ELECTRIC VEHICLE CHARGING SAFETY – THE STATE OF ART, BEST PRACTICES, AND REGULATORY ASPECTS

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Abstract – Boosted by the climate action and price development of lithium-ion batteries, the number of electric vehicles is breaking records globally. This raises new safety issues for both automotive and electrification sectors. This paper focuses on safety and accessibility issues for electric vehicle charging infrastructure and best practices in designing charging sites.
The regular AC charging infrastructure is protected with protective earthing and GFCIs with DC fault current protection, which currently provides an adequate level of protection. The DC fast chargers have built-in protective devices. Electrical accidents with charging infrastructure are rare, as the maintenance work for the charging site can be done de-energized.
The fire safety of the charging site is reviewed and approaches for handling electric vehicle fires in different countries are reviewed. Additionally, as an EV charging is an exceptionally high, long lasting, and repetitive electrical load in comparison to regular household electrical loads, the safety issues in electric vehicle home charging are discussed, as well as accessibility issues.

Index Terms — fire safety, electric vehicle charging, charging safety, home charging safety, battery fire

I. INTRODUCTION

Growing number of electric vehicles requires expanding of charging infrastructure. Globally, the number of electric vehicles is growing exponentially and, in the U.S., the number of battery electric vehicles (BEV) has nearly doubled from 1.1 million (2020) to 2.1 million (2022) in only two years [1]. Electric vehicles themselves introduce new risks for manufacturing, service, repair, roadside assistance, rescue, and scrapyard staff [2]. In addition to the risks caused by the vehicle itself, the expanding charging infrastructure raises safety issues. For large-scale charging stations, risks of degradation of the facility, cybersecurity issues, and stability issues especially with the renewable power generation have been identified [3]. The electric vehicle supply equipment not designed and manufactured according to renowned product standards may cause an electric shock or fire risk [4].

This paper focuses on the electrical safety in electric vehicle charging equipment and charging sites. Examples on regulations in some countries are reviewed, as well as fire and rescue incidents in the Finnish national emergency service database (PRONTO).

II. ELECTRICAL SAFETY STANDARDS FOR THE CHARGING INFRASTRUCTURE

A. *The supply equipment*

The international roof-level standard for electric vehicle charging is IEC 61851-1:2017 [5]. The standard is currently being updated, to include e.g., requirements for bidirectional power transfer [6]. In the standard (clause 6.2), the electric vehicle charging is classified in four modes:

1. Mode 1: connection of an EV to a standard socket-outlet of an AC supply network, utilizing a cable and plug, both of which are not fitted with any supplementary pilot or auxiliary contacts.
2. Mode 2: connection of an EV to a standard socket-outlet of an AC supply network utilizing an AC EV supply equipment with a cable and plug, with a control pilot function and system for personal protection against electric shock placed between the standard plug and the EV.
3. Mode 3: connection of an EV to an AC EV supply equipment permanently connected to an AC supply network, with a control pilot function that extends from the AC EV supply equipment to the EV.
4. Mode 4: connection of an EV to an AC or DC supply network utilizing a DC EV supply equipment, with a control pilot function that extends from the DC EV supply equipment to the EV.

Mode 1 charging is rare and is used only with certain light electric vehicles which usually have a fixed cable with a household plug integrated to them. Mode 2 charging equipment is used in places where a fixed electric vehicle supply equipment is not installed. Mode 2 charging cable consists of a household or an industrial plug, an in-cable control box, and a vehicle connector. Mode 3 charging station consists of a fixed unit connected to the mains and either a fixed cable with vehicle connector or an EV socket outlet for a detachable charging cable. In Mode 4 charging, the AC/DC-conversion is made in the charging station and DC is fed directly into the vehicle via a fixed cable with vehicle connector. Mode 4 charging stations are

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usually referred as “fast chargers”, because such stations are typically designed for high power (50 kW or more) charging. Examples of charging modes are illustrated in Figure 1.

