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Published in:
Sustainable Energy Technologies and Assessments

Link to article, DOI:
10.1016/j.seta.2023.103512

Publication date:
2023

Document Version
Publisher's PDF, also known as Version of record

Sustainable Energy Technologies and Assessments 60 (2023) 103512

Contents lists available at ScienceDirect

Sustainable Energy Technologies and Assessments

journal homepage: www.elsevier.com/locate/seta

Experimental validation of onboard electric vehicle chargers to improve the efficiency of smart charging operation

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ARTICLE INFO

Keywords:
Efficiency
Electric vehicles
Onboard charger
Smart charging
Transport sustainability

ABSTRACT

Electric vehicles (EVs) are at the center of the power and transport sector coupling; however, smart charging is required to not compromise the integrity of the grid. In this work, we propose, test, and validate a method for investigating EV onboard chargers via the OBDII port. We present the charging efficiency and reactive power characteristics of 38 different EV models from the last 11 years. Data show that, due to added losses, smart charging through current modulation can increase global charging energy demand from 1%–10%. In addition, EVs consume a relatively large amount of reactive power at lower currents, and some models violate the power factor limits for the low-voltage grid. Our projections show an efficiency of 88%–95% by 2030 and a saturation between 90%–96% by 2035. Therefore, the newly presented AC-to-DC conversion efficiency values help achieve better results when calculating life cycle assessment, grid integration and energy simulation that consider EVs. Curtailed smart charging can further integrate charging needs by implementing phase balancing and matching with behind-the-meter local generation. Finally, our results urge regulators and automakers to further improve charging technology and legislation based on other technological experiences, e.g. solar inverters.

Introduction

An increased penetration of EVs can reduce a large portion of CO2 emissions when coupled with renewable energy sources (RES)[1]. On the one hand, RES suffer from intermittency, which requires a flexibility source to cover their absence or abundance. On the other hand, EVs are parked most of the time, making their charging patterns an attractive source of flexibility [2,3]. However, concurrent charging or more specifically instantaneous power can compromise grid integrity [4] and reduce power quality [5].

Smart charging aims at making EVs an asset for the grid [6]. Benefits can be observed in higher EV penetration levels [7], fewer investments in grid upgrades [8,9], greater utilization of RES and charging infrastructure [10], and higher economic benefits for end users [11].

However, smart charging faces both technical barriers, e.g., grid observability [12], battery degradation [13,14], charging technology [15], cyber security [16], and market barriers, e.g., value framework [17], data privacy [18], interoperability [19], transparency and fairness [20].

Furthermore, smart chargers require a higher investment cost compared to dumb chargers [21]. Second, the avalanche and rebound effects due to market synchronization could amplify the instantaneous power challenge rather than solve it [22,23]. Third, according to [24], the energy costs are 46%–54% of the levelized cost of electric vehicle charging in Europe. Furthermore, due to industrial privacy, commercial OBCs efficiency is an area that has barely been investigated [25].

We investigate mode 2–3 OBC from IEC61851 (charging from 6–32 Amps) [26] in combination with Type 2 plug, which are widespread technologies [26,27]. This investigation is of paramount importance to understand the sustainability and energy efficiency of EVs as a mode of transport [28]. In the charging scheme, OBC is between the vehicle's AC charging plug and battery management system (BMS).

Furthermore, the authors of [29] predicted that the nominal efficiency of commercial of OBC would be 97% by 2020 and 98% by 2025. Previously, the authors of [30] presented their 22 kW modular OBC technology, in which the efficiency numbers are between 85% and 94%. The contradiction in such a predicted efficiency value increases when General Motors data display 93% [31], and the authors of [25,27] suggest that the efficiency of OBC should be in the range of 94%–96%.

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https://doi.org/10.1016/j.seta.2023.103512
Received 20 June 2023; Received in revised form 28 September 2023; Accepted 16 October 2023
Available online 25 October 2023

A literature review highlights the lack of tested AC-to-DC conversion efficiency values for EVs OBC [32,33], albeit the most energy-intensive load in the household. Such conversion efficiency values from AC to DC are critical for the EV optimal large and small-scale management charging strategies [34], life cycle assessment [35] and understanding the global energy implications of charging demand [36].

The knowledge gap is even recognized by the European Commission (EU) for their European efficiency labeling regulation [37,38]. The European efficiency label has been successful in helping consumers make better decisions and reducing European energy needs [39]. We explore this research gap by proposing an investigation method based on vehicle on-board diagnostics port (OBDII) and conducting an extensive test campaign for OBCs of 38 commercial vehicle models. The objective is to answer four research questions.

- Are BMS data reliable across different manufacturers?
- What are the energy conversion efficiency, PF and reactive power curves of commercial OBCs? And does the information change between automakers?
- How has OBC technology evolved and what can we expect in 2030?
- For three-phase OBCs, how do they behave compared to single-phase charging?

The charging efficiency is an important factor when calculating the EV total cost of ownership [40]. Therefore, the investigation in this article is vital on the consumer protection front. Second, it is important for charging point operators (CPOs), aggregators and EV owners due to the direct impact on their economy and business models. Third, maintaining the required PF values is essential for grid operators to not compromise the quality of supply and for regulators to be able to govern the deployment of technology. Consequently, charger manufacturers must follow the guidelines and provide the user with a manual on how to use their chargers according to the regulations. Furthermore, the proposed setup to read the data from BMS via an OBDII dongle has the potential to drastically facilitate future diagnostics of EVs. Thus, such an investigation has the potential to bridge the data visibility gap of EVs and commercially use it to highlight the best charging efficiency and reactive power consumption.

The remainder of the paper is structured as follows. Section "Methodology" describes the methodology of the research and the tools used to conduct the investigation campaign. Further, Section "Investigation campaign results" presents the results from a global to local approach. In addition, it provides a comprehensive overview and future predictions for EVs charging characteristics. Finally, Section "Conclusions" concludes the article with the main findings.

Methodology

Measurement and data acquisition setup

Depending on their design, OBCs are built as standalone units. The OBC converts the AC charging current from the grid to the equivalent DC current required by the battery management system (BMS) to supply the lithium-ion battery. We built two modular EV laboratories, as shown in Fig. 1. The objective is twofold: first, to determine the AC-to-DC power conversion efficiency of the OBC, and second, to measure the rest of the grid side parameters (such as reactive power and power factor). Four main parameters are measured/derived for each vehicle:

1. Active power [kW] consumed from the grid.
2. Reactive power [kVAr] consumed from the grid.
3. Apparent power [kVA] consumed from the grid.
4. DC active power [kW] on the battery side of the vehicle after AC-to-DC conversion.

The OBC stands between the vehicle's Type 2 AC plug and the BMS-DC battery pack. On the one hand, finding the reactive power and power factor curves is straightforward by measuring the AC side consumption values with a DEIF multimeter (Fig. 1a). On the other hand, the principle behind the AC-to-DC conversion efficiency compares the charging measurements from the DEIF multimeter (grid-side data) with those from the vehicle's internal DC battery side (BMS-side data).

Furthermore, most EVs, in Europe, do not charge more than 32 Amp AC [15]. Thus, from left to right in Fig. 1(a), the laboratory requires a 32 Amp three-phase supply from the grid side (Labcell). This supply is done through a CEE 32 Amp plug that connects the Labcell and the smart charger; see Fig. 1(a). Between the grid side and the smart charger, a DEIF multimeter is located to measure electrical parameters on the grid side. Such measurements are transmitted via the DTU cloud and stored on the operator's computer. The smart charger is the central piece of this investigation, as it allows for the manipulation of the charging current in order to characterize the operational values of OBC.

The connection between the smart charger and the EV is achieved through a Type 2 cable. Type 2 cable is responsible for delivering energy and control signals to EV. Therefore, it has seven pins indicating phases 1,2 and 3, earth, neutral, proximity pilot, and control pilot [41]. The control pilot is the communication path for the pulse width modulation (PWM) signal, which controls the charging process.

The purpose of the operator's test sequence is to compare the charging data on the grid side with the BMS side. DEIF multimer measures grid-side data, and BMS data are recorded through the OBDII port. BMS records data on the DC side; thus, after AC-to-DC conversion is performed. A smart charger is necessary to investigate the full spectrum (from minimum to maximum current) of the OBC. The operator, see Fig. 1(b) can control the vehicle OBC charger by providing the desired charging current limit in Amps. This numerical value is translated by the smart charger to a duty cycle value for the PWM; see Fig. 1(b).

$$I_{ch} = D \times 0.6 \text{ Amps} \tag{1}$$

where I_{ch} is the charging current, D is the duty cycle, and 0.6 Amp is the charging current step [42]. The BMS reads the allowed duty cycle through the control pilot of the Type 2 plug. In combination with the OBC, it draws the required current from the grid; see Fig. 1(b).

It is important to mention that the OBC is located between the AC plug and the BMS and we intend to explore the knowledge that the BMS offers. There are two important components inside the OBC. The AC-to-DC converter converts the AC charging current to the DC equivalent. The DC voltage output is designed for the 400 or 800 V battery pack architecture. Another component is located after the AC/DC converter, which is the DC/DC converter. The role of the DC/DC converter is to supply the 12 V battery, the auxiliaries, and the electronic control unit (ECU) [43].

In general, the data on the BMS side can be extracted from the OBDII that is located on the driver side. BMS communicates to the OBDII via the CANBUS communication [44]. The internal vehicle computer and BMS converge their data sets at OBDII. Here, an OBDII dongle is used to read the data through a phone app via Bluetooth. The proposed method, OBDII data readings, does not require components to be disassembled from EV, and has previously been utilized for battery degradation matters in [45]. The article showed that OBDII is successful in understanding battery degradation of Nissan-brand vehicles. However, our methodology proposes that OBDII can be used to evaluate the characteristics of all commercial OBC. We extended the research work to 14 automakers and 38 vehicle models released in a window of 11 years.

