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Electric Vehicle AC Charging Efficiency at Low Charging Power and Consequences on Local Charging Strategies

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Executive Summary

As EV market share increases worldwide, charging points at home or at worksites need to be developed. To avoid local available power constraints, charging at low power can be preferred by some users to avoid high grid subscription or by a local energy management system that will share the available power among charging EVs. Consequently, EVs can spend long durations at low charging efficiency causing significant energy overconsumption and additional charging costs for the users. To assess this generally unknown phenomenon, we carried out charging tests of three different EV models at 8, 10, 16 and 32 A. We estimated the charging efficiency and evaluated the impact of the charged energy. We used these results to assess the charging efficiencies in three real charging configurations with different energy management strategies and point out the negative impact of low charge currents for certain EV models.

1 Introduction

As Electric Vehicles (EVs) market share increases worldwide to meet CO2 emissions reduction targets mandated by various legislative measures, expanding charging infrastructure is becoming increasingly crucial for EV users. In Europe, the 2035 new vehicles and vans ban will require a massive development of charging solutions, especially at home or at worksites, and upgrade of distribution network to allow millions of EV be charged at costs seen reasonable by their owners.

At home or at work, charging operations can be an issue since the EVs add a power burden to the local network, which can come at a cost for the users, either by additional grid subscription tariffs if charging at full power is requested, or by extending charging durations if the power is low or modulated during the charge. The latter situation if often encountered by EV users who use for instance domestic plugs at home with limited current capacity (typically 16 A or less) or adopt smart local charging solutions with wallboxes connected to smart meters or use worksite charging points with a local energy management system.

What an EV user does not generally know though is the actual global charging efficiency of the car when such low power charge or charge modulation are performed, especially on a regular basis. Depending on the car model and the type of charging solution, the total charged energy and therefore the yearly charging costs can be significantly increased, sometimes by more than 30 % as it has been already reported [1][2].

To assess this often-ignored phenomenon, we propose below an analysis of the EV charging efficiency and the consequences on charging energy consumption with respect to the charging solutions and situations.

2 EV charging efficiency

2.1 General consideration

When an EV is charging from a supply equipment, not all the supplied energy is transformed into usable energy for driving. Along the way, energy is lost in different charging sections and components of the EV. In

AC charging (32 A max 1Ph or 3Ph), main energy losses are caused by the on-board charger inefficiency at certain power ranges, the auxiliaries that are required to maintain the EV in adequate charging status, and by the electrochemistry charging process of the battery. Generally, an on-board charger has an optimal or close to optimal efficiency from 50 % to 100 % of nominal power. Even though modern on-board charger can reach 95 to 98 % efficiency thanks to SiC or GAN semiconductor technology [3], lower charging powers still lead to much lower efficiency, sometimes well below 90 %. Additionally, auxiliaries such as electronics devices, various running actuators or pumps can represent up to several hundred watts on certain EV models, thus deriving significant amount of power during the charge process, especially impactful at low charging powers. On the battery side, the charging efficiency can stay reasonably constant and often above 97 % (low C-rate on current AC charging powers).

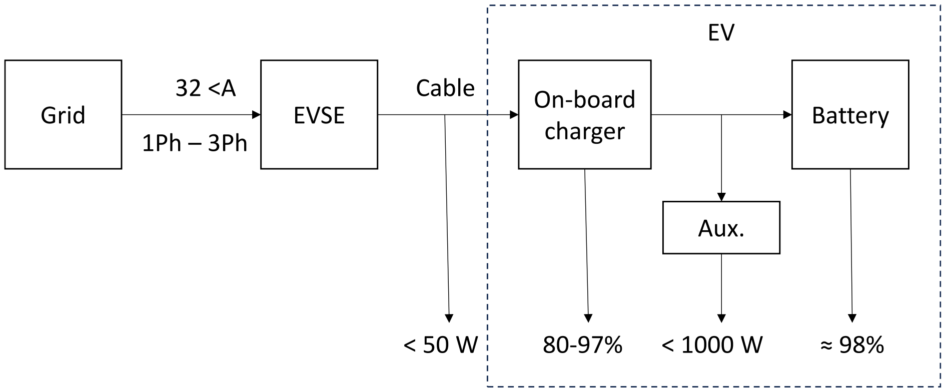

Figure 1: Simplified AC charging losses model for a generic EV

Overall, the EV charging efficiency is mainly driven by the charging power. The lower the charging power, the lower the charging efficiency. And for the user, this situation leads to more energy consumed when the power is reduced from the EV nominal value. We can define this "overconsumption" by the ratio of the energy charged at a certain current profile by the energy charged at nominal power, generally 32 A, in the same battery initial and final conditions.

In the rest of the paper, we only consider one-phase charge only, which is the most used charge type in France, in particular at the domestic level.

2.2 EV charging efficiency and overconsumption experimental setup

To assess EV charging efficiencies and overconsumption in conditions close to actual situations, tests were carried out at EDF R&D e-Mobility Lab on 3 different EVs: an Opel e-Corsa, a Nissan Leaf e+, a Renault Zoé 3. They all have around 50 kWh of battery energy. To represent real charging configurations at home or at workplace with existing charging equipment (but with no dynamic power modulation such as V1G), charging tests were performed as described in the table 1 below:

Table 1: test configurations

Test	Current (A)	Power (kW)	Power reduction	Typical charging installation correspondence
Reference scenario	32	7.4	1	Mode 3 charge on typical residential wallbox
Reduced power	16	3.7	0.5	Mode 2 charge with "Green Up" cable and socket (newer version)
Reduced power	10	2.3	0.38	Mode 2 charge with "Green Up" cable on unknown domestic plug (older version)
Reduced power	8	1.8	0.25	Mode 2 charge with "Green Up" cable on unknown domestic plug (newer version)

The “Green Up” (Legrand brand) mode 2 cable, provided by some OEMs in France, allows a recognition[1] of an EV-dedicated reinforced and protected domestic socket and on which it can perform a 16 A charge (14 A for the older version). Otherwise, charge is performed at 8 A (10 A for the older version).

