Mobility in the smart grid: roaming protocols for EV charging

Mobility in the Smart Grid: Roaming Protocols for EV Charging

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***Abstract*—While most smart grids approaches assume that the user consumes services in a fixed location, the case of charging Battery Electric Vehicles (BEVs) adds an interesting mobility dimension. Drivers increasingly need to rely on public charging facilities, and given local grid conditions, such facilities often cannot offer their services without smart charging and tight integration in the smart grid. In analogy with mobile telecommunications, stakeholders in the field of EV charging have developed EV roaming protocols to allow for a mobility dimension, and, for some, add smart grid integration. However, this development is still in its early phase, and in Europe, there are at least four different, mutually incompatible protocols in use. In this paper, we investigate the history of these protocols, their characteristics – especially in relation to the smart grid – and investigate their openness and neutrality. We then explore scenarios for future development towards a single standard, also taking the regulatory dimension into consideration. We end with a reflection on the development of standards for the smart grid.**

***Index Terms*—EV charging, EV roaming service, protocols, standards, OCHP, OICP, eMIP, OCPI, IEC 63119.**

I. Introduction

SMART grids integrate electrical grids and communication infrastructures and form an intelligent electricity network working with all connected components. As such, they enhance the overall efficiency of power grids and help to realize sustainable electricity supplies [4]. In such smart grids, interoperability is increasingly becoming a cross-sectoral challenge [5], in which communications technologies play a key role [6]. In most current smart grid approaches, the user's location is fixed, such as its home or office location. Yet, users themselves are mobile, which can have implications for energy services smart grids as well.

Charging Battery Electric Vehicles (EVs) is a case in point. Currently, most EV drivers charge their vehicle at their own home, typically using a privately installed charge point on their private driveway. Highway fast DC charge points complement their charging needs when driving larger distances. However, as the adoption of Battery Electric Vehicles (BEV) goes forwards, more and more users do not have such an option, because they have no private driveway. To charge their car, they need to use a public curbside charger in the neighborhood they live in, charging facilities in the garages of their flats or multi-dwelling building, at their offices, or public parkings. Here, several challenges arise. Firstly, as these are shared charge points, how do billing and accounting take place? While direct payments with bank cards etc. may be suitable for occasional charging at a highway fast-charge point, such an approach is, for various reasons, likely not feasible for everyday charging (see at IV, below). Secondly, multi-dwelling buildings, parkings, and clusters of curbside chargers seldom have a grid connection that would allow all users to charge their car at the maximum rate at the same time. This calls for demand management and smart charging. EV electricity demand can be managed through smart charging, which implies managing the EV charging process to optimize for collective needs (e.g., local grid capacity) and/or individual preferences of EV owners (e.g., charging when local solar energy production is high) [7]. It differs from regular charging, whereby the EV charges at maximum capacity until its battery is full. Smart charging requires tight integration of these charge locations into the smart grid, but also opens up interesting opportunities for solar-powered charging, such as in [8]. Thirdly, especially in flats or multi-dwelling buildings, a fleet of EVs offers promising Vehicle to Grid (V2G) to deliver stored energy back to the grid, or grid balancing services [9], [10]. Also here, forms of coordination are required, and integration into the smart grid is needed. Fourthly, even though the number of public charge points is growing at a high pace [11], users may have difficulties finding spots that are not yet occupied, that offer energy at prices they are willing to pay, that use truly green energy, etc. This calls for information availability about charge point status and future availability, real-time price information, local energy sources, and more.

These challenges can be addressed through roaming for EV charging, already identified as a solution for smart charging in a 2014 review of EV-integration [12]. Roaming is supported by roaming protocols for data exchange between parties connected to different charging networks. Thereby, they allow drivers to use charge points at different locations and exploited by different operators. Ideally, EV drivers can, with a single

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contactless Radio-Frequency Identification (RFID)/Near Field Communication (NFC) chip card – or via a communication protocol in the charging connector itself – and a subscription at a mobility service provider (MSP), pay for their services, make choices for (green) energy, express their charging needs and preferences, and more. When drivers plug in their EV at a foreign charging network, their MSP can communicate these preferences to the local charge point operator (CPO), allowing smart charging and V2G to take place based on user preferences. Furthermore, optimal roaming protocols should allow charge point operators to communicate recommendations on where and when to charge based on grid conditions.

However, the current situation does not reflect this optimal case. As of today, there are four mutually incompatible EV roaming protocols in common use in Europe, and there are still a number of 'islands'. Hence, drivers often need take out subscriptions at multiple mobility service providers in order to connect through roaming to any charging facility. The lack of interoperable roaming standards is also identified as a hindrance for the adoption of BEV by the 2022 Report of the Intergovernmental Panel on Climate Change (IPCC) [13]. Improved interconnection between all service providers and charge point operators has the promise of seamless usage, much like we know it from mobile telecommunications services (2G to 5G). Such improved interconnection, however, also calls for interoperability between the protocols in use, or the adoption of a single, harmonized protocol.

Such challenges can be addressed by the development of the EV roaming protocols that are the focus of this paper. To provide insight in how such interconnection can be improved, we study the history, technical characteristics, and governance of these protocols. We pay special attention to how the origins of the protocols are reflected in their technical design, which is particularly relevant for their neutrality towards EV charging business models, and to the degree they support smart charging and vehicle-to-grid functionality. As the current EV roaming market is immature, we can expect it to be organized differently in the future. We explore the future of EV roaming by discussing scenarios for future development of protocols for EV roaming, also taking the regulatory dimension into consideration. We end with a reflection on the development of standards for the smart grid.

While our paper directly contributes to the literature on EV charging, we believe our analysis and findings are also relevant in a wider context, as end-users will increasingly use (energy) services away from their home (car-based or otherwise), and thus energy systems will increasingly need to take the mobility dimension into account in their design. This paper demonstrates to what extent current roaming protocols already support this mobility dimension, how the interconnection in the field can be improved, and the role of standardization dynamics, regulation, and market structure in shaping communication protocols on which smart grids are based.

The remainder of this paper is structured as follows: The following two sections discuss the scope of our investigation and our methodology. Section II discusses how EV roaming standards relate to the smart grid, and provide both opportunities and challenges. Section III presents and compares current EV roaming protocols. Section IV discusses the governance of the protocols and the degree to which they can be considered open standards. Section V briefly discusses direct payments as an alternative to roaming. Section VI presents stakeholder views on scenarios for the future of protocols for EV roaming. Section VII discusses the role of regulators in standardization processes in Europe. Section VIII concludes the paper and discusses the significance of this work.

