from projections
Charging networks	Roaming: provides access to CPs of different CPOs	BANULA : provides access to CPs of different CPOs; provides access to charging contracts related to energy
Electricity supply	Related to charging points	Related to charging contracts
Charging point	Electricity consumers	Can be seen as grid infrastructure

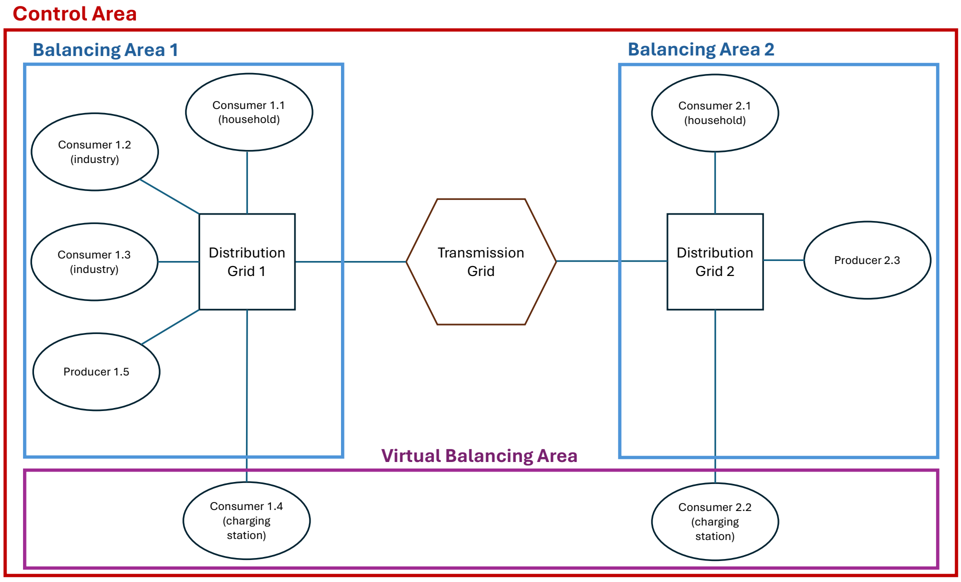

Figure 4. Organizational aspects of the electricity ecosystem with its concepts of balancing groups and balancing areas as it is applyed in the BANULA ecosystem. Charging stations are treated as grid infrastructure components and charging electricity is related to charging contracts.

4.3. BANULA in Terms of Information and Communication Technology

First and foremost, the BANULA architecture was designed from the beginning with the aim of bridging existing IT systems used by market participants in the e-mobility sector with those in the energy sector.

With regard to CPOs, this means that they are able to use their established charging infrastructure with CPs connected via OCPP to their respective charge point management systems (CPMSs). The system is extended by linking the CPMSs via the open charge point interface (OCPI) protocol to the BANULA network to exchange information, mainly charging details records (CDRs) and user authorization data. User authorization data are sent by EMSPs via the OCPI to the BANULA network.

Figure 5 is giving an overview on the communication and information exchange in the BANULA network. It is important to note that the BANULA network is not a central platform but rather a cluster of decentralized components. It contains nodes of the open charge network (OCN) routing the required messages, complemented by a cluster of remote procedure call (RPC) nodes that can be addressed. Based on the data provided by CPMSs and EMSPs, RPC nodes can provide higher-level services to all participants involved. It also includes interfaces to the Ethereum BC and RPC nodes that can provide higher-level business or analytical data. A typical service is the energy allocation and market communication service. It is responsible for assigning the charging electricity to the correct EMSP's balancing group, as well as distributing the balancing group data to relevant market partners such as EMSPs, DSOs, and TSOs. Hence, in the BANULA network, the OCPI serves as a uniform interface for market participants in the e-mobility sector, connecting them with those in the energy sector. Doing so contributes to overcoming the problems of data fragmentation and satisfies the requirement of (UC: data availability).