To verify that such BMS readings are accurate, one can compare the OBDII values when the vehicle is fast charging (DC charging). This is because with DC chargers, the OBC is bypassed and the current goes directly to the BMS/DC battery. Consequently, the values observed on the fast charger (outside of the vehicle) should be the same (or very close to as there can still be some cable losses) as the values coming

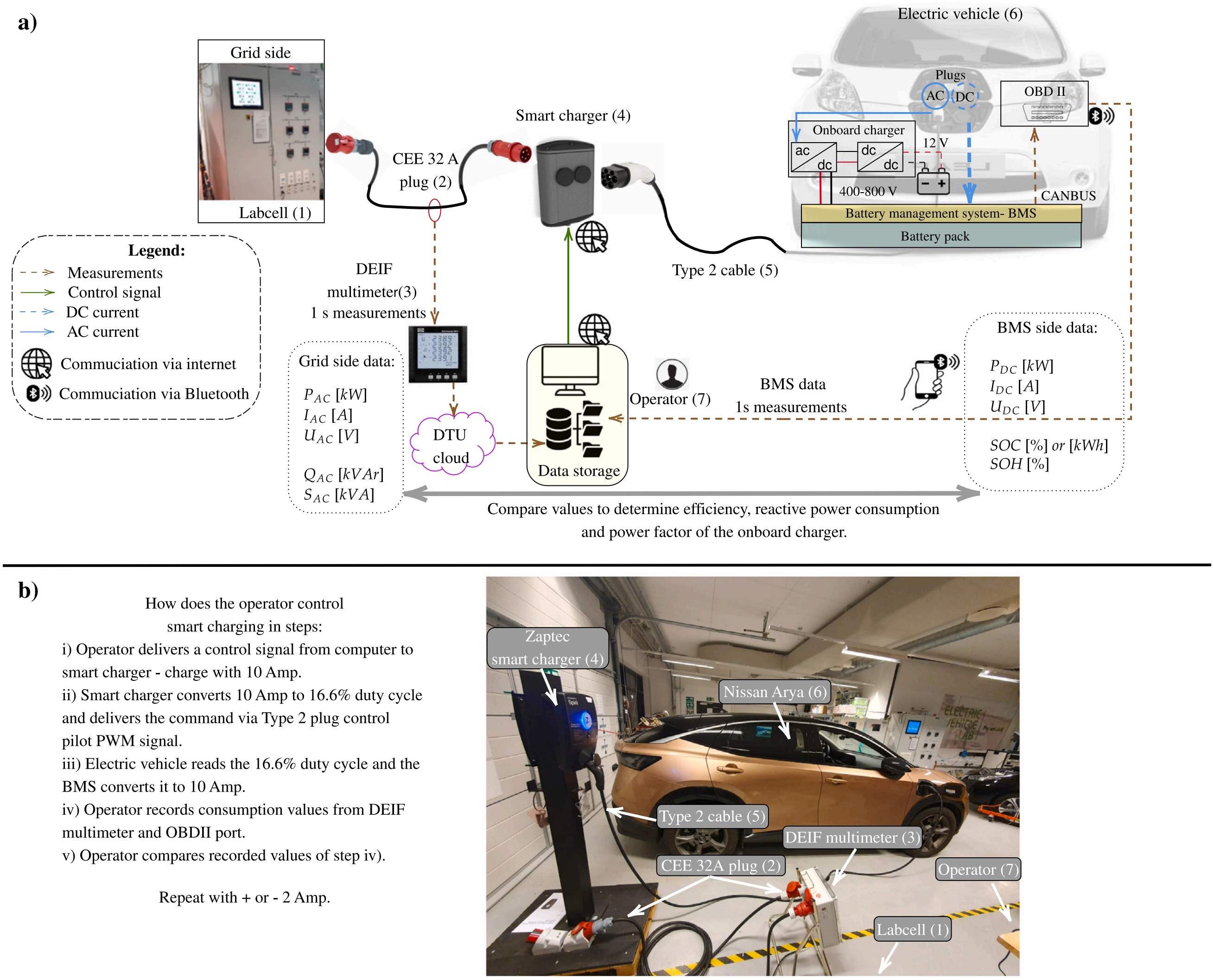

Fig. 1. (a) Overview of the methodology and tools used for the testing campaign. (b) Physical setup representing the method.

from the BMS through the OBDII port. This article, in addition to expanding the work from [43] to multiple vehicle brands, highlights the benefits and challenges of such an approach. For example, a single app cannot read the information from all vehicles. Therefore, in the following section, we present the devices used to collect data from the different models.

Testing campaign tools

In order to have a complete view of light-duty vehicles, we investigated 38 vehicles, from early EVs that have a Type 1 plug (such as Nissan LEAF from 2012 and Peugeot iOn from 2011) to the latest models (such as Tesla Model Y, Kia EV6, etc.) that commonly use a Type 2 plug for their AC charging process. Previously, Fig. 1(b) displayed the physical location where the laboratory is built for the testing campaign. One can observe that the laboratory is modular and does not rely on a specific smart charger.

Similarly, the Type 2 cable is used at all times, even though some older vehicles do not support it. 38 vehicles from production years 2011 to 2022 are tested. Two of such old vehicles have a Type 1 plug instead of the common Type 2 plug. In that case, to make such a plug transition (from Type 2 to Type 1) for the charging cable, we have designed and built a plug converter from Type 2-to-Type 1. To check the physical plug converter device please see Fig. A.1(b) in the Appendix. The Type 2 plug remains connected to the smart charger, while the Type 1 plug connects to the vehicle. To read the vehicle DC side data (battery side) from BMS, an OBDII dongle is required. The dongle communicates via Bluetooth to an app on the smartphone. To check the screenshots of apps please see Fig. A.1(a) in the Appendix.

The DC side data include the displayed state-of-charge (state-of-charge (SOC)) [%], state-of-health (SoH) [%], battery energy content [kWh] at the moment, charging power [kW] and the DC current [A] and voltage [V] during charging. By reviewing different apps, it was found that the Car Scanner app [46] can serve most vehicles; whereas the LeafSpy app [47] is more specific for Nissan LEAF models and the scan my tesla app [48] is the only one compatible for Tesla models. In addition to the app and OBDII dongle for Tesla models, an OBDII adapter is needed [48]. Lastly, for Volvo and Polestar, it was not possible to read DC-side data due to encrypted OBDII port readings. For such vehicles, the article discusses only the data on the AC side. Finally, for a complete overview of the tools used for each automaker please check Table A.1 in the Appendix.

Performance indicators and testing sequence

The test procedure is designed with the aim of harmonizing EV testing by defining key performance indicators (KPI). Such KPIs are as follows:

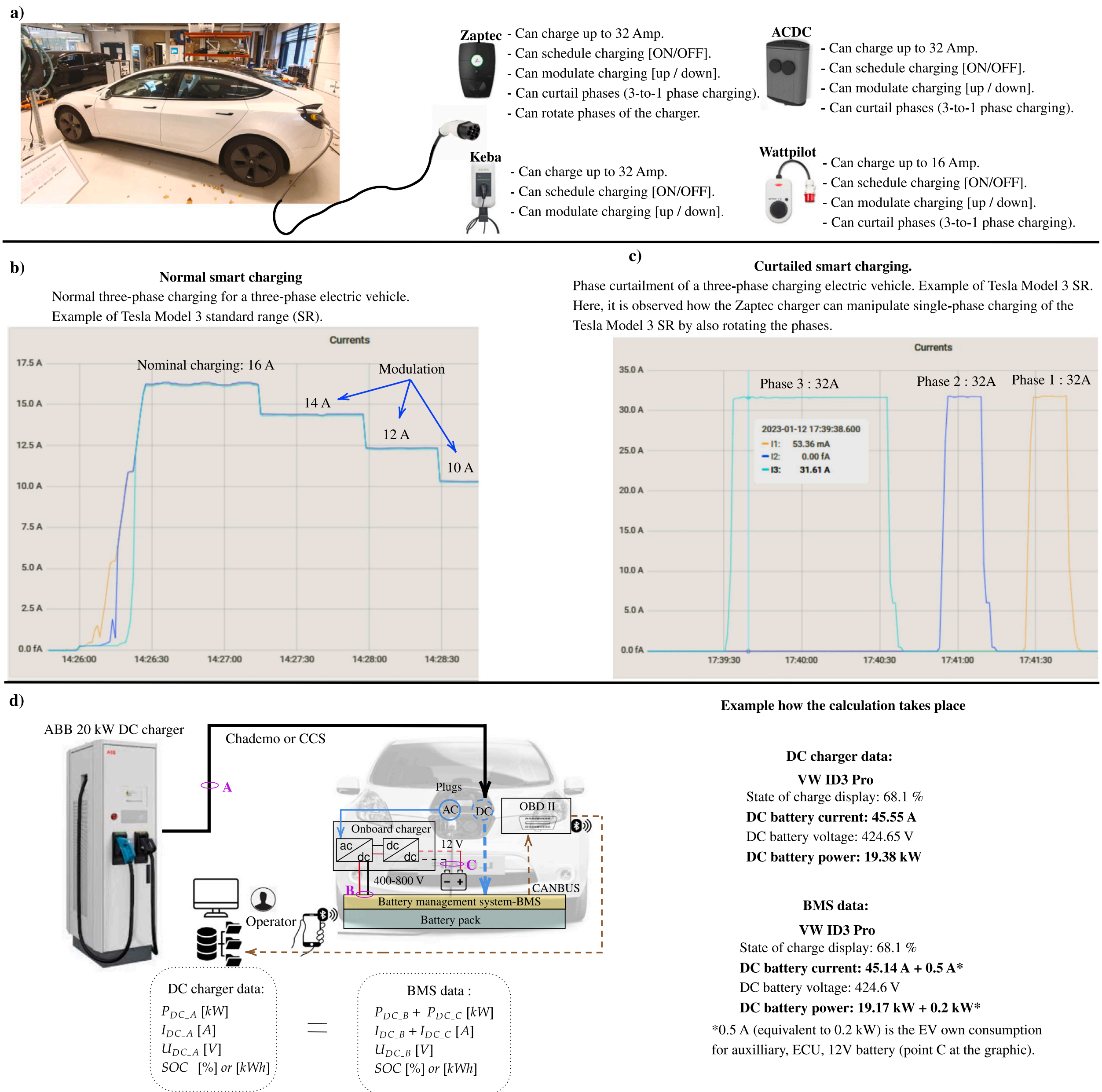

Fig. 2. (a) State-of-the-art of smart chargers and corresponding characteristics. Screenshots of the Grafana measurement interface of the DEIF multimeter during (b) three-phase charging and (c) curtailed charging of the Tesla Model 3 SR. (d) The approach followed to verify the BMS readings on the DC charger side.

- Maximum and minimum charging power.
- Maximum and minimum recorded efficiency.
- Maximum and minimum recorded power factor.
- Maximum and minimum recorded reactive power.

To quantify such KPIs, we charge EVs by controlling the PWM signal of the smart charger. First, EV is charged with the maximum charging current (16 or 32 A) and later is reduced by 2 Amps every 30 s until the minimum charging current (6 A) is reached. The opposite is performed to complete a cycle of down- and up-modulation. Such a testing cycle is performed twice, below and above 50% SOC to investigate whether SOC affects the KPIs. In addition, to better understand possible patterns, the KPIs are combined with the necessary metadata for each vehicle, such as the year of production, the price, the size of the battery, the state of health (SOH), the voltage of the battery system and the charging phases.