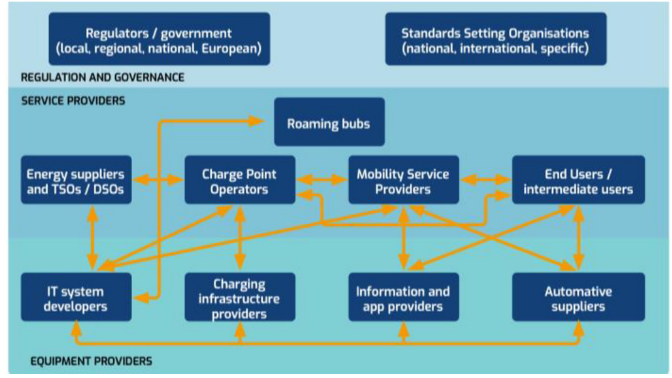

Fig. 1. Market involved in the whole value chain roles and connections in the EV ecosystem.

A. Scope of This Study

In our study, we focus on what is increasingly referred to as 'EV roaming service system' [14]. In essence, this refers to a system where an EV driver has a relation (e.g., a subscription) with a Mobility Service Provider (MSP), while the actual charging may also take place at charge points exploited by different parties, known as Charge Point Operators (CPOs). Just like in mobile telecommunications, EV roaming services may also engage intermediate parties, such as roaming hub or clearing house. The value chain does also involve other stakeholders (Fig. 1), that all play an important role, but may or may not be directly implementing an EV roaming protocol to perform their role. In addition to the market roles discussed above, we identified regulators/governments at different levels (regulating and stimulating roaming), energy suppliers and TSOs/DSOs (relevant for smart grid communications), IT system developers (who develop and implement protocols, and software that needs to be compatible with these), charging infrastructure providers (who implement protocols), information and app providers (who exchange data through these protocols), and automotive suppliers (who implement software that should be compatible with the protocols).

In our study, we focus on protocols (or standards)[1] for EV roaming that are currently in use, for which complete protocol documentation is publicly accessible (in a final form), and where the protocol can, in principle, be implemented by any party. Based on these criteria, we selected four protocols: the Open Clearing House Protocol (OCHP), the Open InterCharge Protocol (OICP), the eMobility Inter-Operation

[1]The specifications that we investigate in this paper describe themselves as 'protocols', while much of the literature we consulted (including that on IEC deliverables) uses the word 'standard' when talking about them. In the context of this paper, both terms may be considered interchangeably.

Protocol (eMIP), the Open Charge Point Interface (OCPI). It is worth noting that while the recognized, global standards body International Electrotechnical Commission (IEC) is also developing a standard in this area (IEC 63119), this work is – as per November 2021 – still in the draft discussion phase, and no standard has been adopted yet [14]. For all protocols investigated in this paper, we considered the information as it was publicly available up to 11 April 2022.

Finally, our analyses focus on Europe. It is here that the first protocols were developed and put into use. Several of these protocols were later exported to other parts of the world,[2] reflecting that Europe is an important if not the most important region in the development of EV roaming protocols. In the ongoing global standardization effort in this area (IEC TC 69, WG 9 'Electric vehicle charging roaming service'), Europe is the region with the highest share of participants.[3]

B. Methodology

Our work is based on an extensive study of the public documentation for the selected protocols, and our analysis of the technical aspects of the roaming protocols is based on the most recent versions of publicly available protocols documentation [18], [19], [20], [21], [22]. To gain a better understanding of the views of stakeholders, we conducted 35 semi-structured interviews with 38 roaming experts from 8 different countries (Germany, Netherlands, Austria, France, Portugal, Sweden, Belgium, and Spain), covering the entire value chain as depicted in Fig. 1 (except that of automotive supplier).

II. EV Roaming Protocols and the Smart Grid: Opportunities and Challenges

Smart grids are based on real-time information exchange between various stakeholders using communication technologies to control the physical electric grid through the information grid [23]. The exchanged information can, for instance, relate to supply, demand, tariffs, priorities, time-shifting, and energy type preferences (e.g., renewable energy).

Mobility of end users brings opportunities (see Section I) but also challenges to the smart grid. Mobile customers, when they charge their EV cars, represent significant energy users, and the power grid can be restrained in capacity, especially if these mobile customers cluster together (for instance in parking lots). Smart grid solutions, if able to deal properly with EV roaming protocols in this mobility dimension, can provide solutions that reduce the load on the grid at peak times. Furthermore, smart grids can support smart charging to allow EV drivers to decrease charging costs or to increase their use of renewable energy, according to user preferences.

[2]For instance, in California, the authorities proposed to mandate OCPI, noting that "As no national interoperability billing standards have been adopted, CARB is proposing the use of OCPI 2.1.1" [15] and the roaming protocol developer Hubject is active in the Chinese EV charging infrastructure market with its EV roaming hboxplatform [16].

[3]In IEC TC 69 WG 9, membership is distributed as follows: Europe (42%), followed by South Korea (21%), China (19% plus the chair), U.S. (8%), Japan (6%) and India (4%) [17].

The main challenges to incorporate this mobility in the smart grid are that (a) the required EV roaming protocols required to support mobility in the smart grid are still under development, and (b) there are multiple such protocols, posing questions on which to adopt, and (c) these protocols should properly interwork with the other information exchange protocols in the smart grid. In the remainder of this section, we will discuss these challenges in more detail.

A. Positioning EV Roaming Protocols in the Smart Grid

In the typical reference frameworks for the smart grid, customers are primarily represented as households. Examples are the NIST Smart Grid Framework 1.0, as shown in Figure 2 [24], and its updated version 2.0 [25], as well as the frameworks presented in [26], [27]. It is in these household where the customers' devices and appliances are located (which may also include heat pumps, solar cells, or storage). Smart grid information exchange takes place via a smart meter or energy services interface. Depending on the nature of the local devices and appliances, they may be part of the local premises network. For other stationary settings (buildings like offices, factories), similar situations apply.

However, for use cases where the customer consumes electricity outside the regular household context (e.g., curbside, multi-dwelling parking, public parking, office parking), other approaches that allow for such mobility are required. This is not yet included in influential reference architectures such as the Conceptual Reference Diagram for Smart Grid Information Networks by the National Institute of Standards and Technology (NIST) (Figure 2) and the Smart Grid Architecture Model (SGAM) Framework jointly developed by the European Committee for Standardization (CEN), European Committee for Electrotechnical Standardization (CENELEC) and European Telecommunications Standards Institute (ETSI) [26]. Here, the EV roaming protocols that are central to this paper come in.

Interviewees working in the field of EV changing point out that, from their perspective, there is a lot of uncertainty surrounding smart grid (protocols). There are many protocols (see also below) and it is not always clear which one(s) will prevail. Moreover, for them it is not clear yet who will really be 'in control'? Which party will take the final operational decision (e.g., to charge, how much and at what time), versus parties that are merely expressing their preferences?