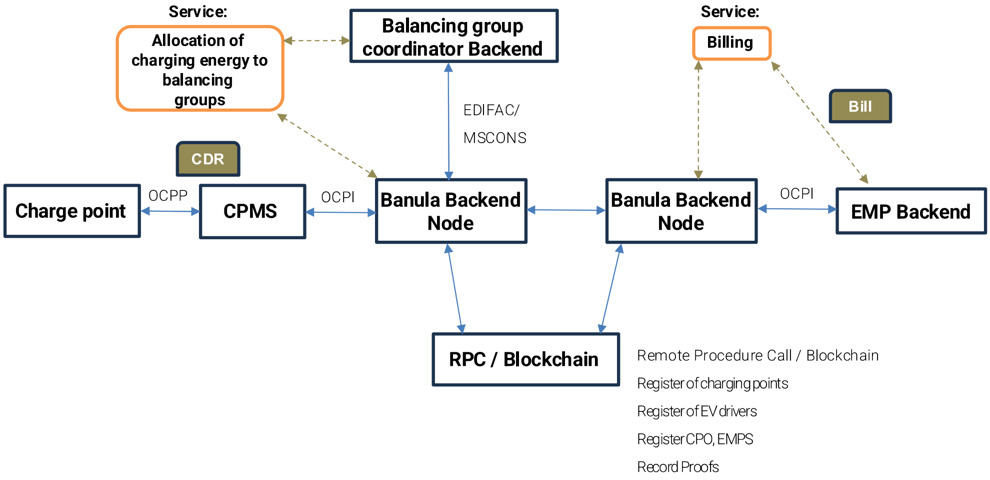

Figure 5. BANULA communication and information exchange overview.

4.4. The BANULA Workflow

In Figure 6 the main ideas of the BANULA workflow are shown. If users want to use a BANULA CP of their choice, they must first authenticate themselves at the CP using either an RFID card or a smartphone app (UC: unified access). Apps provided by EMSPs are preferred. A user who wants to charge his EV at any CP sends a request to his EMSP, and the EMSP backend authorizes the request and sends it via the BANULA OCN nodes to the CPMS and a BANULA verification service. The verification service logs the authorization for the charging transaction to the BC.

At the same time, the CPMS and CP verify the user's credentials and authorize the charging process. Once the charging process is completed, the charging information is sent from the CP to the CPMS via OCPP. The CPMS creates an extended CDR, containing the electricity usage in a 15-min resolution and the EV driver's contract ID. The extended CDRs are sent from the CPMS to the BANULA network using the OCPI protocol [30]. The CDRs are routed by the OCN nodes of the BANULA network to the relevant market participants and services.

The most important market participant that directly receives CDR information is the EMSP, which accesses the CDRs for billing purposes. Additionally, a verification service receives the CDRs and writes hashes of them to the energy web chain [31]. As shown in Section 4.3, this enables data verification and building trust between different participants in the ecosystem (UC: trust).

Finally, the CDRs are sent to the market communication service. There, based on the contract IDs, the received 15-min energy time series of the CDRs are allocated to the identified EMSPs' balancing groups. The market communication service coordinates the communication of the VBA to all related market partners in the energy sector. This is performed using standardized market processes and data exchange formats.

Table 2 is a summary on how the BANULA architecture adresses the different UCs on a technical level.