The test setup is described at figure 2. We used an energy MID meter (precision < 1 %) as well as a CAN logger in the EV to log the SoC and other useful information, if available, such as current and battery voltage of auxiliaries’ consumption. All tests were performed at 20°C +/-5°C.

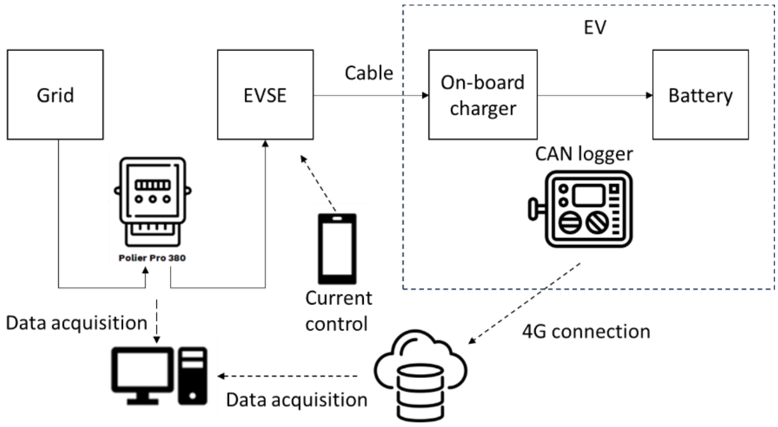

Figure 2: Test setup

2.3 Results

Tests were carried out for all cars and all defined currents. Figure 3 below shows an example of an actual charging result of a e-Corsa charging at 8 A and overconsumption.

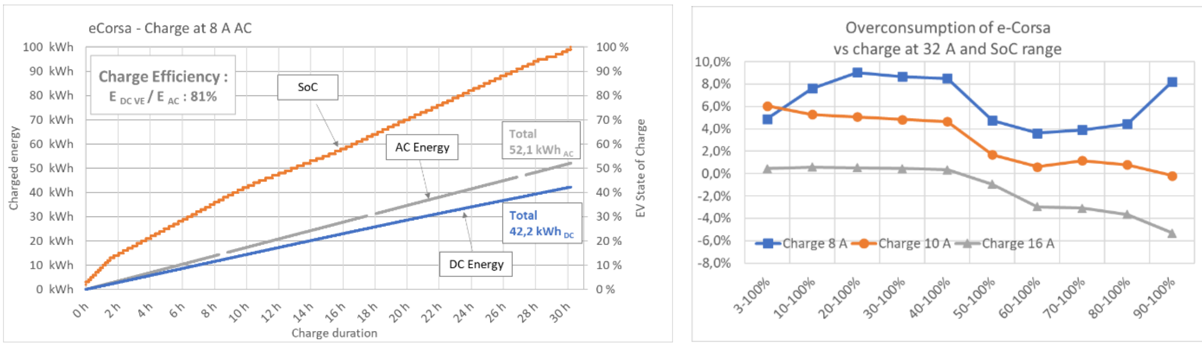

Figure 3: Charge test result of e-Corsa at 8 A (left)
and overconsumption results at 8, 10, 16 A vs charge at 32 A (right)

We can see that the overconsumption is quite noticeable at 8 A and 10 A, whereas it is negligeable at 16 A. The effect of SoC is also seen and can lead to different overconsumption patterns when high SoC is achieved or when the charge occurs on certain narrower SoC ranges. At 8 A, charging efficiency is estimated at 81 % and the overconsumption is almost 10 % compared to 32 A.

For the other tested EV models, the synthesis results are presented in Table 2, with charging efficiencies and derived overconsumptions. All values correspond to a full battery charge.

[1] The « Green-up » socket holds a small magnet which closes a metallic contact in a compatible plug et relays this information to the circuit controller of the mode 2 cable.

The Zoé presents by far the worst results at low currents. This is economically impactful for users who charge their EVs on a standard domestic plug at home. Since the Zoé's on-board charger is peculiar (it is not a real charger but an assembly of the inverter working backward and motor inductances), it is not surprising that overconsumption can reach almost 30 % at 8 A or even higher on certain SoC ranges.

Table 2: Charging efficiency and overconsumption relative to charged energy at nominal power

EV model	8 A	10 A	16 A	32 A
e-Corsa	80,8 % / +9.2 %	83,8 % / +5.3 %	88,0% / +0.2 %	88,2 %
Leafs e+	88,0 % / +2.1 %	89,1 % / +0.8 %	90,7% / -1.0 %	89,8 %
Zoé	65,0 % / +29.1 %	70,4 % / +19.9 %	82,1% / +2.2 %	83,9 %

For the Leaf e+, it seems that this vehicle handles low charging powers quite well, with overconsumption limited to 5 % at 8 A.

As far as 16 A charge is concerned, we found that there is almost no real difference in consumption compared to 32 A for all tested EVs.

These findings can have a strong interest when EV smart charging strategies are concerned. Local energy management systems that are provided either by EVSE (Electric Vehicle Supply Equipment) manufacturers or by CPOs may cause significant overconsumption if they do not consider actual EV charging behavior. It can be also the case if the EVSE at home is a basic domestic plug, or a walbox connected to a smart meter or a power meter that reduced the charging current for long durations.

3. Application on charging scenarios

3.1 Introduction

In this section, we would like to assess the charging efficiencies of our chosen EV types in more practical situations, especially when they are submitted to energy management strategies, such as current limitations or tariff signals, for local or grid constraints. In these situations, the actual charge may vary strongly during the charge sessions, possibly exacerbating poor charging efficiencies when the charge current is low, below for instance 10 A. This may lead for substantial energy overconsumption.

Apart from charging at home with no current limitation, other charging situations may require current modulation strategies. It is especially the case in multiple charging points stations such as condominium parking lots, work charging stations and small building charging stations.