B. Relation Between EV Roaming Protocols and (Other) Smart Grid Standards

EV roaming communications take place within a larger smart grid energy infrastructure and EV charging ecosystem [12], [28], [29], [30]. To allow smart charging preferences and constraints to be communicated to all relevant parties, the roaming protocols should be compatible with other common communication protocols in this smart grid energy infrastructure and EV charging ecosystem. The smart grid is comprised of many standards, and at least several dozens of Standards Development Organizations (SDOs), and alliances are involved in developing these; for an overview, see [31, ch. 3].

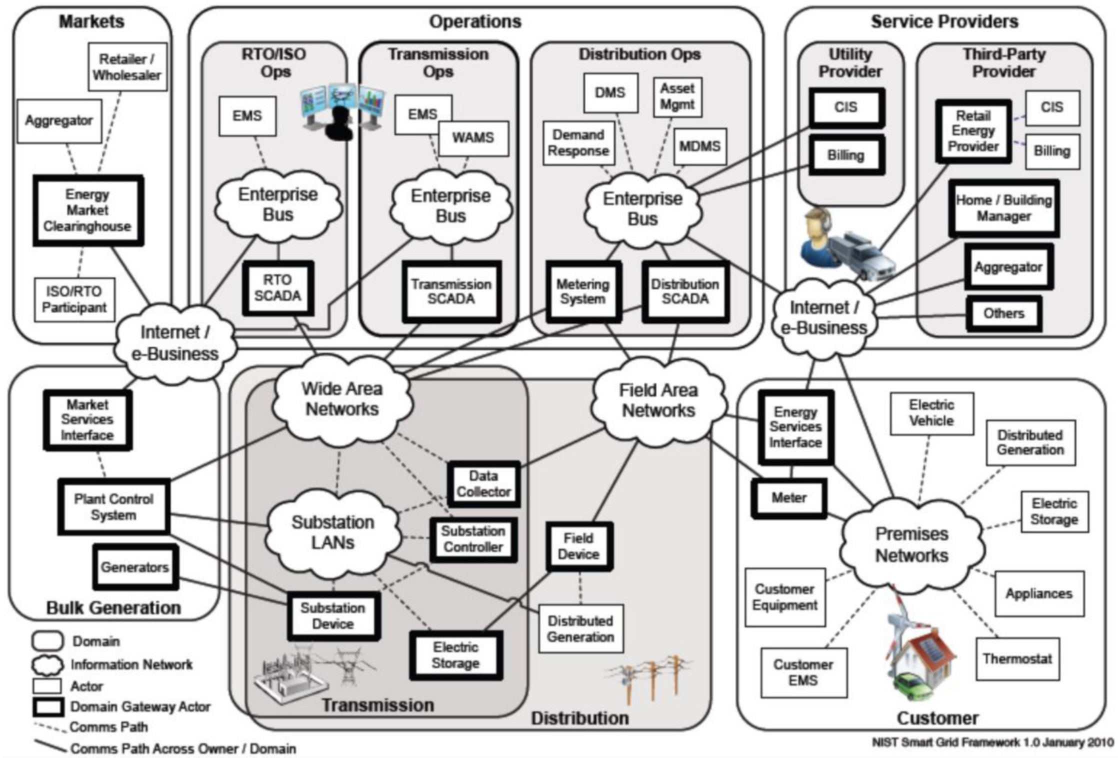

Fig. 2. NIST Conceptual Reference Diagram for Smart Grid Information Networks (source [24]).

On the international level, these SDOs include the IEC, the International Organization for Standardization (ISO), the Institute of Electrical and Electronics Engineers (IEEE), the International Telecommunication Union (ITU), and the Internet Engineering Task Force (IETF). On the regional level there are NIST, American National Standards Institute (ANSI) (both U.S.) and ETSI, CEN, CENELEC (Europe). Commissioned by the European Commission, the CEN/CENELEC/ETSI Joint Working Group on Standards for Smart Grids identified hundreds of standards relevant to the smart grid [32]. It goes beyond the scope of this paper to discuss all possibly relevant standards in this context, but we will focus on the most important ones, distinguishing two levels.

The first level concerns the relevant smart grid protocols, such as those used between the charge point and the energy supplier/distributor. Here, the most important standards are IEC 61850, the generic, core standard for grid automation. While this standard originates from the substation automation domain, it has a wide scope, and its latest advancements include automation in the context of Distributed Energy Resources (DER), making it relevant to the E-Mobility domain [33]. Another important standard here is Open Automated Demand Response (OpenADR), developed in response to the 2002 California energy crisis and in 2019 formally adopted as IEC 62746 [34], [35], [36]. The latter standard aims to automate and simplify Demand Response (DR) and Distributed Energy Resources (DER) to enable utilities and aggregators to cost-effectively manage growing energy demand & decentralized energy production, and customers to control their energy system [34]. An important protocol specific to EV charging infrastructure is the Open Charge Point Protocol (OCPP), which is the most commonly used communication protocol to manage charging stations. Combining OpenADR and OCPP offers opportunities such as using EV batteries as temporary storage for the grid using V2G [36].

The second level includes the relevant protocols between the EV and charge point. Particularly important here are the standards ISO/IEC 15118 and IEC 61851, which cover the *communication* between the charge point and EV (as opposed to standards such as IEC 62196, covering the physical, electrical, functional and performance specifications of the charge connectors, including the Type 1, Type 2, CCS Combo 1 and CCS Combo 2 plugs, and are further discussed in Section VII, below). These communication standards are relevant in our context because they affect to what degree smart charging and V2G are actually supported by the EVs themselves. A particular challenge here is that there are substantial differences between the '−2' version of the ISO/IEC 15118, and the newer '−20' version, and some of these differences are relevant to this discussion, like support for multiple MSPs.

To reap the full benefits of a smart grid in the context of mobile EV drivers, the EV roaming protocols discussed in the next section should be aligned and interoperate with the smart grid standards discussed above – and the other way round. As will be shown later, this is already happening to some degree. For instance, one of the EV roaming standards, OCPI, defines Charging Profiles that are similar to those in the OCPP smart grid standard, thus facilitating interworking between the two standards.

III. Current Roaming Protocols for EV: History and Characteristics

The first EV roaming protocol to be publicly available was OCHP, of which v1.0 was released 2013. OCHP was developed by Smartlab Innovationgesellschaft and ElaadNL, which are organizations founded by German and Dutch utilities, respectively. OCHP is used by the not-for-profit roaming hub e-clearing.net, which was launched by the same parties in 2014, and is currently a privately held company. The most recent version of the protocol, v1.4, was released in 2016 [18], together with its extension OCHPDirect v0.2 [19].