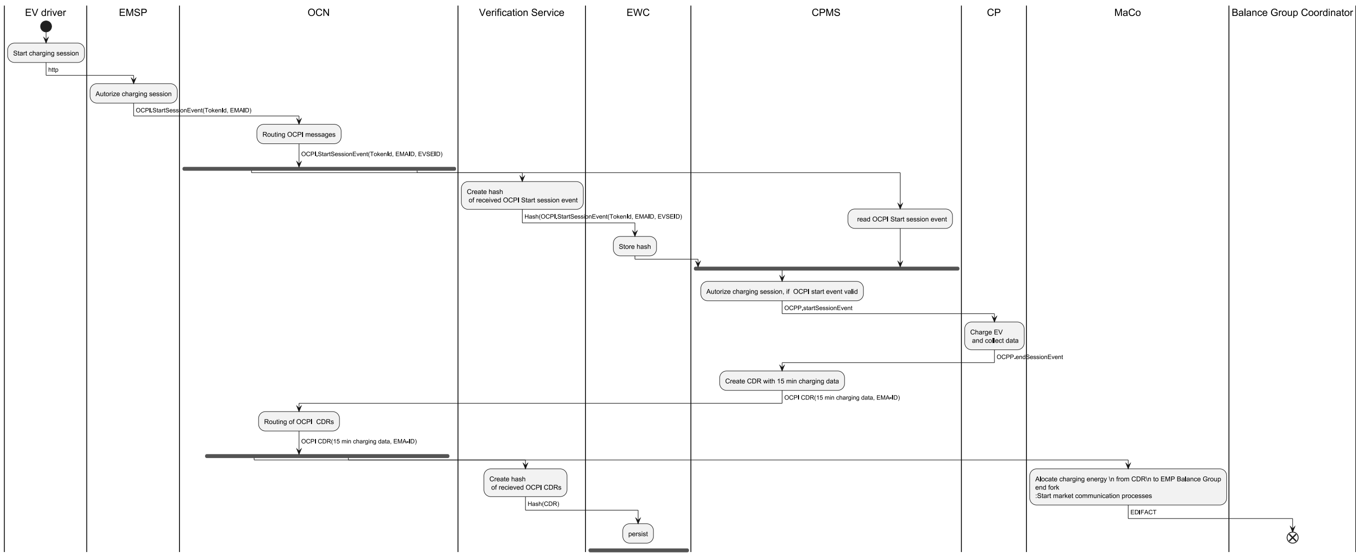

Figure 6. BANULA core workflow.

Table 2. Architectural design and its relationship to requirements.

UC Name	Problem in Current System	Solution within BANULA
Unified access	Many EV drivers have more than one charging card/app due to limited availability of EMSPs at CPs	Decentralized networks and balancing groups ease the access of EMSPs to CPs; one contract at all CPs
Electricity allocation	Used charging energy at a certain CP is always allocated on a balance to the CPO independent of the user's EMSP	EMSPs have their own balancing group to which charging energy is allocated.
Responsibility	Balancing power is allocated to CPOs or DSOs and not to EMSPs	Separation of CPs from distribution grids and grouping them into separate VBAs; EMSPs require their own balancing group
Competition	Low competition at CPs	Non-discriminatory access for EMSPs to CPs
Data availability	Data fragmentation	BANULA network with OCN nodes; interfaces to Ethereum BC; RPC nodes to provide higher-level business or analytical data
Trust	Trust can only be built between large partners that are well known to each other, but not with a huge amount of anonymous partners	Utilizing BC technology for data verification and integrity

5. Evaluation

Our evaluation is based on [14], where Hoess et al. presented six design objectives (DOs) and 18 matching design requirements (Rs) that can serve as a "starting point for researchers to develop a design theory for eRoaming and similar service systems" [14]. The design objectives and requirements were identified via a structured literature review and validated via semi-structured expert interviews. The following section discusses the BANULA architecture in the context of the referenced framework.

5.1. Design Objective 1—Disintermediation

In today's e-mobility environment, the presence of central actors like roaming platforms or clearing houses often carries the risk of the potential abuse of market power and increased systemic costs. Therefore, the intention is to avoid the concentration of market power (R1) by developing eRoaming systems that are independent of intermediaries [14]. The BANULA project addresses this requirement from multiple perspectives.

From an organizational perspective, BANULA is an open-source project [32]. Since the codebase is not controlled by a single organization and can be accessed and modified by anyone who wants to contribute to its development, the risk of vendor lock-in or monopolistic misuse of market power can be avoided. The same applies to the OCPP and OCPI protocols used [30]. Both are open standards with wide acceptance, which allows for greater collaboration and innovation among developers. Building on standard protocols makes it easy for CPOs to connect to and participate in the BANULA network and enables them to leverage its benefits.

In terms of market communication, BANULA is based on the standard MSCONS format, and there are multiple commercial products available to support it.