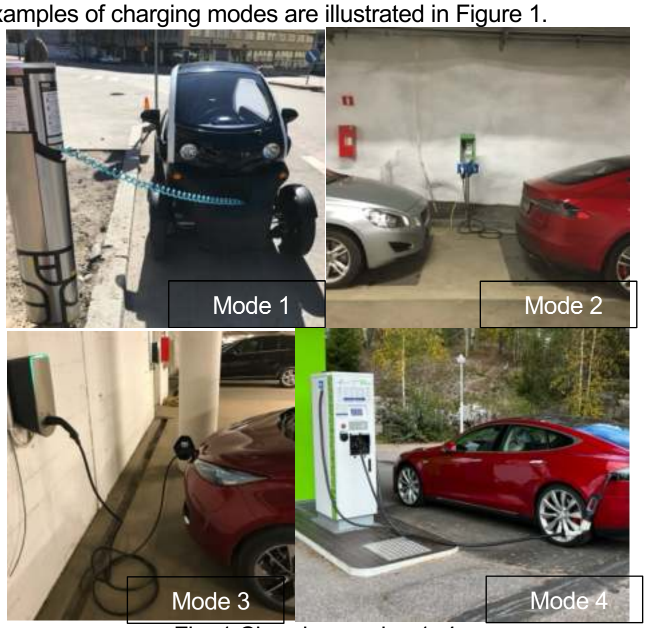

Fig. 1 Charging modes 1–4.

B. Electrical Safety in Mode 1 charging

The charging mode 1 is used only with certain light electric vehicles. According to IEC 61851-1:2017 clause 6.2.1, it is prohibited by national codes in the US. In Canada, Mode 1 charging is not permitted without integral ground fault leakage interruption.

As the battery capacity is small in light electric vehicles, the charging power and therefore the charging current is relatively small, 10 A or with two-wheelers even less.

As not all old socket outlets are fitted with GFCIs, handling a damaged cable can lead to an electric shock.

C. Electrical Safety in Mode 2 charging

The difference between Mode 1 and Mode 2 charging is that in mode 2 charging, the cable is fitted with an in-cable control box providing both residual current protection and control pilot signal for the vehicle. The in-cable control box (ICCB) or function box has its own product standard IEC 62752:2018 [7].

Some of the mode 2 charging cables with a household plug are fitted with an integrated temperature sensor in the plug. The standard is currently under revision and the 2024 edition shall include a mandatory control device that detects the temperature of the current carrying parts in the plug. If the temperature of the current carrying parts in the plug reaches 70 °C, the IC-CPD shall switch off within 10 seconds [8, p. 37]. The requirement is mainly due to experiences with Type F household plug and socket outlet. The plug and outlet, also known as Schuko (German: Schutzkontakt, “safety plug”), is popular in continental Europe and rated at 16 A. However, experience has shown that plugs and sockets of this type cannot handle repetitive, continuous and long-term 16 A or even 13 A current even though they are designed and tested according to their product standard [9]. The requirementis only for household plugs, not for industrial (single or three phase) plugs as they are designed for continuous rated current. An example of overheated vehicle charging plug and wall socket is provided in Figures 2 and 3, respectively. In the specific incident, the vehicle was being charged with a 7 A current. National recommendation in Finland is 8 A, and the maximum current selectable is 13 A. According to the vehicle logs, the charging current had been stable from 3pm to 7:45pm, after which the temperature had begun to rise. At 8pm sharp, the charger control box had terminated the control pilot signal to end the charging. It is possible that the poor connection in the socket heated up so fast and resulted in arcing so that the socket and the plug damaged badly before the overheating heated up the plug temperature sensor enough to terminate the charging.

Fig. 2 An overheated Schuko (Type F) socket outlet assembled and disassembled.

Fig. 3 An overheated Schuko (Type F) plug in a Mode 2 electric vehicle charging cable. Signs of rapid overheating can be seen in the plastic parts, as well as overheating and arcing marks in the conductive parts.