We present here 3 typical and existing situations in France with real charging configurations. Based on those retrieved information, we can estimate the charging efficiency from the actual current profiles for our 3 EV models.

3.2 Condominium charging station

This scenario deals with a typical charging station configuration we can find in condominiums in France, where 12 charging points (7,4 kW – 1 phase) are supplied by a DSO delivery point with a diversity factor of 0.7. This means that the station maximum charging power is limited at 70 % of the sum of the charging point powers by a local or distant energy management system (EMS).

To assess the charging efficiency in this configuration, we decided to simulate the charging scenario with the following hypothesis:

- EVs are arriving and leaving with a gaussian time dispersion around 8 am and 6 pm.
- All EVs have a 50 kWh battery.
- Four values of average initial energy in the battery, identical for all EVs: 10, 20, 30 and 40 kWh with a gaussian dispersion given by a mobility simulation tool. EVs with more initial energy are more flexible.

- For each energy requirement, we performed 100 simulations (1 simulation = 1 day of charging for the 12 EVs)

Two charging strategies are considered:

- "Smoothing" charging strategy: EVs are charged as soon as possible, and the available power is spilt equally in real time among EVs.
- "Optimized" charging strategy: we add a tariff signal so that the EVs can take advantages of low electricity prices, using on/off signals most of the time. The algorithm is based on linear programming to optimize the EV charging sessions and the reduction of the energy costs and has a perfect knowledge of arrival and departure times and initial battery energies.

Results

The Figure 1 below represents the distributions of charging powers (excluding zero null powers which do not affect the charging efficiency). They are quite similar for of all 3 EVs. The results show that EVs spend their charging sessions mainly at intermediate charging powers (between 5 and 5.5 kW) due to the diversity factor of 0.7. Only for 40 kWh initial energy, the algorithms allow charging at nominal or nearly nominal power of 7.4 kW since these EVs are more easily placed in favorable moments to be charged at nominal power.

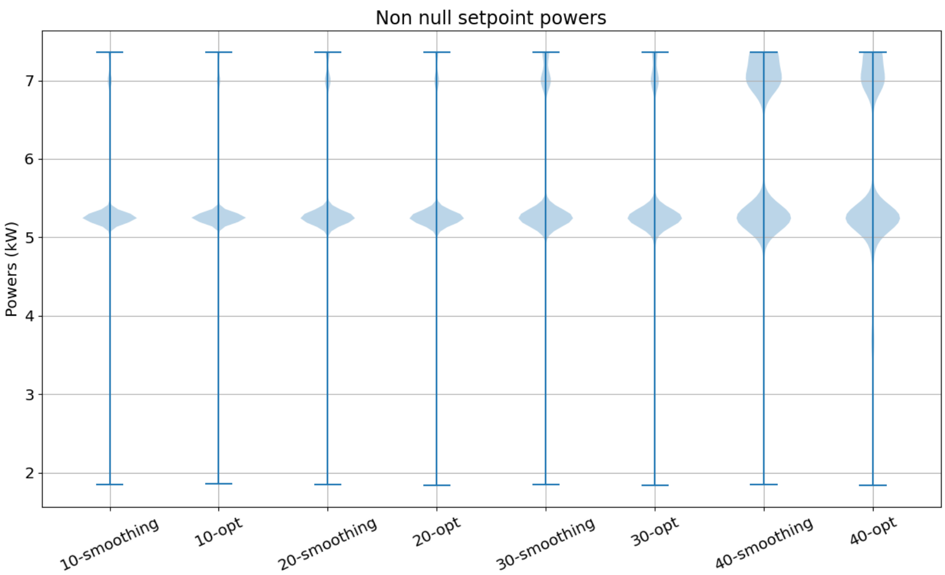

Figure 4: Charging powers distribution for all EVs with respect of charging strategies and initial battery energies

As shown in Figure 5 above, the charge simulation with the two algorithms and the four initial energy values exhibits charging efficiencies very close to the EV charging efficiencies at nominal power (88 % for e-Corsa, 90 % for Leaf e+ and 84 % for Zoé). For the e-Corsa and the Zoé, the power reduction (even though limited), can still alter the charging efficiency by additional 1 % to 2 %. For the Leaf e+, charging at a reduced power seems to increase the charging efficiency by a few tenths of percent. The "Optimized" strategy slightly degrades the charging efficiencies by increasing the time spent at lower charge currents.

Overall, charging those EVs in this condominium configuration with a limited access to the charging power from the grid only marginally alters the charge efficiencies and does cause no more than 2 % increase of energy consumption.

Of course, situations where the diversity factor fall below for instance 0.5, forcing for more charging arbitrage and charging power reductions, may decrease charging efficiencies significantly.

