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Bridging eMobility and Energy - Depot of the future

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Summary

The needs of vehicles and electric grids converge with transportation electrification. The electrified depot plays a pivotal role to enable both efficient electrification of transit systems and reliable integration with electric utlities. With the improvement of autonomous technology, the optimization of depots is paramount and also offers opportunities for deeper integration of different systems. Future depots will maintain multiple different modes of charging via pantographs and plug in while the current charging speed will remain largely unchanged. Major advancements will support autonomous operations via robots and more efficient leverage of installed charging infrastructure. We will see the development of more strict and more generally accepted standards on both the electro-mechanical and communications side.

Keywords: electric vehicle supply equipment (EVSE), DC Fast Charging, conductive charger, V2G (vehicle to grid), automated.

There are a number of things that broadly contribute to and affect future technologies: need, infrastrucuture, commercial acceptance, and standards are among the factors that broadly contribute to and affect the development of future technologies. While "need" is a factor that may develop independently, the other three factors tend to be intertwined and usually influence one another as each develops gradually overtime. Generally, none of these factors will move ahead significantly without the others. A lack of standards can inhibit market growth because it increases costs to the consumer and reduces competition among manufacturers. Infrastructure and standards will develop slowly as consumers vote for particular solutions with their dollars. The market uses this information to learn, incremently, what solutions have achieved commercial acceptance. The following is a review of technologies evolving and vying for the electric vehicle's and future markets.

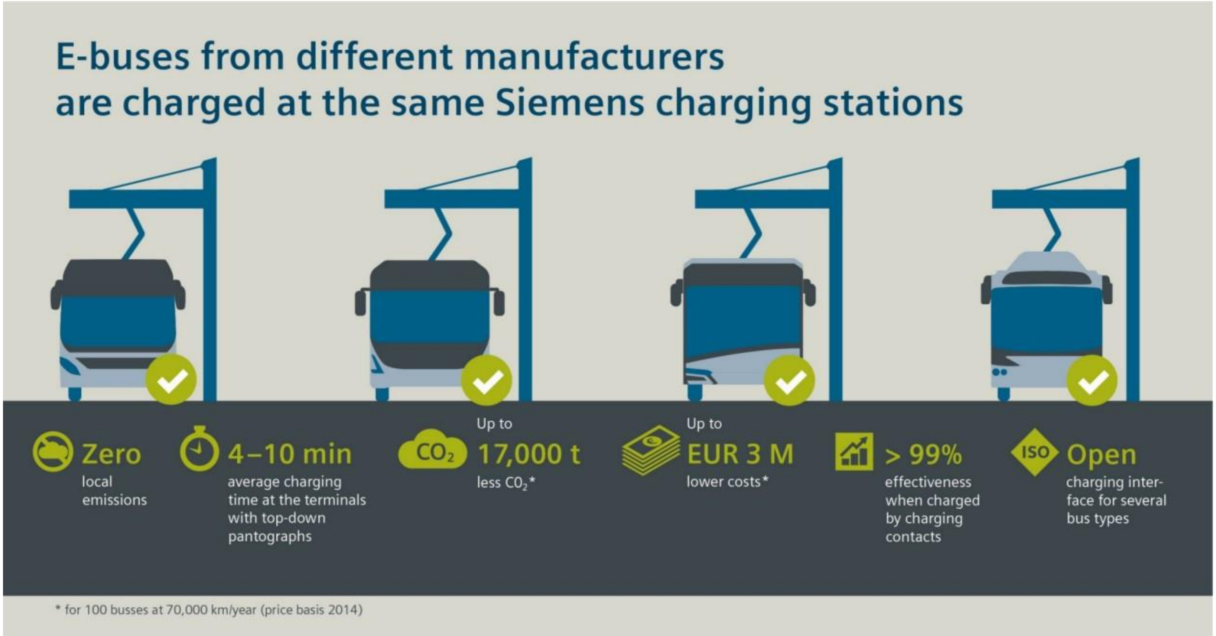
1 Current implementations of electric charging in bus depots