In the UK, a temperature sensor will not be required [8, p. 37] as the construction of the plug and socked outlet is more robust: the conducting parts of the plug are rectangular and introduce a larger contact area compared to continental European plugs.

The fact that 16 A rated plugs and socket outlets do not withstand a 16 A current has not been an issue because typical household appliances usually take 10 A (2.3 kW) or less current. The issue was noticed in the beginning of 2010's when charging electric vehicles with a 16 A current. The first remedy was to limit current to 10 A or 8 A and introduce plugs with temperature sensor and control device. The revised plug and socket outlet standard IEC 60884-1:2022 introduces high load (HL) versions [10, p. 188] of plugs and socket outlets, which have same dimensions but are type tested with long and repetitive high current.

D. Electrical Safety in Mode 3 charging

The Mode 3 charging is the preferred way for charging electric vehicles: as the supply equipment is installed with fixed feeding cable and the work is done by a qualified electrician, the adequate sizing of the wiring and residual current protection is achieved. Unlike Mode 2 supply equipment, Mode 3 charging can be used with load control so that charging power is limited during price peaks and load peaks of the supply connection.

Both the IEC and UL standards have strict requirements for flammability and fire protection. The UL 2594:2022 [11] requires design and type tests for mechanical durability (impact test and vehicle drive over test), environmental conditions (water, ice) and flammability. In the IEC standards, the electrical safety requirements are defined in the IEC 61851-1 and requirements for flammability and fire safety are in the IEC 61439-7 [12]. Both UL and IEC standards, if followed, should prevent an internal fault causing a structural fire. In part V of this paper and the incidents in Table 1, the goal seems to be met, as most of the incidents happen when using regular (household or industrial) socket-outlets and none with internal faults of the electric vehicle supply equipment.

For electrical shock protection with RCD/GFCI, UL 2594 requires either a 5 mA or 20 mA tripping current for the residual current protection, defined as charging circuit interrupting device (CCID). The implementation and requirements for residual current protection are defined in UL 2231-1 [13] and UL 2231-2 [14]. The tripping level depends on the voltage level used and on the other protective measures. For instance, for a 120 V system, 5 mA CCID is required if only basic insulation is used, and with safety grounding or double or reinforced insulation, 20 mA CCID is required (UL 2231-1 clause 6.1.3). The IEC 61851-1 and IEC 60364-7-722 [15] require a 30-mA residual current protection, which can be implemented with:

- An RCD type B
- An RDC type A with a 6-mA residual direct current detecting device (RDC-DD) defined in IEC 62955 [16].

A type A RCD reacts to an AC and pulsed DC direct currents and type B to a wide range of different residual currents including higher frequency and continuous DC current. A sole type A is not considered adequate protection, as a rare but possible high-impedance ground fault after the three-phase rectifier in the vehicle internal charger can cause a DC leakage current, which can saturate the sum current transformer of a normal type A residual current device and prevent it from reacting to an actual AC fault current. The 6 mA RDC-DD will detect such direct currents. Typically, the electric vehicle charging station has an integrated RDC-DD, and the type A RCD is installed in the main board.

An important issue for electrical shock protection is distinguishing Mode 2 and Mode 3 charging with portable chargers. A common and potentially dangerous misconception in Europe is to forget the definition of the charging types and think that Mode 2 refers to light portable cable with in-cable protective device and Mode 3 means the heavy box on the wall. The difference in the IEC 61581-1 standard is in how the supply equipment is connected to the mains, not on how portable it looks. There have been cases in Finland where the customer buys a Mode 3 charging equipment and asks the electrician to connect it to mains with an industrial plug, so that they can take the "charger" with them to their summer cottage. The danger looms in the fact that as Mode 2 chargers always contain a GFCI as it is required in the Mode 2 product standard IEC 62752 (as older wall sockets do not have residual current protection) [7], Mode 3 chargers typically do not contain a GFCI, but it is to be installed in the main board. If a Mode 3 charger is connected to the building via an industrial wall socket with residual current protection, the electrician cannot guarantee that the user has residual current protection in their summer cottage.