From a technical perspective, the use of BC technology as a central concept in the BANULA architecture was chosen to enable a distributed data structure. Storing data across multiple network nodes enhances security and reduces vulnerability to attacks. Furthermore, a decentralized network enables communication and avoids dependency on any given party. For example, the roles of CPO, EMSP, or power supplier can deal and communicate with each other without relying on a centralized component, reducing the risk of vendor lock-in.

From a system-level and business perspective, it is intended that CPOs can either operate their own VBA or join the BANULA VBA that will be operated by a BANULA organization. Having one VBA for all CPOs within a control area creates opportunities for both large and small CPOs to participate in the BANULA ecosystem. This means that even small CPOs with a limited number of charging points can join the ecosystem and benefit from its advantages.

For EMSPs, BANULA enables the direct sale of energy to customers (EV drivers) without the need for an intermediary rent seeker as it is in today's ecosystem.

In conclusion, the objective to avoid the concentration of market power (R1) is addressed at various levels within the project, including project organization, technical implementation, and system-wide considerations, making it possible to mark this requirement as fulfilled.

5.2. Design Objective 2—Accountability

Every actor involved in a charging event must be authenticated (R2) [14]. In terms of EV drivers, the BANULA architecture enables the use of common authentication mechanisms. The current prototype implementation supports app-based and RFID card authentication, as well as ad hoc charging with the support of credit or debit card payment options. When RFID tags are used for authentication, the issuing EMSP must provide either a whitelist of acceptable tokens to all CPMS in the BANULA network or authenticate and authorize at the time the RFID card is read at the charging point. Despite being less secure, whitelisting is recommended by the OCPI protocol to avoid waiting times and offer a better user experience.

In the context of BANULA, the preferred method is authentication via an EMSP app. When approaching CPs, EV drivers use a smartphone app to start a charging attempt. The EMSP generates an authorization token. To initiate the charging transaction, the EMSP forwards the authorization token via the OCPI protocol to the CPO and triggers the start of a charging session.

Aside from charging via a contractual relationship between the EV driver and their EMSP, ad hoc charging needs to be supported by European legislation. EV drivers must be able to charge their EVs without a contract at the charging station by using their credit cards or other external payment providers. In this case, authorization is still performed by an EMSP providing ad hoc charging at the CP. However, it is not based on a contract or knowledge of the customer, only on the grounds of securing the needed funds. The authorization event contains a pseudo-anonymous ID to ensure that the charging transaction can be related to the user.

In addition to authorizing charging events, it is also necessary that, in the case of misuse, cancellation, or expiration, an EMSP can revoke the permission and the respective contract (R3) [14]. Since every charging session in the proposed BANULA network needs to be authorized by an EV driver's EMSP, the authorization can also always be revoked by the EMSP. If pre-authorization (whitelisting) is used, the authorization can be removed by sending a new invalid authorization token. When using app authorization, the EMSP can choose not to send a valid authorization token; as a result, the charging session cannot be initiated.

Once a charging transaction has taken place, reliable eRoaming must also ensure that charging events cannot be declared invalid retroactively [14] due to non-repudiation or data integrity (R4) [14]. In the BANULA network, only digitally signed messages are accepted by the different nodes. Upon submission of a message, the signatures are validated against an entry in the BC registry. Additionally, data integrity may be ensured by storing the hashes of events or CDRs on the BC. Every participant who has access to the original CDRs now has technical proof of the correctness of the CDRs and no longer relies solely on trust.

Storing the hashes of events on the BC not only allows users to verify the amount of charged energy but also enables many other use cases. For example, authorization tokens issued by the EMSP are part of the start session command, which is also sent via the network. Hence, the authorization of the charging session by the EMSP can be proven by the CPO. Since CPOs have received the tokens from the EMSP, the EMSP can no longer question the responsibility for a charging process. Consequently, CPOs can charge service fees to EMSPs, and the allocation of charging energy to the EMSP's balancing group cannot be contested by that EMSP.

Additionally, when storing the hashes of the CDRs on the BC, they are used and structured as Merkle Trees. This allows for verification that a specific 15-min series of a charging process is included in a balancing group's daily aggregate time series. Moreover, the same kind of Merkle proof can be used to verify that the sum of all energy charged in a 15-min time interval across all EMSPs of a particular charging station, along with its default self-power, is equal to the meter operator-measured energy at the grid connection point.

