FLOW

Flexible energy systems Leveraging the Optimal integration of EVs deployment Wave

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Deliverable 3.1

Requirements and Specifications for the Development of Interoperable Software

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List of Acronyms

Acronym	Meaning
ACK	Acknowledgement
Alim	Ampere Limit
AMI	Analog Measurement Information
AR	Authentication Request
AuthR	Authorization Response
BEV	Battery Electric Vehicle
BLE	Bluetooth Low Energy
BMS	Battery Management System
BRPs	Balancing Responsible Parties
CA	Certificate Authority
CAN	Controller Area Network
CDRs	Charge Detail Records
CHAdeMO	Charge de Mov
CP	Charging Point
CPMS	Charge Point Management System
CPOs	Charge Point Operators
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
DER	Distributed Energy Resources
DSO	Distribution System Operator
EMSPs	E-Mobility Service Providers
EV	Electric Vehicle
EVCC	EV Communication Controller
EVSE	Electric Vehicle Supply Equipment
FEC	Forward Error Correction
G2V	Grid-to-Vehicle
JSON	JavaScript Object Notation
LoRa	Long Range (wireless communication technology)
MAC	Medium Access Control
OCPP	Open Charge Point Protocol
OCPI	Open Charge Point Interface
OEMs	Original Equipment Manufacturers
OpenADR	Open Automated Demand Response
OSI	Open Systems Interconnections
PDU	Protocol Data Unit
PLC	Power Line Communication
SECC	Supply Equipment Communication Controller
SoC	State of Charge
SV	Sampled Values
ToU	Time of Use
TSOs	Transmission System Operators
V2B	Vehicle-to-Building

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V2G	Vehicle-to-Grid
V2H	Vehicle-to-Home
V2L	Vehicle-to-Load
V2V	Vehicle-to-Vehicle
V2X	Vehicle-to-Everything
XML	Extensible Markup Language

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Executive Summary

To effectively integrate electric vehicles (EVs) into the power grid, communication protocols and standards are necessary to ensure seamless integration, safety, and efficiency by facilitating interoperability among charging infrastructure, EVs, energy management systems, and the grid. The FLOW deliverable 3.1 offers an extensive analysis of diverse communication protocols within the EV ecosystem, placing emphasis on essential requirements for enhancing interoperability and enabling smooth communication among the various stakeholders.

The aim of this deliverable is threefold:

1. To review standardised communication protocols, analyse their characteristics, and identify knowledge gaps that need to be addressed to achieve the desired interoperability goals outlined by the FLOW project. We have reviewed the functionality of the protocols across multiple use cases, considering communication between primary and secondary actors, and analysed them based on openness, interoperability, maturity, and market adaptability.
2. To conduct a requirement analysis for the development of the FLOW middleware, focusing on the business layer and supporting the creation of an interoperable platform within the EV ecosystem. Taking into consideration the grid connection and control mechanism, we have categorised the services into vertical and horizontal segments. We have identified gaps and requirements for standards to facilitate standardised interfaces for horizontal services, aiming to promote EV usage, enhance the user experience, and encourage widespread adoption of electric vehicles within the ecosystem.
3. To perform a communication network analysis to identify the latency, throughput, reliability, and security requirements necessary for the effective management and coordination of charging activities within the EV ecosystem.

Through our comprehensive evaluation of the protocol, we concluded that there are several technical barriers hindering interoperability among stakeholders in the EV ecosystem. In addition, we addressed the horizontal Vehicle-to-Everything (V2X) requirements and provided our recommendations to be considered in standardised protocols. Furthermore, this document encompasses a review of various communication technologies in the domain of EVs and the power grid. As a result of this review, we have outlined data communication requirements, including considerations for latency and bandwidth, to facilitate effective communication between EVs and the power grid.

The deliverable initiates an exploratory phase, aimed at identifying requirements and emphasising research and development opportunities. However, it is vital to acknowledge the necessity for additional investigations and laboratory tests to establish robust charging infrastructure, precise standards, and comprehensive regulations. The ultimate objective is to align these advancements with drivers' demands, optimising the operation of the power system effectively.

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1. Review of Communication Protocols and Standards in the EV and Flexibility Ecosystem

The transportation sector is a significant contributor to greenhouse gas emissions, and the adoption of electric vehicles (EVs) is essential for achieving decarbonization targets (Liu, Q., et al., 2020). To effectively handle the significant charging load within the current power grid infrastructure and fully leverage the potential of vehicle-to-grid (V2G) technology, the integration of electric vehicles into the power grid requires the use of communication protocols and standards that ensure seamless integration, safety, and efficiency. Consequently, the communication protocols and standards used in the EV and flexibility ecosystem for private and public charging infrastructure enable communication between the charging infrastructure, EVs, energy management systems, energy aggregators, and the grid and are critical for ensuring interoperability, safety, and efficiency. Different standardised protocols offer various types of services based on the needs of entities involved in the EV ecosystem. For instance, the widely adopted Open Charge Point Protocol (OCPP) at the EU level encounters compatibility challenges among its various versions and with legacy protocols, potentially leading to difficulties in seamless communication and integration between different charging stations and legacy systems during OCPP implementation in EV charging infrastructure. Consequently, conducting a thorough analysis of these protocols is essential to determining their feasibility for different use cases and aligning them with the requirements of the entities involved. The ISO 15118 standard classifies the EV ecosystem into primary and secondary actors based on protocol scope, emphasising the significance of effective communication and linkages across entities, as shown in Figure 1 (Schmutzler, J., Andersen, C. A., & Wietfeld, C., 2013, Nanaki, E. A., 2020). The communication between the primary actors (EVs and supply equipment (charging stations)) is covered by ISO 15118, CHAdeMO, and a few more proprietary protocols. Secondary actors, including charging point operators (CPOs), e-mobility service providers (EMSPs), distributed system operators (DSOs), and original equipment manufacturers (OEMs), fulfill their communication needs by utilising other standard protocols such as IEC, IEEE, OpenADR, and OSCP, as illustrated in Figure 2.

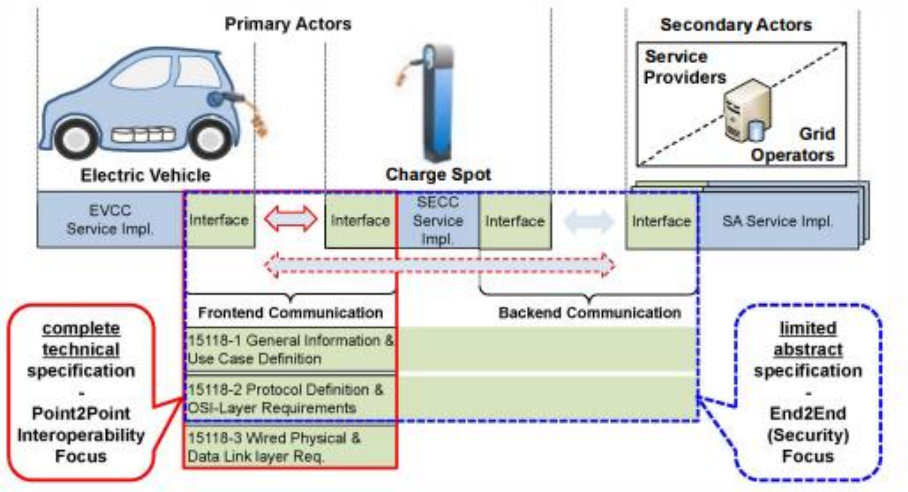

Figure 1. Categorization of the entities into primary and secondary actors in the EV ecosystem according to the ISO 151181 standard protocols (Schmutzler, J., Andersen, C. A., & Wietfeld, C., 2013, Nanaki, E. A., 2020)

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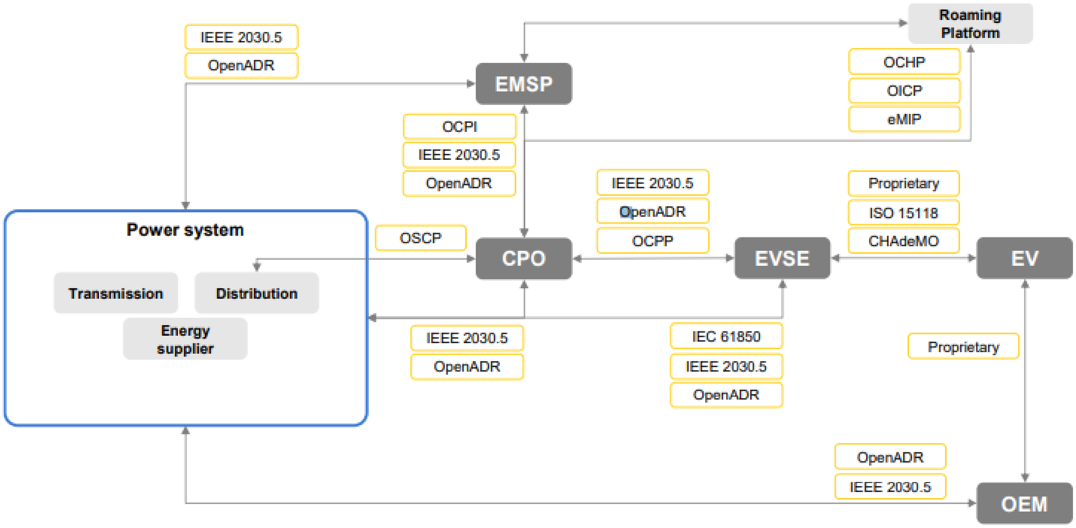

Figure 2. An overview of the different stakeholders in the EV ecosystem and their interaction through various protocols [Source: IEA CC BY 4.0]

1.1. ISO 15118/IEC 61850

The ISO 15118 protocol is a series of standardised communication protocols that facilitate the exchange of information between the primary actors (EV and EVSE) during the charging process by enabling communication between the EV Communication Controller (EVCC) and Supply Equipment Communication Controller (SECC). The IEC 61850 standard is a widely recognized international standard for electric power systems, primarily focusing on the communication and interoperability of substation automation systems. It enables efficient monitoring, control, and protection of power systems through the exchange of information between intelligent electronic devices (IEDs) in a substation, while also playing a crucial role in supporting the seamless integration and management of EV charging infrastructure. The IEC 61850 provides an interface between the primary and secondary (charging point operators - CPOs) actors, enabling them to monitor and manage the charging infrastructure from different manufacturers, ensuring interoperability, scalability, and security between the primary and secondary communicating entities. The protocols aim to enable interoperability between different EV charging infrastructure components and vehicles. The protocol is designed to facilitate bidirectional communication between the EV, the EVSE, and the CPOs, allowing for the exchange of data such as charging rates, metering information, and charging schedules, along with control over the power consumption of EVs from a Charge Point; consequently, the standard is significant for the Open Charge Alliance. The key features of the ISO 15118 protocol are its plug-and-play support, flexibility, and bidirectional secure communication, as discussed in the following. The protocol supports plug-and-play functionality, which means that the charging station can automatically detect and communicate with the plug-in EV (PEV) as soon as it is connected.