E. Electrical Safety in Mode 4 charging

Although Mode 4 does not specify the charging power but only the method (AC/DC conversion is done in the supply equipment and the vehicle internal charger is bypassed), most Mode 4 chargers are 50 kW or more fast chargers used in public charging locations. Currently, for passenger cars, the charging power can be as high as 300 kW and for heavy vehicles even more. The requirements for electric shock protection for Mode 4 DC charging are stated in IEC 61851-23 [17] and UL 2202 [18]. IEC 61851-23, the DC side of the supply equipment is protected with an insulation monitoring device and residual current monitoring. In UL 2202, standards UL 2231-1 and UL 2231-2 are referred for shock protection. In UL 2231-1 clause 6.2.4, isolation monitoring is required.

Mode 4 chargers are typically engineered more rigorously than Mode 3 and Mode 2 chargers, as they are high-cost devices with the possibility to cause damage to the vehicle itself which could lead to expensive lawsuits: Mode 2 and Mode 3 are basically just switchgear delivering AC to the vehicle inlet, but Mode 4 charger feeds DC directly to the vehicle battery and has therefore the possibility to damage the battery by malfunctioning. Mode 4 chargers are also installed and maintained by professionals. As mode 4 chargers have a fixed cable, visual inspection should be performed regularly, and the customers should have an easy way to report problems such as a damaged cable or cracked vehicle connector.

III. ELECTRICAL INSTALLATION CODES

In European countries, the regulations for electric vehicle charging installations are based on the IEC 60364-7-722 standard *Low-voltage electrical installations – Part 7-722: Requirements for special installations or locations – Supplies for electric vehicles*, which is a part of the IEC 60364 series. The first edition, IEC 60364-7-722:2015 and the second and current edition IEC 60364-7-722:2018 do not have significant differences. The requirements can be summarized as follows:

- Each AC connecting point shall be individually protected by a residual current device (RCD) with a rated residual operating current not exceeding 30 mA.
  - Where the EV charging station is equipped with a socket-outlet or vehicle connector complying with IEC 62196, the RCD shall be
    - type B or
    - type A in conjunction with a residual direct current detecting device (RDC-DD) complying with IEC 62955.
- For conductive power transfer, EV charging stations shall comply with the appropriate parts of the IEC 61851 series.
- When installed outdoors, the equipment shall be selected with a degree of protection of at least IP44 according to IEC 60529 [19] (protected against ingress of solid objects of ≥1.0 mm diameter and splashing water).
- Each connecting point shall be supplied individually by a final circuit protected by an overcurrent protective device.
- Every socket-outlet or vehicle connector shall be located as close as practical to the EV parking place to be supplied.
- Portable socket-outlets shall not be used.
- EV charging stations for public use shall be designed to facilitate easy access to the charging point regardless of where the vehicle inlet is located on the electric vehicle.

The main difference between the 2015 and 2018 editions is the requirement for the 6-mA residual direct current detecting device (RDC-DD) to fulfill the product standard IEC 62955. The rationale behind the RDC-DD is that the type A residual current devices are designed and tested to work if there is a maximum of 6 mA direct current flowing through the device.

In the UK, the wiring regulations are based on the IEC 60364 series like in many European countries. As TT distribution system is used in some installations, simultaneous contact assessment shall be made [20].

In the NFPA 70 [21], the regulations for electric vehicle charging systems are defined in Article 625 *Electric Vehicle Power Transfer System*. The requirements can be summarized as follows:

- Each outlet installed for the purpose of supplying EVSE greater than 16 amperes or 120 volts shall be supplied by an individual branch circuit.
- For EVSE and WPTE rated more than 60 amperes or more than 150 volts to ground, the disconnecting means shall be provided and installed in a readily accessible location.
- All receptacles installed for the connection of electric vehicle charging shall have ground-fault circuit-interrupter protection for personnel.