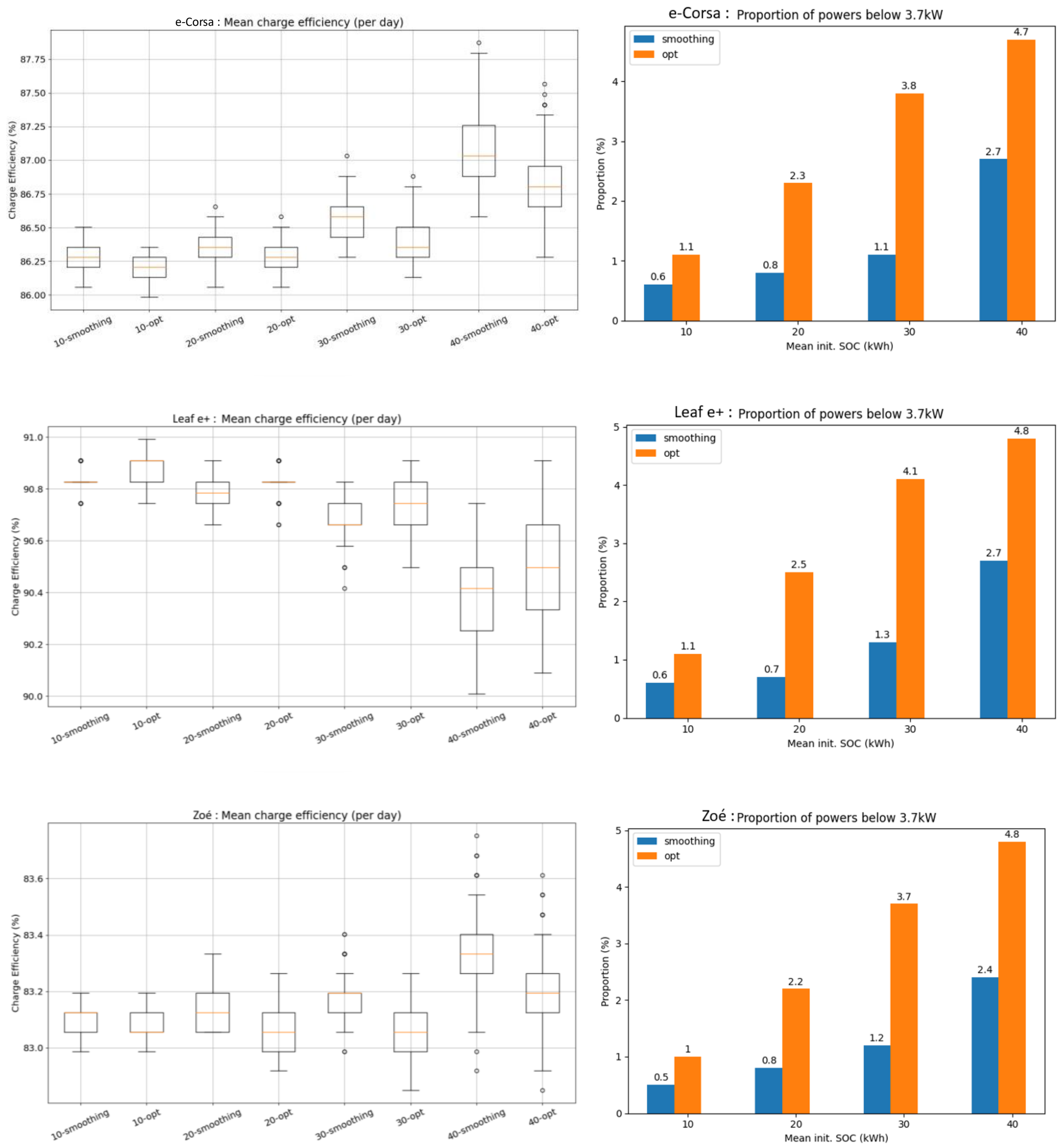

Figure 5: Simulation results of each EVs. Both charging efficiencies and proportions of low power (below 3.7 kW) are displayed for both algorithms and initial energy

3.3 Company charging station with tariff "Ecocharge" signal

In this scenario, we study an actual situation of a company charging station which allows its employees to charge during the day. Electric service cars can charge overnight. The Charging Point Operator (CPO) proposes a peculiar "Ecocharge" charging profile based on the electricity price signals. In the example shown in Figure 6 below, the CPO switches alternatively from 32 A (during the renewable production peak) to 8 A (lower renewable production, morning and evening consumption peaks) twice per day.

The CPO prefers maintaining the 8 A charge instead of suspending it at 0 A, since it allows the EVs to be charged even marginally when plugged only for a few hours during the day.