OICP was created in 2013 by Hubject, a joint venture of mainly German organizations: BMW Group, Bosch, EnBW, Enel X, Mercedes-Benz, Innogy, and the Volkswagen Group. The protocol can be used to connect with Hubject's own roaming hub, called Intercharge. The most recent version is OICP 2.3, which was released in 2020 [20].

The eMIP protocol was released in 2015 and was designed by GIREVE, founded by the French organizations EDF, Renault, CNR, and Caisse des Dépôts. GIREVE also runs a roaming hub, and eMIP can be used to connect to it. The first operating versions of eMIP, v0.7.4, was released in 2015. Even though new features have been added as recently as 2020, this was done by means of additional definition tables and did not require an update of the protocol itself (see also below) [21].

The first version of OCPI, released in 2015, was developed by eViolin, a collaboration of Dutch CPOs and MSPs, in cooperation with ElaadNL (see above). The protocol was then transferred to the public organization Netherlands Knowledge Platform for Public Charging Infrastructure (NKL), and currently is managed by a foundation, the EVRoaming Foundation, whose board as of 20 July 2022 consists of NKL, Last Mile Solutions, Freshmile, Chargepoint, GIREVE, and Google. The most recent version of the protocol, v2.2.1, was released in 2021 [22]. Out of the four protocols discussed here, OCPI is the only protocol *not* managed by a party that at the same time manages a roaming hub.

The above protocols aim to facilitate EV roaming between different parties by enabling the exchange of data needed for roaming transactions. The basic functionalities needed to support this are present in all four, namely authorization, billing, providing information on the charge point and charging session, and giving remote start/stop commands to the charge point, see Table I. Furthermore, all protocols support real-time charge point status information (e.g., occupancy status). Some areas where we note interesting differences in functionalities include:

- OICP does not offer peer-to-peer connections, and OCHP only does so in its 'direct' variant. This important aspect is further discussed in Section III-A, below;

- eMIP is the only protocol offering charge point search functionality;

- eMIP and OCPI support real-time session information, OCHP only does so in its 'direct' variant, and OICP does not offer this feature.

- OCPI is currently the only protocol supporting smart charging, though it does not seem unlikely that smart charging functionalities will be added to the other protocols in the future. We discuss this aspect further in Section III-C, below.

TABLE I
Supported Functionalities of Roaming Protocols

	OCHP v1.4	OCHP Direct v.02	OICP v.2.3	eMIP v0.7.4	OCPI v2.2
Roaming via hub	**X**		**X**	**X**	**X**
Roaming peer-to-peer		**X**		**X**	**X**
Ad hoc payment			**X**		
Authorization	X	X	X	X	X
Reservation			**X**	**X**	**X**
Billing	X	X	X	X	X
Provide static charge point information	X	X	X	X	X
Provide real-time charge point status information	X	X	X	X	X
Provide future charge point use information	X	X	X	X	X
Charge point search functionality				**X**	
Provide session information	X	X	X*	X	X*
Provide real-time session information		**X**		**X**	**X**
Remote start/stop	X	X	X	X	X
Smart Charging					**X**
Platform monitoring				**X**	**X**
Asynchronous data exchange	X	X	X†	X†	X†
Synchronous data exchange			**X†**	**X†**	**X†**

Functionalities not supported by all protocols in bold. * Supports signed meter data which can be used to conform to Eichrecht (German calibration law). † The pattern used depends on the specific message

Additionally, in terms of comparing protocols, we note that the eMIP protocol has a different approach in the sense that the protocol is written on a higher level, whereas specific implementation elements can be later added via definition tables. This way, new user authentication methods, for instance, can be added later without the need to change the protocol. Following this approach, it is less 'hard-wired' than the other protocols, and this is also the reason why the 2015 version of this protocol did not require updates in order to implement new features.

A. Asynchronous/Synchronous Data Exchange

User authentication is an essential functionality in any EV roaming protocol. The earliest protocol, OCHP, relies on asynchronous approaches to do this: it uses a 'white lists' of users which are allowed to authenticate. For instance, an MSP forwards a list of authorized subscribers to the hub, which is then downloaded by the CPO. In such an asynchronous approach, the system is robust to some sorts of failures (for instance, when connections to or from an MSP or CPO are down). A consequence, however, is that at the time of charging, the actual status of a user may not be up to date and EV drivers that are no longer entitled to use services by their MSPs may still be able to consume services – which may remain unpaid. Frequent updates of the whitelists are required to prevent this.

The more recent protocols OICP, eMIP, and OCPI, use synchronous data exchange. This way, they offer actual, real-time authentication of users using the information present at the MSP, ensuring that recently blocked users are indeed properly

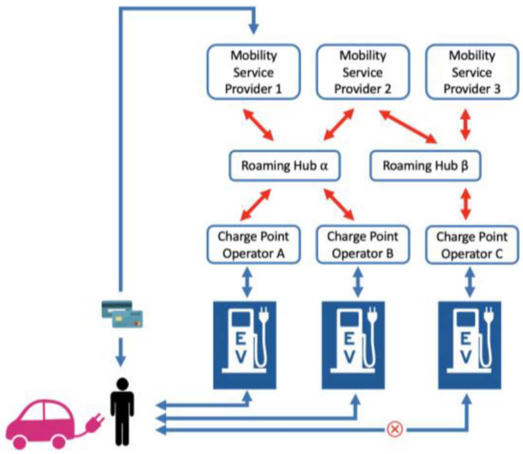

Fig. 3. Architecture based on roaming hubs. Red arrows denote EV roaming protocols.

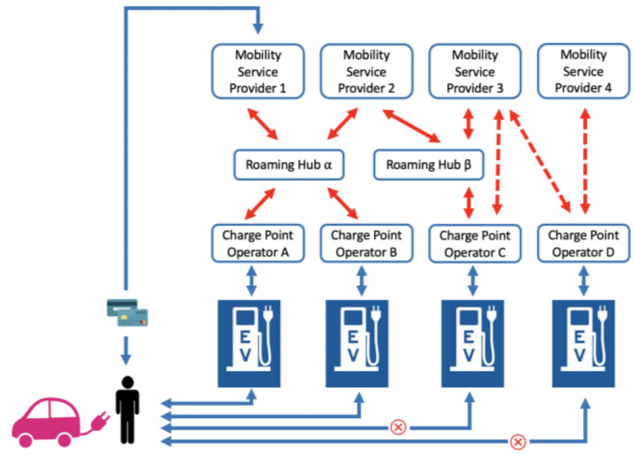

Fig. 4. Hybrid architecture based on roaming hubs and p2p connections. Solid red arrows denote hub operation, dashed red arrows denote p2p operation.

recognized as such. The switch to a synchronous mode can be understood in the context of increased availability/reliability of on-line communications between all nodes in the system. Note, however, that these newer, synchronous protocols also support an asynchronous mode in case of real-time communications failures, by means of a whitelist database as back-up.

