Smart Charging Testing

Technical verification of Machine to Machine (M2M) communication between vehicles and charging stations

ElaadNL – September 2025

Contributors

Editorial
The report *SMART CHARGING TESTING - Technical verification of M2M communication between vehicles and charging stations* is published by ElaadNL (The ElaadNL Foundation). Arnhem, September 2025.

Editorial committee
Editor-in-chief – Frank Geerts

Authors – Koen Renkema, Wouter Rekswinkel, Jan Karens, Thijs van Wijk, Robert Italiaander, Dennis Linn, Marisca Zweistra

Thanks to – Dutch Ministry of Infrastructure and Water Management, NAL core team of the program “Smart Charging for All”, RAI, DOET, participating vehicle - and charging station manufacturers and Vereniging Elektrische Rijders (VER).

Language advisor
Lizzy Freed

Photos
All photos are by ElaadNL unless otherwise stated.

Design
Spankracht Ontwerpers, Lunteren

Contact Details
Visiting – Westervoortsedijk 73
Building KB7, 6827 AV Arnhem, The Netherlands
Postal – Postbus 882, 6800 AW Arnhem, The Netherlands

Phone +31 (0)26 3120223
Mail info@elaad.nl
Website www.elaad.nl (in Dutch and English)

Content

Management summary

Introduction

In the transition towards a sustainable mobility and electricity system, smart charging - the intelligent management of when and how electric vehicles (EVs) are charged - plays a pivotal role. Smart charging entails adjusting the timing and speed of EV-charging based on various factors such as electricity prices, the availability of renewable energy, and avoiding peak demand on the grid. Smart charging of EVs can be a game changer in providing storage and flexibility to the electricity system. To ensure that smart charging is both effective and user-friendly, it is essential that EVs and charging infrastructure are fully compatible with smart charging technologies.

From May 2024 to April 2025, ElaadNL conducted the world's largest smart charging test program known to date, commissioned by the Dutch Ministry of Infrastructure and Water Management as part of the national program "Smart Charging for All" (part of the Nationale Agenda Laadinfrastuctuur). Over a period of 11 months, 114 different Battery Electric Vehicles (BEVs) and 28 Plug-in Hybrid Electric Vehicles (PHEVs) of all types and models were thoroughly tested at the Elaad Testlab in Arnhem. With a side-note that first generation vehicles were under-represented, this sample group of 142 vehicles is broadly representative of the current Dutch passenger car fleet.

In the interpretation of test results, the scores have been calculated in comparison to the total test group size, as well as for the market share (using the data on the Dutch EV fleet distribution of December 31, 2024). As such, the results from the tests give a meaningful insight into the current status of smart charging and its opportunities in the Netherlands. The primary aim of the tests was to verify the technical feasibility of smart charging across a broad range of vehicles and both public and private charging stations that are currently available on the Dutch market. The findings in this report not only serve to reach national ambitions, but also provide insights for international developments in smart mobility.

Test methodology

This program involved most of the established automotive brands as well as many of the newcomers to the EV market and formed a broad and representative sample of the state of smart charging integration in the Netherlands. A wide range of available electric models was tested, from new to old, from compact city cars to luxury vehicles—and everything in between. On average, a vehicle was available at the Elaad Testlab for a period of 48 to 72 hours. Ten types and models were selected for the Electric Vehicle Supply Equipment (EVSE) or charging equipment side, based on the components that are most common in public and private charging stations in the Netherlands. As the "Smart Charging for All" program focuses on destination locations such as home and work, the scope of the technical tests was restricted to Alternating Current (AC) chargers.

The foundation for the smart charging tests was based on IEC 61851-1 (2019), which outlines the general requirements for conductive charging systems for EVs. In addition to this standard, tests were added to simulate everyday behavior. These are essential for understanding how vehicles interact with smart charging infrastructure in realistic settings. Finally, some more extreme scenarios were tested. The control signal in all test scenarios originated from the charging station, and therefore the results provided in this report mainly reflect the capabilities of the onboard charger in the car.