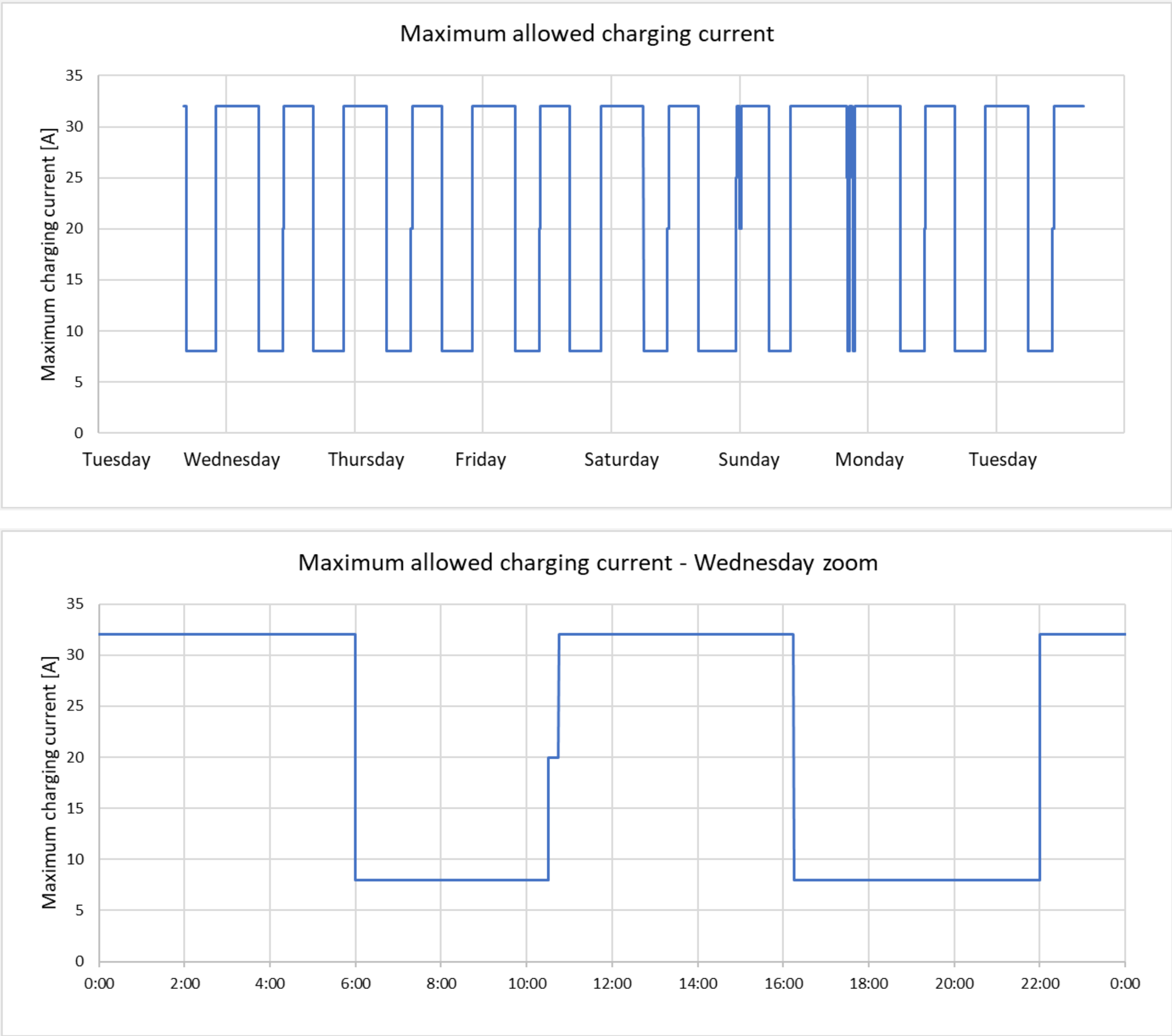

Figure 6: Maximum allowed charging current profile of the studied company charging station (top) and focus on Wednesday (bottom)

Since we know that charging at 8 A may significantly alter the charge efficiencies, we have simulated the EVs charging behavior with the following hypothesis:

- EVs are arriving and leaving with a gaussian time dispersion around 8 am and 6 pm.
- EVs charging energy is around 30 kWh with a gaussian energy dispersion
- For each energy EV type, we performed 100 simulations (1 simulation = 1 charging session).
- There is no global power limitation of the charging station.

Two charging strategies are considered:

- "Smoothing" charging strategy: EVs are charged as soon as possible, with no power modulation other than internal. Charging efficiency may vary a little depending on the EV SoC as seen in section 2.
- "Ecocharge" charging strategy: the charging power will not exceed the charge point maximum allowed current as shown in Figure 6.

Results

As a result, Figure 6 presents the charged energy distribution for all simulations, mainly explained by different initial SoC and charge durations. The charged energies range from 7 to 50 kWh.

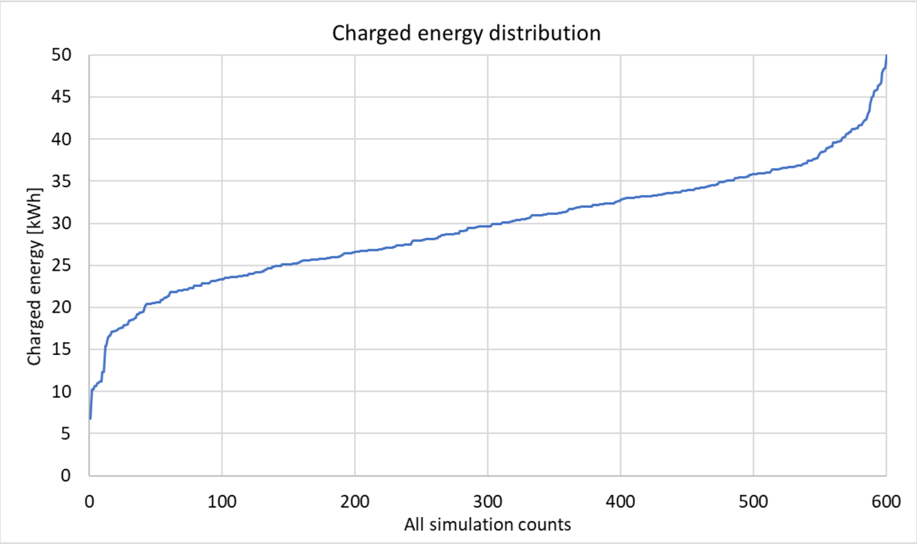

Figure 7: Simulated charged energy distribution

When we look at the results shown in Figure 8 in a monotonous form, we can see with no real surprise that charge efficiencies are particularly deteriorated (by several percents) with Ecocharge profile for certain charge sessions, especially for Zoé and e-Corsa EVs since these EVs are quite inefficient at low charging current.

For those charge sessions, overconsumption can therefore reach several percents, which may not be as dramatic since the economical gain by putting optimized charge tariffs such Ecocharge may be more advantageous for the users and/or the CPO.

The comparison between Smoothing and Ecocharge charging profiles for all EVs is shown at Figure 9. Leaf e+ strong insensitivity to Ecocharge profile is remarkable and enlightens its good charging efficiency at all charging currents.

Nevertheless, for low efficiency EVs at low charge current such as Zoé, the users may be made aware that short charge sessions only occurring during low charge current signals may lead to substantial and additional costs by increasing the charged energy.

