

Avoid the DC charging trap – high power everywhere charging

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Abstract

Fast charging is key to enable long range E-Mobility. The mainstream vehicle solution is based on DC, which is not regarding the driver's needs and infrastructure trends. We have analysed deeply the consumer's needs and have revealed, that a combination of both, DC ultra fast charging and AC fast charging up to 43 kW is needed on board of electric vehicles. Supporting these needs, a new system for electric vehicles comprising of e-machine, inverter and DC booster with a minimum of additional components for fast charging is developed and currently integrated into a demo car. The *AllCharge* system is capable for all kinds of conductive charging with reduced system costs.

Keywords: charging, conductive charger, EVSE, V2G, EV

1 Introduction

There are basically two techniques to charge an electric vehicle: Using alternating current (AC) or direct current (DC). Since a DC battery powers the vehicle but the power grid is based on AC, a conversion is always necessary. Classically AC charging is realized with a dedicated on-board charger, a separate unit which needs installation space and whose costs scale with the charging power. To be compatible to the widespread access points to the grid, the AC charging function is a must for every electric vehicle. To keep the vehicle's cost low, the car makers usually remain on low AC charging power. Today we see typically 3 to 11 kW in the field, which corresponds to driving range charging of ~0.3 to ~1 km/min. To shorten the charging time, the mainstream solution is dedicated DC charging along travel axis. Here the AC to DC conversion is done inside the charging station, which makes that unit very expensive and space consuming to install. Today we see DC charging stations of up to 50 kW in the field, which corresponds to ~4.5 km/min. Within the next years we will see DC charging power of 150 kW and later up to 350 kW, which promises a charging time reduction of 3 to 7 times (13.5 km/min to >30 km/min). At first glance this roadmap seems to be a good solution, but it could end in the *DC charging trap*.

In this paper we are going to present an analysis of end consumer use cases for charging and for smart-grid solutions based on the infrastructure in different regions worldwide. This analysis proofs that most of the charging events are based on AC charging. Indications to this result have been seen before [1] [2] [3]. In many cases, typical vehicles focusing on fast DC charging cannot exploit the full capability of the infrastructure. This leads unexpectedly to range anxiety, which we call the *DC charging trap*.

The use case analysis promote a system which for sure allows the ultra fast DC charging, when available, but which also supports fast AC charging ability at 43 kW. The economically optimized solution *AllCharge* was already presented in [4] (Bidirectional Charge and Traction System (BCTS)).

2 Use Case analysis

In this analysis, we focus on the end-user’s applications. For this purpose, we consider charging use cases, which are already applied in practice and the future vehicle-2-X applications. Technically, a charging power is discussed in the unit of *kW*. The end-user’s view is more interested in the unit of *km/min*. The conversion requires an average energy consumption of the vehicle. To meet a good average value for C-segment cars in real drive, we assume a consumption of ~180 Wh/km. This leads to following rule of thumb:

11 kW charging power corresponds to **1 km/min** charged range

Chapter 2.1 gives an overview of the charging use cases linked to technical boundary conditions. Chapter 2.2 summarizes some charging market publications. The model based analysis in chapter 2.3 shows that fast AC charging could strongly reduce the overall charging time. In chapter 2.4 we present an infrastructure analysis, showing today’s distribution of charging stations. We find a lack of DC charging stations, which fits to the statements of chapter 2.2. Finally, chapter 2.5 shows potential future bidirectional use cases.