Next to authorization, data exchange to support billing is another essential functionality for which protocols differ in their approach. Billing processes in EV charging make use of Charge Detail Records (CDRs), a description of the charging session containing the information necessary for billing, to be exchanged between the CPO and the MSP after the charging session has ended. Similar to the authorization functionality, OCHP supports only asynchronous CDR exchange, while OICP, eMIP, and OCPI support CDR exchange in both modes.

B. Roaming Hub vs Peer-2-Peer Architecture

An implied technical aspect of these roaming protocols relates to the possible architectural topographies of the roaming networks, which has significant strategic consequences. The earliest protocols started from a hub-based concept (Fig. 3). These hubs allow an MSP to offer services via a large number of CPOs without having to enter into bilateral negotiations which each single one of them. The hub arranges the necessary contracts, sets the rules, and physically facilitates all traffic between the parties. There may be multiple hubs active in the market, and MSPs may connect to one or more hubs, thus increasing their service area. Yet, when a given CPO is not connected to the same hub as a given MSP, then no service is possible (indicated by the red cross in Fig. 3).

Recent years witnessed increasing attention for (adding) peer-2-peer (p2p) approaches to the model, as depicted in Fig. 4. Here, direct communication is also possible between MSPs and CPOs, without the intermediate role of a hub.

For market parties, the two different architectural designs offer distinct advantages and disadvantages (Table II). In short, roaming is attractive for smaller players that lack resources to enter bilateral discussions on commercial and technical aspects with all CPOs operating in the area where they want to offer services to their EV drivers. In contrast, p2p approaches are preferred by both larger MSPs and CPOs that have significant traffic between them and want to agree on their own conditions, instead of these being drawn up by an intermediate party. Hubs and p2p modes can be seen as complementary, and during interviews, many parties expressed their belief that in the future hybrid systems will be dominant, with possibly additional roles for hub-to-hub or meta hub systems. Already, most companies have connection to roaming hubs as well as p2p relations. Some interviewees believed that in the future, when markets have scaled up, larger MSPs and CPOs would dominate the market and use p2p systems, and the role for hubs would diminish.

TABLE II
COMPARING ROAMING AND P2P ARCHITECTURES

Roaming hub operation	Peer-2-peer operation
Advantages	
Allows immediate access to all the other parties connected to that roaming hub	Flexible and customisable: parties can discuss and agree upon all technical and commercial aspects
Offers a single, harmonized set of technical agreements (protocols, implementation, etc.)	
Hub party often implements, maintains, and updates the roaming protocols	
May include a single, harmonized framework of commercial roaming agreements, and may managing changes these agreements, for instance due to legal changes, tariffs changes or operational changes	
May include certification / implementation testing services	
May allow connection between parties using different protocols	
May offer administrative services such as billing, invoicing, payment settlements, and netting	
Disadvantages	
Lower span of control: roaming hubs decide what protocols to use, and may define the business rules	Negotiating many individual roaming connections can be time-consuming and expensive
Less possibility to customize or adapt to individual needs	Can require significant technical implementation costs, especially if implementation differs between individual connections
Roaming hubs will charge a fee for their services	

C. Smart Charging

A particularly important difference in the context of smart grids is that OCPI, as noted above, is currently the only protocol that includes a smart charging module, though the other protocols include, to some extent, functionalities relevant for smart charging. OCPI defines a special role for a Smart Charging Services Provider (SCSP) that sends the user preferences regarding smart charging to the CPO and can also send additional data in real time to influence an ongoing charge session. If desired, the SCSP role can also be performed by the MSP. The required user preferences include expected departure time, requested amount of energy, whether EV discharging is allowed for V2G functionality.

They are similar to the Charging Profiles in OCPP, a common protocol used by CPOs within their own infrastructure to manage their physical charge points [37], [38] (see also at Section III, above).[4] By ensuring this interoperability, OCPI contributes to moving away from the current situation as identified by Chen *et al.* [39], in which a reliable communication system for smart charging is difficult to realize due to the large number of propriety protocols employed in the charging infrastructure. The CPO can, but is not required to, use this information to vary the charging speed during the session based on local grid conditions to reach the user aims as much as possible. If the CPO rejects the requested charging profile the user will be informed about this through the SCSP or MSP. Note that even if the CPO accepts the requested profile, there is no guarantee that the EV will charge exactly as requested, as there are many factors that can impact the charging speed (e.g., battery temperature, cable type, local energy limits). Furthermore, the user preferences can be changed and send to the CPO during the session (who in turn can again accept or reject them).

While the other protocols do not include specific smart charging support, there are still some noteworthy differences between them relevant for smart charging. Firstly, OCHP, eMIP and OCPI support real-time information exchange of charging sessions, while OICP does not. EV drivers may want to check on the charging process if they are smartly charging their car, for example to see if it is already full enough in case they want to leave earlier than indicated. Secondly, OICP and OCPI have charge point information fields specifically for smart charging. Through OICP, CPOs can indicate whether the charge points support dynamic pricing, provide dynamic power, and offer charge plans (compatible with the EV to charge point communication protocol ISO/IEC-15118-2). OCPI allows CPOs to link to an URL with real-time energy prices and to indicate whether the charge point supports charging profiles and preferences (compatible with OCPP). Furthermore, both protocols have specific information fields for the energy source and environmental impact, information that is likely of interest to many of the users interested in smart charging and vehicle-to-grid. OCHP and eMIP do not have these functionalities. Table III summarizes the smart charging functionalities of the protocols.

[4]In Fig. 1 to 3 below, the OCPP protocol could be found between a CPO and its EV charge points. But since OCPP is internal to the CPO and not a roaming protocol as such, it is out of the scope of our study.