Autonomous vehicles have delivered a new twist to the old bus, but bus depots of today do not really look any different than they did 50 years ago. Depots are still largely made up of diesel-run vehicles, possibly some alternate-fuel run buses and even a few electric vehicle buses for pilot programs. The depot layout/footprint remains largely untouched with a fueling area, maintenance area and fleet parking. But change is just around the corner. Government regulations to reduce greenhouse emissions are providing the impetus to look to other forms of energy to power vehicles. This need to move to other fuels has moved markets toward cheaper, cleaner fuels like electricity, compressed natural gas (CNG), liquefied natural gas (LNG), biodiesel and propane and hydrogen, but this transition has left transit authorities managing at least two types of propulsion technologies until the transition is complete.[1]

Hybrid-electric buses are capable of delivering about 25 percent better fuel economy and producing 90 percent fewer emissions than the buses they replace.[2] In 2015, 41 percent of buses were either hybrid-electric or using alternative fuels.[3] Today, all-electric vehicle (EV) buses still come with a higher price tags than many of the competing alternatives. The average diesel bus will cost approximately $500,000 while an EV bus can cost $750,000 to purchase.[4] The initial cost of an EV bus will most likely come down significantly as technologies improve and economies of scale are established. The price tag alone is not the only barrier to EV bus adoption. Weather and terrain can affect battery life, and deficiencies in charging infrastructure may lead to range concerns with respect to certain bus routes. Despite perceived barriers, transit depots will move to electrification because of technological improvements like more energy-dense batteries, the ability to manage charging costs by delaying charges to off-peak hours, peak shaving, load balancing, and improved battery range, as well as state and local mandates for cleaner air.

1.1 Pantograph based charging

Short-range bus routes with fixed routes and stops make it easier to plan and provide the necessary charging infrastructure. On-route charging can be planned for along the route or can take place at the terminal. Pantographs are the ideal solution for on-route charging due to the high degree of automation that does not require any interaction of the driver and today much higher speeds are available for charging. A pantograph can recharge an EV bus in 4-10 minutes, providing a significant state of charge (SOC) increase.[5]



* for 100 busses at 70,000 km/year (price basis 2014)

Graphic coursesty of Siemens[6]

On-route, Pantograph DC fast-charging solutions range from 150 kW to 600 kW charging power. While Plug-in DC fast chargers are better suited for depots/terminals due to the decreased mechanical complexity and lower price point, we also see a trend to lower power (150kW) pantographs in depots. Today, top-down pantographs are fully automated, at lease for those that are grid-connected with wireless communications and positioning capabilities. This solution offers versatility, zero local emissions, and helps support sustainable traffic solutions. The depot of the future will have vehicles drive into the depot, park, wireless communications will trigger the pantograph to connect and begin charging without human interaction. Pantographs historically were developed for light rail and high speed trains, and then adapted to meet the needs of electric heavy-duty vehicles. The first iterations of pantographs were fairly expensive developments that made them cost prohibitive for in-depot use. All major pantograph vendors have lower cost, simpler models in the product pipeline to cater to the needs of in-depot charging, and the expectation that 150kW pantograph charging will a grab significant share of the future depot's charging mode for electric buses. Medium-duty vehicles like vans and most trucks, however, are not by default equipped with overhead pantograph solutions which will make plug-in charging the technology of choice.

The decision between top-down and bottom-up pantographs is still open. It depends on the limitations of the site versus the added equipment to the vehicle. The North American installations are almost solely top-down pantographs, whereas in Europe, bottom-up pantographs are more common.

For on-route charging, as mentioned, the pantograph will compete with the in-development MW charging concepts on the power side. The fully automated pantograph will again dominate the landscape for buses, as it caters to their specific need—short stops with high power top-off charging. Megawatt (MW) charging is the technology for heavy-duty trucks who are not equipped with pantograph ready equipment, and the use case here is longer stops along highways with a bulk-energy transfer over longer periods of time.