2.1 Charging Use Cases

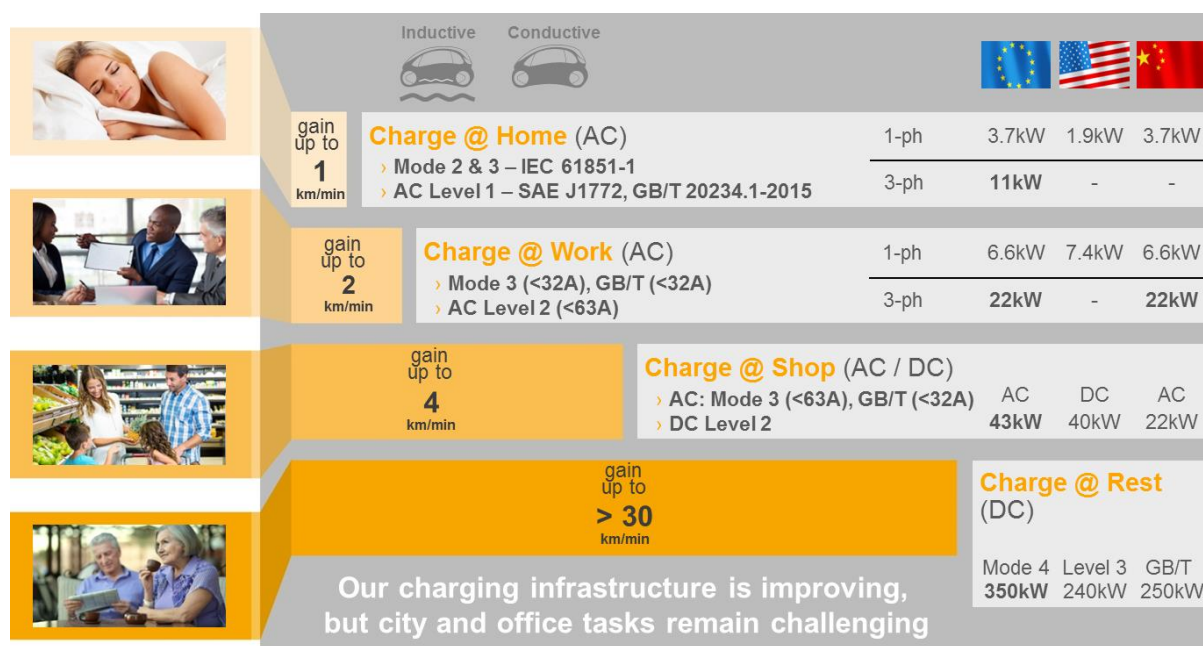


Figure 1: Charging Use Cases

Charging can be subdivided mainly into the 4 uses cases shown in Fig. 1: *Charge@Home*, *Charge@Work*, *Charge@Shop* and *Charge@Rest*. They basically distinguish in available time. In Figure 1 we match them with infrastructure capability on the use case depending locations and different regions worldwide. It can be seen, that AC charging is dominating most use cases worldwide and only travelling, so *Charge@Rest* is focusing on high power DC charging.

2.2 Charging Market Forecast

In [5] it is explained that “AC Charging is the dominant type of plug-in vehicle charging and will remain that way into the long term. This is because domestic charging is the domain of AC Charging. It is a cheap and convenient way of charging. AC will also play an important role in the public domain also.” This is reflected in a forecast in market numbers that [...] globally by the end of 2016 there were just under 3 million AC

charging stations cumulatively. This is set to rise to over 32 million by 2023. Furthermore, [5] estimates that in 2016 there were 3,300 DC charging stations cumulatively, which is set to rise to over 62,000 by 2023.” So the total amount of AC charging stations will be a factor of ~500 higher than DC charging stations and this is not taking the home charging possibilities into account. This difference in numbers is driven by the higher cost of the DC stations, which can be as low as 370\$ for a level 2 charger and more than 45.000 \$ for a DC charging station [5]. This deviation is even higher than former publications indicated [6]. It can be explained by increasing charging power demand in the last years, which dominate the DC charging station costs.

Employees with access to charge@work are six times more likely to purchase an electric vehicle [7]. Therefore, as also stated in [5], charge@work is a clear market trend and discussed at many companies and governments to increase attractiveness and market penetration of EVs.