Smart charging and OBDII data reliability

The testing campaign encompasses all types of OBC, including single-phase, two-phase, and three-phase. Furthermore, the fleet being tested ranges from production years 2011 to 2022, providing a rare opportunity to compare the OBCs included by automakers in their commercial EVs. The IEC 61851 standard [42] allows charging between 6–51 Amp. However, AC smart chargers by accordingly changing the duty cycle can deliver 6 to 32 Amp per phase [15]. For that reason, we built the EV testing laboratory to analyze the entire charging spectrum of EVs and to handle up to 32 Amp per phase (Fig. 1). Previously, a definition for the smart charger has been proposed in [15] from which we provide an adjusted version in the following: *Smart charger is an electric device providing protection, communication, at least scheduling and at most modulation, phase curtailment (3 to 1-phase switch) and phase switching for the EV charging process.*

Fig. 2(a) explains the characteristics of the smart chargers and, together with parts (b) and (c), displays how a Tesla Model 3 standard range charges in normal smart charging and curtailed smart charging mode.

Smart charging can be achieved by all smart chargers. However, there exists a special case, curtailed smart charging, for EVs that have a three-phase OBC, which is called phase curtailment. Phase curtailing means that a three-phase EV can charge in a single phase by curtailing two of the phases. It should be mentioned that the first phase should always remain energized [49]. Recognizing such technological development, it is necessary to characterize not only normal smart charging, but also curtailed smart charging. To avoid relying on data from a single charger, four state-of-the-art smart chargers are used to further investigate normal and curtailed smart charging.

More specifically, Fig. 2(b) presents how the Tesla charger reacts to the nominal three-phase 16 Amps charging and how modulation occurs to lower charging currents part of the testing sequence. Additionally, Fig. 2(c) demonstrates the ability to switch the 16 Amp three-phase charging of the Tesla Model 3 to a single phase 32 Amp. When switching the Tesla charging from 3-to-1 phase, one can notice that OBC can deliver up to 32 Amp compared to 16 Amp. This feature is investigated for different brands.

In addition, Fig. 2(c) reveals a state-of-the-art attribute of the Zaptec smart charger, the ability to rotate the charging phases. Lastly, each charger was tested to measure its own power consumption, resulting in the following values: Keba 12 Watt, Zaptec 8 Watt, ACDC 10 Watt and Wattpilot 9 Watt. These values are deducted from each test case accordingly.

EVs typically have two charging ports for AC and DC charging, respectively. The AC port connects to OBC and BMS to charge the battery pack, as shown in Fig. 2(d). The DC port connects directly to the battery pack. This design allows verification of the reliability of BMS data, such as SOC, current, voltage, and power of the DC battery. To confirm the accuracy of the BMS data, EV can be charged with a DC charger, bypassing OBC and any potential losses associated with OBC. By doing so, the readings from BMS should match the current and voltage measured on the DC charger, as shown in Fig. 2(d).

Measurements at point A (see Fig. 2 (d)) are compared with the sum of measurements at points B and C. The comparison allows us to determine the quality of BMS data. Point A represents the charging data from the DC charger outside or off-board the vehicle. Point B represents the charging data that flows to the DC battery pack. Point C accounts for the auxiliary energy data that the vehicle is consuming for its own operation. On average, tested EVs consume 150–350 watts for their internal normal operation when on or awake.

This procedure is used for each vehicle model tested, using an ABB 20 kW DC charger. BMS data can also be accessed through the OBDII port and viewed on applications. In our tests, the difference between ABB DC charger readings and BMS data was negligible (4–10 Watt).

Investigation campaign results

Global view

The results reflect the average values of the test for the vehicle in a controlled temperature environment. Four test cycles are conducted per vehicle, two when SOC was less than 50% and two when SOC was greater than 50%. However, before presenting any result, the measurement error range should be highlighted. For example, the AC-to-DC conversion efficiency, hereafter referred to as efficiency, suffers from 2%–3% uncertainty at 6 Amps and is linearly reduced to 0.2–0.5% at 32 Amps. The reason for such a difference is the embedded losses in OBC power electronics [50,51]. Their size remains almost constant during the charging current range. Nevertheless, the losses-to-charging current ratio is higher on lower charging currents and significantly lower on higher charging currents. Finally, the reactive and apparent power measurements are affected only by the quality of the DEIF multimeter (class 0.1) [52].

Fig. 3 shows a parabolic efficiency pattern during normal smart charging for three-phase vehicles. As mentioned above, this is explained by the losses-to-charging current ratio in different current ranges.

The values reflect normal smart charging for three-phase vehicles. The position of vehicles on the heat map is randomly chosen. The coloring label for AC-to-DC conversion efficiency is capped from 65%–95% to provide a clear view of the evolution of efficiency over the years and brands. However, it should be mentioned that Renault Zoe R90 (2019), Renault Zoe ZE50 R110 (2020, 2021), and Nissan Townstar (2022) have 0% efficiency at 6 Amps charging current, thus, a darker color.

The results show a gradual improvement in efficiency from 2011 to 2022 in all charging current values. The same model from the same automaker displays different efficiency curves, depending on the year of production. Consequently, one can observe the versions of Peugeot e-208 (2020 and 2022), Renault Zoe ZE50 R110 (2020 and 2021), or Nissan LEAF e+ (2019 and 2022). In addition, if the vehicle model is from the same year and the same original equipment manufacturer (OEM), the efficiency curve is very similar; see VW e-golf (2017 x2) in Fig. 3.

Furthermore, PF is the ratio of active power to apparent power. It indicates the efficiency of the electrical power usage. A PF of 1 means that all the power supplied is being used to do useful work, while a PF of less than 1 indicates that some of the power is being wasted. Consequently, a lower PF can be caused by inductive loads (e.g. electric motors), reactive power, and nonlinear loads (e.g. electronic equipment). The legend of the PF heat map, in Fig. 3, is restricted from 0.9 to 1, as required by the EU Commission Regulation 2016/1388 for the connection of demand to the low-voltage grid [53].

The PF values are being improved with newer models, where the majority are close to unity PF. Data suggest a correlation between lower PF values and higher reactive power consumption. During charging on low currents, some models violate the regulation for connection of demand to the low-voltage grid. Additionally, some models consume a large amount of reactive power. Thus, the regulation regarding such large reactive power consumption needs to be re-addressed as it threatens the integrity of the low-voltage grid. Renault Zoe R90 (2019), Renault Zoe ZE50 R110 (2019, 2020), and Nissan Townstar (2022) have a PF lower than 0.9 for currents less than 14 Amps, so these vehicles are colored black. Such specific models experience a 0 PF at 6 Amps. Similarly to the efficiency in Fig. 3, there is a different behavior for the same model produced in different years by the same automaker. For example, the Peugeot e-208 (2020 and 2022), Renault Zoe ZE50 R110 (2020 and 2021), and Nissan LEAF e+ (2019 and 2022) versions have different PF behavior across the same charging current. However, the same model produced in the same year by the same automaker (2017 VW e-golf) experiences the same PF behavior.

In addition, the reactive power consumption for each model is introduced in Fig. 3. The data show six clusters of reactive power consumption curves. The majority of EVs from early to the latest models consume reactive power in the range of 200–700 VAr, following a similar curve as Polestar 2 Long Range Dual-Motor (LRDM) (cluster 1). This means that reactive power consumption reduces when the charging current increases. The opposite is true for the Tesla Model S P90D (400 V battery architecture) and the Kia EV6 LR (800 V battery architecture), representing clusters 2 and 3 respectively. Consequently, this is not a feature of a specific battery voltage architecture (400 or 800 V), as it can be found on both architectures.

Hyundai Kona is representative of cluster 4. Such a cluster experiences an almost complete parabolic pattern, where the highest reactive power consumption is in the middle charging current range (10–12 Amps). Tesla Models 3/Y represent cluster 5, which are very close to 0 VAr reactive power consumption. Lastly, an outlier of reactive power consumption are those EVs that employ an OBC similar to the Renault Chameleon/Zoe [27] (cluster 6). That is, the case of an integrated OBC with the electric motor [27]. The rest, clusters 1–5, represent behaviors of dedicated OBC, which are the majority in the automotive industry.

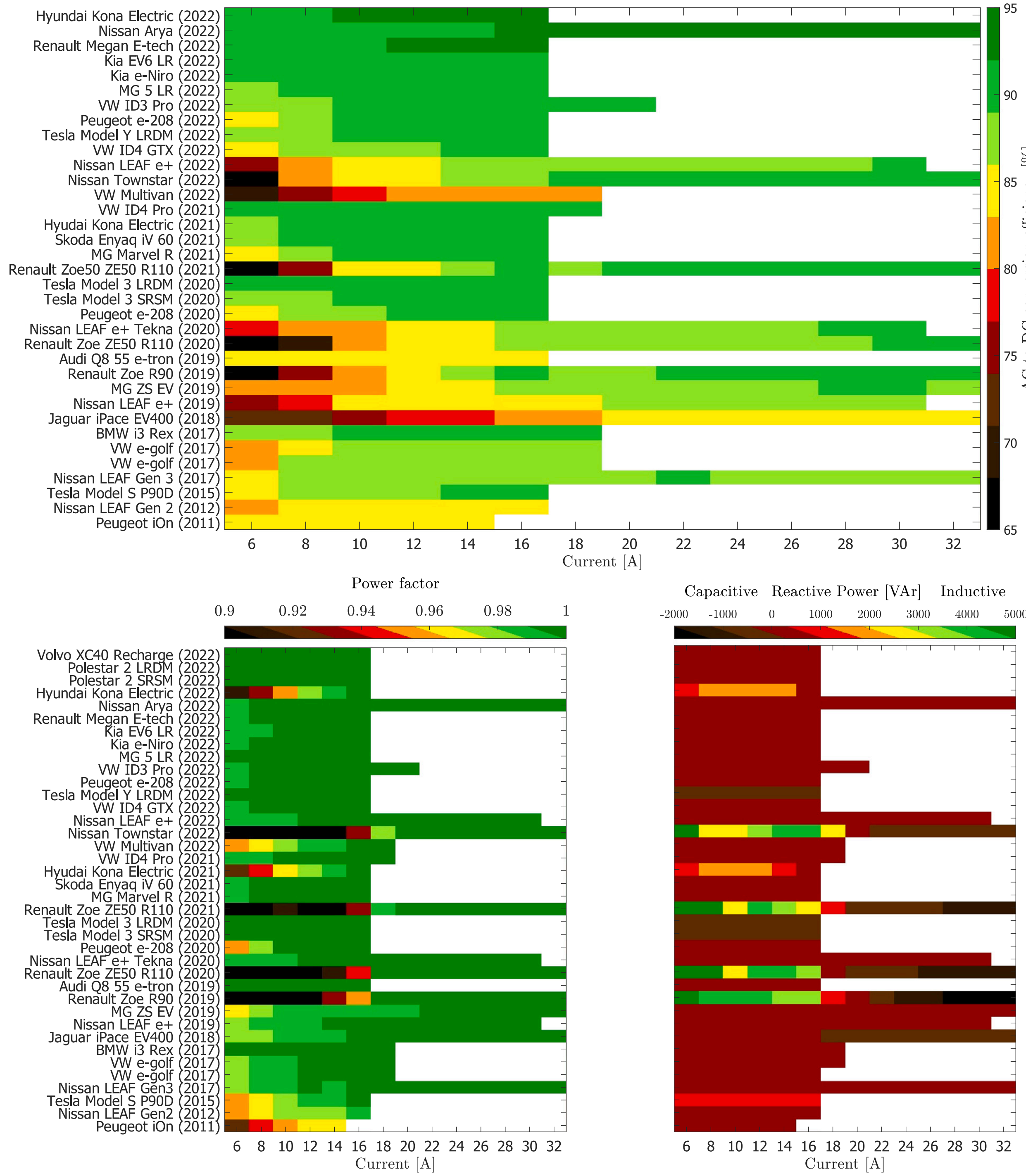

Fig. 3. EV OBC characteristics (up) AC-to-DC conversion efficiency, (down-left) PF, and (down-right) reactive power consumption from 2011 to 2022.