The significant difference between the NEC and IEC standards is that there are no guidance or rules on load management in the IEC standards.

IV. FIRE SAFETY, ACCESSIBILITY AND MISCELLANEOUS ASPECTS

Following the wiring regulations is essential for preventing electrical fires and electrical accidents, but for safe and accessible use there are several other design aspects that should be considered.

F. Fire safety of charging sites

As following local wiring regulations and using electric vehicle supply equipment fulfilling the IEC and/or UL standards is essential in preventing electrical fires in the fixed installation, focus should be also put in the general fire safety of the site, as the vehicle can also ignite. If the electric vehicle fire does not involve the traction battery, it can be extinguished fast with a branchpipe (i.e. the regular firefighting hose with nozzle) or foam. If the fire involves the battery, it requires excess amount of water to be extinguished [22]. In large-scale and structural fire safety, electric vehicles and their traction batteries do not pose new significant threats, as the fire load is comparable to traditional vehicles. The fire will probably not spread as a battery fire from vehicle to vehicle, as evidence from Stavanger airport fire suggests [23, p. 75]. However, the fire behavior between parallel electric vehicles has not been well studied in laboratory experiments. In one experiment, a battery electric vehicle (BEV) and a plug-in hybrid electric vehicle (PHEV) were parked in parallel, and the traction battery of the BEV was ignited, and a full-scale fire test conducted. The fire did spread from the BEV to the PHEV faster than a traditional vehicle fire, due to jet-like flames from the traction battery. Also the PHEV battery began to vent flammable gases which burned in the fire event. [24] The test was conducted outside, and with two vehicles. Fire behavior of a full row of electric vehicles in a confined parking space needs further research.

One challenge in especially older parking facility fire safety is the increased size and increased amount of plastic in vehicles. Vehicles are larger and therefore nearer each other in facilities which are designed for older cars. Increased amount of plastics increases the fire load. The jet flames from EV battery combined with the previous can speed up the spread of fire. As the electric vehicle battery fire needs excessive amount of water to handle, adequate supply of water is important in parking facilities [25].

The newest edition of NFPA 88A [26] has no special requirements for electric vehicles. For charging systems in parking facilities, UL 2202, UL 2594 and NFPA 70 shall be followed.

In Finland, there is no obligatory legislation for fire safety of parking facilities with EV charging. The Association for Co-operation of Fire Brigades in Finland has released a guideline [27] with the following recommendations:

- There should be a clearly marked switch for disconnecting the power supply to charging equipment.
- The location of the switch as well as the location of the charging stations shall be clearly documented.
- As an EV battery fire can release an excessive amount of smoke, extra care should be taken when designing the smoke ventilation.
- Adequate supply for extinguishing water shall be designed.
- The charging stations should be placed near the exits especially in underground parking facilities, to make it simpler to overhaul burned electric vehicles.

It shall be noted that placing the charging stations near exits does not help in the long run, as till the end of 2030's the majority of passenger vehicles in many countries may be electric and therefore electric vehicles are parked everywhere in the parking facility. This is mentioned in the Finnish construction industry national recommendation on charging stations in buildings [28], which lists also the following additional fire safety recommendations:

- If speed bumps are used inside the facility, they shall be placed so that they do not unreasonably hinder towing or moving vehicles
- Fire stops for the cabling of the charging stations shall be implemented properly
- The fire protection technology (sprinklers, alarms, and smoke ventilation) as well as the charging stations are under professional maintenance and tested regularly
- The staff is properly trained for electric vehicle incidents