The EV and EVSE exchange various message types during charging, including a Certificate Signing Request (CSR) that the EV sends to the EVSE to facilitate the Plug and Play capability of the ISO 15118 protocol. The CSR message is typically a few hundred bytes long and contains several fields that provide information about the EV and the desired digital certificate. The CSR message includes the protocol version, charging connector type, public key, charging station ID, and charging station URL. The EVSE

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sends a Certificate Authority (CA) response message back to the EV, which contains the digital certificate and other information required for ensuring secure communication between the EV and the EVSE by providing authentication and encryption of data transmitted between them. The size of the CA response message depends on the size of the digital certificate and other information, but it is typically a few kilobytes. A typical CA consists of the authorization version of the certificate, serial number, signature algorithm, issuer name, validity period, public key information, and the basic constraints. The AR message plays a critical role in secure communication between the EV and the EVSE, as it authenticates the EV's identity and verifies the authenticity of the message, ensuring that only authorised devices communicate and that data transmission is encrypted and protected from unauthorised access. The EVSE sends an authorization response (AuthR) message to the EV, indicating that the EV is authorised to use the charging station. By utilising the AuthR message, the EVSE ensures that only authorised EVs are permitted to charge, providing a clear indication of the authorization result to inform the EV of its status and enable appropriate actions, such as disconnecting from the charging station if unauthorised.

The protocol allows for bidirectional communication between the PEV and the EVSE, which means that the charging station can receive information from the vehicle and adjust the charging rate accordingly. The overall communication consists of setup, charge, and finalisation phases, with sequences of the different messages shown in Figure 3 and detailed in the following (Schmutzler, J., Andersen, C. A., & Wietfeld, C., 2013, Shin, Minho, et al., 2016).

1. **Connection setup:** When an EV is connected to an EVSE, the EV's communication controller (EVCC) initiates a session setup request to the SECC to establish a communication session. The SECC acknowledges the request by responding with a session setup response. Each communication session is uniquely identified by a session ID, which is included in all messages exchanged between entities to manage the communication sessions on the application level. The session ID allows for the ability to pause and resume a charging session using multiple communication sessions.
1. **Service discovery**: Once a communication session is established between the EVCC and the SECC during a charging session, the EV sends a "discovery of all services" message to the SECC. This message includes the charging service and potential future value-added services that have been standardised. Each service is defined by parameters that allow the EVCC, using profile information, to choose the most suitable charging service. If the service discovery is successful, the SECC responds by providing a list of all available services that meet the specified criteria. This process empowers the EVCC to select the appropriate charging service for the EV based on its profile, ensuring efficient and reliable charging for the vehicle.
2. **Authorization:** Once a service is selected from an EVSE, the EVCC sends an authorization request with security credentials and status information, which is then validated by the SECC to determine whether authorization is granted or denied.
3. **Charging parameter discovery:** Upon successful authorization at the EVSE, the EV shares charging parameters such as estimated energy requirement, charging system capability, expected departure time, and payment information. In return, the EVSE offers details about power discovery results, its own charging parameters, a suggested charging schedule, and a

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pricing table. This enables the EV to efficiently schedule its charging session and ensures a transparent and reliable payment process for the charging service.

4. **Line locking:** The message pattern is used to lock the connector on the EVSE side in order to prevent unintentional removal of the connector during the charging session. This mechanism ensures that the connector remains securely attached to the EVSE, preventing any damage to the charging equipment or the EV. The locking mechanism is initiated through a specific message exchange between the EVCC and the SECC, which allows the EVCC to confirm that the connector has been securely attached before the charging process begins. Once the charging session is complete, the locking mechanism is released to allow the user to safely remove the connector.
5. **Power delivery:** After the successful authorization and parameter exchange, the EV is able to request the switching of power from the EVSE and confirm the charging profile that it will follow during the charging process. As part of this request, the EV also accepts the pricing conditions that were transmitted in the power discovery response. This enables the EVSE to provide a specific charging profile that is tailored to the EV's charging requirements while also ensuring that the charging process is transparent and predictable in terms of pricing. Once the charging profile has been agreed upon, the charging session can begin.
6. **Metering status and receipts updates:** During the charging process, the EVSE and EV periodically exchange metering status and metering receipts in an alternating order. The metering status exchange is used to check the proper operation of the charging process on both sides and to monitor the progress of the charging session. The EVSE sends power delivery status updates (i.e., PowerDeliveryRes) to the EV, which contain information about the current charging parameters, such as the amount of energy transferred, charging time, and charging power. In response, the EV sends metering receipts back to the EVSE, which acknowledge the received metering status and confirm the successful transfer of charging data.
7. **Power off and line unlock:** When the charging session is complete or the EV driver initiates an interruption of the charging process, the EV sends a power off message to the EVSE, requesting to stop the power supply. The EVSE confirms this request by sending a response message to the EV, which acknowledges the power-off request and unlocks the connector on the EVSE side. This message pattern is used to unlock the connector on the EVSE side, allowing for the safe removal of the connector.

The sequence of communication signals involved in the charging and session closing processes between the EV and EVSE in accordance with the ISO 15118 standard is illustrated in Figures 4 and 5 (ASSURED, 2017–2021). The steps involved in the initiation, maintenance, and termination of a charging session, presented in the time domain, are outlined below from t0 to t18.

Step t0: At time step t0, the charging process is initiated through high-level communication, which is then followed by a sequence of handshakes involving the exchange of charging parameters.

Steps t1 to t1c: At time step t1, the EV transmits its maximum limits for DC supply output current and voltage (3a), and the EVSE responds with the corresponding maximum values (3b). A compatibility check is conducted between the EV and EVSE, and if they are incompatible, the EV does not transition to the ready state and follows the normal shutdown sequence until step t16. In time step t1b, the EV positions itself correctly for charging, and a DC supply check is performed. If the DC output voltage remains below 60 V, the process continues; otherwise, the supply session is terminated. The EV

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initiates the connection process (4a) by sending a Cable Check Request, and the DC supply sets its status to "EVSE_Reserved_8" until the automated connection device is in the working position. At time step t1c, the EV supply equipment confirms secure mechanical contact, and the DC supply checks the voltage. If the DC output voltage remains below 60 V, the charging process proceeds, but if it exceeds 60 V, the supply session is terminated.

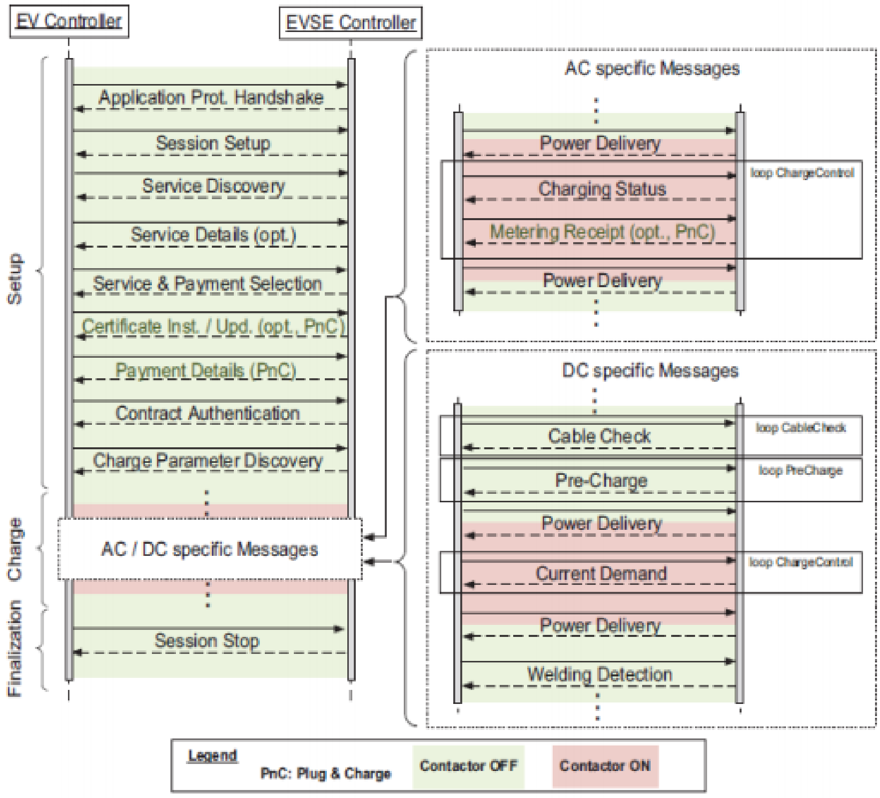

Figure 3. Communication and message flow between the EVs and the EVSEs according to the ISO 15118 and IEC 61850 protocols (Schmutzler, J., Andersen, C. A., & Wietfeld, C., 2013; Attanasio, L., et al., 2021)

Step t2: During time step t2, the Electric Vehicle (EV) transitions the control pilot state from B to either state C or D by closing state 2, effectively concluding the connecting phase. Then, the EV sends a signal (4b) to request cable and insulation checks. At this point, the DC supply initiates the inspection of the high-voltage system insulation and consistently reports the insulation state throughout the process.

Step t3: In time step t3, the DC supply evaluates the insulation resistance of the system and confirms it to be above 100 ohms/V. Upon successful completion of the insulation check, the DC supply promptly communicates the status as "Valid" through a subsequent message.

Step t4: In time step t4, the EVSE Status Code transitions to "Ready" as indicated by the Cable Check Response (4c).

Step t5: During this step, the pre-charge phase is initiated with the EV sending a Pre-Charge Request (5a). This request includes both the requested DC current, which is set to be less than or equal to 2 amperes (A), and the requested DC voltage. In response, the DC supply adjusts the DC output voltage to the requested value specified in 5a while ensuring that the current is limited to a maximum of 2 A, even if the requested current is 0 A.