2.3 Fast AC charging enables time saving and Vehicle-2-X

Estimating a typical driving distance of 15.000 km per year with 180 Wh/km and a charger system efficiency of 90 % the vehicle needs to charge 3000 kWh per year. Doing that with 3.7 kW would last for 811 hours per year.

Since charging incorporates the battery, an estimation of the charging acceleration with higher charging power cannot be done with rule of three. Based on measurements of series vehicles, we propose following model. The maximal charging power of a battery depends on the C-Rate, which is the factor power/capacity. The C-Rate today is limited at 2 for all mass production cars. An additional limitation comes via the battery’s state-of-charge (SOC): 0.1C at 0-5 % and 95-100 % SOC, 0.5C at 5-15 % and 90-95 % SOC, 1C at 80-90 % SOC. Temperature dependencies are not regarded here. Assuming further a 50 kWh battery for a typical future mass production car, we come to an effective average charging power over all SOC values like shown in Tab. 1. This effective charging power is considering 0 % to 100 % charge with reduced C-rate at beginning and end of the charging process as shown in Fig. 2.

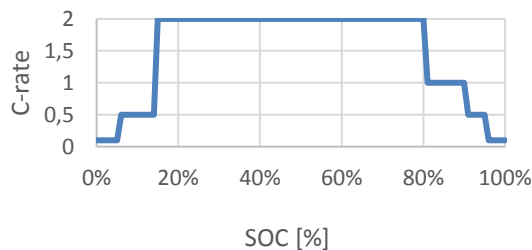


Figure 2: Charging C-rate over SOC for state of the art C-class vehicle from measurements at room temperature

Table 1: Effective average charging power for 0-100 % SOC charging

Charging station [kW]	Effective charging power [kW]
3.7	3.7
11	10.4
22	20.3
43	36.5
150	74.3