G. *Extinguishing* an electric vehicle

As electric vehicle fires are rare and professional experience for electric vehicle firefighting is still accumulating, the best way of extinguishing an electric vehicle is still being discussed. For instance, in Finland, over a thousand passenger vehicle fires happen yearly, but only a couple of them are electric vehicle fires. The main reason for the low number of EV fires is the low number of electric vehicles, but some reports suggest that the overall risk for fire is lower for electric vehicles than traditional gasoline or diesel vehicles [29], [30], [31], [32]. As the EV stock gets older, the fire risk might increase, as older vehicles are more prone to fires due to technical faults [29]. The instructions for EV firefighting in different countries are very similar. In the UK, standard emergency services operating practices for vehicle fires are encouraged, and usage of significant quantities of cold water to cool down the battery is considered the most efficient process for extinguishing an EV fire. Opening or removing the high voltage battery shall not be done [33]. In the NFPA instructions (US), offensive extinguishing is recommended if the traction battery seems not to be involved in the fire. If the battery is involved, the fire should be put out by cooling the battery with excess amount of water, or alternatively choose the battery to burn itself out. The extinguished vehicle should be overhauled to a place further that 15 meters of vehicles and buildings, in case of re-ignition of the battery [34]. In Finland, several approaches for fighting EV fires have been reviewed, but using a regular branchpipe or an underbody sprinkler for cooling down the battery are recommended [35]. For instance, submerging a burning EV [36] is one way and will extinguish the fire rapidly, but in Finland, moving a burning vehicle is considered too hazardous and the vehicle is extinguished on site and sometimes submerged to prevent re-ignition. Overhauling the burned vehicle inside a container with no initial submerging also gives an option to put out the fire rapidly if the vehicle re-ignites while in transport.

H. *Accessibility*

As electric vehicles gain popularity, more focus should be put on accessibility issues. Electric vehicle drivers using a wheelchair or having vision impairment shall also be able to use public charging stations. One possible scenario for electric vehicle users with a wheelchair is when one plugs in their vehicle but another vehicle parked too close blocks the path from using wheelchair to detach the charging cable. This can be prevented by designing the charging area so that there is extra space left between the parking spaces (Figure 4). Handicap parking spaces as well as fast chargers should be designed accessible. For every charger, using large and clear fonts and displays and placing the charger so low that very short people can access the user interface of the charger are low or zero-cost accessibility improvements. As an example, the touch screen of the fast charger in Figure 4 is located so high that persons with short stature can not reach and read it properly and such design should be avoided.

Fig. 4 Leaving a gap between parking spaces is essential for wheelchair users.

A good design practice is to locate the electric vehicle supply equipment so that damaging it by hitting it by car is not possible. For fast chargers typically mounted on the floor or ground, this can be achieved by protecting the equipment with bollards as in Figure 4 or wall-mounted obstacles as in Figure 5.

Fig. 5 Damaging the EV supply equipment by hitting them with the vehicle should be obstructed.

Fast charging stations and some of the mode 3 charging stations are fitted with fixed cables with a vehicle connector. Both North American FMVSS 305 [37, p. S5.4.6.3] and European UNECE E100 [38, p. 5.3.3.] vehicle type approval regulations require that the vehicle cannot be driven when the cable is connected. However, an accident where the cable is accidentally or by mischief wrapped over the tow hitch of the car is possible. This can be avoided with a cable management system where the cable is not loosely on the ground but hanging from a specific cable arm. That approach reduces also the probability that the cable is left on the ground and gets driven over (Figure 6).

The North American and European vehicle regulations have the same requirements for the final result for safety and the differences are typically in the small details and phrasing. The manufacturers design the vehicles in a way that both regulations are fulfilled. For the prevention for accidental driving with cable connected, for instance, the FMVSS 305 requires "preventing the vehicle movement of more than 15 cm by its own propulsion system when the vehicle charging system is connected to the external electric power supply in such a way that charging is possible", and the UNECE E100 required that the "vehicle movement by its own propulsion system shall be impossible as long as the vehicle connector is physically connected to the vehicle inlet".

Fig. 6 An example of a cable management solution which decreases the likelihood of the cable being driven over or getting looped around the tow hitch of the vehicle.