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Step t6: In time step t6, the DC output voltage of the charging system attains the requested voltage within the specified tolerances outlined in IEC 61861-23-1 CD3 chapter 101.2.1.2. If necessary, the EV makes periodic adjustments to the requested DC voltage through cyclic messages (5a) to ensure that the deviation between the DC output voltage and the EV battery voltage remains below 20 V.

Step t7: At time step t7, once the deviation of the DC output voltage from the EV battery voltage is below the threshold of 20 V, the EV proceeds to close its disconnecting device. Simultaneously, the EV sends a Power Delivery Request (6a) with the Charge Progress set to "Start," enabling the output of the DC power supply and setting the EV's Ready status to "True." Subsequently, after disabling any pre-charge circuit if present and activating the power supply output, the DC supply provides feedback (6b) indicating its readiness for energy transfer.

Step t8: During this step, the EV initiates the energy transfer phase by setting the DC current request using message 7a. In response, the DC supply adjusts its output current and voltage to match the requested values. Subsequently, the DC supply relays important information back to the EV through message 7b, including the present output current, output voltage, current limit, voltage limit, and its current operational status.

Step t9: At time step t9, the DC output current aligns with the requested DC current within the defined delay time (Td), as specified in IEC 61851-23-1 CD3 chapter 101.2.1.3. (i.e., the time span between t9 and t8 is equal to Td; this is denoted by a bold line when a request is made). Following this, the EV adjusts both the DC current request and DC voltage request cyclically, based on its specific charging or supply strategy, using message 7a.

Steps t10a to t10b: In steps t10a–t10b, either the user or the vehicle system signals for the charging process to cease. In response, the EV decreases the current request in order to conclude the energy transfer phase. The reduction in current is determined according to the specific charging or supply strategy employed by the EV.

Step t11: During time step t11, as the current requests are reduced to 0A, the EV proceeds to request the DC supply to deactivate its output power. The EV sets the Charge Progress to "Stop" in order to communicate the termination of the charging process.

Step t12: In time step t12, the DC supply deactivates its output and opens any contactors if present. Additionally, upon receiving a message with the "Power Delivery Request (Charge Progress)" set to stop, the DC supply actively discharges any internal capacitance within its output circuit. It is crucial to note that during the discharge process, the DC supply ensures no current flows into the EV input, preventing any unintended current flow.

Step t13: In time step t13, within 2 seconds after disabling its output, the DC supply reports the EVSE Status Code as "Not Ready."

Step t14: In order to ensure that the DC supply has fully discharged its output by time step t14 (in case the message was lost), the EV transitions the control pilot signal state to B. This transition occurs either upon receiving a message with the Power Delivery Request and EVSE Status Code set to "Not Ready" or after a timeout period. Additionally, the EV has the option to conduct a welded contactor check and communicate the results to the DC supply.

Step t15: At the earliest, during step t15, the EV activates its isolation monitoring mechanism to ensure the ongoing evaluation of electrical isolation within the EV system. This proactive monitoring enables

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the EV to swiftly identify and address any potential faults or anomalies in the electrical insulation of its components. By continuously monitoring the isolation status, the EV enhances safety and ensures the reliable operation of its electrical system.

Steps t16: During time step t16, a voltage check is conducted to ensure that the DC output voltage remains below 60 V DC. This verification process is crucial for maintaining the safety and compliance standards of the charging system. By confirming that the DC output voltage remains within the specified limit, potential risks associated with high voltage are mitigated, and the overall integrity of the charging process is upheld.

Step t17: In time step t17, the system receives the Session Stop Request, signifying a request to terminate the ongoing charging session. Concurrently, the system observes a State A, which serves as an indication that the charging process is transitioning towards the disconnection phase, signifying that the resources allocated for the charging session are ready to be released.

Step t18: In the final step t18, the EV is mobilised only when the automated connection device is verified to be in the home position. This confirmation is obtained through a Session Stop Response message with a response code indicating "Ok." Once this confirmation is received, the EV is effectively mobilised, ensuring that it remains securely in place and is able to move after the disconnection process.

The ISO 15118/IEC 61850 standard is published in eight parts (ISO 15118), and the document structure covers the communication between the EVs and EVSEs according to the seven layers of the Open Systems Interconnections (OSI) communication protocols (Gasto, A. L., 2016).

Part 1: The ISO 15118-1 protocols establish the terms and use cases for the V2G interface, outlining the communication protocols employed throughout the charging process. Key terms, such as electric vehicle supply equipment (EVSE), charge point operator (CPO), and E-Mobility service provider (EMSP), are defined within these protocols. The use cases encompass a range of scenarios, including immediate and delayed charging, and outline the sequence of events and message exchanges between the EV and the charging infrastructure.

Part 2: The ISO 15118-2 is a technical protocol that specifies the message flows, data structures, and communication requirements for the V2G interface. It defines application layer messages for vehicle identification, charging status monitoring, and billing information exchange using a request-response mechanism. The standard uses XML for message formatting and specifies TCP/IP as the transport layer protocol for reliable data transfer. TLS is mandated for secure communication, ensuring the confidentiality, integrity, and authenticity of exchanged messages.

Part 3: The ISO 15118-3 focuses on the wired physical and data link layer requirements for the V2G interface using Power Line Communication (PLC) technology. It specifies the frequency range (3 kHz to 148.5 kHz) and sub-bands for PLC communication, along with transmission parameters. The standard also defines the use of ISO-TP, a modified version of the Controller Area Network (CAN) protocol, for reliable data transfer over power lines. The ISO-Transport Protocol (ISO-TP) employs segmentation and reassembly of data packets to accommodate large messages within the limited bandwidth of the power lines.

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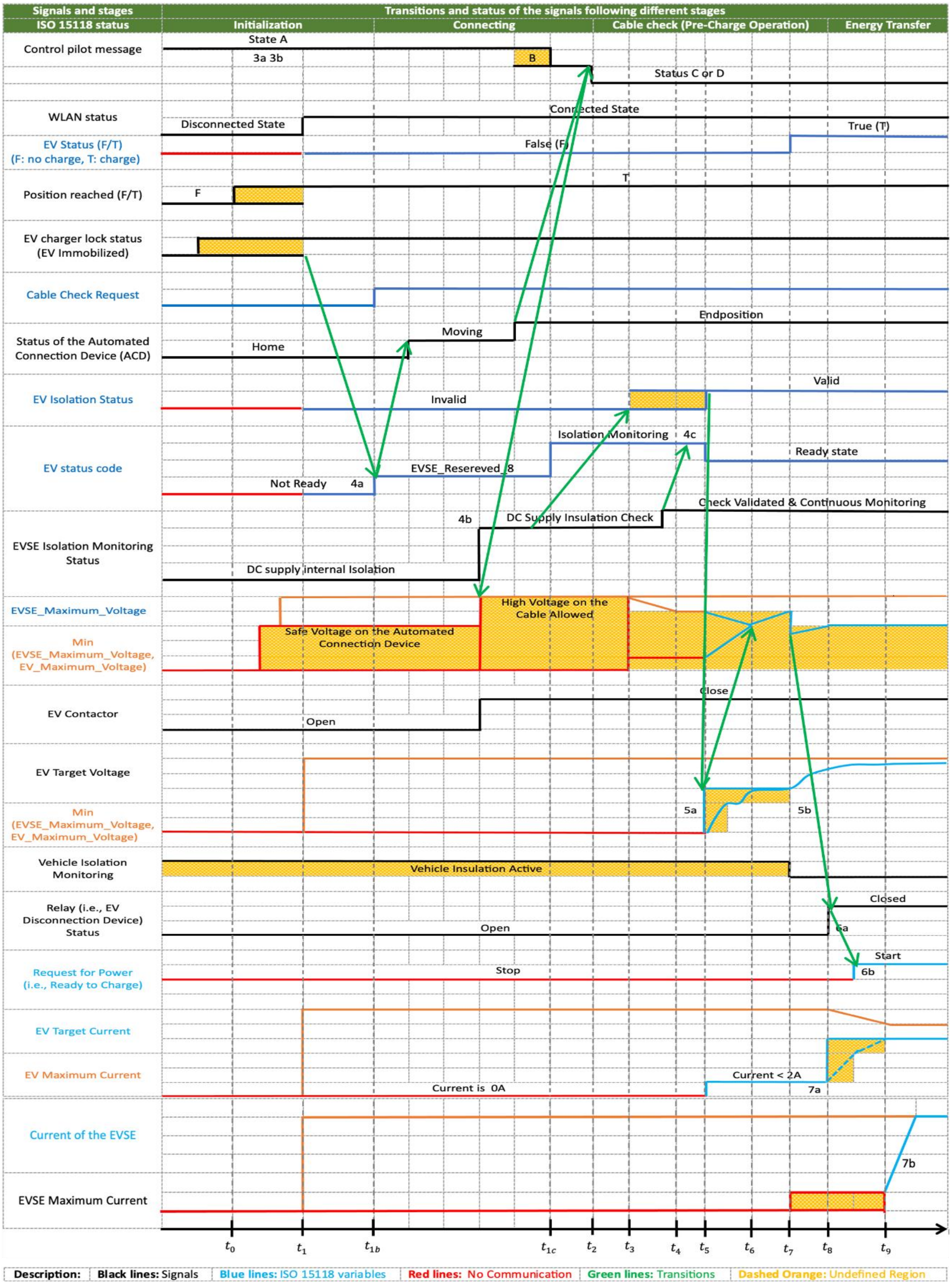

Figure 4. Charging signalling diagram representing the sequence of charging startup process between an EV and EVSE