Whether the pantograph will be an accepted solution for heavy-duty vehicles, like Siemens e-highway research test site[7] is still to be determined. For specific use cases of predictably electrified routes, the pantograph is a solid solution for electric heavy-duty trucks. Notably, feeder routes for ports and shorter main arteries between hubs can be electrified by setting up overhead lines similar to trains and eliminate the need for depot charging altogether by allowing trucks to recharge while driving. This solution, however, will be limited to shorter distance niche applications.

1.2 Sequential plug-in charging with AC or DC charging stations in depot

At the depot charging with SEA J1772 (also known as the J plug) or combined charging system 1 (CCS1) plug-in solutions are usually used for charging vehicles while they are not in use (overnight). The most commonly used solution is DC CCS1 based charging at up to 150kW. Many implementations include one dedicated charger per electric vehicle. Other solutions provide several remote dispenser units per power electronics cabinet and charge vehicles in a sequential charging order. Sequential charging allows for automated switching between connected vehicles without human interaction and maximizes utilization of the charging equipment. It is, however, limited to charging only one electric vehcle at a time.

Sequential charging installations reduce the amount of infrastructure needed in a depot which is how these installations are usually marketed today. The grid connection is smaller resulting in a lower initial investment and reduced cost. One cabinet is paired with multiple charger boxes to service multiple vehicles. Once the first vehicle is charged, the next vehicle charge begins automatically, but this is still one-vehicle-at-a-time charging. It is expected that sequential charging will be a stop-gap solution until true parallel charging is established and offered to the market. Parallel charging offers the same advantages of infrastructure-light installations, but adds the capabilities to precisely allocate the available power to different vehicles.

1.3 Grid impact mitigation and resilience

Some electric buses have energy capacity in excess of 600 kWh, and utilities will need to manage a large number of these coming on the central grid as depots electrify. Additionally, most depots have not been designed and built around the grid connection beyond powering the essential building management systems. With current charging levels of 150kW and up, the power needs of depots are rising quickly to become a major constraint in how the depot is managed. To handle this increased load, utilities are planning ways to handle the increased EV load by encouraging depots to add battery storage, renewable energy, distributed energy resources (DERs), and microgrids. The smarter the grid can be by using software to manage load, virtual power plants, and added infrastructure/storage, the more this helps utilities balance load and reduce utility infrastructure investment. The basic idea is to utilize the existing connection as optimal as possible while ensuring the power supply needed to operate the fleet.

Depots take a page from the grid transition handbook by implementing measures in tiers. A first step is some level of scheduled and smart charging capability, whereby charging is regulated throughout the fleet to avoid peaks in demand and throttled accordingly, if needed. Some depots, depending on location and infrastructure, add on-site storage to the technology stack and achieve an additonal goal: the capability to remain partially functional during outages. The next tier is on-site local generation, either with renewable (solar) or conventional (usually small gas turbines) sources.

Current implementations are limited and can be considered pilots with respect to true microgrid powered depots, but the interest in the market is growing and goes along with the trend to ask for bi-directional charging capabilities and vehicle-to-grid concepts. A major hurdle is by on large not the charger technology, but the grid interconnection that is becoming increasingly complex to manage, especially if a depot transitions from consumer to prosumer on a grid scale.

2 New concepts currently under evaluation – the depot of the future

As the industry is moving quickly beyond the pilot and test fleet stage, implementations of electric charging in depots will become more sophisticated and refined. The driving forces behind the transition is electrification of transportation and the trend to increase autonomous operation of vehicle and depot. Those can be identified as the defining trends that drive technological advancements. The major supporting trends are standardization and the need for resilience. Today, the industry of street-based transportation electrification is still relatively young. De facto standards like Open Charge Point Protocol (OCPP) stem from pundit groups who take the lead to unify and define approaches. In other areas we still see conflicting methods that lead to inefficiency and interoperability issues such as CHAdeMO / CCS / Tesla is one of the drivers that force manufacturers to support multiple standards and effectively lock out vehicles from infrastructure. While this conflict largely effects passenger EVs, missing standardizations for the upcoming MW charging-plug infrastructure is similar. The matured landscape in the electric vehicle supply equipment (EVSE) space, and organizations like CharIN and Electric Power Research Institute (EPRI), are beneficial because they actively push towards standardization before networks of chargers are being rolled out.