V. SURVEY ON CHARGING SITE RELATED INCIDENTS

While severe incidents with the high voltage systems inside the vehicles are extremely rare [2], electric vehicle charging stations pose similar electrical work safety risks as any other fixed installations. For instance, in Virginia, a 32-old foreman electrician died while compacting duct sealant in a conduit inside an energized switch gear of a new fast charging station. His head made contact with an energized bus bar and he was electrocuted [39] [40].

In Finland (population 5.5 million, passenger car stock 2.7 million of which 0.2 million are plug-in hybrids or electric vehicles), there has been no reported electric-vehicle or charging system related severe or fatal electrical work accidents neither in the electrical safety authority's records [41] nor in the public media. For the fire rescue service database (PRONTO), several electric vehicle charging or charger related incidents have been recorded in 2018–2023. The incidents are summarized in Table 1. Only the incidents associated with the charging equipment or feeding installation are included. For fires starting from the vehicle itself, see [22], [29], for instance.

TABLE I
EXAMPLES OF INCIDENTS ASSOCIATED WITH ELECTRIC VEHICLE CHARGING EQUIPMENT

PRONTO ID	Incident		
	Short description	When	Where
1800349096	Smoke from a transformer booth of electric bus charging station. Possibly a short circuit.	August 2018	Turku
3T28-01W5T-MS1	Electric vehicle was in Schuko charging in a car dealership. The in-cable control box ignited, the fire did not spread.	July 2020	Raisio
3DVT-81W5R-YZ4	A charging outlet (16 A CEE outlet) started fire and a tarp garage was destroyed. Short circuit in the box suspected.	July 2021	Parainen
RDE8-1W8JB-6Z	A charging station in fault mode and spreading a smell of burning. No actual fire.	November 2021	Espoo
2NEJ-81W6C-E79	A charging cable ignited due to overdriving in a car dealership. Fire did not spread.	February 2022	Helsinki
14M2-81W7Y-G86	A Schuko charging outlet ("slow charger") on fire. Does not spread.	February 2022	Helsinki
1GTW-M1W2G-MWG	A joint in the junction box in the feeding cable of an electric vehicle charging station overheated and started a residential fire.	November 2022	Pyhäjoki
1GTW-M1W3Z-2E4	A vehicle in fast charging had slid due to ice and crashed and damaged the charger.	April 2023	Rovaniemi
5DYS-R1W44-63J	A building fire, four cars inside involved, of which one was a PHEV being charged. The electrical wiring or the charging station was suspected in later investigation.	May 2023	Kouvola
1GTW-M1W6X-A63	A driver crashed a fast charger when reversing their car and escaped the scene. The charger was isolated by the fire brigade.	June 2023	Kärsämäki
4698-M1W95-SRA	A Schuko charging cable ignited from the joint between cable and the plug. Burning plastic ignited a small fire on the ground.	October 2023	Naantali
RDMM-1WE6D-K3	A loud bang from a charging station while charging. No fire, smoke but a smell of "burning electricity".	October 2023	Helsinki
RDMM-1WE7E-N7	Smoke from an electric vehicle charging station in a supermarket. No actual fire.	October 2023	Hyvinkää
1X1G-M1WA6-VVG	A driver crashed to a charging station and escaped the scene. The charger was isolated by the fire brigade and the utility company called in.	December 2023	Kittilä

The best known [42], [43] and the most expensive incident with clear link to EV charging in Finland has been the Pyhäjoki fire in November 2022. At 3pm, the owner of the house was alerted by the smoke alarm and noticed smoke coming behind the main board. He rushed outside and noticed flames in a storage building associated with the house and called the emergency number. The owner managed to extinguish the fire with a garden hose. The fire brigade opened the wall and the inner roof to ensure there is no burning material inside.

The origin of the fire was found in a junction box feeding an electric vehicle charger in the storage room. There was an electric car in charging, and in the junction box, there was exceptional fire marks in the wiring of the L1 phase conductor joint. The charging station was installed to an old cable originally feeding an industrial outlet (3 x 16 A) in the storage room, and the cable had been split to feed the outlet and the charging station. There were marks of screw-joints in the conductors which had now been connected with spring-loaded connectors. It is possible that those old marks from screws had caused a loose joint in the new connectors.