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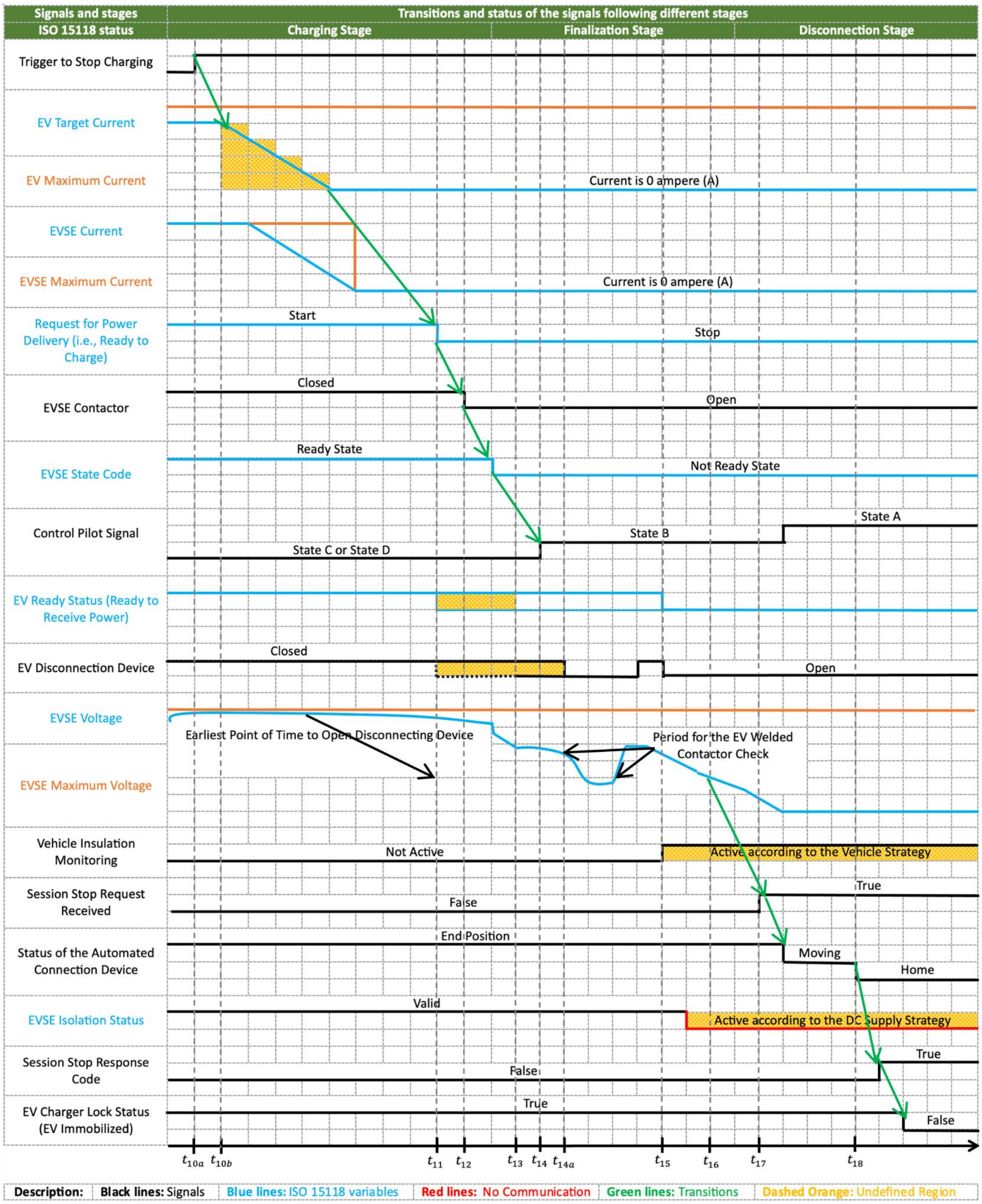

Figure 5. Sequence diagram of various signalling involved in closing the charging of an EV between an EV and EVSE

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Part 4: ISO 15118-4 specifies network and application protocol conformance test requirements for the V2G interface between EVs and charging infrastructure. It defines a set of test cases for verifying the conformance of V2G implementations to the network and application protocols outlined in ISO 15118-2 and ISO 15118-3. The test cases cover communication initiation, message exchange, error handling, and more. The standard outlines the use of reference implementations, provides guidelines for their selection, and sets requirements for the conformance tests, including reporting test results and deviations from the standard.

Part-5: The ISO 15118-5 is a standard that defines requirements and procedures for testing the compliance of the physical layer and data link layer communication protocols between the EV and the EVSE. The physical layer test verifies the interface's physical characteristics, while the data link layer test checks the compliance of the communication protocol, including data format, message structure, error handling, and security features.

Parts 6 and 7: The ISO 15118-6 standardised wireless communication requirements between the EV and the charging station, supporting technologies like Wi-Fi, Bluetooth, and cellular networks. It facilitates the exchange of charging-related information, authentication between the EV and charging station, negotiation of charging parameters, and ensures secure and efficient charging sessions. While ISO 15118-7 governs the IEEE 802.11 (Wi-Fi) standard, it operates in the 2.4 GHz or 5 GHz frequency bands with a minimum data transfer rate of 1 Mbps. The protocol ensures secure communication through encryption and authentication mechanisms. It adopts an XML-based message protocol for data exchange, supporting various message types for transactions, responses, and status updates.

Part-8: The ISO 15118-8 covers the physical and data link layer requirements for wireless communication between EVs and EVSE using the IEEE 802.11 standard (Wi-Fi) supporting the 5 GHz frequency bands. The protocol employs spread-spectrum modulation for interference resilience and offers various transmission rates based on channel conditions. For the data link layer, it utilises the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) protocol for shared channel access and ensures error-free communication through forward error correction (FEC) codes.
The V2G Technology Protocol (V2GTP) payload consists of multiple fields, with some being mandatory and others optional. Here are the key fields in the V2GTP payload, along with their respective sizes (Kwon, Bohyun, et al. 2014).

1. **V2GTP Message Type (2 bytes):** This field indicates the type of V2GTP message being sent, such as request, response, or notification.
2. **Payload Length (2 bytes):** This field indicates the length of the payload in bytes.
3. **Message ID (4 bytes):** This field contains a unique identifier for the V2GTP message, which is used to correlate requests and responses.
4. **Session ID (1 byte):** This field contains a unique identifier for the V2GTP session, which is used to identify the communication session between the EV and the charging station.
5. **Payload Data (variable):** This field contains the actual data being exchanged between the EV and the charging station. The size of this field can vary depending on the type of data being exchanged, such as a charging profile, pricing information, or status updates.
6. **Message Authentication Code (MAC) (variable):** This field contains the MAC value for the V2GTP message, which is used to ensure message integrity and authenticity.
7. **Payload Signature (variable):** This field contains the digital signature for the V2GTP message, which is used to ensure message authenticity and non-repudiation.

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The ISO 15118/IEC 61850 standard is used for communication between EVs and EVSEs, while the object model for electric mobility proposed in IEC Technical Report 61850-90-8 is used for communication between the EVSE and the infrastructure operators (i.e., CPOs). The architecture of the communication interface for charging EVs is incorporated into a typical IEC 61850 client-server setup, demonstrating the mapping of ISO/IEC 15118 and IEC 61850 (Gasto, A. L. 2016). The communication between the EV and the EVSE follows the principles defined by the ISO/IEC 15118-2 V2G communication interface, where the EVCC always acts as the client and the SECC always acts as the server. Information transmitted by the EV is transferred to the ISO/IEC 15118 server via the V2G Communication Interface. Subsequently, the relevant information is mapped to the IEC 61850 information model via IEC 61850-90-8 and provided to the CPO client-side.

1.2. ChAdeMo

ISO 15118 and IEC 61850 are applicable to EV charging in residential and public settings, supporting both AC and DC charging. However, it is important to note that they do not specifically cater to the requirements of fast DC charging. These standards primarily emphasise communication protocols, interoperability, and integration of EV charging infrastructure with the power grid rather than high-speed DC charging capabilities. The CHAdeMO protocol, developed by the CHAdeMO Association, facilitates high-speed DC charging for EVs and is widely adopted, with over 10,000 charging stations globally and increasing support from EV manufacturers. The protocol comprises multiple layers, such as the physical, data link, and application layers, facilitating communication between EVs and charging stations. It utilises a modified version of the well-established CAN bus protocol at communication speeds of up to 500 kbps while leveraging a 500-volt DC power supply to facilitate efficient and rapid charging of EV batteries. The protocol uses a message-based approach at the data link layer for data exchange between the EV and the EVSE. Messages (e.g., requests, responses, and notifications) are transmitted via the CAN bus with additional data elements for DC charging requirements. At the application layer, the protocol handles various data types (e.g., charging status, parameters, EV information). Communication involves cyclic transmissions of CAN protocol data units (PDUs) across multiple stages (Chertkova, I., 2021).

1. **CAN communication setup:** Once the charging station (SECC) detects the connector input signal, it initiates the relevant response from the charging application. The CAN communication between the EV and the EVCC starts after the "d1" switch is closed, indicating the beginning of the charging sequence.
2. **The process of pre-charging data exchange:** A battery parameter compatibility test is conducted to ensure compatibility between the EV and the EVSE. This test evaluates the maximum charging current, minimum and maximum charging voltage, and maximum charging power for the entire charging process. The test results also help calculate the charging time, including the maximum charging time, based on the battery parameters.
3. **Isolation test in the power circuit:** During the insulation test phase of DC charging, it is crucial to ensure compliance with IEC 61851-23 standards for the charging cable. The CHAdeMO specification specifies a minimum insulation resistance of 20 kOhm. If the measured insulation resistance is below this threshold, the charging process will be halted, and an error message will be shown.

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4. **Battery connection:** The DC breaker on the EVSE side is responsible for connecting the load voltage. However, the control of the contactor in the EV is not within the scope of the EVSE application. Instead, the CHAdeMO implementation in the vehicle uses dedicated CAN signals to perform the contactor control.
5. **Charging control process:** Upon receiving a chargingCurrentReq message from the EV, the EVSE initiates the supply of the requested charging current, which is typically determined by the EV's battery management system (BMS).
6. **Termination of charging process**: The charging process typically ends when the EV or EVSE initiates a stop signal, reaches the predetermined charging time limit, experiences a CAN communication failure, detects a hardware error in the EVSE, reports overvoltage, undervoltage, overtemperature, or detects a ground fault.
7. **Welding Detection and Session Stop:** After completing the charging process, the EV performs a check on the DC disconnectors to ensure there is no welding or sticking. This check involves disconnecting the battery from the EV and monitoring the measured voltage (presentOutputVoltage) for a specific period. If the voltage drops below 10 volts during this period, it indicates a successful disconnection without welding. Subsequently, the connector lock is released, allowing the user to disconnect the charging cable. Once the EV concludes its communication with the EVSE, the EVSE opens switches "d1" and "d2" and deactivates the CAN communication.