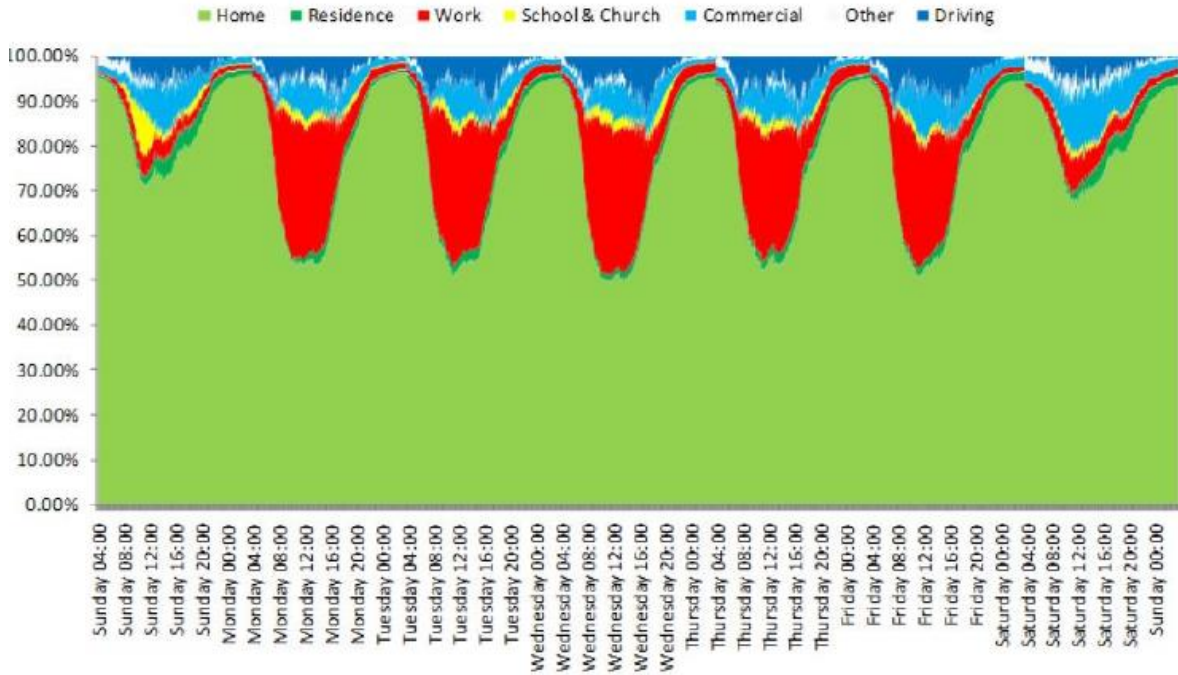


Figure 3: US fleet distribution during week [8]

Turning to user data in Fig. 3, it is found that the majority of charging is charge@home according to [7] 60 % to 80 % at home. If available, the second important charging use case is workplace charging with 30 % to 40 %. Public charging, like DC fast charging is only minor used 3-4 % as solution for longer range driving and if no charging at home was available. Our investigation of today’s installed infrastructure (see chapter 2.4) often showed the use case charge@shop as motivation. Taking all together, we assume the use case occurrences, like shown in Tab. 2.

Table 2: Power levels for charging (230 V)

	Occurrence	Effective Power [kW]	Hours / year
Charge @ Home	55%	10.4	159
Charge @ Work	30%	20.3	44
Charge @ Shop	10%	36.5	8
Charge @ Rest	5%	74.3	2

This model results in a charging time per year of only 213 hours, which is just 26 % of the 811 hours of a pure 3.7 kW charging system. A typical car with DC fast charging and only 3.7 kW AC charging would still require 772 hours. A driver of such a car got the promise of a fast charging car, but charging takes effectively 3.6 times longer than with a system supporting also fast AC charging. We call this phenomenon the *DC charging trap*.

Furthermore, the fast AC charging can be regarded as enabler for vehicle-2-X functions, since the gained flexibility in charging is mandatory for shifting demands. On the opposite it can be stated, that with slow AC charging power in the vehicle, only little vehicle-2-X is possible, since the vehicle has often to be charged at maximum available charging power in order to keep up availability of the vehicle [9].

2.4 The infrastructure point of view

Technically, the residual charges could be both, AC and DC. But in [10] it is stated, that the DC residual chargers for the use cases *charge@home* or *charge@work* are unlikely to come due to limited power of the local grid (max. 10 kW). Further the costs of a 10 kW DC charging stations is estimated therein to be about five times higher than that of a 9.6 kW AC charging station.

In the public area, this trend is also reflected by our case study of charging stations in Regensburg region. Fig. 4 shows location of Regensburg in Germany and key figures for city and county of Regensburg. It can be regarded as a good example for many medium sized German cities, with some specifics, like the world heritage old town.

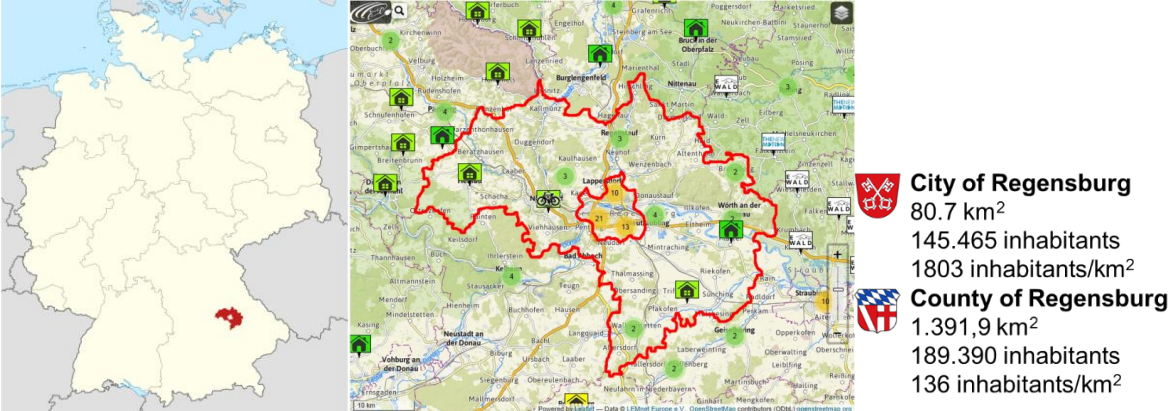


Figure 4: Case study County and City Regensburg [11] [12]; inhabitants at 2016-12-31 [11]