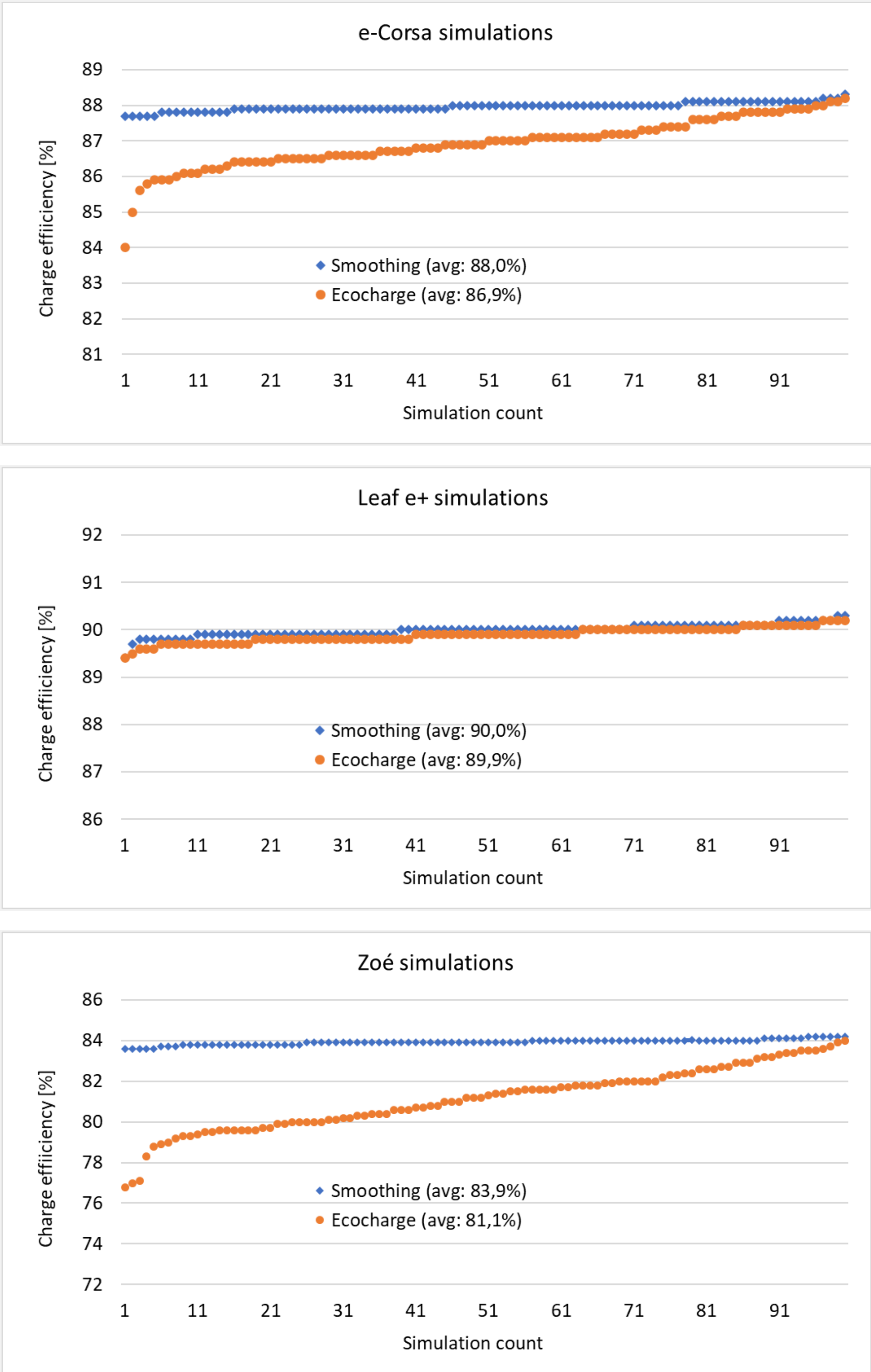

Figure 8: Ecocharge vs. Smoothing charging efficiency simulation results

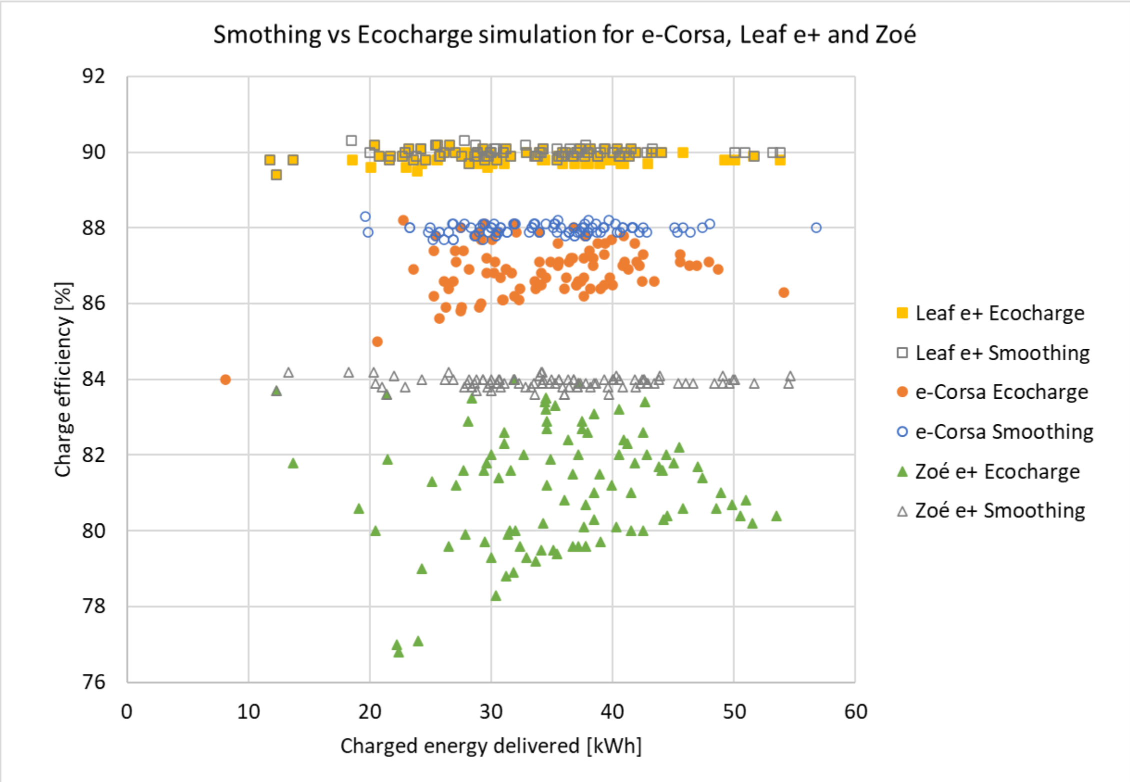

Figure 9: Simulation comparison between Smoothing and Ecocharge for e-Corsa, Leaf e+ and Zoé

3.4 Dynamic load management at a professional charging station

Dynamic Load Management (DLM) is an energy management option that some EVSE manufacturers propose. It is a technology that tracks a building's energy requirements and compares them to its maximum capacity. When energy demand is below the limit, DLM redirects excess power to the charging station. If demand meets or exceeds the limit, no extra power is allocated to charging stations, preventing electrical system overload.