In summary, the use of the OCPI authorization mechanism fulfills the requirements for authorization (R2) and the possibility to revoke the permission and the respective contract (R3). The integration of BC technology satisfies the requirement for non-repudiation and data integrity (R4). Hence, all requirements from the design objective "accountability" are met.

5.3. Design Objective 3—Efficiency

For the sake of economic efficiency, end-to-end process automation (R5) [14] is inevitable.

In the BANULA architecture, the whole process, from the first user contact at the CP to the final steps of distributing the EMSP's balancing group data, is based on standard protocols, such as OCPP and OCPI, and for the prototype, the German standardized electricity market communication protocol. As shown by the first prototype, integration with payment providers is also possible, closing the circle for the user.

From the authors' point of view, standardized, machine-readable information exchange between CPOs and EMSPs (R6) can also be considered fulfilled by the process chain described in (R5). Using the quasi-standard OCPI for data exchange between CPOs and EMSPs enables not only automated data exchange but also the continuous utilization of existing processes.

In addition, for interoperability reasons a standardized ID schema (R7) [14] is essential. In the first prototype, EMAID [22] was used to identify charging contracts sent via OCPI. The next step in the BANULA project will involve the use of digital identities as defined in [33] and digital signatures. However, one shortcoming of OCPI is that the used message field is too short to hold a Decentralized Identifier (DID). An alternative approach could be to use a separate protocol to enable authentication [21], as used in the Rebeam project [24]. However, BANULA aims to have an integrated approach within the OCPI protocol.

DIDs serve as the basis for trustworthy public registries (R8) [14]. Hoess et al. [14] highlighted the fact that public registries "can additionally provide information on certified charging points". In the BANULA system, a registry with master data on the BC contains DIDs and other metadata about different market participants, such as CPOs, along with their charging points, or EMSPs. The goal is to choose trustworthy partners and to provide possibilities for secure and reliable data exchange by making use of DIDs.

In addition, in terms of registries for market participants, other registries are also under discussion. The stored data can serve as a basis for further services or smart contracts. Examples include pricing/tariff registers so that EMSPs can publish their pricing structures and users can verify the correct prices when charging their EVs.

Location services with information about charging station availability can be used by users to find appropriate charging stations. In future versions, smart contracts can be applied to verify CPOs' promised availability of their CPs.

To this end, we can state that all requirements in this design objective are met.

5.4. Design Objective 4—Data Protection

There is no doubt that eRoaming solutions should comply with data protection regulations, such as the GDPR or the CCPA, and that correlations between personally identifiable and charging-related information beyond information required for eRoaming should be avoided (R9) [14].

This requirement is addressed in the BANULA data concept using pseudo-anonymous contract ID numbers and market location IDs. Only market participants with a legitimate need to know are able to relate these IDs to specific users, typically participating EMSPs.

However, pseudo-anonymous data alone are not sufficient. It is also important that the confidentiality of sensitive data is ensured (R10) [14] and that only authorized entities are able to access charging-related information, as data minimization based on the need-to-know principle (R11) can, for instance, help CPOs and EMSPs only receive information that is directly relevant to authentication and billing [14].

In the current BANULA implementation, only the hashes of CDRs are written to the BC so that data can be verified, but the original data remain with the directly involved parties. Therefore, sensitive information, for example, regarding which identity charges how much, and where, is not stored on-chain. This fulfills (R10) and (R11).

To avoid the centralized storage of data (R12), the BANULA architecture was designed from the beginning with a focus on decentralized structures. CDRs are exchanged between partners using the OCPI protocol [30], and the energy web chain [31] is used as BC technology to store the CDR hashes. Sensitive data about charge details may be stored by the respective market roles and may be exchanged only between related market partners.

In summary, all requirements in this design objective are addressed by an appropriate data structure on the BC.

5.5. Design Objective 5—Usability

Targeting a wide user group requires that eRoaming solutions be easy to use and require at most as many user interactions as traditional charging systems (R13) [14].