Tab. 3 shows the comparison of key figures of Regensburg City and County compared with the top 4 European countries in number of charging points (CP). Several interesting statements can be picked out of this analysis. First, the charging infrastructure mainstream is based on AC, DC is centralized in urban regions and the motorways with focus on long range support. Regensburg County has no DC charging point at all. Second, the main countries, except The Netherlands, have density values comparable with Regensburg County, which means the cities are not so dominant. Third, the Netherlands did show, that a complete country's infrastructure could come close to that of a city like Regensburg, which is a promising show case.

Table 3: Charging Infrastructure Regensburg and Europe – key figures: Number of charging points (CP), number of CPs below or equal to 22 kW, charging power per inhabitant and per km² and relative content of AC CPs [13] [14] [11] [12]

	Regensburg City	Regensburg County	The Netherlands	Germany	France	United Kingdom
# CPs	119	71	26700	24667	15883	12583
<= 22kW	104	71	26088	22857	14290	10336
W/inhabitant	21.4	4.9	< 36.0	< 7.4	< 6.1	< 5.6
kW / km ²	38.5	0.7	11.8	1.7	0.6	1.5
AC CPs	88%	100%	> 98%	> 93%	> 93%	> 90%

Having a closer look on the charging stations it can be seen from Fig. 5, that there is a large variety of providers, but they clearly focus access point wise on AC charging.

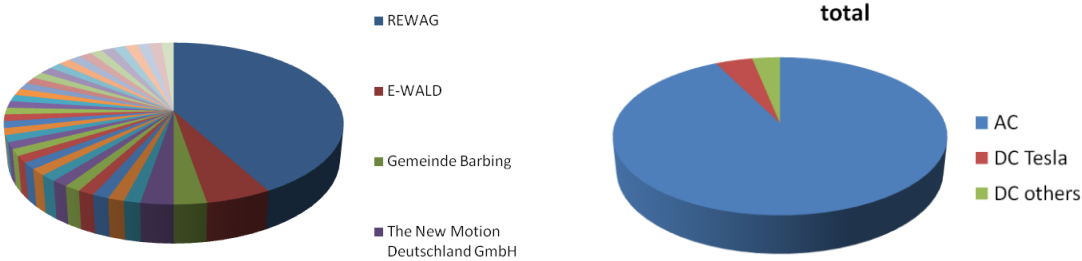


Figure 5: Charging station distribution in the example of Regensburg (total = City+County)

If we have a closer look on the AC charging points, it can be seen, that the majority of charging points is 22 kW capable (see Fig. 6). We have seen a trend of increasing power at established locations by updating

the infrastructure. If this trend would be extrapolated towards the future, the peak would move to even higher values than 22 kW. We found in Regensburg one and in Germany 734 of 43 kW AC charging points, which shows that it's technically possible but today not supported by the vehicle fleet.