A major benefit of DLM is its ability to utilize low-demand periods, powering the charging network without raising overall consumption. This efficient method supports electric vehicle charging while optimizing energy use.

In some DLM configurations, it may happen that when the building's consumption is high and fluctuating and EVs are charging at the same time, the charging limitation algorithm – especially if it is poorly designed - leads to very slow charge regime, with long observation periods. This may dramatically affect the charge duration and possibly the charging efficiency.

To assess what can happen in this situation and evaluate the impact on the charging efficiency of our EVs, we decided to set up an experiment replicating an actual charging installation for 3 EVs charging at 32 A on the same phase with a maximum delivered current of 75 A at the building delivery point. The setup is shown in Figure 10.

For this setup, we have chosen the following parameters:

- 3 EVSE (1 master, 2 slaves) with DLM features linked via un communication bus.
- 4 flexible electric loads, 8 A each to simulate the load in the building.
- All devices are connected to the same phase.
- The EVSE master is connected to a current transformer and the current limit is set at 75 A.
- 1 real EV is plugged to the EVSE Master, 2 emulated EV plugged with current modulation are plugged into the EVSE Slaves.

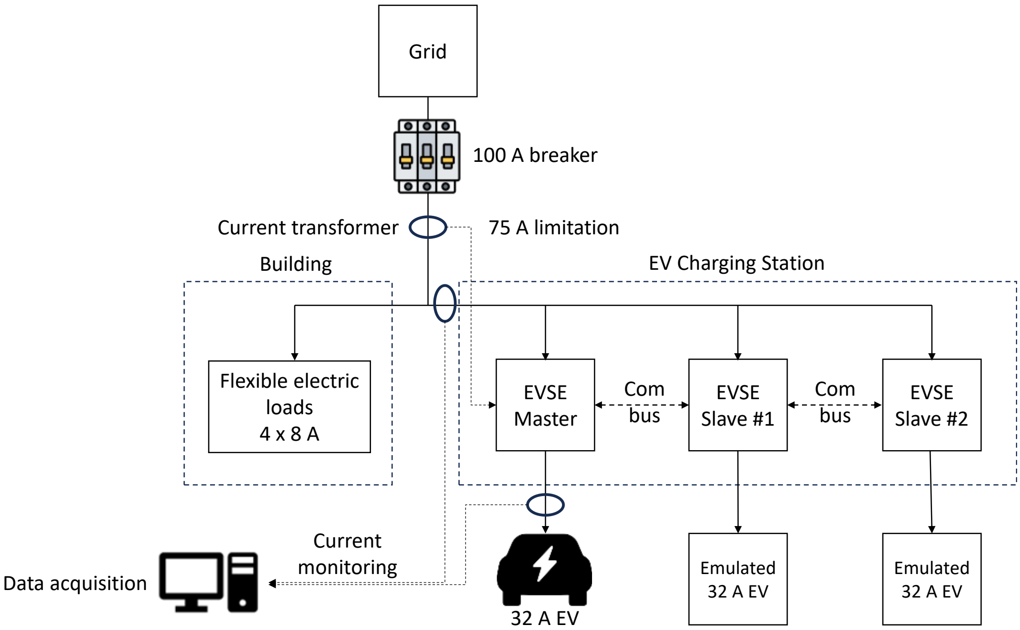

Figure 10: DLM experimental setup

During the test we started by plugging one EV after another and then after stabilization at 70 A, we then added extra building loads with a scheduled order.

Results

Figure 11 shows the results of this test, at the grid level and at the EVSE Master level where a real EV is connected. We can clearly see that with the 75 A limitation: the energy management system (EMS) in the EVSE Master gradually and simultaneously for all EVs increases the charging current up to 23 A instead of 32 A.

When extra building electric loads are connected, the energy management system abruptly suspended all 3 EV charge sessions (0 A). After a 5-minute observation period, the EMS starts increasing the load again, but with a lot of instabilities, reduced charging currents and several additional 5-minute observation periods. The total test duration was 9000 seconds. The energy delivered to the real EV was 7.4 kWh with an average charging current of 13 A. The charging performance is therefore quite poor for the EV user, with extended charging duration.

From this current charging profile, we can calculate the charge efficiencies of our 3 EV types and their overconsumptions relative to their nominal charging powers. The results are shown in Table 3 below.

We can see from the current distribution that the EV spends less than 20 % of the time charging below 10 A (0 A excluded) where charging efficiency is degraded. Consequently, only the Zoé is strongly impacted with an overconsumption reaching 4.6 % with this charge profile. On the contrary, the Leaf e+ spends most of the time in a very favorable current range, even increasing its charging efficiency from the nominal power's one. Finally, this charging profile marginally affects the e-Corsa.

As a conclusion, charging station with such unoptimized energy management mainly affects the user and the EV availability by strongly extending the charging duration. The charging efficiency is only detrimental for EVs, such as Zoé, which have very low charging efficiencies at low charge current.