1.3. IEEE 2030.5

IEEE 2030.5 is an IP-based application protocol designed for smart metering, demand/response automation, and load control in local or home area networks (Energy Research and Development Division, 2020). It supports both residential and commercial settings, facilitating connectivity and management of devices within the smart grid framework. In IEEE 2030.5, devices can act as clients or servers, with servers hosting resources, including demand response programs provided by energy service providers, while clients access and modify server resources, such as receiving text messages. IEEE 2030.5 utilises function sets to categorise resources and functionalities, including *support, common, and smart energy function* sets (Mater, J., 20219). The protocol is designed based on the representational state transfer (REST) architecture, commonly used for web services over HTTP. It follows a client-server model where servers contain and operate on resources accessible to clients through unique URIs. Clients interact with these resources using standard HTTP operations (GET, PUT, POST, and DELETE). Function sets in IEEE 2030.5 are interdependent, with some relying on other resources. For example, the Demand Response Load Control (DRLC) function set depends on response resources to communicate with energy service providers for load shedding or curtailment.

Support Resources: Function sets in IEEE 2030.5 are essential for device operation, supporting security, network connectivity, and device management. They enable device discovery, communication, and service identification. The DeviceCapability Function Set provides discovery services, while the Response Function Set allows devices to acknowledge messages and provide status information. The responseRequired attribute determines if a client needs to respond to events. Other function sets include EndDevice (information exchange), FunctionSetAssignments (program

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specification), Subscription/Notification Mechanisms (rapid resource change notification), and Time (time distribution). Although not mandatory, subscriptions improve network efficiency, and FunctionSetAssignments group inverters for efficient command execution in DER scenarios.

Common Resources: This category encompasses essential function sets that are shared among multiple applications in smart grid systems. These function sets provide general-purpose functionalities, including obtaining the current time (Time Function Set), querying network interface status (Network Interface Status Function Set), checking device and component status (DeviceStatus Function Set), retrieving device manufacturer information (Manufacturer Function Set), upgrading firmware over-the-air (Firmware Upgrade Function Set), and logging events for tracking and troubleshooting (Log Event Function Set). Together, these function sets enable scheduling, event notifications, metre data management, power status determination, device information retrieval, firmware updates, and event analysis in smart grid systems.

Smart Energy Resources: This category comprises function sets specific to the Smart Grid, aimed at supporting advanced functionalities in energy management. These function sets align with the business objectives of utilities and energy aggregators and include the following resources:

1. Billing: Enables generating billing information for energy consumption and related services offered by the utility or aggregator.
2. Demand Response/Load Control (DRLC): Supports managing energy demand by controlling or reducing customer energy consumption during peak periods. It involves sending signals to devices for consumption reduction and receiving status updates.
3. Distributed Energy Resources: Facilitates managing and controlling distributed energy resources like solar panels, energy storage systems, and electric vehicles in an integrated and coordinated manner.
4. Messaging: Provides the ability to send and receive messages between devices on the network.
5. Metering: Allows collecting and reporting energy consumption data from meters or other devices.
6. Energy Flow Reservation: Enables reserving and managing energy flow in the grid to ensure reliability and stability.
7. Prepayment: Supports customers in prepaying for energy consumption while allowing utilities or aggregators to track and manage these payments.
8. Pricing: Enables setting and managing prices for energy consumption or other services provided by the utility or aggregator.

These function sets are designed to support advanced functionalities such as demand response, load control, renewable energy integration, billing, messaging, metering, energy flow management, prepayment, and pricing in the context of the Smart Grid.

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1.4. OpenADR

The Open Automated Demand Response Communications Specification (OpenADR) is a crucial component in establishing interoperability standards for the U.S. Smart Grid. Its primary objective is to enhance coordination between electricity supply and demand by automating DR actions at the customer level, such as load shedding or shifting. OpenADR has gained significant adoption due to its ability to meet diverse market needs, including fast DR, dynamic pricing, integration of renewable resources, grid-scale storage, electric vehicles, and load-based generation.
The model facilitates information exchange between two main components: the Virtual Top Node (VTN) and the Virtual End Node (VEN). The VTN, acting as a server, registers devices and enables communication with the load aggregator or utility, while the VEN, functioning as a client, receives messages from the VTN and communicates with the represented devices. The VEN provides relevant information back to the server, such as device participation details, opt-outs, and reporting. It's important to note that the VTN-to-VEN relationship is one-to-many, with a single VTN connecting to multiple VENs while each VEN connects to a single VTN. This communication process allows end-users to receive demand response signals, enabling them to automate their response strategies based on pre-programmed settings. The protocols are characterised by the following defining features:

- Continuous, Secure, and Reliable Communication: The protocol ensures uninterrupted, secure, and reliable two-way communication between energy service providers and end points, allowing for the reception and acknowledgment of DR signals.
- Translation Capability: It supports the translation of DR event information into continuous internet signals that can interoperate with various energy management and control systems, lighting, and other end-use controls.
- Automation: The protocol enables the initiation of automation through pre-programmed demand response strategies determined and controlled by the end-user participant upon receiving external signals.
- Opt-Out Mechanism: OpenADR provides an opt-out or override mechanism to all parties in case a DR event occurs at an inconvenient time for making changes to end-use services.
- Comprehensive Data Model: It includes a detailed data model and architecture for communicating price, reliability, and other DR activation signals.
- Scalable Architecture: The protocol offers a scalable communications architecture that can accommodate different forms of DR programs, various end-use buildings, and dynamic pricing.
- Based on Open Standards: Built on open standards-based technology, such as Internet Protocol (IP) and web services, the protocol ensures interoperability and compatibility.

There are two common implementation models for Virtual End Nodes (VENs) in OpenADR:

1. Cloud-based VENs are typically used in residential and commercial sectors, with numerous smart devices controlling smaller loads. In this model, the VEN is hosted on the device company's or load aggregator's existing control platform. Each product company creates one VEN per Virtual Top Node (VTN) and registers all participating devices within the VTN's

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program territory. Device control logic in response to OpenADR signals is handled by the existing device control infrastructure, reducing complexity in managing individual devices.

2. On-site VENs are more prevalent at large commercial and industrial (C&I) sites. In this model, a VEN may be integrated into the on-site energy management system hardware, or a separate hardware device may be installed as the VEN. This approach involves a manual process and incurs some cost, but it is easier to justify due to the higher load control per device and per site with the assistance of an on-site professional energy manager.

1.5. OCCP

The Open Charge Point Protocol (OCPP) is a communication protocol that facilitates seamless communication and efficient management of EV charging infrastructure. It promotes interoperability among various charging equipment and central management systems, irrespective of the manufacturer or charging station model. With OCPP, charge point operators can remotely monitor charging stations, control access, configure hardware settings, perform firmware updates, and integrate different payment and billing systems (Van Amstel et al., 2016). The protocol is essential for the seamless operation of EV charging networks, allowing charge point operators to monitor the status and performance of charging stations in real time. It provides valuable data, including energy consumption, charging duration, and transaction details, for analytics and reporting (Alcaraz, C., et al., 2017). The protocol enables communication between the charging point (client) and the central system (server), with the charging station acting as the client and providing information about charging session availability, status, and energy consumption through its connectors (Open Charge Alliance, 2020). The backend charge point management system (CPMS) utilises OCPP to establish communication with the charge point, enabling the CPMS to effectively monitor and manage charging sessions while collecting crucial data on energy consumption and billing. The backend charge point management system (CPMS) utilises OCPP for communication with the charge point, enabling effective monitoring, management of charging sessions, and collection of crucial data on energy consumption and billing. The protocols support two types of messages between the EV and the charging point.

1. Simple Object Access Protocol (SOAP) is a message-based protocol that uses XML format for data representation. However, its implementation requires both the backend and the Charge Point to act as servers, which poses limitations on operating multiple Charge Points behind the same router. Additionally, the large size of XML messages can result in delays and timeouts, creating challenges for real-time communication, especially in the presence of unreliable internet connectivity.
2. JavaScript Object Notation (JSON) is a lightweight and versatile data interchange format that offers improved readability and ease of writing compared to XML. It also provides enhanced diagnostic capabilities and facilitates the transmission and reception of data through HTTP requests, relying on websockets for two-way communication. This approach requires only one entity, typically the backend, to function as a server in the OCPP context, simplifying the implementation and operation of the communication system.

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1.6. OSCP

The Open Smart Charging Protocol (OSCP) enhances OCPP protocols to enable effective communication and negotiation between DSOs and CPOs. The DSO generates a detailed 24-hour forecast of supply and demand at 15-minute intervals. They inform the CPO about the allocated capacity and available spare capacity for negotiation. During negotiation, the CPO can request capacity adjustments based on their specific needs. Once the negotiation is complete, the CPO creates a comprehensive charge plan for charge points, specifying power limits for specific time slots (Portela, C. M. et al., 2015). The charge plan is transmitted using the OCPP protocols with two main messages.

1. UpdateCableCapacityForecast: This message facilitates the transmission of forecasted cable capacity and backup capacity information from the DSO to the CPO. The current implementation involves sending one forecast per cable every 15 minutes within a 24-hour period. However, the protocol allows flexibility in determining the optimal frequency based on the specific needs of DSOs and CPOs. The backup capacity is provided to CPOs to accommodate potential additional demand, enabling them to request extra capacity when necessary. Currently, the DSO assigns backup capacity to CPOs using a fair and impartial first-come, first-served strategy to ensure equitable allocation.
2. RequestAdjustedCapacity: This message enables communication between the CPO and DSO to request additional capacity. The DSO assesses capacity availability and decides whether to accommodate the request. The CPO can also use this message to return unused capacity to the DSO, making it available for other CPOs.

1.7. OCPI

The Open Charge Point Interface (OCPI) is an automated protocol based on JSON used for communication between charge points and their connected charging networks (EV Roaming Foundation 2021). It enables roaming services by facilitating communication between roaming hubs, allowing CPOs and EMSPs to exchange data even without a direct peer-to-peer connection. OCPI utilises a JSON API with HTTP, supporting real-time synchronous and asynchronous operations. It efficiently facilitates information exchange between EMSPs and CPOs for direct and hub-mediated communication. The OCPI protocol facilitates data exchange among network operators, allowing them to share information on reservations, charging records, financial transactions, and location details. This interoperability enables network operators to track customer activities across different charging networks. As a result, EV drivers can conveniently access charging stations that comply with OCPI standards and stay informed about pricing and availability. The OCPI 2.2 version introduces various features to enhance the roaming experience (Van der Kam et al., 2022).

1. P2P roaming allows direct collaboration and monitoring between service providers, providing EV drivers with access to multiple charging networks and seamless tracking of their charging activities.
2. Roaming via hub functionality establishes connections among a group of networks using a central hub as an intermediary. This expands charging options for EV drivers within the interconnected network of providers, enhancing convenience and accessibility.