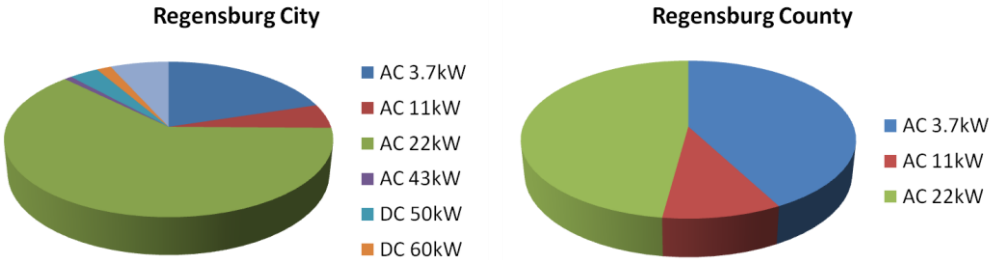


Figure 6: Charging type distribution in the example of City and County Regensburg

A vehicle, which is not offering fast AC charging, cannot fully utilize public infrastructure and will be less value for the customer. From our understanding, the majority of today's vehicles does not support infrastructure sufficiently in terms of DC and fast AC charging capability. The user will encounter with many vehicles the *DC charging trap*, since he is expecting everywhere reasonable charging (50 kW) and only gets 3.7 kW.

2.5 Vehicle-2-X Use Cases

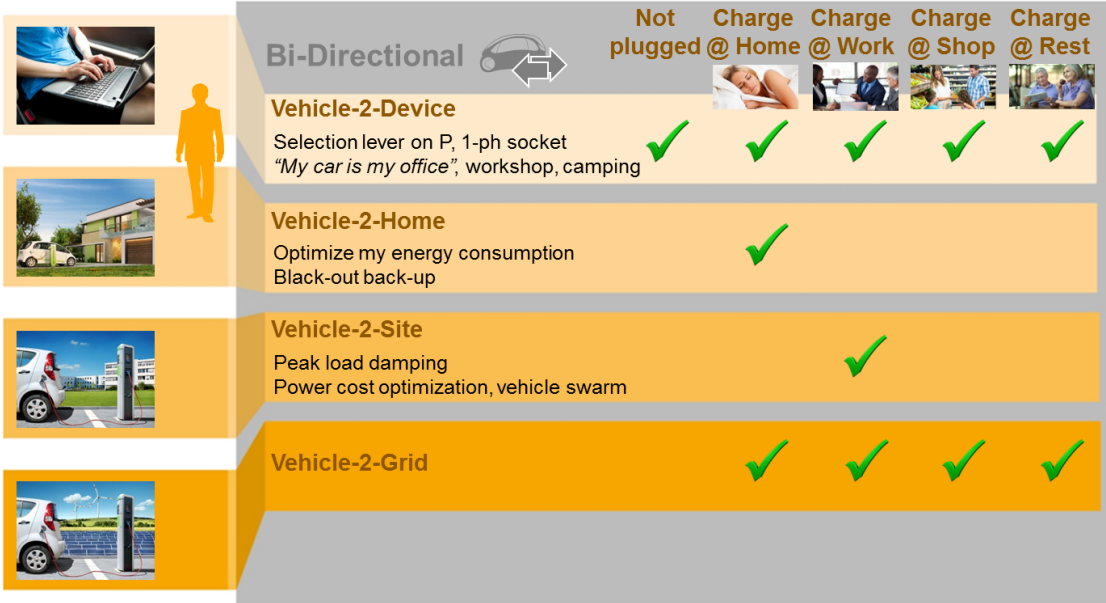


Figure 7: Bidirectional applications in connection to charging use cases

Electric vehicles will be beneficial for more applications than classical vehicles today, due to their high electric power on board. Beyond today's charging use cases, we regard in our analysis 4 vehicle-to-X use cases shown in Fig. 7: *Vehicle-2-Device*, *Vehicle-2-Home*, *Vehicle-2-Site* and *Vehicle-2-Grid*. Often they are associated with the previous charging use cases, sometimes, like in case of *Vehicle-2-Device*, not. This analysis emphasizes again the need of AC connection. It is beneficial, if the vehicle provides AC power directly, like the *AllCharge* does and emphasized for *Vehicle-2-Device* in Fig. 8.