With fully electrified fleets, the power grid/depot symbiosis enters center stage. Currently the transportation sector is largely unaffected by black- or brown-outs on the grid side. Tomorrow the grid conditions will bleed over into the transportation sector, so the need for depot power supply resilience rises and, concurrently, the growing power needs of depots effects the stability of the grid infrastructure. We can expect to see preventative measures to mitigate grid impact, as well as on-site storage since it is the most widely used and understood; on-site generation will be the next wave of technology to be pushed to depots in order to increase resilience for critical infrastructure.

What will the depot of the future look like? We predict that depots will achieve the following by 2030:

- All hardware will use OCPP or the emerging International Electrotechnical Commission (IEC)63110 standards compliant, and seamlessly work together providing greater competition and lower costs among manufacturers. The interpretation of frameworks like OCPP will be harmonized between the different market participants and dramatically reduce the need for interoperability testing.
- All utilities will use advanced metering infrastructure (AMI) with two-way connections to the depot which will enable: 1. Reduced infrastructure costs because of demand shifts to off-peak hours and peak shaving; 2. More control by the customer over billing, costs and consumption; and 3. The ability to move energy bi-directionally, if needed, and technically and economically sound at the specific site.[8]
- Some depots will be prosumers, they will both produce and consume energy, offsetting operating costs by selling energy back to the utilities.
- Depots will have DC charging using pantagraphs on-route and plug-in, parallel charging at the depot/terminal.
- Software management of the depot load will work to support utility infrastructure and keep investment down.
- Renewable energy generation, or conventional energy generation, will be on site.
- DERs and battery storage will be part of the future depot and keep the operation running in case of an outage.
- Microgrids—the larger the depot operation, the greater the benefit to the operation, and depot operations will get help from utilities to institute microgrids.

Beyond 2030 the depot characteristics are less defined:

- We will see the introduction of induction charging, whether it is inductive Wireless Power Tranmission (WPT) or capactive. Currently prohibitive, especially on the standardization and efficiency side, we will see fully automated depots which add inductive charging to the available mix.
- Vehicle-to-Grid (V2G) charging. While pilots are being run in the UK, Japan[9] and the US, it is too soon to predict if the technological issues can be resolved successfully to bring this to the mass market. The grid interconnection and safety of the building infrastructure are limiting today, and it remains to be seen if these issues will be resolved and provide enough value to demand the more complex installations.
- Megawatt charging. While use for in-depot MW charging is limited, we will see efforts to unify plugs and MW capable chargers in depots. There are niche use cases where bi-directional MW chargers could support the grid or local facilities for a short burst of time, but we predict a very selective implementation in depots. However, MW charging will be the standard for long haul truck stop installations much sooner than 2030, but we predict only partial implementation within depots and the peak of the installations will come when the currently installed 150kW chargers are due for replacement in 10-15 years.

2.1 Vehicle-to-grid (V2G) integration

While V2G sounds attractive because the energy sitting in your EV at home is not used 95% of the time and that makes an EV a convenient storage/source, if you can access it,[10] unfortunately, it is not just about battery access, it is also about stress on an EV's battery and depot vehicles are in use more than the EV in your driveway. The battery is one of the most expensive parts of the vehicle to replace and degredation of the battery severely interferes with the operation of fleets. Enough stress on the battery will cause early replacement, and premature degredation can cut the range of vehicles by more than 15%.[11]

Plug-in electric vehicle original equipment manufacturers (PEV OEMs), generally, are uwilling to permit discharge of energy from the battery by any control other than the vehicle's powertrain control system. This assures battery function is always tied to incremental miles added to the odometer, which contributes toward their warranty liability reduction. It also assures control over onboard components that need to meet high reliability performance standards. By opening up the electrical storage systems (ESS) to external control interfaces (i.e., price or regulation signals from utilities or aggregators), there is incurrence of additional risk.[12]

To use this storage option, complex software will need to be developed, the infrastructure needs to be upgraded to manage the two-way flow of power, and government regulations will need to be put in place. While privacy issues may not be a barrier to a commercial depot options, to be viable, V2G will need to be commercialized to a larger market.