This requirement can only be partially evaluated, as it also involves systems from external participants, such as CPOs and EMSPs, and the BANULA architecture can only provide the required interfaces and organizational framework. The main idea is that EV drivers can bring their own contracts to the charging station and use them with one card and/or app. Consequently, by having only one contract and bill, the system becomes easier to use.

In order to counteract user reservations against BC, the BANULA implementation simplifies the signing-up process through the concept of account abstraction [34]. Instead of using wallets secured with cumbersome seed phrases that are typically used in the BC context, the BANULA wallet integration enables authenticating and restoring access using either the username or password. These concepts from the Web 2.0 environment are well known and understood by a wide range of user groups. Using an e-mail account for authentication facilitates the recovery of an account or wallet [34]. However, as mentioned above, signing up for an EMSP's respective charging contract involves the EMSP's customer registration process, which is outside the scope/control of the BANULA architecture.

Another requirement is the principle of one face to the customer (R14). That is, seamless eRoaming should be possible using a single contract, app, or RFID card [14]. This requirement is identical to the use case of unified access. It is addressed by the core concept of VBAs and the idea of a real supplier change at CPs. This goes hand in hand with the paradigm shift away from assigning charging energy to CPOs and instead to the user's EMSP's balancing group. Users can use RFID cards and/or apps for authentication at CPs provided by their EMSPs. If there are appropriate offers, the same contract can be used both at home and for public charging. It should be noted that this requirement is very narrow. The possibilities enabled by the real supplier change at the CP enable many more business cases than simply bringing one's own contract to a different charging location. This topic is elaborated on in more detail in (R17) below.

For a good user experience, factors other than onboarding or the charging event are important. Price transparency is also important. This includes non-discriminatory pricing and transparent communication of tariffs (R15) [14]. In the BANULA ecosystem, there are mainly two pricing components visible to the user: one related to the charging energy determined by the user's EMSP, and one determined by the CPO whose infrastructure is used. Information about both components is included in the CDRs based on the standard OCPI format, which can be made available to EV drivers and EMSPs responsible for billing the charging contract. For example, a tariff for net energy usage and a tariff for a parking fee could be applied.

Considering all participants in the ecosystem, eRoaming systems should be easy for CPOs and EMSPs to apply and require no more implementation effort than current solutions (R16) [14].

As mentioned before, the BANULA architecture extensively utilizes standard protocols like OCPI and OCPP. Although the intention is to minimize additional effort, adding new features or improving functionality and interoperability may require some additional effort.

In addition to the technical feasibility, the flexibility of eRoaming solutions to grant business model independence (R17) may also help the innovation and adoption of eRoaming [14]. From our perspective, this is more of an organizational issue than a technical one. Using OCPP and OCPI for communication allows the transmission of not only energy time series but also tariff data in CDRs. This is important for developing business models. In general, the BANULA network is a means to exchange data but does not impose restrictions on how EMSPs utilize their balancing groups. Giving EMSPs full flexibility in managing their balancing groups in conjunction with the verification possibilities of the BC enables a wide spectrum of business cases. For example, using the two concepts together makes it possible to relate the electricity input and output to each other. This makes it possible for EMSPs to provide a charging service that relates solar power from home to an EV driver's charging process at any CP. In another use case, it is possible that EMSPs verify that only green energy is used for charging.

The architecture lends itself to fostering an ecosystem of further business cases. Many value-added services may be built by leveraging the open interfaces of the standard protocols and using the decentralized infrastructure. Examples of these services could include data visualization or forecasting services.

To this end, we can state that all requirements in this design objective are met, apart from (R13) and (R16). Both requirements can only be partially evaluated because they involve EMSPs as external parties and are at the edge of the system.

5.6. Design Objective 6—Scalability

A major focus of the BANULA project is integrating into the current e-mobility and energy system landscape. Hence, the requirement stated in [14] that "eRoaming systems should also consider their scalability to handle at least as many transactions as centralized eRoaming systems (R18) without outages or long response times" is crucial. It is important to note that the evaluation of this requirement is still ongoing. However, certain design decisions have been made to address it.