The tests performed in this program focused on customer-perspective, power quality immunity and power quality emissions, with smart charging scenarios ranging from present usage to extreme conditions.

Individual test results have been shared with their respective vehicle manufacturers exclusively through a standardized reporting format. Only aggregated and anonymized test results are shared publicly in this report for the purpose of broader industry transparency, without compromising the commercial interests of individual stakeholders.

Test results

An overwhelming majority of 95% of the tested market share passed the different tests with flying colours. This provides a sound technical basis for the large-scale rollout of smart charging functionality. In general, vehicles and chargers perform as should be expected within a normal smart charging operation. Despite the fact that the majority of tests were passed, a small number of technical issues have been revealed. In some of these cases, deviations could be mitigated easily by the vehicle manufacturer through firmware updates. Other vehicle manufacturers are internally assessing and prioritizing the identified issues, which might also be solved through firmware updates. It is expected that some vehicle manufacturers can only mitigate the issues by replacing hardware elements, which is not guaranteed to happen.

In summary, the following statements can be made based on the test results:

Customer perspective:

- Over 97% of the tested market share successfully passed the smart charging interoperability test.
- Over 99% of the tested vehicle market share supports a typical smart charging profile.
- Over 95% of the tested market share supports low-speed charging at six Amperes (6A).
- Over 95% of the tested market share supports six-hour delayed charging as well as pauses of 20 minutes and six hours.
- Over 90% of the tested market share supports intermittent charging up to 15 iterations of one- minute pause/resume iteration.
- 100% of the tested market share responds to changes in charging speed after long periods of uninterrupted charging.
- A vehicle app could be successfully used by the test team in 54% of all tested vehicle cases. About 30% of the tested market share of vehicle apps show the charging status: when charging is repeatedly paused and resumed, 16% of the tested market share indeed sends notifications for each pause/resume repetition, while 48% sends irregular notifications.

Grid perspective:

- Over 97% of the tested market share is immune to undervoltage, overvoltage, and voltage dips.
- Over 86% of the tested market share can charge when harmonic distortions are present on the supplied power, which is a positive result.
- Over 98% of the tested market share successfully executed the phase-switching test.
- Over 90% of the tested market share stays within the safety voltage limit (< 50 Volt) on inactive phases.
- Over 97% of the tested market share does not inject harmonic distortion into the grid.
- Around 78% (one-phase vehicles) and 75% (three-phase vehicles) of the vehicles do not exceed the CISPR supraharmonic distortion limit.
- Over 95% of the tested market share has a power factor of at least 0.98 (single-phase vehicles) and at least 0.92 (three-phase vehicles), which is well above the threshold of 0.85.

Discussion and recommendations

Thirteen vehicles did not comply to the safety voltage limit (< 50 Volt) on inactive phases. This issue is marked as critical and applicable vehicle manufacturers are urged to solve this safety issue as soon as possible.

A handful of vehicles did not meet the power quality requirements. Although the issues regarding power quality are marked as minor and trivial, applicable vehicle manufacturers are advised to select components which are more resilient to voltage deviations and which operate within harmonic emission limits. Although over 95% of the tested market share passed the majority of tests, a small number of technical issues have been revealed. From a macro-perspective, these issues are exceptions to the rule, but on a micro-level they can have a direct and noticeable impact for the end-user. **Although it is difficult to quantify the number of end-users that might be affected by the issues, all stakeholders are strongly advised to proactively address these issues when possible.**

From a technical perspective, the main recommendations include the following:

- Although 95% of the tested market share complies with the low-speed charging threshold requirement of 6A as described in the IEC 61851-1 (2019) standard, six vehicles do not comply to this threshold. **As a mitigation measure, applicable vehicle manufacturers have been called upon to resolve these issues or to actively inform drivers that they may exist. Additionally, when possible, Charge Point Operators (CPOs) are advised to keep charging at a minimum of 8A to reduce risk, and to minimize the group of customers that could be affected (<5% of the tested market share).**
- Over 95% of the tested market share supports six-hour delayed charging as well as pauses of 20 minutes and six hours.
- Over 90% of the tested market share supports intermittent charging up to 15 iterations of one-minute pause/resume iteration. Although it is unlikely that a charging session will experience more than 15 pauses within half an hour of connection time, this test purposefully illustrated an extreme scenario. Ultimately, about 40 vehicles did not pass the total of 25 iterations in this extreme intermittent charging test, meaning that the vehicles did not resume charging after a number of iterations. From a safety perspective, some vehicle manufacturers have limited the number of pause/resume iterations allowed. As intermittent charging is not defined in the IEC 61851-1 (2019) standard, the number of pause/resume iterations to be supported remains undecided. **Vehicle and charger manufacturers are advised to agree on both the number of supported iterations and a minimum pause time; additionally, they are advised to include both in an updated version of the standard**. In the meantime, when possible, CPOs are advised to minimize intermittent charging and/or to pause for (minimum) 15 minutes to reduce the number of pause/resume iterations. Applicable vehicle manufacturers are called upon to increase the number of supported pause/resume iterations to at least 15. The combination of these two recommendations makes it possible to bridge a period of seven and a half hours (15 pause/resume iterations of 15 minutes).

It is recommended to proactively communicate potential charging issues to end-users, in order to preserve customer trust for the transition in both mobility and energy. Uncontrolled charging already requires pro-active communication. Introducing smart charging on a large scale further increases the information needs of end-users. As part of the program "Smart Charging for All", a simple "opt-out" option that allows the customer to refrain from smart charging for an individual charging session is to be implemented. Users that wish to start charging at maximum available capacity immediately can make use of an "opt-out" option. This functionality may also provide a solution for the limited number of vehicles that face issues with charging at 6A or charging pauses.

In the past, mobility and the power grid were entirely independent of one another; now, they are now becoming inextricably linked due to the rise of electric driving. Grid-friendly charging ensures the smooth integration of EVs into our electricity grid, which enables charging infrastructure to be unabatedly expanded, while simultaneously avoiding local grid overload. **It is essential that the speed of charging (for any vehicle) can be lowered by the CPO at the request of the grid operator (DSO), in case the power grid faces direct capacity restraints and imminent power failure—regardless of any issues that have been found. On request of the grid operator, a minimum charging speed of 6A and/or delaying and pausing as described in the IEC 61851-1 (2019) standard need to supported by the CPO.**

In addition to the IEC 61851-1 (2019) standard, the NEN-EN-ISO 15118-20 standard has been developed. In the coming 15 to 20 years, it is likely that the IEC 61851-1 standard and the NEN-EN-ISO 15118-20 standard will coexist, with a gradual phase-out of the IEC 61851-1 standard. Given this timeframe, it is recommended to update both standards regularly. Vehicle and charging point manufacturers are advised to regularly update their products accordingly.

The smart charging standards currently available are not mandatory and are adopted by the market itself. The compliance to these standards is, as a result, voluntary. **It is recommended that smart charging standards like IEC 61851 and NEN-EN-ISO 15118-20 are made mandatory for both vehicles and charging infrastructure. It is also recommended that power quality requirements are included in the EU Grid**

Code. The obligation for technical smart charging standards/protocols in vehicles can be mandated through UNECE type approvals and/or EU Whole Vehicle Type Approval (WVTA) under Regulation (EU) 2018/858. The obligation for technical smart charging standards and protocols can be included through, for example, an implementing act or delegated act under EU regulations such as the Alternative Fuels Infrastructure Regulation (AFIR), Energy Performance of Buildings Directive (EPBD), Renewable Energy Directive (RED), or Energy Efficiency Directive (EFD).

Although many current EV models (a large total market share) have been tested in this research—with the far majority passing the tests—we recommend continuing to test new models as well as implementing software updates on existing models. Furthermore, monitoring the charging behavior of EVs and how they deal with smart charging in daily practice continues to be important. **Considering that smart charging standards are not mandatory and no formal conformity test are available, the Elaad Testlab will continue to test vehicles and chargers free of charge** until formal standards (including certification) have been set. All relevant parties are invited to make use of these testing options and/or to inform other relevant manufacturers. The ambition is to further enhance smart charging tests so they also include options such as: other routes for the control signal (car and energy management system), bidirectional charging, EU grid codes, cybersecurity, interoperability and more advanced power quality tests.