Current and future OBC performance conundrum

When looking for trends in the behavior of OBC, the vehicle SOC is an important variable. Figs. 4(a–d) show that the SOC state does not affect the efficiency of OBC or the reactive power consumption. This outcome confirms that SOC affects only the size of the charging current requested by OBC. For example, a charging current of 10 Amps has the same efficiency and reactive power consumption at low (i.e. 40%) and high (i.e. 92%) SOC.

Moreover, Figs. 4(e, f) show the three most efficient OBC models and the three most grid-friendly vehicles, out of 38 vehicle models over 11 years. The former is diverse in automakers, while the latter is dominated by Tesla. The concept of grid-friendly means that it is almost neutral to reactive power consumption during all charging currents.

In Figs. 4(g, h) historical efficiency data are plotted alongside a second-order fitted function. The OBC maximum efficiency has progressed over the years; however, for 2022 it averages the efficiency of 90%, while the OBC minimum efficiency is around 83%. Based on 11 years of data, a second-order polynomial prediction of efficiency is displayed up to 2040. The prediction considers a conservative approach in which the technology will develop at a faster rate until it saturates at a 96% efficiency value in 2035. These saturation levels for the development of OBC efficiency agree with historical developments in solar inverters, which are a good example of technological progress [54].

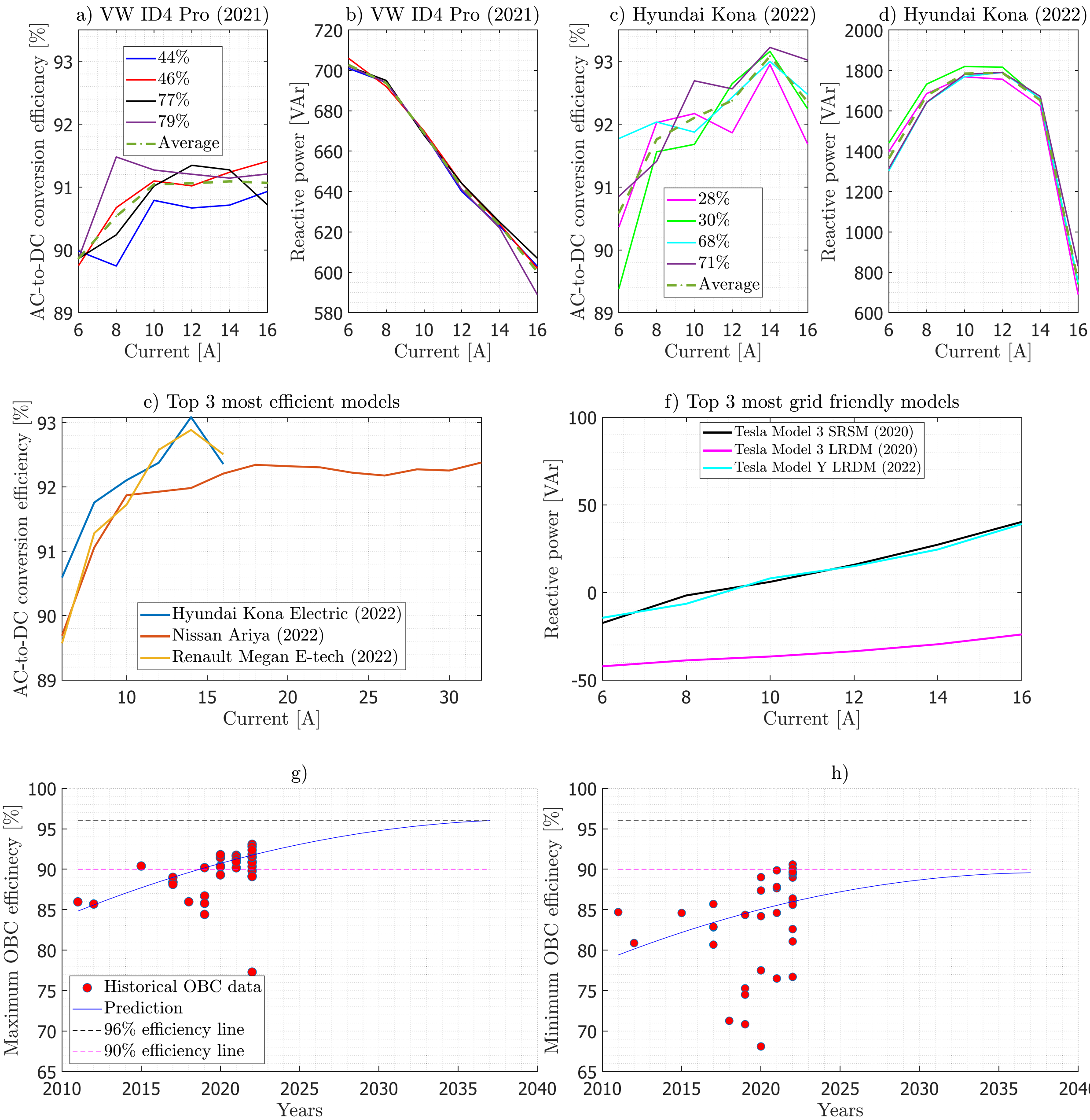

Fig. 4. Charging efficiency and reactive power consumption curves under different SOC for ID4 Pro (2021) (a, b); Hyundai Kona Electric (2022) (c, d). The three best performing models in (e) efficiency and (f) reactive power. Evolution of (g) max and (h) min OBC AC-to-DC conversion efficiency.

Therefore, only by 2030 could it be possible to reach a maximum OBC efficiency of 95% as a market average product. Similarly, by 2030 it could be possible to support a value of 88% for the minimum efficiency of OBC and a saturation of efficiency of 90% in 2035. The data suggest that the fleet of EVs varies considerably in its efficiency values. This uncertainty complicates the optimization of EVs; therefore, it needs to be addressed with technological improvements.

Finally, the results of the test campaign are summarized in Table 1 with respect to four key performance indicators (KPI) (charging power, recorded efficiency, PF, and reactive power) and the official automakers' data.

Furthermore, 9 of 38 (9/38) are single-phase models. Two are two-phase models and 27/38 are three-phase models. Three models have a Type 1 plug, while the rest have a Type 2 plug. Similarly, the combined charging system (CCS) plug dominates (30/38), while the Chademo plug is found in 5/38 models. The EV battery architecture can be 400 or 800 V. Of the vehicles tested, only one has 800 V architecture (Kia EV6 LR) according to data from [55].

The data set is more diverse when you look at the price and battery size range. Prices can be clustered into three groups: 30–45k Euro, 46–65k Euro, and 66–120k Euro. Although the nominal battery size ranges from 16–95 kWh, with 50 to 75 kWh being the most common sizes.

Table 1 highlights the charging current recorded versus official values. According to the IEC 61851-1 standard, between 10%–85% duty cycle the vehicle should draw between 6–51 Amps. However, the maximum charging current is subject to limitations, and 32 Amps is the industry norm.

Consequently, there is a mismatch between the automakers' official Min and Max charging current values with those recorded from the test campaign. The mismatch is smaller for the min values and significant for the max values. For example, Nissan Arya consumes 5.88–32.1 Amps while the official numbers are 6–32 A Amps. The measurement equipment is class 0.1. The majority of vehicles suffer from higher

Table 1
Results from the nominal testing of the investigated fleet. Ranking is done randomly according to the production year. Green highlights three models that perform best in their respective categories. The price values and nominal battery capacity are taken from [55].