TABLE III
SMART CHARGING RELATED FUNCTIONALITIES

	OCHP v1.4 & OCHP Direct v.02	OICP v.2.2	eMIP v0.7.4	OCPI v2.2
Defines smart charging services provider				X
Communication of charging preferences				X
Real-time session information	X		X	X
Fields for smart charging availability at charge point		X		X
Fields for energy source and environmental impact at charge point		X		X
Link to real-time pricing information				X

TABLE IV
GOVERNANCE ASPECTS

	OCHP v1.4 & OCHP Direct v.02	OICP v.2.2	eMIP v0.7.4	OCPI v2.2
Managed by	e-clearing.net	Hubject	GIREVE	EVRoaming Foundation
Managing organization is also hub operator	Yes (but hub role is non-exclusive)	Yes	Yes	No
Documentation and protocol free of charge	Yes	Yes	Yes	Yes
Open-source copyright license	MIT license	CC BY-SA	None	CC BY-ND
Organization of user *feedback*	Yes	Yes	Yes	Yes
Open community-based *development*	No	No	No	Yes (OCPI community)

IV. GOVERNANCE AND OPENNESS

None of the current EV roaming protocols we investigated in the previous section comes from a recognized Standards Development Organization (SDO), such as the IEC or the Comité Européen de Normalisation Electrotechnique (CENELEC). Therefore, it is interesting to investigate how these protocols are governed, and to what degree they comply with the principles of 'open standards' that are nowadays becoming increasingly important.

Table IV summarizes the main governance aspects of the four protocols we investigated. OCPI is the only protocol not managed by a company but by a foundation (with representatives from five stakeholders). All four protocols support roaming hubs, and for three of them, the managing organization is at the same time operating a roaming hub implementing the protocol, meaning that the protocol manager also has its own commercial stake.

TABLE V
COMPLIANCE WITH OPEN STANDARDS CRITERIA*

	OCHP	OICP	eMIP	OCPI
1. Transparency (regarding documentation on proposal for standards and final standards)	+	+	0	+
2. Openness (open membership at every stage of standardization process)	0	0	–	+/0
3. Impartiality and consensus (no privilege or favouring interests of a particular party)	0	–	–	+/0
4. Effectiveness and relevance (facilitating international trade)	+	+	+	+
5. Coherence (no duplication of or overlapping with other the work of other standardization bodies)	+	+	+	+
6. Development dimension (developing countries should not be excluded de facto from the process)	0	0/–	0/–	0

* + indicates high compliance, 0 indicates medium compliance, - indicates low compliance with the WTO criteria for open standards [44]

Of these three, only OCPI specifies that also other hubs can adopt the protocol. In contrast, the protocol documentation of OICP and eMIP explicitly name Hubject and GIREVE (i.e., the respective platforms owned by the protocol manager) as the roaming hub to be used. Three of the protocols have an open-source copyright license. Two of these allow derivates, meaning that licensees are allowed to make derivate works (that is, modified versions), and distribute those. While in the spirit of open source, this creates the risk that different and incompatible versions of a protocol come into circulation. All four protocols seek user feedback, one protocol sports community-based development.

Increasingly, society is expecting the principles of open standards to be respected. Policymakers may require that products or services they procure are based on open standards, and regulators may have concerns that standards that are not open can distort markets. The use of open protocols for EV charging infrastructure has already been recognized by governments in the Netherlands, U.K., and California [30]. How open are the four standards we study? Even if three of four have the word 'open' in their name, a more thorough investigation is justified. While different definitions of open standards have been proposed in the literature [40], [41], [42], [43], the six conditions for Open Standards as formulated by the World Trade Organization's Committee on Technical Barriers to Trade (WTO TBT) are nowadays considered as the universal reference [44], [45]. These are: transparency, openness, impartiality and consensus, effectiveness and relevance, coherence, and addressing concerns of developing countries. Based on an extensive investigation of the governance of each of the four protocols, we assess their openness on these six dimensions as shown in Table V. An in-depth discussion on this assessment is provided in [1]. Overall, we can summarize the compliance with these WTO criteria as low for OICP and eMIP, and medium for OCHP and high (but not perfect) for OCPI.

V. DIRECT PAYMENTS AS AN ALTERNATIVE TO ROAMING PROTOCOLS

To what degree are roaming protocols as discussed in the previous section actually necessary to allow for public charging? In the world of Internal Combustion Engine (ICE) vehicles, the purchase of petrol is usually done by a direct payment (e.g., cash, debit card, or credit card). In Europe, direct payment for EV charging (also known as Ad Hoc access to public charge points) is already required by European legislation, though it does not define the payment means (Directive 2014/94/EU [46], amended in 2018 [47]).

There are several reasons, however, why direct payments (alone) are not likely to be a realistic alternative for everyday (or every night) charging. With a projected total of 1.7 million (semi-)public charge points in 2030 for a small country like the Netherlands alone [48], cash payment at all these devices is impossible, and installing bank card terminals at each of them will be infeasible capital costs but also operational costs (including bank fees).

Also, direct payments lack the advanced opportunities offered by EV roaming protocols for smart charging and V2G, which require user input. Without services such those as provided by roaming protocols, users would need to provide smart charging preferences separately for each charging session rather than relying on default settings. Ad hoc payments also do not align well with other emerging mobility markets models such as carsharing, intermodal transport, and mobility as a service [49]. Furthermore, ad hoc payments do not (or less well) allow many of the rich functionalities that roaming systems allow for, such as actual price information, charge point locations and availability, and reservation of charge points. While 'ad hoc apps' may address some of these limitations, this would likely result in a fragmentation of such apps, not serving the user either with a single, easy to use environment when driving through the country and cross-border.

VI. SCENARIOS FOR THE FUTURE DEVELOPMENT OF EV ROAMING PROTOCOLS

The existence of several roaming protocols with similar functionalities has led to a fragmented roaming landscape. Fig. 4 provides a stylized view of that fragmentation, which aligns with reality. While the development of EV roaming nowadays has a strong cross-border focus, it was organized very locally in the early years. The roaming hubs served local markets, and different parties implemented different roaming protocols, depending on which roaming hub was active in their region. Fig. 5 illustrates this situation: several roaming hubs use the roaming protocols they developed themselves to run the hub and connect with MSPs and CPOs. If these parties want to expand their connectivity through different roaming hubs, they must implement multiple roaming protocols (as MSP 2 in Fig. 5). Today, several roaming hubs use gateway technologies (i.e., systems that interface with two or more different protocols to the best degree possible) to offer the additional possibility to connect with OCPI, meaning that MSPs and CPOs need only one protocol to connect to different

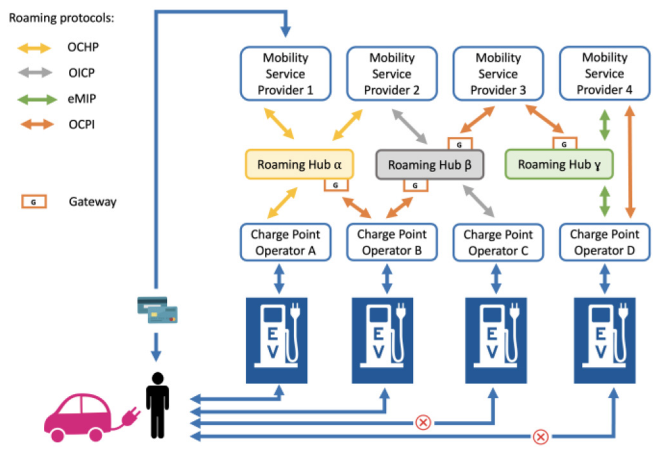

Fig. 5. Reflection of current roaming landscape. The four roaming protocols are represented by different colors.

hubs (as CPO B in Fig. 4). This way, the hubs make themselves more attractive to small parties who may lack resources to implement multiple resources themselves. At the same time, gateways imply various costs, both financial and otherwise (see below). Large parties may want to connect peer-to-peer with other large parties, in addition to connecting to roaming hubs to connect with smaller parties (as MSP 4 and CPO D in Fig. 5).