About this document

In the transition towards a sustainable mobility and electricity system, smart charging—the intelligent management of when and how EVs are charged—plays a pivotal role. To ensure that smart charging is both effective and user-friendly, it is essential that EVs and charging infrastructure are fully compatible with smart charging technologies.

From May 2024 to April 2025, ElaadNL conducted the world's largest smart charging test to date, commissioned by the Dutch Ministry of Infrastructure and Water Management as part of the national program "Smart Charging for All." Over this period, 114 Battery Electric Vehicles (BEVs) and 28 Plug-in Hybrid Electric Vehicles (PHEVs)—in total representing 142 passenger car models—were thoroughly tested at the ElaadNL Test Lab. The primary aim of the assignment was to verify the technical feasibility of smart charging across a broad range of vehicles and charging stations currently available on the Dutch market. The anonymized results presented in this report provide crucial insights into the compatibility and behavior of EVs and charging stations during smart charging scenarios.

By proactively testing vehicle compatibility, this project supports the reliable, large-scale implementation of smart charging, reinforces consumer and industry confidence, and helps to future-proof the EV ecosystem. The findings serve not only national ambitions but also offer valuable input for international developments in smart mobility.

This report is *structured* as follows:

- Chapter 1, "Introduction to smart charging", contains a contemplation on smart charging. Why is smart charging a must-do? Who benefits from smart charging, and why is there a need to verify the technical feasibility of it?
- Chapter 2, "Test Methodology", details how the smart charging tests were designed. What was the scope? Who was involved? What exactly was tested? How have the test results been evaluated?
- Chapters 3, 4 and 5, "Results", contain the outcomes of the tests for the Customer Perspective, Power Quality Immunity and Power Quality Emissions respectively. What was the goal of each specific test? What did the test set-up look like? What were the pass/fail criteria? What are the key outcomes and results in detail?
- Chapter 6, "Summary of Results", gives a combined overview of all results.
- Chapter 7, "Discussion & Recommendations", reflects on the outcomes of the smart charging tests in relation to a large-scale rollout. It provides practical recommendations to scale up smart charging.
- In the appendices, relevant background information or detailed information is provided.

For those readers who have limited time, it is recommended to read the management summary (Introduction to smart charging (Chapter 1)), Test Methodology (Chapter 2) and Discussion and Recommendations (Chapter 6). For readers who want to fully understand all test results, Chapters 3, 4 and 5 are recommended.

Chapter 1

Introduction to Smart Charging

Introduction

Smart charging refers to the intelligent management of EV charging to minimize costs, optimize sustainable energy use and enhance grid stability. It involves adjusting the timing and speed of EV-charging based on various factors, such as electricity prices, the availability of renewable energy, and avoiding peak demand on the grid. You simply plug in your car and smart technology ensures that it is charged at the best time and at the optimum speed.

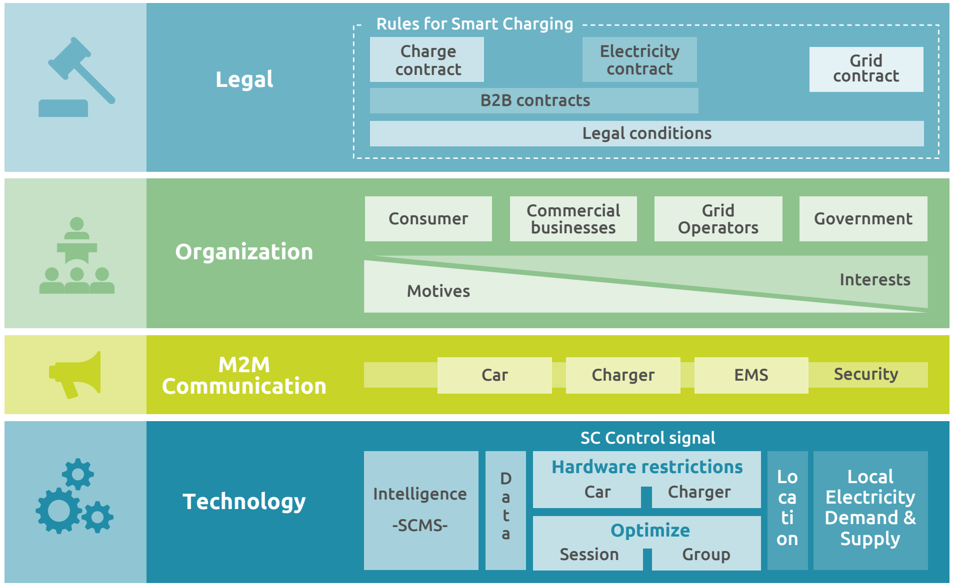
Most cars are charged at home or at work. Home charging can occur on public parking spaces or on private property (behind the home connection). For long distances, fast chargers can be used for a top-up during the drive. Especially with home charging or charging at work, the car is stationary for much longer than is needed to charge, which creates opportunities for smart charging.