According to the record, it was a matter of minutes that the fire did not spread through the inner roof, which would probably have caused a total fire in the house. Additionally, investigating the exact origin of the fire is difficult or impossible if the building was destroyed totally.

The incident in Kouvola in May 2023 destroyed an old cattle shed being used as warehouse as car shelter. [44] In the initial PRONTO record, the charging system was not suspected, but later police fire investigation revealed that a charging system fault was the most probable reason for the fire, although no doubtless result was obtained. [45]

When running the PRONTO search and pruning the search matches, multiple incidents with power tool charging were found. Such incidents are not in the scope of the paper but they remind of an important safety issue as small electronics, e-bikes, toys, power tools and similar equipment with lithium-ion batteries are also very popular and cause fire accidents regularly, even deadly ones [46], [47], [48].

The fire departments handle also other incidents related to rescue, not only fires. For instance, in one PRONTO record in April 2023 in Rovaniemi, a vehicle was connected to a fast charger and had slidden by itself and crashed the charging station. A similar incident has been documented in a social media post in February 2022 in an electric vehicle user group: the car parked at home and being charged in a carport on a slightly sloping terrain, had slid downhill overnight so that the cable was tensioned in a way that disconnecting it was impossible without moving the car with a tow truck [49]. In states with snowy and icy conditions in winter, adequate sanding or other means of anti-slippery action should be taken to prevent such accidents. Although the car cannot move by its own power source when plugged, accidental sliding is possible.

None of the fires has started inside a Mode 3 charger but several have resulted from charging from household or industrial sockets. The only fire associated with Mode 3 charging (Pyhäjoki incident) started from a faulty joint in the feeding function box.

Not all risks are electrical: when dealing with vehicles and expensive equipment, hindering the damage by accidental or deliberate crashing should be carried out by bollards or similar structures.

VI. CONCLUSIONS

Based on the review of the incidents, the following good practices are suggested when comparing the different practices and codes as well as incidents:

- For domestic electrical installations, an electric vehicle is an exceptionally high-power load when compared to normal household loads. Overnight charging poses an extra risk for casualties as the occupants are sleeping. Taking care of basic fire safety, like installing and regularly testing the smoke alarms reduces the risk. Using a direct cable from the main board (without using existing cables and junction boxes) to the charging station is recommended, as every joint introduces a fire risk. Extra care should be taken when making joints in the wiring, as the load is high. As the electrical joints cause an extra risk and can wear out due to heating and cooling during years, it could be reasonable to require using a single cable, without joints or branching, from the main board to the charging station.
- The fire safety of the materials used is essential to prevent the fire spread from the supply equipment itself to the building.
- Using regular household or industrial wall sockets for charging increases fire risk. Using Mode 3 charging equipment should be encouraged by the vehicle industry, insurance companies and public safety sector.

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VIII. VITA

Mr. Vesa Linja-aho was born in Raisio, Finland, in 1981. He received his M.Sc. degree in electrical and electronics engineering from the Helsinki University of Technology in 2006. From 2006 to 2009, Linja-aho worked as a university teacher in Helsinki University of Technology. From 2009 to 2020, he worked as a Senior Lecturer in Automotive Electronics in Helsinki Metropolia University of Applied Sciences. He has specialized in electrical safety and electric vehicles and has authored three national textbooks on electronics, batteries, and electric vehicle electrical work safety. Currently, Linja-aho is a full-time electrical safety consultant and textbook author, focusing on battery and electric vehicle safety. In the IEC, Linja-aho is the chair of working groups IEC TC 1 MT 100, which maintains the international electrotechnical vocabulary on fundamental concepts and IEC PC 128 WG 2, which aims at developing an international standard on safety of operating electrical installations.