The complexity is not only added to the vehicle-charger interface, but also on the building-grid barrier. Today buildings, both commercial and residential, are built with a clear topology and breaker to protect this topology. If a grid connection is cut off, the building has no power. This is important for maintenance and other construction because it relies on that principle. High-voltage batteries that are connected to the building introduce massive safety concerns and complexity. The grid, on the other hand, operates in a very well maintained steady state of frequency, power, reactive power and also functions with a clear hierarchy of generation, first being high voltage transmission, next is medium voltage distribution and, lastly, low voltage feeder to buildings. While this changes with the introduction of prosumer, local solar generation, unpredictable and moving generation like electric vehicles add another layer to the grid. Common commercialization strategies beyon local peak shaving usually involves frequency regulation and reserves for the power grid. It is technically possible to leverage the enormous energy and power levels that fleets can provide but, at this stage, the economical feasibility is very unclear.

2.2 Parallel charging

One of the major challenges in fully electrified depots is the efficient allocation of available (grid and output) power to the vehicles in need of a charge, based on schedules. In an ideal world, the available power could be allocated precisely to the vehicle to match requests from the battery management system (BMS). While technically possible, this adds complexity to the charging solution and requires a trade-off between the added complexity of the charger side and the added benefit on the vehicle side—does one out weigh the other? For some background:

A charger today provides a certain power to the outlet whether it is a pantograph or plug-in based output (for this example assume: 150kW). The conversion internally matches the voltage that the BMS of the vehicle requests with the voltage that is provided. The most common architecture only allows a full allocation of the available power of 150kW to a single outlet. More complex architectures internally consist of multiple power blocks on the charger side that can be allocated to the outlets and, with that, provide charges to multiple vehicles at the same time.

In scheduled charging scenarios, the overall time to charge between sequential charging and parallel charging would not differ much. That is because, as long as a charger provides close to its nameplate power to the vehicle, the sequence of charging on a depot scale would not matter. There are, however, scenarios where parallel charging will provide benefits. All scenarios have in common that they are maximizing the output on the charger side at a given point in time.

1.) **Maximizing the DC Charging curve:** The charging process of electric vehicles can be separated into three phases. First, the battery needs to be brought to a certain temperature. After that, a bulk energy transfer phase starts. Last, a phase in which the battery charges at a slower rate to protect and balance the battery. They will follow each other with bulk energy transfer being first and then battery balancing being second. As a rule of thumb, 0-90% of the charging (SOC-wise) will be done as bulk energy transfer, and then 10-20% as battery balancing. In the battery balancing phase, the necessary power drops significantly to a fraction of the available power. This is the main reason why vehicle manufacturers today make general claims like, 0-80% state of charge in only 20 minutes. The time it would take to charge 81-100% would be much longer. If the vehicle side requests much less power than the charger side could provide, the equipment itself is not utilized optimally. For some OEMs battery balancing of the charger will only provide power for auxiliary systems to keep the vehicle online, and not actually charge the battery anymore. In a sequential charging topology the battery balancing phase drops output of the charger below the limit, as a (example) 150kW capable charger only provides 20-30kW and the remaining 120-130kW are not utilized. A parallel charging capable charger would provide the 20-30kW to one vehicle, and allocate the remaining 120-130kW to a different vehicle to start the bulk energy transfer phase. In recent simulations the expected time savings to charge all vehicles in a depot would be around 2h daily for a depot of around 50 commercial busses

2.) **Vehicle pre-conditioning**: In very cold/hot areas vehicles would be temperature pre-conditioned before entering daily service. As both heating or cooling a vehicle takes substantial energy, this would ideally be serviced directly from the connected charger and not from the internal battery. In a similar scenario as battery balancing, the pre-conditioning depending on the vehicle make and model takes around 10-20kW. If the connected charger in that scenario is only capable of sequential charging, the remaining 130-140kW are effectively lost to the depot as the charger is blocked to pre-condition a single vehicle.