No	Year	OEM	Model	Variant	Original price [Euro]	Plug type AC/DC	Nominal capacity [kWh]	Ch. phases	Official max/min ch. current	Tested max/min ch. current	Max ch. power [kW]	Min ch. power [kW]	Max efficiency [%]	Min efficiency [%]	Max reactive power [VAr]	Min reactive power [VAr]	Max power factor [%]	Min power factor [%]
1	2011	Peugeot	iOn		29k	Type 1/Chademo	16	1	16/6	13.65/6	3.16	1.26	85.97	84.7	218	147	96.9	92.6
2	2012	Nissan	LEAF	Gen 2	32k	Type 1/Chademo	24	1	16/6	16.6/6	3.82	1.36	85.7	80.88	541	332	98.2	95.7
3	2015	Tesla	Model S	P90D	120k	Type 2/CCS	90	3	16/6	15.5/5.2	10.83	3.55	90.4	84.5	1468	861	99.2	95.2
4	2017	Nissan	LEAF	Gen 3	33k	Type 1/Chademo	40	1	32/6	31.5/6	6.9	1.41	89	85.7	323	190	99.8	97.7
5	2017	VW	e-golf		32k	Type 2/CCS	36	2	16/6	16/6	7.23	2.62	88.39	82.82	644	454	99.4	97.5
6	2017	VW	e-golf		32k	Type 2/CCS	36	2	16/6	16/6	7.14	2.6	88.43	82.9	644	455	99.4	97.5
7	2017	BMW	i3	Rex	37k	Type 2/CCS	33.2	3	16/6	16/6	10.9	4.04	88.13	80.68	292	176	99.7	99.1
8	2018	Jaguar	iPace	EV400	76k	Type 2/CCS	90	1	32/6	31.5/6	7.26	1.41	85.98	71.27	196	−60	99.6	97.3
9	2019	Nissan	LEAF	e+	37k	Type 2/Chademo	62	1	32/6	30/6	6.75	1.34	87.42	75.28	293	176	99.7	97.2
10	2019	MG	ZS EV	Standard	34k	Type 2/CCS	51,1	1	32/6	32.11/5.77	7	1.22	86.7	70.85	393	211	99.5	96.8
11	2019	Renault	Zoe	R 90	34k	Type 2/-	44.1	3	32/6	32/7	22.08	0	90.19	0	4300	−1870	99.7	0
12	2019	Audi	e-tron	Q8 55	80k	Type 2/CCS	95	3	16/6	15.9/6	11.07	4.07	85.79	84.36	548	507	99.8	99.1
13	2020	Renault	Zoe	ZE50 R110	37k	Type 2/-	54.7	3	32/6	30.4/7.5	20.68	0	90.4	0	4563	−976	99.8	0
14	2020	Tesla	Model 3	Standard range Single Motor	53k	Type 2/CCS	60	3	16/6	16.4/6	11.59	4.39	91.42	87.37	40	-18	99.9	99.9
15	2020	Tesla	Model 3	Long range Dual Motor	62k	Type 2/CCS	78.1	3	16/6	16.3/6	11.63	4.39	91.8	89.02	-24	-42	99.9	99.9
16	2020	Peugeot	e-208		35k	Type 2/CCS	50	3	16/6	15/6	10.05	3.98	90.3	84.2	400	200	99.5	96
17	2020	Nissan	LEAF	e+ Tekna	41k	Type 2/Chademo	62	1	32/6	30/6	6.66	1.35	89.3	77.5	422	192	99.7	98
18	2021	Renault	Zoe	ZE50 R110	37k	Type 2/-	54.7	3	32/6	32/7	19.6	3.08	91.73	0	4615	−800	99.9	0
19	2021	Hyundai	Kona	Electric	43k	Type 2/CCS	67.5	3	16/6	15.7/6	10.69	3.38	91.6	87.65	1650	701	99.6	92.3
20	2021	Skoda	Enyaq	iV 60	42k	Type 2/CCS	62	3	16/6	16/6	10.93	4.16	90.18	87.82	643	529	99.8	98.4
21	2021	VW	ID4	Pro	48k	Type 2/CCS	82	3	16/6	16.3/6	11.54	4.31	91.25	89.86	703	594	99.8	98.4
22	2021	MG	Marvel R		47k	Type 2/CCS	69.9	3	16/6	15.05/5.76	10.57	4.05	90.92	84.61	507	473	99.7	98.9
23	2022	VW	ID4	GTX	53k	Type 2/CCS	82	3	16/6	15.9/6	11.01	4.22	89.80	85.99	633	493	99.8	99
24	2022	VW	Multivan		45k	Type 2/CCS	13	1	16/6	16.5/6	3.58	1.31	77.29	54.12	362	290	99.3	95.8
25	2022	Nissan	Townstar	N-Connecta	34k	Type 2/CCS	45	3	32/6	29.82/6.95	21.08	4.73	90.91	81.08	4970	−445	99.9	0
26	2022	Tesla	Model Y	Long range Dual Motor	59k	Type 2/CCS	78.1	3	16/6	16.4/6	11.32	4.27	90.34	86.39	39	-15	99.9	99.9
27	2022	Peugeot	e-208		30k	Type 2/CCS	50	3	16/6	15/6	10.27	4.11	90.83	85.61	504	460	99.8	98.9
28	2022	VW	ID3	Pro	35k	Type 2/CCS	62	3	16/6	16.3/5.2	11.3	4.18	90.95	87.43	536	480	99.7	98.6
29	2022	MG	5	Long Range	38k	Type 2/CCS	61.1	3	16/6	15.01/5.7	10.59	3.99	91.48	88.97	499	462	99.7	99
30	2022	Hyundai	Kona	Electric	43k	Type 2/CCS	67.5	3	16/6	16.5/4.76	11.16	3.16	93.08	90.59	1788	726	99.5	91
31	2022	Kia	e-Niro		42k	Type 2/CCS	67.5	3	16/6	16.2/6	11.51	4.17	91.53	90.11	722	437	99.9	98.2
32	2022	Kia	EV6	Long Range	56k	Type 2/CCS	77.4	3	16/6	15.9/6	11.3	4.23	91.87	89.37	606	472	99.6	98.7
33	2022	Renault	Megan	E-tech	47k	Type 2/CCS	65	3	16/6	16.5/6	11.14	4.09	92.8	89.57	523	471	99.8	98.8
34	2022	Nissan	Aryia		63k	Type 2/CCS	87	3	32/6	32.1/5.88	22.15	4.06	92.37	89.68	610	522	99.8	98.8
35	2022	Nissan	LEAF	e+	37k	Type 2/Chademo	62	1	32/6	29/6	6.65	1.4	89.1	76.7	306	191	99.7	98
36	2022	Polestar	2	Standard range Single Motor	47k	Type 2/CCS	69	3	16/6	16.3/5.94	11.3	4.26	–	–	443	184	99.9	99.3
37	2022	Polestar	2	Long Range Dual Motor	55k	Type 2/CCS	78	3	16/6	16.2/5.9	11.18	4.18	–	–	440	185	99.9	99.3
38	2022	Volvo	XC40	Recharge	48k	Type 2/CCS	69	3	16/6	16.14/5.88	11.1	4.02	–	–	425	174	99.9	99.5

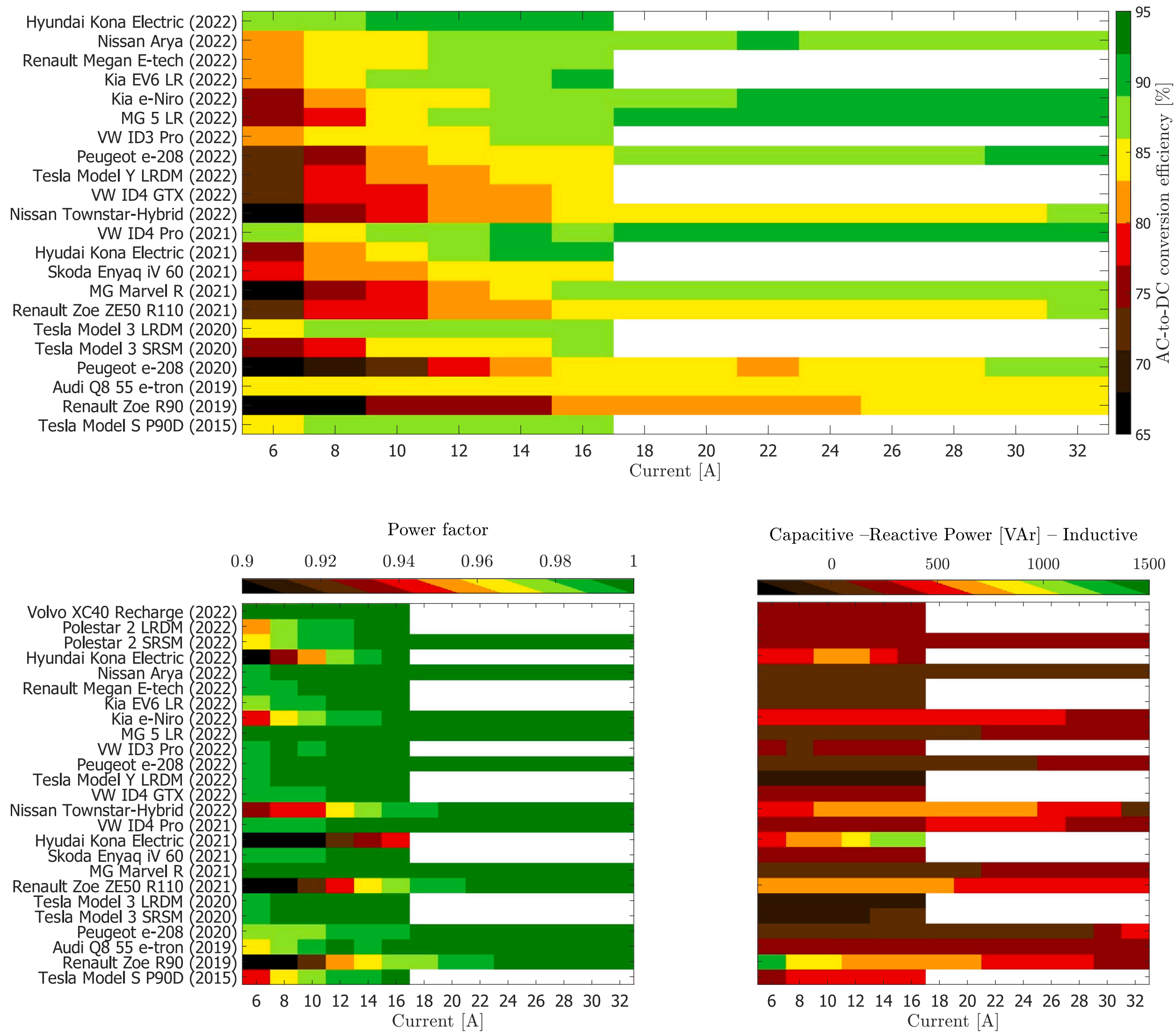

Fig. 5. Characteristics of the curtailed three-phase EV OBC (up) AC-to-DC conversion efficiency, (down-left) PF, and (down-right) reactive power consumption from 2015 to 2022.

mismatches, and some even overshoot the official max values. The data are not conclusive on whether such a pattern is dedicated to a particular brand; thus adding uncertainty to the smart charging process.

The uncertainty expands towards official active power when considering grid voltage oscillations. The official maximum active power values are 3.68 kW (16 Amps) or 7.36 kW (32 Amps) for single-phase charging and 11.04 kW (16 Amps) or 22.08 kW (32 Amps) for three-phase charging. However, such values do not match by vehicles; see Table 1. The reason for this discrepancy is the IEC 61851 standard. The standard quantifies an upper limit for the duty cycle; however, it does not quantify the quality of following such a duty cycle for the vehicle. This issue complicates smart charging control and hinders the ability of aggregators to forecast real-time demand.

Smart charging curtailment

EVs that have a three-phase OBC can charge in a single phase by curtailing two phases [49]. This curtailment is vital for places that are limited to a single-phase grid connection. The importance of curtailed charging increases for residential areas because it can be combined with single-phase photovoltaic (PV) installations. Thus, increasing the utilization and economic benefits of residential PV and the ownership of an EV.

Fig. 5 displays the curtailed efficiency of the tested models. The position of vehicles on the heat map is randomly chosen. The coloring label for AC-to-DC conversion efficiency is limited from 65%–95% to provide a clear view of the evolution of efficiency over the years and brands.

The data show that efficiency deteriorates when the three-phase OBCs are forced to charge on a single phase. Again, Renault Zoe R90 (2019), Renault Zoe ZE50 R110 (2021), and Nissan Townstar (2022) have 0% efficiency at a charging current of 6 Amps in a curtailed charging mode. Additionally, the curtailed data reconfirm that the same models from different production years experience different results.

Moreover, the ability to draw more current in a single phase is observed for some of the models. For example, Kia e-Niro in three phases can draw 16 Amps on each phase. However, when the Kia e-Niro is in curtailed charging mode, it can draw up to 32 Amps from a single phase. This capability is not common and should be verified on a vehicle-model basis.