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3. Mixed roaming enables any OCPI EV charging station to establish connections with other networks, giving EV drivers the freedom to access charging stations across a wide range of networks, maximising convenience and choice.
4. Real-time data provides EV drivers with up-to-date information on station availability and cost, enabling informed decisions for effective charging session planning and optimization.
5. Charge session authorization ensures secure access to charging infrastructure by allowing authorised users and handling reservations for a smooth charging experience.
6. Billing and tariff functionality enables standardised payment processes across OCPI-compliant networks, simplifying financial transactions for EV charging services.
7. Platform monitoring allows network operators to track and manage charging infrastructure, providing real-time data and analytics for maintenance, optimization, and resource allocation, enhancing the overall user experience.

1.8. OCHP

The Open Clearing House Protocol (OCHP) connects different market actors within the electric mobility charging infrastructure domain (Martinenas, S., et al., 2017). These actors include EV users, Electric Vehicle Service Providers (EVSPs), EVSE Operators, Navigation Service Providers (NSPs), and Clearing House Operators. The EVSPs, EVSE Operators, and NSPs are commonly referred to as "partners" in the clearing house system. They collaborate in data exchange, interoperability, and service provision. The Clearing House Operator acts as the administrator, overseeing and managing the system's operation. The clearing house acts as an intermediary, simplifying roaming by establishing a central connection and enabling EV users to conveniently charge their vehicles at different charging stations operated by various EVSE operators. The typical process involving OCHP protocols follows these steps:

1. Partner A, an EVSP, uploads EV user authorization data to the CH, ensuring seamless roaming and charging services across different networks connected through the Clearing House.
2. EVSE operators with roaming contracts download authorization data from the CH, validating and authenticating roaming authorizations for EV users associated with Partner A.
3. EVSE operators enable downloaded authorizations to be used on their charge points, allowing EV users with valid roaming authorizations to conveniently access and utilise the charge points within the roaming network.
4. Successful utilisation of roaming authorizations enables EV users associated with Partner A to charge their vehicles at all charge points operated by the mentioned EVSE operators.
5. EVSE operators upload charge data to the CH using Charge Detail Records (CDRs), providing detailed information about charging sessions for data exchange and transparency within the roaming ecosystem.
6. The CH securely and efficiently routes the uploaded charge data to Partner A using OCHP, enabling access and utilisation for purposes such as billing, analytics, and reporting.
7. Partner A calculates charges based on the received charge data and agreed-upon tariff rates with the roaming partner, generating bills for its customers and facilitating compensation for charging services provided by the roaming partner.

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1.9. OICP

The Open Intercharge Protocol (OICP), introduced by Hubject in 2012, standardises interoperability and data exchange among EV charging infrastructure stakeholders while offering additional solutions such as an ad-hoc payment system and a contractual framework for EV roaming, enhancing convenience and accessibility for EV drivers (Buamod, I., et al., 2015). Registered partners in the OICP ecosystem have the ability to consolidate sub-providers or operators under their system, serving as intermediaries between the sub-partners and Hubject, simplifying communication and technical aspects, while OICP supports web-service communication using SOAP or REST architecture. The OICP protocol supports various use cases:

1. Roaming via the Hubject hub: This enables EV drivers to access charging services from different network operators through the central Hubject hub, using OICP for authentication and communication.
2. Ad-hoc payments: Allow EV drivers to initiate and complete real-time payment transactions at charging stations without pre-established contracts or subscriptions.
3. Authorizations: Facilitates the exchange of authorization requests and responses between the charging station and the central system, ensuring only authorised users can access the charging infrastructure.
4. Real-time exchange of charge point information: Supports real-time sharing of data such as availability, location, status, pricing, and capabilities of charging points between infrastructure operators, service providers, and navigation systems.
5. Billing: Enables the exchange of charging data and transaction details between charging infrastructure operators and service and payment providers.
6. Reservations: Allows EV drivers to pre-allocate and reserve specific charging stations, ensuring availability when needed, with processes for request, confirmation, and cancellation between the driver and the infrastructure operator.

1.10. eMIP

The eMobility Interoperability Platform (eMIP) provided by GIREVE offers a solution for seamless access to charging services by providing a charge authorization and data clearinghouse API, along with a comprehensive charging point database (GIREVE, technical report, 2019). The platform categorises actors into roles, including GIREVE's Platform, Data Aggregator, CPO, and eMSP, each with specific responsibilities in the EV ecosystem. Here is an overview of the roles:

1. GIREVE's Platform: It serves as a central entity facilitating interoperability and communication within the e-mobility system. Implementing the eMIP protocol, it provides infrastructure and services for seamless interaction between actors, utilising SOAP web service interfaces.
2. Data Aggregator: This role involves collecting, aggregating, and managing data on charging infrastructure and sessions. The Data Aggregator gathers information from CPOs and other sources, offering a consolidated view of charging point data to eMSPs and relevant entities. It utilises SOAP web service interfaces for data exchange.
3. CPO: Charging Point Operators (CPOs) own and operate charging points, ensuring infrastructure availability and managing charging transactions. They interact with other actors

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via SOAP web service interfaces to exchange charging point information, handle charge authorization requests, and transmit session data.

4. eMSP: eMSPs are service providers offering e-mobility services to end-users, including EV charging, payment solutions, and value-added services. They act as intermediaries between EV drivers and charging infrastructure. eMSPs utilise SOAP web service interfaces of the eMIP protocol for charge authorizations, charging point information retrieval, and data exchange with other actors.

2. Analysis and Recommendation of the Protocols

Table 1 presents communication protocol services, while Table 2 assesses electric vehicle grid integration protocols based on openness, interoperability, maturity, and market adoption (Neaimeh, M., et al., 2020). The evaluation uses a scale (low, medium, and high) to indicate the protocols' level of openness, compatibility with various systems, development/stability, and market acceptance/implementation for the different use cases. These use cases encompass various charging scenarios, ranging from communication between primary actors to roaming services, and are extensively discussed in the ElaadNL (2018) report. The assessment of these properties, based on the study by ElaadNL (2018), considers factors such as accreditation, intellectual property rights, and accessibility. Openness is evaluated to determine the wider participation of e-mobility entities in protocol development (Van der Kam et al., 2020). Interoperability refers to the seamless operation of multiple systems without restrictions, and its assessment includes evaluating the effort required to replace a component, such as a charging station, in a communication link (EPRI, 2019). Factors considered in this assessment include technical interoperability, which involves syntax and semantics, the specificity of protocol behaviour definition, and the clarity of specifications (EPRI, 2019). Maturity is determined by the number of releases, duration of usage, potential for certification at an official test laboratory, and availability of testing tools. Market adoption is assessed by considering the current user base of the protocol, indicating its level of acceptance and implementation in practical applications (EPRI, 2019).

Table 1. Overview of the different services of the communication protocols in the EV ecosystem (ElaadNL., 2018)

Protocols	Services
ISO 15118	Residential and public AC charging (G2V and V2G)
CHAdeMO	Public fast charging (G2V and V2G)
IEC 61850	On-site or local control
OCPP	Remote monitoring, control, and management of EVSEs
IEEE 2030.5	Energy management between utility operators and aggregators, industrial, residential, and commercial customers
OpenADR	Demand- side management at price level, customer level based on prices, load shifting, and optimising the electricity consumption
OSCP	Energy management based on DSO forecasted supply and demand of energy

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OCPI	Hub roaming and mix roaming (connection with other CS networks), P2P roaming, Providing charge point information, Authorising charge sessions, Reservation, Remote start and stop, Providing session information, Billing, Smart charging support, Charging platform monitoring
OCHP	Hub roaming, P2P roaming, Authorising charge sessions, Remote start and stop, Providing session information, Billing
OICP	Hub roaming, Charging point information, Authorising charge sessions, Reservation, Remote start and stop, Providing session information, Billing, Ad-hoc payments, smart charging, Charging platform monitoring
eMIP	Hub roaming, P2P roaming, Charge point information, Charge point search (on the move), Charge point search module, Authorising charge sessions, Billing, Charging Platform monitoring

Table 2. Analysis of communication protocols based on openness, interoperability, maturity, and market adaptability (ElaadNL., 2018, Neaimeh M., et al., 2020)

Use case	Entities	Protocols	Openness	Interoperability	Maturity	Market adaptability
Primary	EVSE and EV	ISO 15118	High	High	High	High
		CHAdeMO	Medium	Medium	High	High
Monitoring and control	CPO and EVSE	IEC 61850	High	High	High	High
		OCPP	High	High	High	High
Demand response	DSO, Aggregator, CPO, EVSE, and EV	IEEE 2030.5	High	Medium	High	Low
		OpenADR	High	Medium	Medium	High
Smart charging		OSCP	Medium	High	Low	Low
Roaming		OCPI	High	High	Low	Low
		OCHP	Medium	High	High	Medium
		OICP	Medium	High	High	High
		eMIP	Low	High	High	Medium

2.1. Challenges and recommendations for open communication protocol adoption

To promote the widespread adoption of open and interoperable communication protocols in the EV ecosystem, it is essential to address the challenges that impede their implementation. This section outlines these challenges, presents relevant examples, and provides recommendations for necessary actions.

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2.1.1. Prevalence of proprietary protocols

The adoption of open communication protocols in vehicle grid integration is hindered by the prevalence of proprietary protocols developed by different companies. This obstacle prevents the establishment of standardised and interoperable communication systems in the industry. To enable seamless integration of EVs into the power grid, it is crucial to establish universal communication protocols that allow any entity in the EV ecosystem to interact and participate in advanced charging strategies. However, the current landscape is dominated by semi-open protocols like CHAdeMO (Table 2) and trial-based standards such as ISO 15118 (Elaad, 2018), which restrict widespread implementation. Additionally, proprietary secondary protocols hold a significant market share, impeding interoperability and standardisation efforts for smart charging strategies.
Integrating primary and secondary actors to effectively coordinate EV charging demand in various settings is a complex task due to the diverse services, interfaces, and constraints imposed by proprietary protocols. To address this challenge, it is essential to establish a standardised and open protocol that encompasses the necessary functionalities for both primary and secondary communication. This unified protocol would facilitate the integration of demand response management strategies, enabling seamless coordination among the power grid, DSOs, aggregators, and parking lot operators. For instance, by integrating diverse standardised protocols like ISO 15118, IEC 61850, OCPP, OCPI, etc., a unified framework would enable EV manufacturing companies to establish a standardised platform that facilitates seamless data exchange, reduces complexities, and ensures adherence to uniform charging strategies, thereby leveraging the advantages provided by these protocols.