Figure 81: *Vehicle-2-Device* system function example

3 AllCharge Demo Car

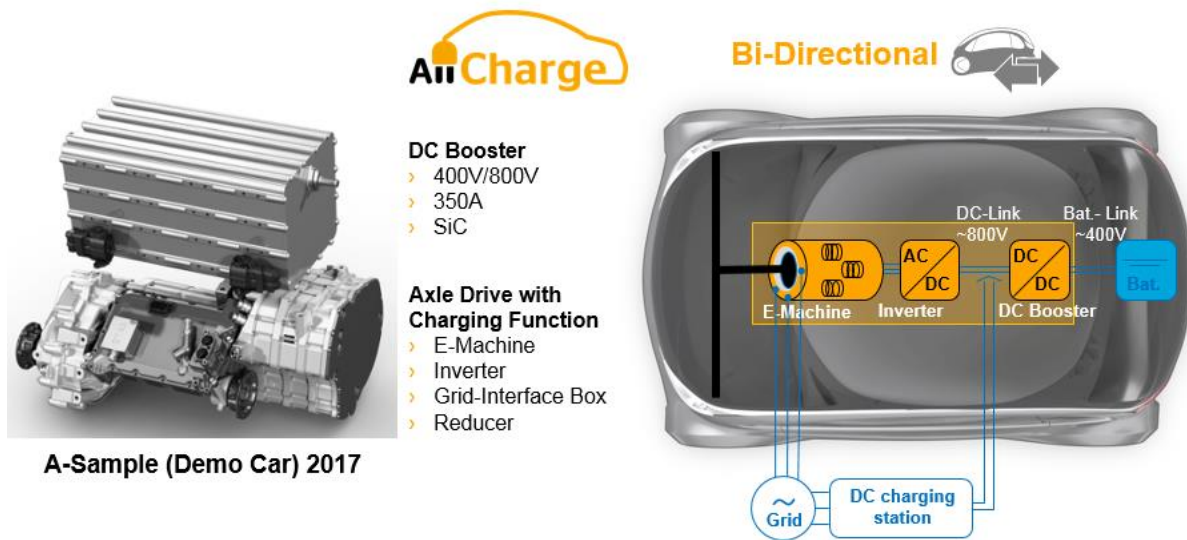


Figure 9: *AllCharge* System [4]

We are currently converting the already presented concept (see Fig. 9) into a demo vehicle (see Fig. 10). Fig. 10 left shows the vehicle at the test facility in Regensburg and on the right the vehicle to device socket at the former charging inlet. It has a battery capacity of more than 50 kWh, a >100 kW drivetrain, 43 kW AC 3-phase charging, 11 kW AC 1-phase and 150 kW DC (400 V and 800 V) charging capability via a Combo connector on the front. Furthermore three vehicle Schuko sockets for 10 A, 50 Hz and 230 V.



Figure 10: AllCharge demo car / Vehicle-2-Device outlet at former fuel intake

4 Summary

The paper showed in the use case analysis the need for fast charging for charge@work and charge@shop. Furthermore in the case study and a market analysis that this is supported infrastructure wise with AC charging stations and not with DC charging stations. Therefore, it is necessary to equip vehicles with powerful AC chargers. By functional integration of traction and charging, this can be achieved at low cost and with the benefit of additional bidirectional capability e.g. with the *AllCharge* approach. Bidirectionality enables the system for new use cases. Since the battery is the most expensive component of the vehicle, it is sensible to use it for more than driving, e.g. vehicle to device functions.

The *AllCharge* system offers maximum flexibility towards existing und upcoming infrastructure. It also supports charging at 800 V up to 190 A in the current design and potentially in the future up to 350 A. Charging at 400 V at 350 A is already supported. At low battery state of charge, the *AllCharge* booster supports higher charging power since it can increase charging station output power by increasing the charging link voltage and battery current. This results in our simulations to a 10 % charging time decrease for a 0 % to 80 % charge.

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