Furthermore, Fig. 5 introduces the PF and the reactive power consumption of the curtailed OBC. PF of 1 means that all the power supplied is being used to perform useful work, while a PF of less than 1 indicates that some of the power is being wasted. Similarly to Fig. 5 the PF values deteriorate during curtailed charging. While for three-phase charging the average reactive power consumption was 800 VAr, for curtailed charging it is 400 VAr. The higher reactive power consumption agrees with vehicles that have a lower PF. Consequently, the results show that some vehicles charging on low currents do not comply with the requirements for low-voltage demand installation. Renault Zoe R90 (2019), Renault Zoe ZE50 R110 (2020), and Hyundai Kona Electric (2021,2022) have a PF lower than 0.9 for currents less than 8 Amps. In addition, the lack of capacitive behavior is the most important change in the reactive power consumption pattern during curtailed charging.

Three-phase versus curtailed charging

The possibility of curtailing three-phase charging OBCs opens up the opportunity to better optimize charging operation in parking lots, fleets, or clusters controlled by an aggregator. Such a strategy has as its objective the fulfillment of the required energy demand (in kWh) without compromising the grid capacity connection (in kW) and the allowed consumption of reactive power (in kVAr).

Grid connection capacity is generally the biggest constraint for charge-point operators. Therefore, smart charging is employed to maintain the acquired grid connection capacity from the distribution system operator (DSO). However, modulating the charging current has additional implications for OBC efficiency, as shown in Fig. 6.

The OBC efficiency results can be clustered into six patterns.

1. Vehicle that charges with 16 Amps in three-phase (11.04 kW) and single-phase (3.68 kW) (cluster representative Skoda Enyaq iV 60). The efficiency of single-phase charging is lower than three-phase charging.
2. Vehicle that charges with 16 Amps in three-phase (11.04 kW) and single-phase (3.68 kW) (cluster representative Hyundai Kona Electric). The efficiency of single-phase charging above 14 Amps (3.22 kW) is higher than the efficiency of three-phase charging below 8 Amps (5.52 kW).
3. Vehicle that charges with 32 Amps in three-phase (22.08 kW) and single-phase (7.36 kW) (cluster representative Renault Zoe ZE50 R110). The efficiency of single-phase charging greater than 16 Amps (3.68 kW) is higher than the efficiency of three-phase charging below 12 Amps (8.28 kW).
4. Vehicle that charges with 16 Amps in three-phase (11.04 kW) and 32 Amps in single-phase (7.36 kW) (cluster representative Kia e-Niro). The efficiency of single-phase charging is lower than three-phase charging.
5. Vehicle that charges with 16 Amps in three-phase (11.04 kW) and 32 Amps in single-phase (7.36 kW) (cluster representative Peugeot e-208). The efficiency of single-phase charging is sometimes better than that of three-phase charging.
6. Vehicle that charges with 32 Amps in three-phase (22.08 kW) and single-phase (7.36 kW) (cluster representative Nissan Arya). The efficiency of single-phase charging is lower than three-phase charging.

Moreover, curtailed charging should be carefully considered if it is viable by also considering the reactive power consumption. Fig. 6(a, b and c) introduces the pattern of reactive power consumption for curtailed charging.

Similarly to three-phase charging, there are six typical curves for curtailed charging. However, two patterns behave differently, specifically Hyundai Kona and Renault Zoe. Finally, when curtailed charging is considered, the three-phase reactive power is not equal to that of three single-phase charging. Here, there are two options:

1. Lower reactive power consumption. For example, Kia EV6 Long Range (LR) consumes 471–606 VAr in three-phase charging. However, it consumes 135–186 VAr in curtailed charging. Therefore, $3 \times (135 \text{ to } 186)[\text{VAr}] < (471 \text{ to } 606)[\text{VAr}]$.
2. Higher reactive power consumption. For example, polestar 2 SRSM consumes 442–183 VAr in three-phase charging. However, it consumes 368–257 VAr in curtailed charging. Therefore, $3 \times (368 \text{ to } 257)[\text{VAr}] > (442 \text{ to } 183)[\text{VAr}]$.

The results show that decision making should be made based on a vehicle model. CPOs can benefit from curtailed charging by better utilizing the available grid capacity [kW; however, curtailed charging can reduce power quality by increasing reactive power consumption [kVAr].

So far, small- or large-scale energy simulation models do not consider OBC efficiency. The results presented in this paper highlight the importance of considering such an approach. Depending on the level of modulation required, smart charging could increase the charging energy demand from 1%–10%. Furthermore, the testing campaign showed that efficiency varies between years and vehicle models. These curves are suggested to be implemented on large-scale simulations as a lookup table; otherwise, for better dynamics, every model should be modeled accordingly to the data presented in this paper. However, it is acknowledged that such a method can be computationally heavy. Thus, a more generalized approach is proposed in Fig. 7. Based on the test results, a second-order polynomial is fitted for three-phase, curtailed, and single-phase vehicles. Such polynomials can be replicated to calculate the energy efficiency of EVs in an aggregated manner or for large-scale simulations.

Conclusions

The proposed testing methodology for commercial EV OBCs is proven successful and greatly facilitates vehicle diagnostics. This method relies on having data access at OBDII. The testing campaign highlights that open data from automakers are relevant and could be used for multiple objectives. The OBDII readings can serve independent actors to analyze the performance of OBC and can help:

1. Aggregators to better optimize their fleets and sites, along with providing grid services to grid operators.
2. Regulators to better inform and protect the consumer and require more efficient products from automakers.
3. Consumers to explore possibilities to interact with locally distributed technologies.
4. Academia to expand their research on power electronics, charging behavior, and battery degradation.

The approach to the commercialization of the OBDII data can hinder the progress of EVs and their potential for the transport and power industry. Therefore, automakers should recognize that penetration of EV is a challenge for grid operators and OBDII data can help to better operate and plan the power grid.

Furthermore, the IEC 61851 standard does not define the efficiency values allowed during the modulation of the charging current. This needs to be addressed with an approach similar to the European or California Energy Commission Efficiency for solar inverters. Consequently, regulators can require more efficient technology from automakers. Otherwise, based on the data from this testing campaign, for older models, lowering the current too much (e.g., below 10 A) could lead to areas of low efficiency, and therefore increasing charging losses. However, newer models give more freedom to take full advantage of charging modulation without incurring a significant increase in charging losses.

The global EV fleet efficiency is highly variable between models. Three-phase EVs have higher efficiency (87%–90%) than single-phase

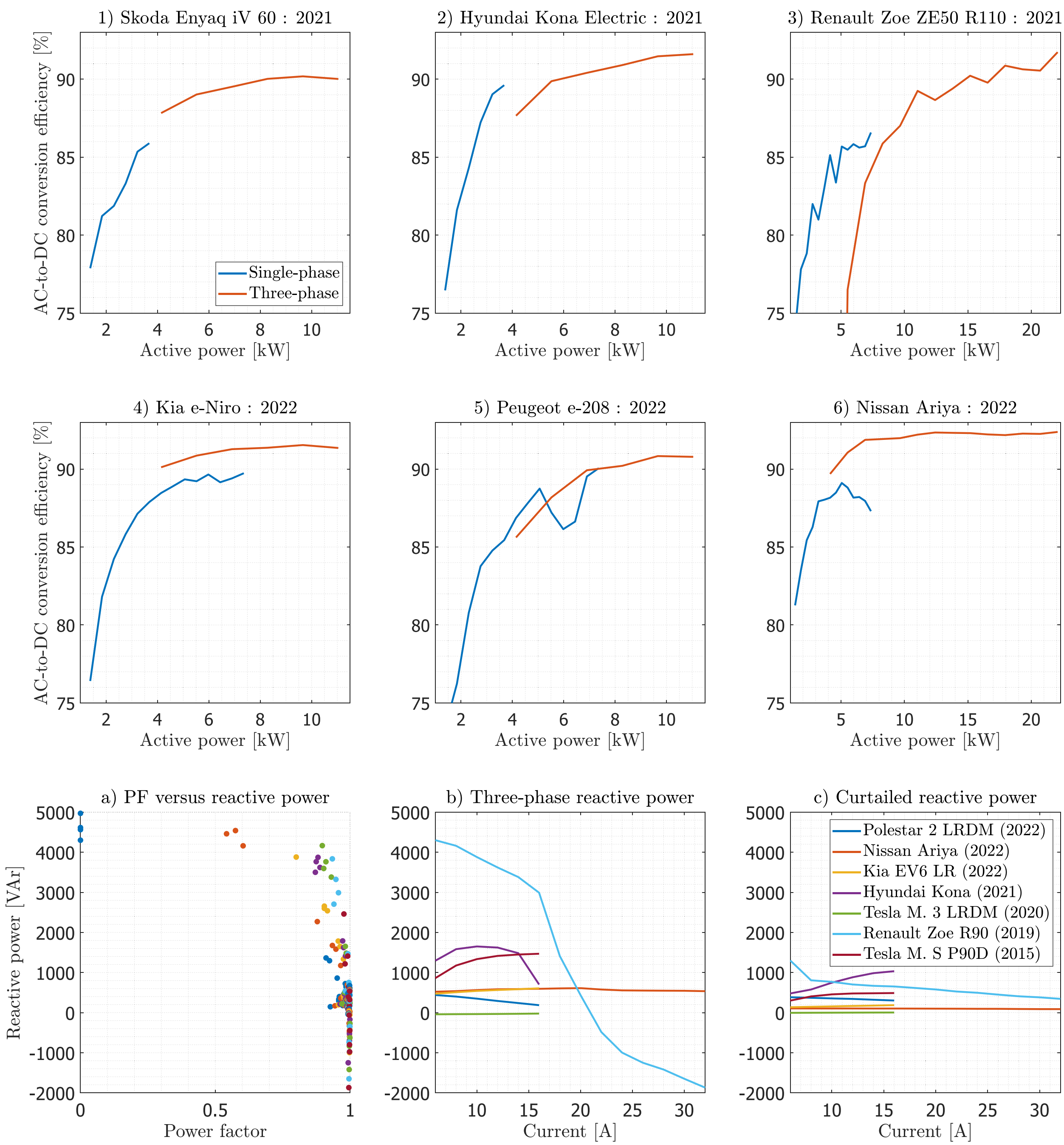

Fig. 6. Clusters of OBC efficiency comparison between a curtailed single-phase and a three-phase charger (1–6). Depending on which efficiency pattern the vehicle belongs, the charging process can be optimized by looking at such efficiency curves. The correlation between lower PF and higher reactive power consumption (a). Seven patterns of (b) three-phase reactive power consumption are similarly experienced during (c) curtailed reactive power consumption.