As an outlook, we see parallel charging as the more common approach moving forward. Most charging equipment manufacturers work on models that support some level of dynamic allocation, and the cost/benefit for larger depots is favourable to parallel charging equipment. The two conflicting methods to achieve parallel charging is to connect multiple smaller (~50kW) chargers via a switching matrix to the vehicle, or to build chargers with internal power blocks that perfom internal switching. There are pros and cons to both methods, and both will most likely be part of the depot of the future. A switching matrix allows for more available power in general, while internal switching is usually more space efficient and hardened as a product approach.

2.3 In-depot charging automation

There is an inherent push towards automation on the vehicle side. One of the best funded and most discussed technology shifts in transportation, besides electrification, is the rise of autonomous vehicles. We will see a similar push for commercial vehicles. To avoid the break in automation between operation and charging of the vehicles, depots will need to change and accommodate that trend.

There are two major breaks that the depot needs to respond to. The first is the positioning of the vehicle in depot. LiDAR and micro positioning with RFID and UWB will be standard tools that future depots will have to ustilize to enable efficient and exact positioning of busses, trucks and vans. The second is the automation of the charging process itself, specifically, the initiation and termination of it. There are different technological concepts in development right now, each with upsides and downsides. We will go into more detail on inductive charging here as pantograph and plug-in types have been explained in detail in sections 1.1 and 1.2

- **Inductive charging**: Near-field wireless power transfer (WPT) "uses a magnetic field coupling between conducting coils, and capacitive, which use electric field coupling between conducting plates to transfer energy."[13]

  There are two types of inductive charging, inductive Wireless Power Transfer (WPT), and capacitve charging. Inductive WPT systems have chargers that are large and include expensive ferrites and use frequencies kept under 100 kHz with large coils and lower power densities. Capacitive, on the other hand, has smaller less expensive chargers and can be operated at higher frequencies. Capacitive WPT could make dynamic EV charging a reality.[14]

  High-performance, safe, and cost-effective dynamic electric vehicle charging has the potential to revolutionize road transportation. What combination of capacitive and inductive WPT will enable this revolution is an open question. Both systems offer tremendous opportunities for research, especially in high-frequency power electronics and near-field coupler design.[15] Inductive WPT charging is already available, although whether it will become widely commercialized, remains to be seen. Several transit authority pilot projects utilizing 50 kW are using this inductive charging, but it has yet to prove commercial feasibility. The real downside is the efficiency level of inductive charging. While today's plug and pantograph based chargers surpass 95% efficiency plug-to-grid, inductive charging usually hovers in the low 80%. For a depot with installed power of 2MW and 50% utilization that could mean 4.8MWh of losses a day, which is economically unfeasible.

- **Pantograph charging**: Pantographs are a proven technology that has been adopted and mature. They can be a great way to automate in-depot charging, but are limited today by the installation cost and, more importantly, by the provided technology on the vehicle side. We are seeing pantograph solutions used for buses and sometimes trucks, but medium-duty vehicles depend on plug-type charging solutions. We predict that for pure bus and truck depots, pantograph installations will be the way to automate charging and costs for the pantograph itself will come down over time. One unresolved issue is communication between vehicle and charger when a large number of vehicles are communicating with a large number of chargers. Today, positioning and communication is done largely via RFID and WiFi which works well for one bus and one pantograph. Larger installtions of 40-50 pantographs in very close proximity with 40-50 buses all trying to position correctly and identify for charging, can overwhelm today's systems. Future standards like ISO 15118-20 DIS address this issue with concepts for a common WiFi across all chargers and will not rely on WiFi to WiFi pairing.