While the current roaming landscape thus enables many different types of connections, our interviewees described the present situation as undesirable, complex and 'messy'. If parties implement only one protocol, they may not be able to connect to all parties they want to, but implementing and updating multiple protocols is costly in terms of operational costs (OPEX) and capital expenditure (CAPEX), and connecting to other protocols through gateway technologies may limit functionality. Furthermore, the existence of multiple protocols creates uncertainty on which protocol(s) to implement.

Given these issues and the benefits of broad interoperability for many market parties, the expectation among the interviewees is that the situation will change to a more desirable one, that is, a single (or at least dominant) protocol. We asked our interviewees to discuss the future of EV roaming and possible scenarios for the future development of EV roaming, including how they evaluated the desirability and likelihood of becoming the dominant future scenario. Table VI presents the identified scenarios, which we discuss further in the remainder of this section.

TABLE VI
SCENARIOS FOR THE FUTURE OF ROAMING PROTOCOLS

Scenario	Description
1. Status quo (fragmentation)	This scenario reflects the status quo, in which multiple roaming protocols are in use, and the actors are not fully connected to each other
2. Harmonization of existing protocols	Protocol developers cooperate to harmonize the existing protocols into a single protocol, keeping all relevant existing functionalities and leading to full interoperability
3. Standards battle with winning protocol	One of the existing protocols is getting adopted much more than the other protocols, thereby becoming increasingly attractive for parties to implement, and ending up as the dominant protocol in use
4. Gateways that connect different protocols	Multiple protocols continue to coexist, and interoperability is achieved through gateway technologies
5. IEC 63119 standard becomes dominant	The IEC 63119 standard, currently under development, is released. Being developed through an international standardization process, is very attractive for international roaming and becomes to dominant protocol
6. No roaming	Access to charge points is not realized through roaming but ad hoc payments

Scenario 1 [Status quo (fragmentation)]: Describes the current situation with 4 competing protocols. Because fragmentation has substantial disadvantages for most involved parties, the interviewees did not think this is a likely scenario for the long term.

Scenario 2 (Harmonization of existing protocols): Can be achieved if the protocol developers will start cooperating much more intensively than they currently do, with the ultimate aim to build a single protocol without loss of relevant functionalities from the current protocols. This could be a slow process, in which each update of the protocol is a partial step towards a harmonized protocol. Most interviewees think that having a single protocol is an advantage for the EV sector, though there is disagreement on whether it is good or bad for the innovativeness of the sector. Perspectives on the likelihood of this scenario differ. Many interviewees did not think it is very likely, as close cooperation amongst protocol developers is not in their interest because they have a vested interest in their own protocol, though regulators could play a role in realizing this scenario by pushing cooperation.

Scenario 3 (Standards battle with winning protocol): In which a single protocol initially becomes (perceived as) more dominant in the market, and thereby increases its attractiveness for parties that want to improve their connectivity. This leads to increased adoption by new parties, and switching from other protocols to this protocol by existing parties. Ultimately, it becomes the only widely adopted protocol. Variations on this scenario are that there are two dominant protocols, or that a winner is selected by governments, as has happened with EV charging plugs [50]. As with *Scenario 2*, this scenario results in a single protocol to implement for parties, which saves resources. Unlike in that scenario, only one party manages that protocol, which will make updating easier but may also lead to that party pushing its market model, which is a clear disadvantage for parties whose business models are not supported, and for society if the protocol does not adhere to the criteria for an open standard. This scenario was often evaluated as most likely by our interviewees, as it fulfils the desire of many parties to implement only one roaming protocol (or a limited number of them), but in a manner that does not require close cooperation between parties that are currently in competition. We do not see the variation in which the government picks a winner as a likely scenario; see Section VII.

Scenario 4 (Gateways that connect different protocols): Reflects the current situation to some extent (see Fig. 4) but differs in that it imagines *full* interoperability achieved through gateway technologies. Gateways have the benefit that they allow for interoperability while reducing the chance for a monopoly to come into existence [51]. Some interviewees thought that this scenario combines the benefits of interoperability with the benefits of cost reduction and innovation due to competition between protocol developers. This comes at a cost, however, both in terms of resources needed to develop and maintain the gateways and in potential limitations in functionality due to incompatibilities between the protocols. One interviewee also argued that this scenario would lead to a roaming system with low transparency and low stability due to errors in data translation between protocols. Several interviewees thought this scenario is the most likely to happen, citing the diverse EV field as a reason multiple protocols will continue to co-exist.

Scenario 5 (IEC 63119 standard becomes dominant): Imagines that this IEC standard, currently under development, becomes the dominant EV roaming protocol (see also Section I-A for this standard). Contrary to current roaming systems that emerged bottom-up, this scenario describes a top-down situation in which a protocol designed based on international consensus becomes widely adopted. It is an open question on whether a standard based on international consensus appeals to parties that want to improve cross-border interoperability, or that regional differences between stakeholders turn out to be too large for such a protocol to be sufficiently attractive to many parties. This was reflected in the mixed assessment of the likelihood of this scenario by the interviewees.

In *Scenario 6 (No roaming):* There is no interoperability through roaming, but EV drivers instead can access charge points ad hoc, paying through means such as cash, debit card, credit card, or mobile apps. Because this resembles the fuelling of Internal Combustion Engine (ICE) vehicles at gas stations, which some interviewees saw as a big advantage. However, most interviewees did not see this scenario as likely, for the reasons cited in Section V above.

VII. The Regulatory Dimension

In addition to technical and business aspects, there are several important regulatory dimensions that can impact the further development of EV roaming. We discuss the most important ones here, again focusing on Europe (see Section I-A).