(78%–88%) EVs. However, curtailed three-phase EVs have an efficiency similar (78%–87%) to single-phase EVs. Overall, by 2030 the EV fleet could achieve efficiency values of 88%–95% and the OBC technology could saturate by 2035 with 90%–96% efficiency. This prediction takes into account a conservative approach from 11 years of data from 38 models. The solution to higher efficiency can come from building OBCs on a modular approach.

As shown in the data, reactive power consumption is not a strong point for many automakers. In fact, some models when charging with a current below 10 Amps violate low-voltage network code by experiencing a PF smaller than 0.9. Due to their large power size and distributed location, regulators should demand close to unity PF from EVs. In addition, to promote smart charging, the power factor correction of OBCs should be optimized for the entire charging current range, similar to Tesla models.

The IEC 61851 standard only quantifies an upper-limit charging current. As data show, this approach hampers the market participation of EV fleets in the Power Markets, because BMS decides on its own how much charging current OBC should draw.

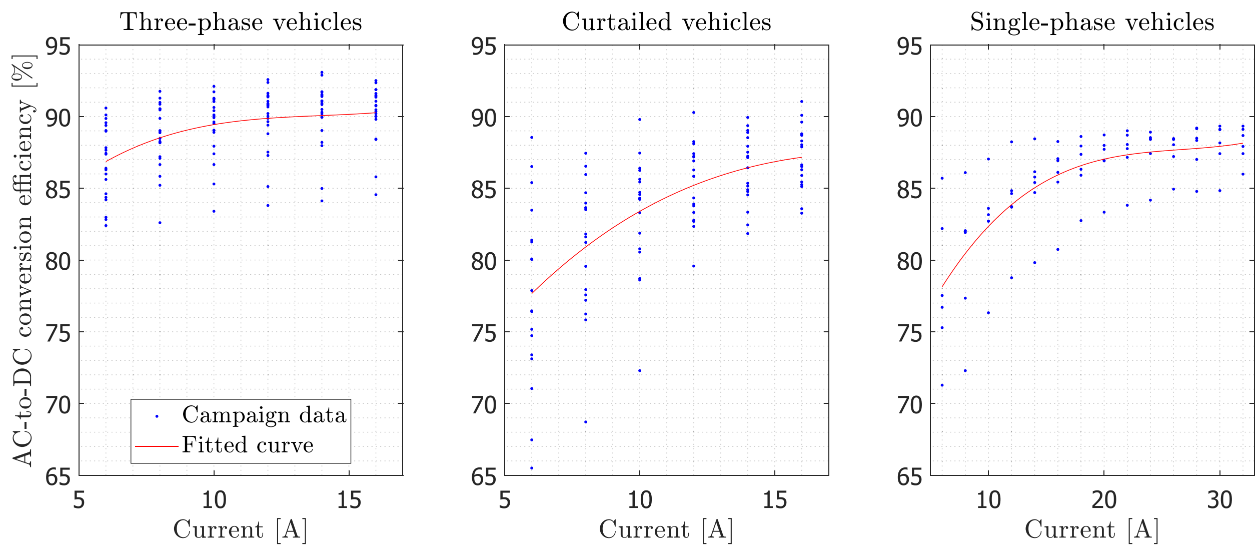

Fig. 7. Efficiency fitted curves based on the data from the testing campaign for (left) three-phase, (middle) curtailed, and (right) single-phase vehicles.

Finally, there is a high demand for better energy simulation models that include EV efficiency. Better results can be achieved by considering each vehicle's efficiency curve; however, such an approach can reduce the computing capabilities. Thus, a feasible computational solution can be found to implement the aggregated efficiency curve.

Future studies can integrate the findings of this article with measurements from full charging sessions (0%–100% state-of-charge SOC) to detect how efficient the vehicle model is during the typical charging session. Future work should focus on expanding the investigation to other automakers, with a special focus on 800 V architecture models, and analyzing the harmonics of OBCs. Additionally, the efficiency values can be combined with the charging curve to determine the efficiency of the charging session.

CRediT authorship contribution statement

Kristian Sevdari: Conceptualization, Methodology, Investigation, Writing – original draft, Visualization, Formal analysis. **Lisa Calearo:** Methodology, Investigation, Writing – review & editing, Formal analysis. **Bjørn Harald Bakken:** Methodology, Writing – review & editing, Supervision, Institutional support for the research. **Peter Bach Andersen:** Methodology, Writing – review & editing, Supervision, Investigation, Project administration, Funding acquisition. **Mattia Marinelli:** Conceptualization, Methodology, Writing – review & editing, Supervision, Investigation, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

The work in this article is supported by the Danish research projects ACDC (EUDP grant number: 64019-0541) and FUSE (EUDP grant number: 64020-1092). The authors thank Magnus Fich Rabjerg, Daniel Arndtzen, Oliver Gehrke, Rasmus Meier Knudsen, Valdemar Cornelio Foss, and Irisa Sevdari for helping on such a testing campaign. Moreover, we are grateful to each participant in the testing campaign, and the fruitful collaboration with Lene Mejdal Iversen (from KIA and MG), Steffen Høj (from Polestar), and Steffen Martiena (from Nissan).

Appendix A: Testing tools

Figs. A.1(a) provides a screenshot of the smartphone applications that were used during the testing campaign. As mentioned in the methodology, the data shown in the applications is proven correct and very useful for EVs investigation. Furthermore, Fig. A.1(b) displays the Type 2-to-Type 1 plug converter that is used for older EV models (2011–2012) that rely on the Type 1 plug.

Moreover, Table A.1 provides a summary of the tools needed to investigate each automaker.

Appendix B: Automakers

Table B.2 summarizes the electrical results and provides a bird's-eye view of each brand.

One has to note that some brands are represented only by one model and others from multiple models. Consequently, having different models per brand is highly beneficial; however, when considering the complete lack of data in such an area, it is crucial to highlight the behaviors observed in the testing campaign. The charging current on each phase is slightly unbalanced for almost all three-phase vehicles. The size of the unbalance differs in the models. Here, it should be mentioned that there are cases in which the difference is smaller than the measurement error (class 0.1). Thus, measurements below 0.1 A are within the DEIF measurement error. Table B.2 summarizes the possible phase unbalanced, scale of oscillations and additional comments on the specific vehicle model behavior. The values are averaged over the test procedure. Fig. B.2 displays the efficiency and reactive power consumption of the tested EVs when compared to their price. The data is not conclusive if a more expensive EV has higher efficiency and lower reactive power. Finally, every efficiency curve from the test campaign is displayed in Fig. B.3.

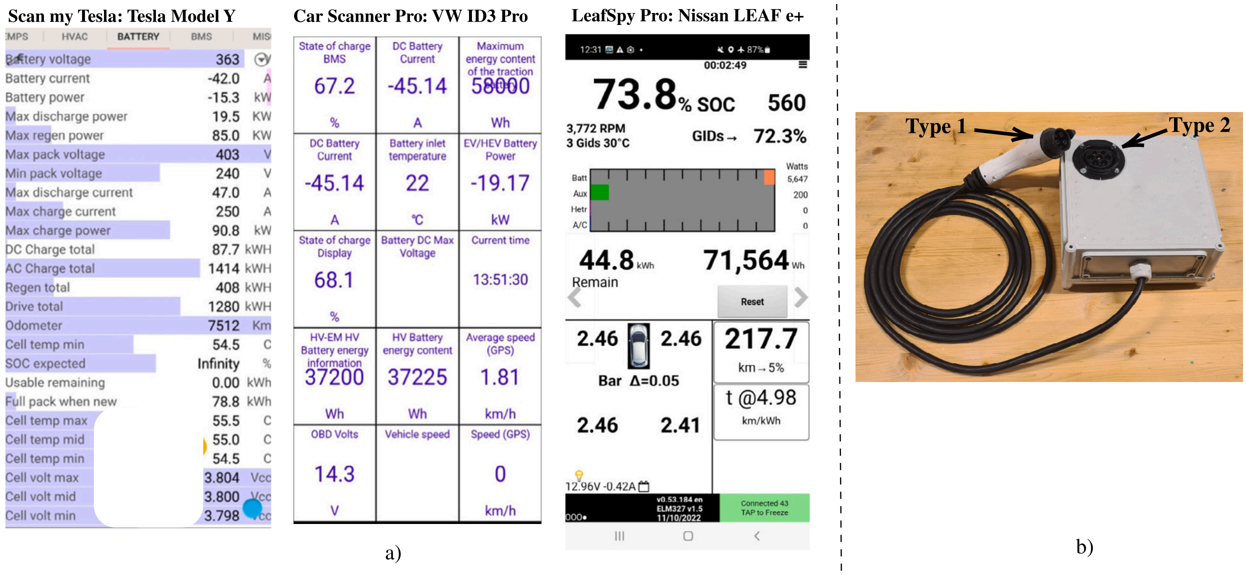

Fig. A.1. (a) Smartphone application to read the data from the EV OBDII port. (b) Type 2-to-Type 1 plug converter built at DTU- EVLab.

Table A.1
Tools for receiving the data from the tested electric vehicle brands. "+" means that OBDII data are available to read with a dongle.

Brand	OBDII reader	App	Plug	DC side data	
Audi	+ via dongle	Car Scanner Pro	Type 2	SoC Battery energy content	Charging power Charging losses
BMW	+ via dongle	Car Scanner Pro	Type 2	SoC and SoH Battery energy content	Charging power DC current DC voltage
Hyundai	+ via dongle	Car Scanner Pro	Type 2	SoC and SoH Battery energy content	Charging power DC current DC voltage
Jaguar	+ via dongle	Car Scanner Pro	Type 2	SoC and SoH Battery energy content	Charging power DC current DC voltage
Kia	+ via dongle	Car Scanner Pro	Type 2	SoC and SoH Battery energy content	Charging power DC current DC voltage
MG	+ via dongle	Car Scanner Pro	Type 2	SoC and SoH Battery energy content	Charging power DC current DC voltage
Nissan	+ via dongle	LeafSpy Pro	Type 1and 2	SoC and SoH Battery energy content	Charging power DC current DC voltage
Peugeot	+ via dongle	Car Scanner Pro	Type 1and 2	SoC and SoH Battery energy content	Charging power DC current DC voltage
Polestar	encrypted		Type 2		
Renault	+ via dongle	Car Scanner Pro CanZe Plus	Type 2	SoC and SoH Battery energy content	Charging power
Skoda	+ via dongle	Car Scanner Pro	Type 2	SoC and SoH Battery energy content	Charging power DC current DC voltage
Tesla	+ via adapterand dongle	scan my tesla	Type 2	SoC and SoH Battery energy content	Charging power DC current DC voltage
Volvo	encrypted		Type 2		
Volkswagen	+ via dongle	Car Scanner Pro	Type 2	SoC and SoH Battery energy content	Charging power DC current DC voltage