2.1.2. Technical gap in interlinking open protocols

The divergence in functionality and maturity levels among different standardised protocols creates a gap in their interlinking for effective communication and the development of advanced energy management strategies. This mismatch hinders seamless integration and coordination among various entities within the energy ecosystem. To bridge this gap, it is crucial to align and harmonise the functionalities of these protocols while simultaneously advancing their maturity levels. To enhance coordination and communication during the charging process, aligning protocols should focus on incorporating services and message exchange compatibilities that cover real-time monitoring of electrical devices, energy management strategy control, and intermediate gateways, meeting the communication requirements, and ensuring effective coordination among the involved components (Neaimeh, M., et al., 2020).

2.1.3. Redundant protocols towards standardised functionalities

The presence of multiple open protocols for the same use cases creates confusion, wastes resources, and hampers efficient identification of protocols with mature functionalities, as some protocols only partially support certain use cases while others offer complete implementation. For instance, IEEE 2030.5, ISO 15118, and IEC 61851 are implemented for the common purpose of facilitating communication between EVs and EVSE. These protocols enable functions such as charging session

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initiation, data exchange, and control between the EV and the charging infrastructure. Similarly, OICP, OCHP, and eMIP offer comparable functionalities. They focus on standardising communication and data exchange between charging networks, service providers, and EV users. While regional variations in protocol adoption may be argued for, global manufacturers have the opportunity to streamline their operations and reduce costs by implementing a unified protocol across their EV products worldwide (Neaimeh, M., 2020). Collaborative efforts play a crucial role in harmonising existing protocols and bringing clarity regarding protocol adoption, thereby minimising wasted investment and the risk of stranded assets during the rollout of charging infrastructure (Andersen et al., 2019). Through collaboration, stakeholders can share knowledge, align their efforts, engage relevant parties, and drive standardisation initiatives, facilitating a unified approach and informed decision-making in protocol selection. This collaborative approach ensures efficient utilisation of resources and reduces the potential for costly incompatibilities or redundant investments.

2.1.4. Lack of support for V2X services

The emergence of renewable energy sources, the implementation of microgrid support, and advancements in V2G technology have opened opportunities for EVs to supply power to buildings, standalone loads, and other EVs. This has led to the adoption of the umbrella term "vehicle-to-everything" (V2X), which encompasses V2G as well as several other applications, including vehicle-to-home (V2H), vehicle-to-building (V2B), vehicle-to-load (V2L), and vehicle-to-vehicle (V2V) (Thompson, A. W., et al., 2020). However, the current standardised protocols lack the necessary communication interfaces for decentralised V2X applications, hindering EV users from selling their surplus energy directly to grid-isolated microgrids and other vehicles. These protocols primarily focus on facilitating communication interfaces with G2V and V2G actors, overlooking the broader potential of V2X. This limitation must be addressed to enable EV users to actively participate in energy trading and contribute to a sustainable energy ecosystem at both the local and global levels. To enable efficient and secure V2X energy trading services within the grid, collaborative efforts are required to develop a common framework that emphasises authentication and security, standardised data formats, transactional messaging, pricing, and settlement mechanisms. This collaborative work will ensure the establishment of standardised communication protocols, fostering a level playing field for EVs and other participants in the energy market.

3. Requirement Analysis of Middleware for Interoperable Software

3.1. Requirements for business layer services

Standardised data flows and universally defined interfaces are essential for facilitating interoperability among actors and enabling the development of interoperable services. In addition, creating an optimal business scenario with associated services is crucial to fostering structured and normalised interactions between actors. The FLOW middleware requirements have been analysed by examining various business scenarios with the goal of facilitating the integration of EVs into the power grid through an

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interoperable software platform. The emphasis is placed on understanding and highlighting the importance of interoperability to enable seamless communication among the entities in the EV ecosystem. The current standardised protocols classify the operations of EVs as either energy consumers at the customer end (G2V) or producers that contribute to supporting the grid (V2G). However, V2G applications enable EVs to support a range of other applications, including V2H, V2B, V2L, and V2V connections with the grid. These applications can be controlled through centralised communications or operate in isolated modes with decentralised communication control. Consequently, EV services are categorised into vertical and horizontal domains based on the grid connection and control mechanism, as shown in Figure 6. Vertical domains involve the energy flow from EVs to the power grid, homes, and buildings through grid connections with centralised control. In these domains, EVs can contribute to supporting the grid and providing energy to external sources. On the other hand, horizontal domains involve the unidirectional or bidirectional energy flow between EVs and loads in a grid-isolated mode with decentralised control. In these domains, EVs can interact directly with local loads and exchange energy without relying on the central grid.

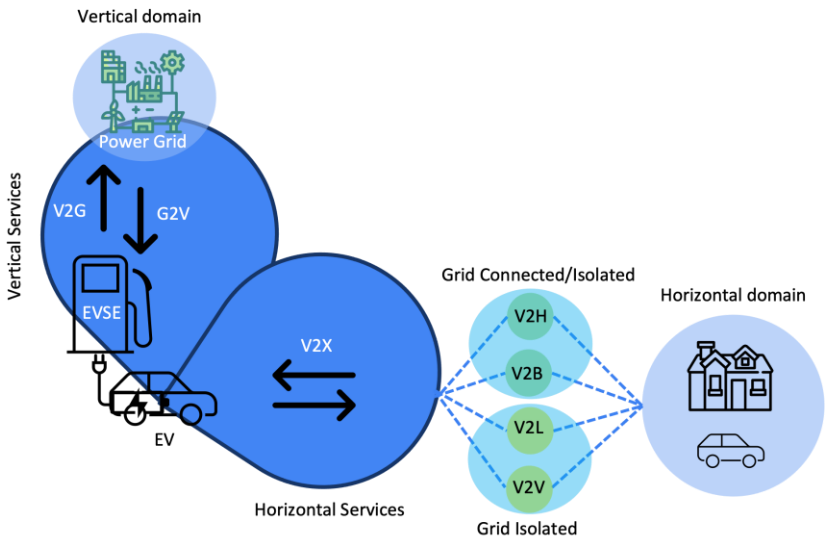

Figure 6. Classification of the vertical and horizontal applications of EVs based on grid connection and centralised and decentralised control mechanisms

Interoperability among actors necessitates standardised data flows and universally defined interfaces to facilitate structured and normalised interactions across vertical and horizontal domains. In the subsequent discussion, we explore diverse business scenarios to determine the specific interoperability requirements for standards and protocols.

3.1.1. Smart control of charging process

Smart control of the charging process encompasses intelligent charging mechanisms that remotely manage the charging process by considering factors such as grid stability, load flow management, power generation, frequency regulation, and dynamic pricing and demand response. Considering these factors, smart charging empowers EVs to actively respond to dynamic signals, fulfilling the roles

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of flexible generators and loads, thereby facilitating the flexible distribution of available power and energy in a manner that economically benefits a wide range of stakeholders. For example, the power grid gains advantages from managing overloading and fluctuations; CPOs benefit by supporting multiple EVs to generate income; and EV drivers benefit from the ability to charge their vehicles when electricity prices are low.

While smart charging is increasingly available in commercial markets, it primarily enables EVs to function as flexible loads, while their role as flexible generators is still in the research and development phase (Gschwendtner, C., et al., 2021). Standardised communication with additional electrical equipment is essential for implementing smart charging and discharging, enabling the exchange of two-way metering data between charging infrastructure, electrical networks, energy markets, CPOs, and EVs. This includes the use of bidirectional inverters to convert DC power from onboard batteries into AC power for both charging and discharging operations, as well as protection equipment to prevent power feed into the grid during faults or maintenance work.

These protocols have to ensure seamless communication among key energy components, including TSOs, DSOs, aggregators, CPOs, and EVs, during the implementation of smart charging and discharging. This standardised communication allows energy aggregators to interact with TSOs and DSOs, proposing various charging schedules to CPOs and EV owners based on dynamic pricing and dispatching markets, and provides them with the opportunity to decide whether or not to participate and offer their flexibility on the market.

3.1.2. Enhancing mobility and reducing range anxiety through advanced itinerary planning

To address the limited driving range, EV owners often need to recharge their vehicles at intermediate locations, necessitating standardised interfaces between TSOs, DSOs, CPOs, fleet management companies, mobility service providers, and EV owners (Hussain, S., et al., 2023). The existing standardised protocols currently utilise proximity-based route planning, which may not always optimise charging decisions due to factors such as diverse load capacities, variable charging prices, and traffic congestion. To mitigate range anxiety effectively, it is crucial to incorporate standardised interfaces that consider multiple variables, including electric power consumption, road topography, weather conditions, vehicle specifications, driver profiles, traffic conditions, and the positions (status) of electric charging stations. By integrating these interfaces, EV itinerary planning can be enhanced, enabling more accurate and efficient charging choices and thus alleviating range anxiety concerns. The establishment of a standardised interface facilitates the exchange of essential information between EVs and smart grids, enabling seamless integration of EVs within the ecosystem. This interface should allow for the sharing of data such as the state of charge (SoC) of the EV battery, current location and destination, availability and status of CPs, pricing information, and real-time road conditions. The purpose of this standardised interface is to encourage EV usage and ensure a smooth and convenient experience for EV users within the ecosystem, promoting the widespread adoption of EVs.

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3.1.3. Enabling seamless cross-provider payments

The limited availability of dedicated charging points poses challenges for EV users, hampering their travel efficiency. Therefore, it is crucial to authorise EVs to charge at any charging point developed by different companies and enable seamless payment acceptance, enhancing convenience and flexibility for EV users. Consequently, the implementation of standardised communication protocols between the CPOs and Electromobility Providers (EMPs) becomes crucial to establish authentication and facilitate payment processing after the completion of charging sessions. It is essential to regulate the secure exchange of information for transaction authorization and payment, adhering to existing industry standards. The standard should ensure seamless cross-charging point authentication and payment through interoperability, which relies on standardised protocols, communication interfaces, authentication mechanisms, payment integration, roaming platforms, and streamlined data exchange. By promoting compatibility and standardisation across different charging networks, interoperability enables EV users to charge their vehicles conveniently and efficiently, regardless of the charging infrastructure they encounter. Cross-authentication and payment for seamless charging of EVs involve a complex interplay of identification, communication protocols, payment authorization, data exchange, and settlement processes. The aim of interoperability is to simplify and streamline the charging experience for EV users, enabling them to access and pay for charging services across different networks without the need for separate accounts or complex payment procedures.