First and foremost, there is the aspect of compliance with applicable law. The European General Data Protection Regulation (GDPR) [52], which is applicable as of May 25th, 2018, includes requirements regarding the storage and exchange of personal data, and has a significant impact on what stakeholders can store and exchange in the context of EV roaming. Protocols may facilitate proper compliance with this law. Moreover, the supply of energy services is often subject to national laws and regulations, which may differ per country. In Germany for instance, such services must comply with the ‘Eichrecht’ (the German calibration law), which states that to sell electricity parties are required to accurately measure and charge only for kWh used by the consumer, and that consumers should be able to verify they were invoiced correctly [53]. The most recent versions of OCPI and OICP added the possibility to exchange signed data that allow such compliance.

Second, there is the aspect of the legal status of standards. Globally, standardization is in principle seen as a voluntary activity. Also, the application (use) of standards is in principle voluntary, bar cases where standards have been mandatorily incorporated in or referred to by law. In the latter cases we speak of de-jure standards, and they are rare. In Europe, the New Approach has defined the fundamental principles towards standardization (and their use in legislation) since the 1980s. In short, this approach holds that legislative harmonization is limited to the adoption of (more abstract) ‘essential safety requirements’; European standards organizations are entrusted with the task of drawing up harmonized standards for products that conform to these essential safety requirements; these harmonized standards are not compulsory and maintain their status as voluntary standards [54].

A. Optimal Regulation

During our interviews, many spoke about the potential benefit or possibility of government intervention in terms of mandating standards. Therefore, we now discuss how regulators may develop specific interventions or policies concerning EV roaming. Policymakers have become increasingly active in the context of electric mobility, on the European level as well as on national levels [39], [55].

The question of what optimum regulation would be in the context of EV roaming protocols is a normative one. We have explained in the previous section that the application of standards is – in principle – voluntary. But, at least in Europe, there are signals of a turning point. In a recent case, the European Union first departed from these principles when it announced a specific standardized charging plug (‘vehicle connector’) for EVs, namely the “Type 2” plus as described in IEC 62196-2, as the common standard for the whole of Europe [50], [56]. In 2014, this was implementing in binding law via Directive 2014/94/EU [46], which mandates the IEC 62196-2 Type 2 for normal power (3.7kW to 22kW) and high power (more than 22kW) AC recharging points. For high power DC recharging points, the EN 62196-3 (“Combo 2”) is mandated. A 2018 amendment to this directive [47] added that publicly accessible low power (less than 3.7kW) AC recharging points shall be the IEC 62196-2 “Type 3A” single phase connector.[5] A similar effort to mandate one specific standard for vehicle-to-vehicle communications, however, failed when the European Council rejected the ratification of that proposal [57]. Furthermore, in February 2022, the European Commission published its long awaited ‘EU Strategy on Standardisation’ [58]. This document suggests a breaking point with earlier policy. Recognizing the need for a more independent and resilient Europe, and acknowledging the large importance of standards for the twin green and digital transitions, it proposes a much more proactive role for governments in standardization. It also suggests that the Commission could

[5] Alternatively, when no vehicle side connector is used, it is allowed to use socket-outlets and connectors compliant with IEC 60884, which basically covers the regular plugs for household appliances used throughout Europe.

use its power to adopt technical or common specifications via implementing acts, should the existing mechanisms (e.g., harmonized standards developed via the New Approach, see previous section) fail to result in a satisfactory situation. Given the much more strategic and proactive stance Europe seems to adopt, we may also see action in the context of standards for EV roaming, as the importance of having a single standard in this area is clearly recognized by European policy makers [59]. Other world regions have less of a tradition than Europe to link policy measures to standardization (whether via harmonized standards, mandating standards, or otherwise). But if Europe would indeed mandate a standard, this would quite surely affect the global market too.

VIII. Conclusion and Outlook

With the adoption of BEV quickly rising, a larger and larger share of BEV drivers will need to rely on public charge points, such as garages in flats and multi-dwelling buildings, curbside chargers, office areas, and public parking. Depending on local grid connections, many of these locations will need to employ smart charging in one way or another to accommodate on-site (peak) demand. New energy sources such as solar panels further the need for smart charging solutions. To achieve seamless smart charging for EV drivers, smart grids architectures should support mobile users, whereas current architecture frameworks are only focus on stationary uses (even if it concerns charging EVs). For this, it is critical that EV roaming protocols support smart charging and align with relevant communication protocols in the larger EV charging ecosystem and energy infrastructure, such as ISO/IEC 15118, IEC 61850, IEC 61851, OCPP, and OpenADR – and the other way around.

Out of the four EV roaming protocols investigated in this paper, the latest version of the OCPI protocols offers extensive support for smart charging, across six relevant dimensions (see Table III for details). The other three standards would need to see significant additional developments to be able to operate in the environment as outlined above.

There are also other technical dimensions of these roaming protocols that are relevant for the broad development of this market. First, several protocols are created by stakeholders that also operate roaming hubs, and in some of these protocols, the hub role by that company is 'hard-wired' in the protocol. This makes these protocols less neutral to use by others, or other business models, including the increasingly important peer-2-peer mode. Second, the oldest protocol OCHP mostly relies on asynchronous approaches (with for instance local storage of lists of authorized users), making it harder to fully integrate true smart mobility functionality. The more recent protocols are synchronous, real-time systems, better suited for dynamic adaptations as required in a smart grid (although we note this is not that black and white; several protocols can be characterized as a hybrid in this respect).

We also conclude that having four, mutually incompatible EV roaming protocols (and a fifth under development) leads to significant interoperability problems. This current, fragmented market stands in the way of a seamless user experience and the development of an open, competitive market for charging. In this paper, we presented six scenarios for the future development of EV roaming protocols, and how the 38 interviewed experts think about the desirability and likelihood of each of these scenarios. We identified a general desire to move towards a single widely adopted protocol, but a widespread skepticism on whether this could be realized through consensus. Rather, the most likely scenario to achieve interoperability seems to a standards battle, in which one protocol becomes dominant through competition.

Finally, our investigation of the regulatory dimension demonstrates that while it is quite unusual for governments to mandate specific technical standards, it is increasingly understood that such actions may be needed if the market fails to satisfactory solutions itself. Recent policy developments in Europe may foreshadow regulatory action for EV roaming standards.

While our study focuses on EV roaming, we think the insights we present have a broader significance. Firstly, it teaches us about the dynamics of standardization and interoperability struggles that play at relatively new technologies, where business models and market roles are still developing, and prompts questions about whether government intervention is appropriate from the standardization perspective. Second, our study reveals an interesting mobility dimension that has not yet been prominent in smart grid studies, where user locations are usually fixed, and discusses technical solutions (with roaming protocols for home networks and guest networks) that allow such mobility. This mobility dimension may grow in importance as smart grids mature, when users more often may be part of guest networks and consume and store energy (think of vessels, trucks, busses, or scooters). Mobile users may even generate energy to deliver to local grids, for example through solar equipped electric vehicles such as the Lightyear One.

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