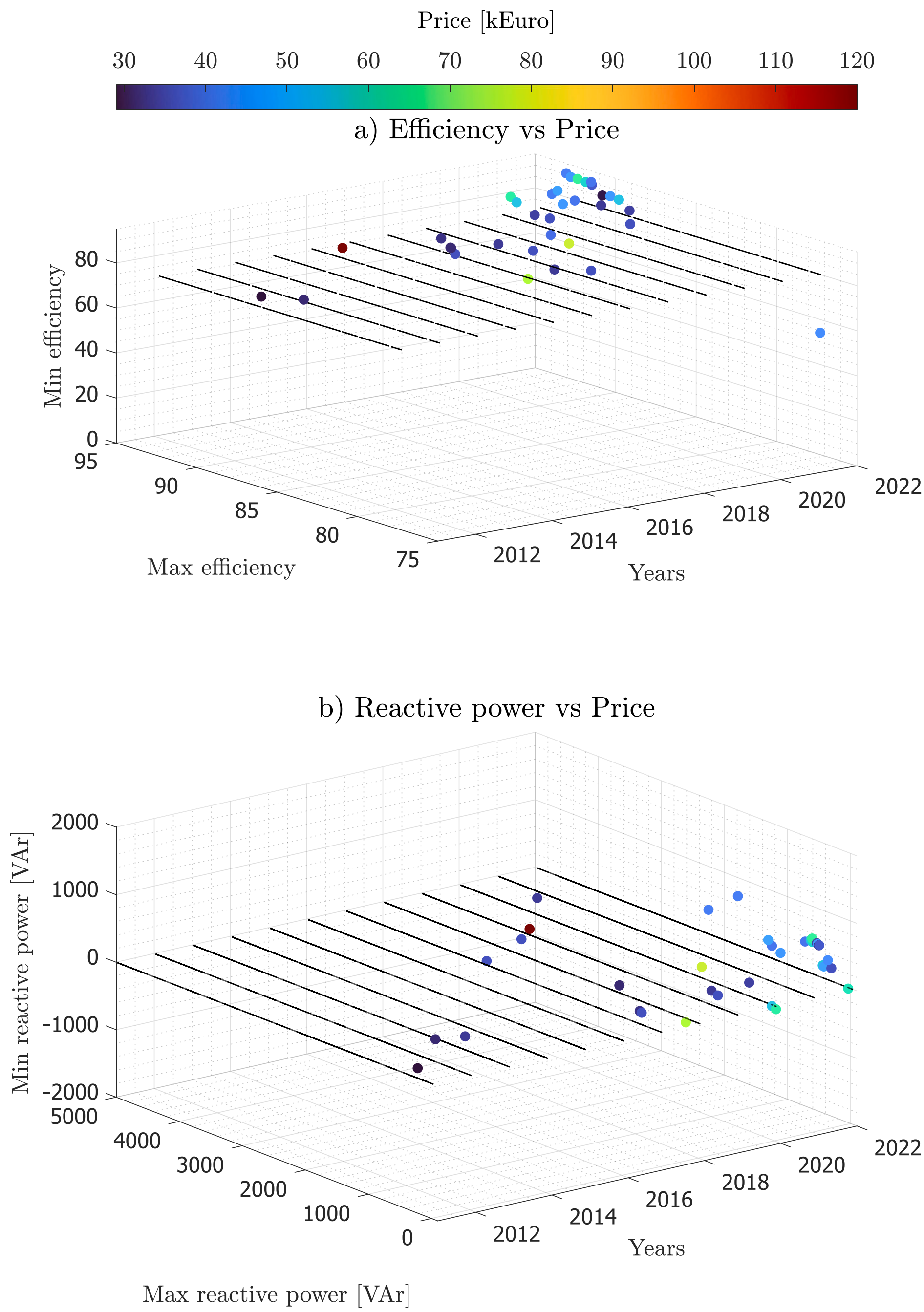

Fig. B.2. a, Correlation between years, maximum efficiency, minimum efficiency, and prices. The horizontal plane is designed at min efficiency equal to 80%. b, Correlation between years, maximum/minimum reactive power, and prices. The horizontal plane is designed at min reactive power to 0 VAr.

Table B.2
Summary of electrical characteristics for charging behavior. Oscillations on the grid are classified as i) not visible (<0.1 A); ii) small (0.1–0.3 A) and iii) moderate (0.3–0.5 A).

Brand	Phase unbalance grid side	Oscillations grid side	Comments
Audi	20 W or 0.08 A	Small	
BMW			- Reactive power in one of phases is capacitive and two others are inductive.
Hyundai	40 W or 0.16 A	Small	-It has difficulties in adequately following the control pilot (CP) at high SOC.
Jaguar	–	Small	-Reactive power consumption changes the state from inductive (below 28 A) to capacitive (28 A and above).
Kia	EV6: 20 W or 0.08 A e-Niro: 60 W or 0.24 A	EV6: not visible e-Niro: moderate	-Kia EV6 has reactive power disbalance between phases (50 VAr).
MG	MG 5: 70 W or 0.3 A Marvel R: 60 W or 0.24 A ZS EV: -	MG 5: small Marvel R: small ZS EV: small	-MG 5 has difficulties in adequately following the CP. (1 A of difference) - MG Marvel R has difficulties in adequately following the CP (1 A of difference). -MG ZS EV experience higher reactive power on higher charging currents.
Nissan	LEAF: - Arya: 20 W or 0.08 A Townstar: 10 W or 0.04A	LEAF: small Arya: not visible Townstar: not visible	-Nissan Arya has a higher reactive power disbalance between phases on higher charging currents and almost linearly reduces towards lower charging currents (80 to 5 VAr). -Nissan Townstar, as the data suggest, has a Chameleon charger. Reactive power consumption changes state from inductive (below 18 A) to capacitive (18 A and above).
Peugeot	e-208: 10 W or 0.04A iOn: -	e-208: not visible iOn: small	-Reactive power for e-208 increases in small amounts as the charging current increases. It has difficulties in adequately following the CP (1 A of difference).
Polestar	30 W or 0.12 A	moderate +	
Renault	Megan E-tech: Zoe: 10 W or 0.04A	Megan E-tech: not visible Zoe: not visible	-Reactive power for Megan E-tech increases in small amounts (10 VAr) as charging currents increase. - Renault Zoe employs a Chameleon charger. Reactive power consumption changes the state from inductive (below 20 A) and capacitive (20 A and above).
Skoda	20 W or 0.08 A	small	
Tesla	Model 3: 40 W or 0.16 A Model Y: 20 W or 0.08 A Model S: 40 W or 0.16 A	Model 3: not visible Model Y: small Model S: small	- Model S P90D has difficulties in adequately following the CP (1 A of difference).
Volvo	30 W or 0.12 A	moderate +	-The data shows that Volvo XC40 Recharge shares same dynamics with Polestar 2 LRDM.
VW	ID4: 30 W or 0.12 A ID3: 20 W or 0.08 A e-golf: 40 W or 0.16 A	ID4: small ID3: not visible e-golf: small	

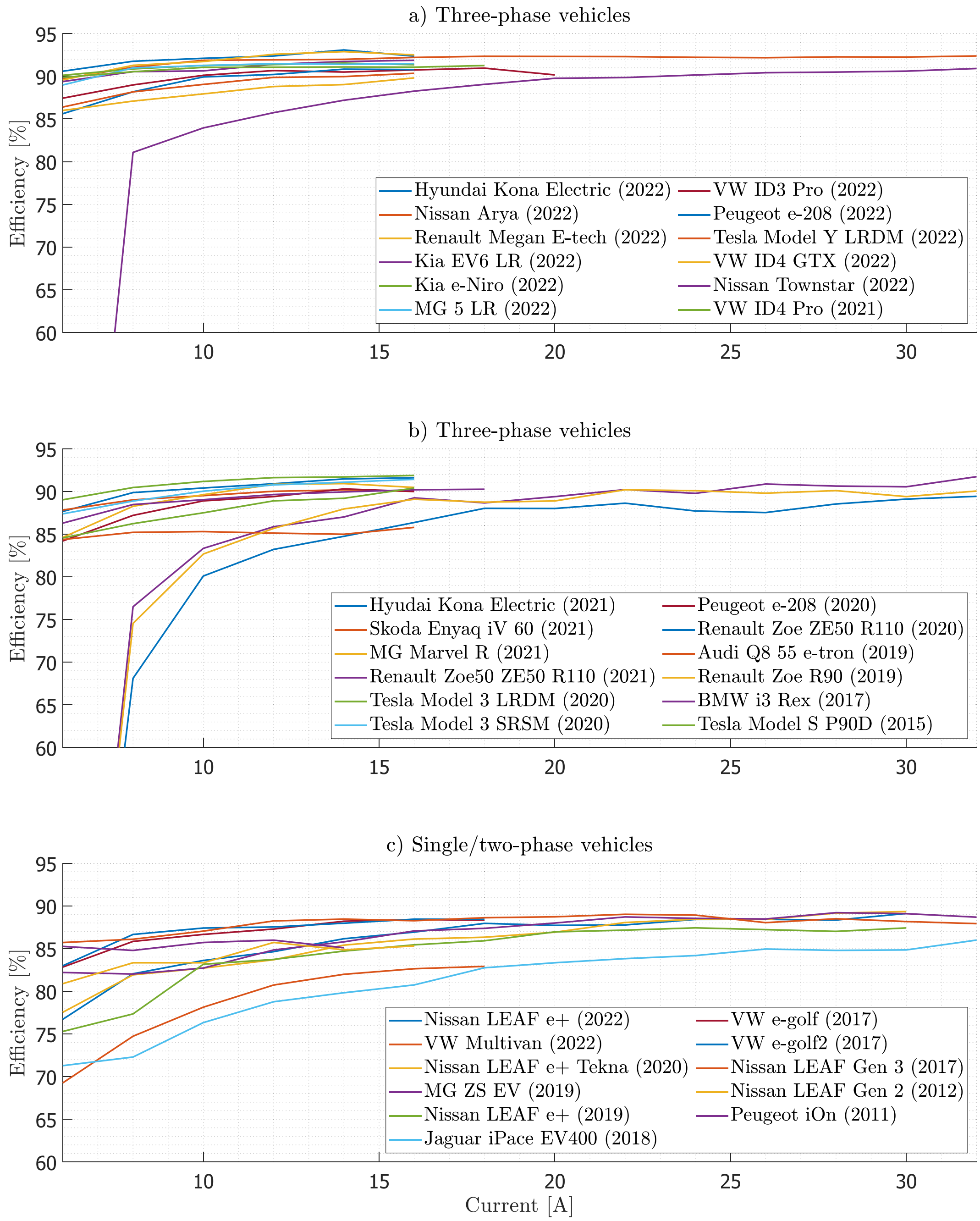

Fig. B.3. Electric vehicle onboard charger efficiency patterns from the testing campaign.

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