3.1.4. Decentralised horizontal services

One of the prominent applications harnessing the potential of EVs is V2G technology, where the EVs are connected to the distribution network, offering valuable services to various stakeholders within the power system. These services encompass congestion management for the DSO, balancing services for the TSO, and energy trading with Balancing Responsible Parties (BRPs). The significance of the aggregator cannot be overstated in the context of smart charging and its role in supporting the power grid on a large scale. By aggregating the power capacity of multiple CPs, the aggregator facilitates the integration of EVs into the power system.

The V2G application also opens up possibilities for V2H, V2B, and grid-isolated microgrid applications, where EVs serve as flexible generators, similar to V2G, from an electrical connection perspective. However, instead of offering services to grid operators or participating directly in energy markets through an aggregator, the services are directed towards the users in homes, buildings, and microgrids where the EVs are connected (Elma, O., et al., 2022). These standardised protocols primarily focus on enabling vertical services and facilitating homes or buildings to respond to specific price signals for importing and exporting electricity. By optimising the scheduling of EV charging and discharging, users can benefit from various charging processes such as Time of Use (ToU) tariffs, Capacity Charges, and Self-consumption. These processes play a crucial role in efficiently managing the charging of EVs in accordance with electricity pricing and consumption patterns (Lozano Dominguez et al., 2019).
In contrast, horizontal services involve the power flow from vehicles to grid-isolated systems through the V2L and V2V applications. V2L applications involve supplying power to loads such as campsites, construction sites, and grid-isolated microgrids, while V2V applications entail providing power to other EVs that lack access to a charging point, such as emergency service required for on-the-road battery

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EVs (BEVs). These horizontal services extend the versatility of EVs by enabling them to serve as a power source for a range of different applications, offering flexibility and convenience in various off-grid or peer-to-peer scenarios. Manifestations of V2L and V2V can be observed in various scenarios, including grid-isolated houses, emergency power shut-down situations, and emergency road recovery services where an EV's battery becomes depleted during a journey. However, the mass market for these horizontal services is not yet fully developed, and there are existing technical barriers that need to be overcome in order to standardise and widely adopt these applications.
It is important to note that while examples of V2L and V2V applications can be found in specific cases, their widespread implementation and standardisation still face challenges that must be addressed. These challenges encompass critical technical aspects, notably initiating the charging request and efficiently managing and completing the charging process. One possible solution involves implementing a client-server architecture in the protocols, where the EV with a high state-of-charge (SoC) acts as the service provider and the EV with a low SoC serves as the client, initiating the charging request. However, resolving these challenges is crucial to ensuring seamless integration between V2V interactions, irrespective of their manufacturer, battery size, or type. This integration is vital for leveraging EVs as power sources in grid-isolated locations and during emergency situations.

4. Requirement Analysis of Communication Networks

As discussed earlier, the ISO/IEC 15118 standard classifies the EV charging system into primary and secondary actors, with the primary actors directly involved in the charging scenario and the secondary actors playing an indirect role. This standard also defines the network and application protocol requirements (15118-2). However, it does not provide specific requirements regarding the size of communication messages or the other communication network requirements, including latency, bandwidth, reliability, and security of message exchange (Ali, I., et al., 2015). This work first discusses the standardised communication network technologies used in the EV ecosystem and then presents the different requirement analyses.

4.1. Communication network technologies

The Internet of Things (IoT) for EVs offers numerous advantages and flexibility by enabling bilateral communication, data gathering, and response control mechanisms through both wired and wireless communication standards. These standards include Ethernet, Zigbee, Bluetooth Low Energy (BLE), LoRa, Wi-Fi, and cellular technologies. Table 3 provides a comprehensive comparison of the parameters associated with these communication technologies, and in the meantime, Table 4 presents the application of these communication network technologies, which the FLOW project should consider in the development of different DEMO testbeds (Tappeta, V. S. R., et al., 2022).

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Table 3. Different communication network technologies and their characteristics for utilisation in EV ecosystem

Technology	Standard	Speed	Range
Fast Ethernet	IEEE 802.3	100 Mbps	100 m
Zigbee	IEEE 802.15.4	250 Kbps	100 m
LoRa/LoRaWAN	IEEE 802.15.g	27 Kbps	10 Km+
WiMAX	IEEE 802.16	70 Mbps	50 Km+
Wi-Fi	IEEE 802.11	100–250 Mbps	70 m
GSM/GPRS	ETSI	114 Kbps	35 Km+
LTE	3GPP	0.1–1 Gbps	28 km/10 Km

Table 4. Application of different communication network technologies in EV ecosystem

Technology	Application and description in EV ecosystem
Ethernet (802.3)	Communication between EVSE and CPOs: in residential charging premises, the communication between the EVSE and the energy management system
Zigbee (IEEE 802.15.4)	Communication between the primary actors (EVs and EVSE), as well as the interaction between the primary actor EVSE and the secondary actor CPO.
LoRa, LoRaWAN	Communication in the EV charging infrastructure by enabling the data exchange between EVs, EVSEs, CPOs, and the grid.
3G/4G/LTE/5G	The communication aspects encompass public charging of EVs, energy trading, garage charging, communication between CPOs and the grid, as well as mobile EVs to control centre communication.
Wi-Fi, WiMAX	Public charging, load shifting, communication between CPOs and the grid, as well as mobile PEVs for control centre communication.

4.2. Requirements for EV charging infrastructure

While the FLOW demo testbed can be built using different communication network technologies and standard IEC/ISO protocols, it's important to note that these standards do not define the communication message size and network requirements (i.e., Timing requirements, bandwidth, reliability, and security) necessary for validating the EV charging infrastructure.

4.2.1. Message type and size requirements

IEC 61850 supports object-oriented modelling for electrical devices in the power system, facilitating configuration, data organisation, and mapping to protocols to ensure consistency and interoperability. The protocols are further enhanced by mapping the IEC 61850 standard data model and ACSI over standard communication protocols and hardware. This approach defines three message types: Manufacturing Message Specification (MMS), sampled values (SV), and Generic Object-Oriented Substation Event (GOOSE) (Ali, I., et al., 2015). The EV initiates an MMS message request to the CP to

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request a power supply. The CP responds with an acknowledgement (ACK) message and subsequently sends an MMS request to the EV, asking for information such as State of Charge (SoC), charging mode, ampere limit (Alim), and voltage limit (Vlim). The EV responds with another MMS message, providing the requested information. Once the information is received, the CP initiates charging by sending a GOOSE message. The EV then updates the CP using an SV message, indicating its battery level. Upon reaching the desired SoC level, the CP sends a GOOSE message to terminate the power supply and stop the charging process. Since each message has a different direction (i.e., from EV to EVSE or from EVSE to EV) and carries a varying amount of information, they have different sizes and are detailed in Table 5 (Erigrid report).

Table 5. Different types of messages and their size requirements in the EV charging ecosystem

<table>
<tr><th>Message Name</th><th>Attributes</th><th>Size</th><th>Message type</th><th>Once/Repeat</th></tr>
<tr><td>MMS_req</td><td>Power request</td><td>105 byte</td><td>Request to EVSE</td><td rowspan="5">Once</td></tr>
<tr><td>MMS_res</td><td>ACK</td><td>54 byte</td><td>Response to EV</td></tr>
<tr><td>MMS_req</td><td>SoC, Charging mode, Alim, Vlim</td><td>165 byte</td><td>Request to EV</td></tr>
<tr><td>MMS_res</td><td>Updated SoC, desired SoC, Charging mode, Alim, Vlim</td><td>315 byte</td><td>Response to EVSE</td></tr>
<tr><td>GOOSE</td><td>Initiate charging</td><td>104 byte</td><td>Request to EV</td></tr>
<tr><td>SV</td><td>SoC-level update</td><td>72 byte</td><td>Response to EVSE</td><td>Repeated</td></tr>
<tr><td>GOOSE</td><td>Terminate charging</td><td>104 byte</td><td>Request to EV</td><td>Once</td></tr>
</table>

4.2.2. Network requirements

To comprehensively understand the impact of GOOSE, SV, and MMS messages on charging schemes, it is necessary to study their performance in terms of end-to-end (ETE) delays, bandwidth and reliability, and security (ElGhanam, E., et al., 2021). The charging system attributes include these messages as well as other monitoring and control data, which can be categorised into two main categories: monitoring and control information (MCI) and analog measurement information (AMI) (Ali, I., et al., 2015). The IEEE 1646 standard specifies timing requirements for transmitting different types of information messages from external, remote, or DER IEDs (Intelligent Electronic Devices) to the substation. This standard provides guidelines for ensuring timely communication within power systems. Regarding end-to-end communication latency requirements for at-home static EV charging, the US Department of Energy has estimated a range of approximately 2–15 seconds (U.S. Department of Energy, 2010). This estimate represents the acceptable duration for communication to complete a full round trip between the electric vehicle and the charging infrastructure.
According to a 2010 report by the US Department of Energy, the bandwidth requirements for home EV charging systems can range from 10 to 100 kbps (U.S. Department of Energy, 2010). However, it is important to note that public charging applications often demand higher bandwidth and data rates, particularly for aggregated charging demand response scenarios. In these cases, the communication link for public charging infrastructure needs to accommodate charging-related messages along with other variable-sized packets carrying different types of information. To ensure effective

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communication, it is desirable to have higher throughput capabilities in the public charging infrastructure (ElGhanam, E., et al., 2021).
Reliability plays a crucial role in effectively managing and coordinating EV charging services. To enable efficient decision-making in charging, uninterrupted and secure data exchange supported by extensive coverage and quality-of-service assurances is essential. It is imperative to prioritise a high level of reliability to ensure smooth operations. Additionally, safeguarding data security is crucial to prevent unauthorised transactions and potential attacks, protecting privacy-sensitive information such as EV location, EV ID, and payment details from misuse by other network entities (ElGhanam, E., et al., 2021, U.S. Department of Energy, 2010). The communication network requirements for EV charging systems, encompassing latency, bandwidth, reliability, and security, are summarised in Table 6.

Table 6. Different communication network requirements for EV charging systems (ElGhanam, E., et al., 2021, U.S. Department of Energy, 2010)

Application	Network Requirements			
	Bandwidth	Latency	Reliability	Security
AMI	10-100 kbps	2-15 sec	99-99.99 %	High
Monitoring and control	Few kbps	1 sec	99-99.99 %	High
Demand response	14-100 kbps	500 ms-several min	99-99.99 %	High
Electrified transportation	9.5-56 kbps	2 sec.–5 min	99-99.99 %	Relatively High

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