- **Autonomous charging plugs:** There are initiatives to automate the plug-in process using robotic arms and chargers on rails. While today's vehicles need the interaction of opening a hatch or a cover to access the charge port, future models will have the ability to open and close the cover autonomously. That removes one barrier to automate plug-in charging. The other is the accurate placement of the plug for different types of vehicles who will all have the port in different spots around the vehicle. In the future, robotic arms can position the plug while the dispenser itself would be mounted on rails to accommodate different locations on the vehicle. Similar proof-of-concepts have been discussed for rest stop charging. This technology, if successfully proven, could be a good solution for medium-duty, automated depots as it is far more efficient compared to inductive charging, and less heavy on the infrastructure on the vehicle side.

2.4 Outlook on charging speeds and supporting technology

Current charging strategies include on-route and depot/terminal charging (typically at the end of the day). High-powered, on-route, fast-charging demand can be on the order of 450+ kW.[16] Routes must be carefully chosen and need high frequency use to make this solution cost effective. The critical factors for high-power fast chargers are use and the ability to spread cost over a large number of vehicles.

Currently, e-buses require overnight cell balancing and charging, and can only be operational for so many hours a day. They are further limited by the size of the battery onboard.

As a response to Tesla's supercharger, one company is piloting a pantograph charger that can perform on-route charging in three minutes.[17]

The discussion around charging speeds is, in reality, more about predictability. Most current bus systems follow predictable patterns with routes that are consistent and planned according to schedules. Busses are in use for a predictable period of time; they travel predictable distances and make predictable stops. The charging needs can be calculated within certain limits that are determined by weather conditions, traffic conditions, make/model of the vehicle and of course distance travelled. Within that system the optimization problem to solve is limiting costly infrastructure installations on site, battery charging restrictions on the vehicle side and supporting the operation of the vehicle. Current vehicles support up to 450kW and 600kW capabilities for upcoming models. Unless we see a technology leap on the battery side, we predict 600kW will be the upper limit due to battery cooling requirements and the cost/benefit ratio. The on-route charging will be augmented by 300kW plug in or pantograph installations in depots.

Trucks, on the other hand, operate with less predictable patterns. The single route is planned and known, but there is no schedule years in advance to plan where a truck will go at what point in time. Distances travelled are usually longer, and longer stops are mandated to give the driver some downtime. Here we see multiple vendors working on plug-in solutions that offer upwards of one MW of charging speed. We will see installations with 1,200kW or more that will recharge large batteries within hours. The current restrictions are one on the vehicle battery side that needs to support higher voltages, and on the plug and cable side where we will see liquid cooled solutions to improve equipment handling. The barrier to overcome is the lack of standardization. Fortunately, organizations like CharIN have dedicated working groups to push for standardized plug and equipment designs.

3 Limitations and proposed changes in technology and standards

Standards evolve along with hardware and the needs seen in use cases. Communications proprietary protocols create barriers for customers who need to charge their vehicles. Whether they need to have a unique application for each network, or they need a dongle for each location, the customer must pay for the energy dispensed as well as an additional charge for the proprietary network. This reduces competition and retards EV adoption. Standards like OCPP are necessary to encourage EVs.

The Open Charge Alliance has promoted the Open Charge Point Protocol (OCPP) standard since 2009. OCPP has not yet been adopted as an industry standard in the US, however, more than 50 countries[18] have adopted this standard along with many US manufacturers. This one standard can move market adoption and open opportunities for communications at the meter, the plug, and the battery. These opportunities for interoperability will speed adoption of V2G and smart grid as well as create greater competition among manufacturers while lowering costs for the customer.

Another standard that needs to be adopted unilaterally is the charging cable/connector. Right now there are two main types of connectors: in North America its the SAE J1772 / CCS combo connector, which incorporates both AC and DC charging into one connector, and the IEC Type 2/mennekes is the prevailing standard in the rest of the world with a CHAdeMO connector.[19] Tesla is using proprietary connectors and protocols. Proprietary protocols add cost to the system and inhibit adoption of EVs and reducing competition. This market needs more competition to spur EV market adoption, not less—standards will ensure less consumer concerns over where to find the next charging station and whether or not they have the right connector for the charging station.

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