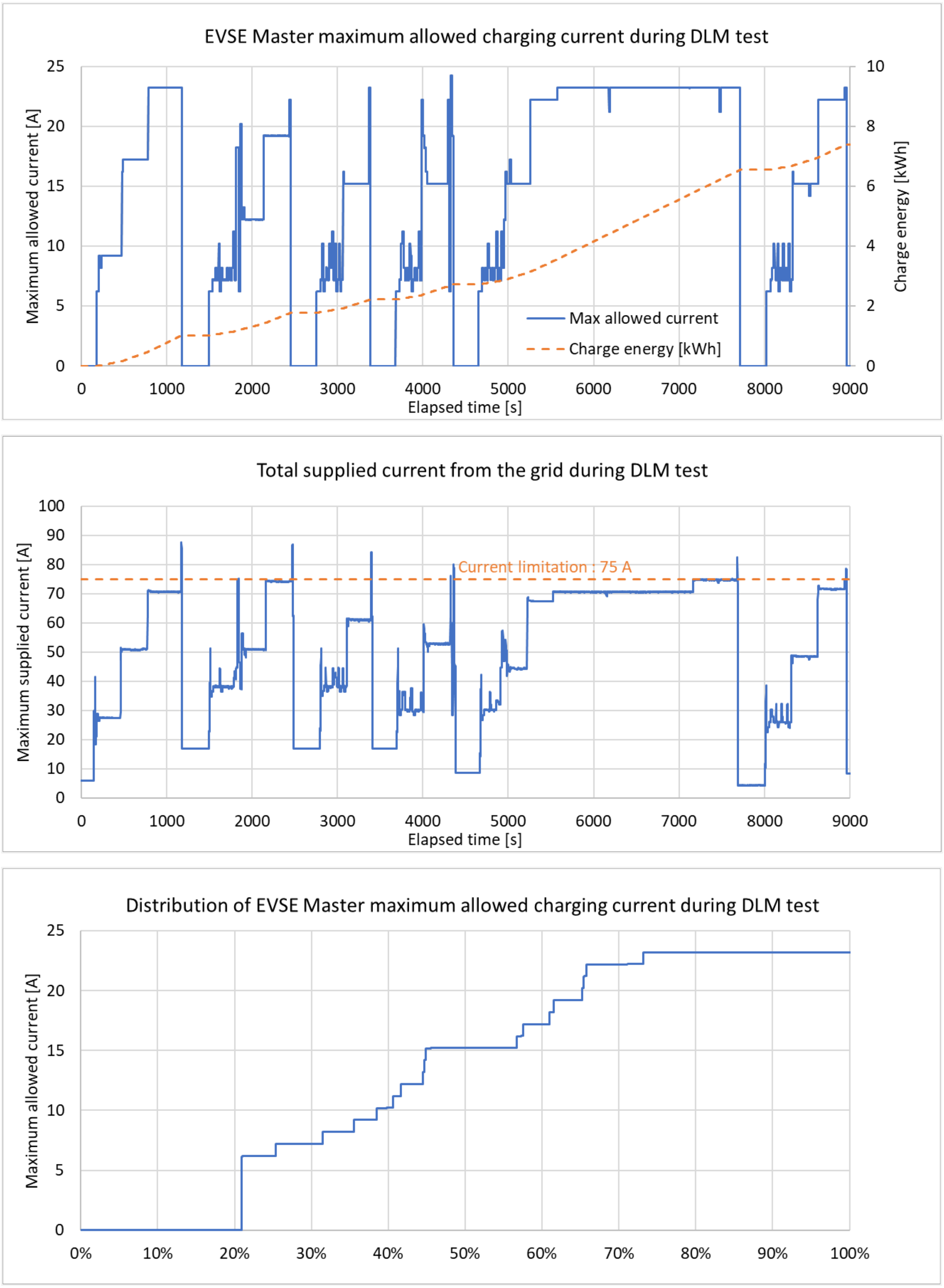

Figure 11: Delivered current during DLM test
Total current from the grid (above), at the EVSE Master level (middle) and current distribution (below)

Table 3: Charging efficiency result derived from the DLM test

	e-Corsa	Leaf e+	Zoé
Supplied Energy (kWh)	7,40	7,40	7,40
Charged Energy (kWh)	6,44	6,66	5,94
Calculated charging efficiency	87,0 %	90,0 %	80,2 %
Charging efficiency at nominal power	88,2 %	89,8 %	83,9 %
Overconsumption	1,4 %	-0,2 %	4,6 %

4 Conclusions

In this paper, we studied the charging efficiencies of different EV models (Opel e-Corsa, Nissan Leaf e+, Renault Zoé) under different charging currents and for the 3 typical charging configurations. These EVs generally present degraded efficiencies when charged at 8 or 10 A, which is particularly true for the e-Corsa and more importantly for the Zoé. On the contrary, at 16 or 32 A, the charging efficiencies at generally closed to the maximum for those EVs.

When we studied the 3 charge configurations with current modulation through tariff signals or EMS local strategies, the results show that the impact of real charges on charging efficiencies are generally lowered by 1 or 2 % compared to nominal power charge, but it can be more noticeable in extreme situations where the charging current is maintained at very low level for a very long time. It is especially the case with the Zoé which is known to have a bad charging efficiency at 8 or 10 A (1 phase). In this case, energy overconsumption may impact the CPO or the EV user.

In any case, energy management strategies for charging stations should be carefully looked at to insure reasonable charging performances and acceptable energy costs and charge durations for the users. On the EV side, recommendations to the public or CPOs by OEM should be made to avoid unexpected bad charging efficiencies, especially at home where most of the charges are made, possibly on domestic plugs at low currents, causing significant and unexpected energy costs.

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Presenter Biography

Thierry BRINCOURT graduated in 1991 in mechanical engineering from Ecole Nationale Supérieure d'Arts et Métiers. In 1993, he started working at EDF R&D on different research and development activities related to underground cables, and from 1999, on Fuel Cells developments and assessments. In 2003, he worked on energy storage related to renewable energy and electrical transportation. From 2007 to 2018, he was the Project leader of the Plug-in Hybrid and Electrical Vehicle Project at Electricité de France Research and Development, managing a team of 30 experts, engineers, researchers, and technicians on working on different issues related to the electric vehicles: development of charging infrastructures, assessment of new electrical vehicles, grid impacts, environmental analysis and standards. He is now as senior e-mobility expert at EDF R&D.