First, the architecture is built on established and well-understood protocols, like OCPI and OCPP, so that CPOs and EMSPs are familiar with the daily operation and can use their existing and already optimized technical infrastructure. A major concern and lesson from related works is the slow transaction speed of current BC systems. Being aware of this architectural design, decisions have been made. Hence, only data with rather slow modification ratios, such as master data, are stored on the BC. In contrast, data that are expected to be large in volume and transaction ratio, such as energy and charging time series, are stored off-chain, with only their hashes stored on-chain. This approach ensures data integrity while reducing the load on the BC system.

So far, it can only be stated that the design process has addressed this requirement, but the final evaluation can only be performed through a large-scale field trial. Such a trial is planned for the first half of 2025.

5.7. Evaluation Summary

To this end, it can be stated that by far the majority of the requirements defined by Hoess et al. [14] have been met. Only (R13) and (R16) in DO 5 cannot be evaluated because they involve EMSPs as external participants, so the processes are not completely known. Also, scalability (R18) can only be theoretically evaluated. From a theoretical perspective, appropriate measures have been taken; however, practical proof must still be provided. Therefore, further progress in this project must be made.

6. Summary and Future Work

In this paper, we identified six use cases with their associated requirements that cause problems at the intersection of the current e-mobility system and the electricity system. We presented the BANULA architecture, which aims to address these requirements by making use of the concept of VBAs. We presented an approach that not only provides EV drivers with access to charging points, as in today's roaming systems, but also allows them to bring their own contracts and EMSPs to the charging station.

From a research perspective, this paper primarily focuses on the theoretical evaluation of the BANULA architecture. It was shown that all initially defined use cases and design objectives have been addressed on a conceptual as well as on a technical level by the BANULA architecture. However, the discussion needs to be complemented by legal and economic perspectives, along with appropriate use and business cases. Moreover, some aspects must be evaluated in field tests. One such hypothesis is that EMSPs can make better projections than CPOs. The continuation of this hypothesis is whether the reduced necessity for balancing energy is significant enough to impact overall grid fees.

In addition, there are organizational and techno-organizational aspects that are yet to be judged. With the current prototype, only a very limited number of charging transactions have taken place. Hence, it has not yet been shown that the required processes related to VBAs are working as expected on a large scale in everyday business. The interpretation of the regulatory framework with regard to the required metrological infrastructure is also essential. From the perspective of the current project, it must be stated that a strict interpretation of current metrological guidelines can be prohibitive to the whole idea of VBAs.

The organizational validation of processes on a large scale and of different metrological concepts will be an integral part of the upcoming field test, which will be conducted in 2025. CPs will be available in at least three out of the four control areas in Germany. There will be a fleet of 15 EVs for testing purposes, and a roadshow through Germany will be conducted to demonstrate the cross-control area availability of the system. Besides the CPs at the locations of BANULA project members, there will be collaborations with at least three external CPOs to build up test CPs.

Another topic to be addressed within the project is assessing the applicability of the BANULA concept to other regulation frameworks, mainly in the European Union. The underlying protocols such as OCPP and OCPI, which form the technical foundation, are widely used throughout Europe. Also, the format MSCONS has a common international base with national adjustments. Moreover, the European electricity market is becoming increasingly integrated from an organizational perspective. For example, Tennet, one of the active TSOs in Germany, also operates as a TSO in the Netherlands and Belgium. This provides a solid foundation for transferring the BANULA concept from the German market to other European countries.

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Abbreviations

The following abbreviations are used in this manuscript:

VBA	Virtual Balancing Area
MSCONS	Metered Services Consumption
CPO	Charge Point Operators
CP	Charging Point
EMSP	Electric Mobility Service Providers
UC	Use Case
DSO	Distribution System Operator
TSO	Transmission System Operator
BC	Blockchain
OCN	Open Charge Network
CPMS	Charge Point Management System
OCPP	Open Charge Point Protocol
OCPI	Open Charge Point Interface
RPC	Remote Procedure Call
CDR	Call Detail Record
RFID	Radio Frequency Identification

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