More and more electric drivers choose to charge their cars *only* when the battery is mostly empty, or to set a start time for charging that would benefit from rooftop solar panels and/or lower electricity tariffs. The latter is a basic form of smart charging that is already common. Scaling up smart charging and automating the smart charging decisions made by the driver, will make it even easier and more comfortable for the driver.

The Smart Charging four-layer model

For smart charging to work well, several aspects have to be implemented in parallel. First of all, smart charging must, of course, be technically feasible. Secondly, communication and information technology (IT) must match one another and be secure. Finally, rules and regulations have to be in place to ensure that stakeholders can work together from organizational (as well as legal) viewpoints.

To understand the different aspects of smart charging and their interactions, ElaadNL developed the Smart Charging Four-Layer model in 2020, of which a general overview is presented in the figure below. An elaborate explanation of this model is provided in the first appendix.



This report addresses the smart charging control signals of the first layer (technology) and the Machine to Machine (M2M) communication of the second layer. For M2M communication, the scope is limited to the communication between cars and charging stations.

Consumer perspective

For a driver, an EV is primarily a device used to get from point A to B. Although this is the main purpose of a vehicle, it is only used as such for approximately 5% of the day, leaving around 23 hours per day to recharge the driven kilometers. This allows for a lot of flexibility in the actual moment of charging and the speed of charging used, creating options for smart charging. There are several incentives for choosing a smart charging strategy, such as:

- Financial: Charging when electricity prices are low;
- Solar Power: Allowing for charging when privately owned solar panels produce more electricity than the home uses, thus avoiding feedback tariffs;
- Battery Life: Charging up to 80% instead of 100% of battery capacity positively impacts battery lifetime;
- Social and Societal: Charging when there is capacity on the local electricity grid, so the grid in the neighborhood does not need to be reinforced. This helps maintain a steady power supply and prevents unnecessary grid investments.

Whatever choices someone makes, the principle should be that smart charging is as easy as regular charging, with the best-fitting strategy chosen automatically. This way, everyone can switch to driving emission-free passenger cars without concerns about the costs or the availability of the power needed to recharge. The service must positively impact the user's perspective on:

- Reliability: Users should trust the charging service to be consistent and dependable;
- Convenience: Charging should be easy and hassle-free;
- Choice: A wide range of smart charging services and providers.

Lower electricity prices for charging EVs?
Energy companies create both supply and demand in the electricity system. Therefore, they have so-called energy-balance responsibility. With all the changes around electricity demand and supply, it becomes increasingly challenging for energy suppliers to fulfill this responsibility. As more electricity is generated from solar and wind, the impact of weather on the energy balance also increases. Peaks and valleys will occur more often.

Since the timing of charging can be very flexible, EVs can play a significant role in balancing supply and demand. Therefore, energy suppliers are interested in making use of the battery capacity of EVs in order to balance their energy programs (by incentivizing smart charging). From the supplier perspective, smart charging offers the consumer more flexibility in charging their cars, which in turn will give them further financial benefits (i.e., lower recharging prices).

Power grid perspective

Mobility and the power grid

The energy transition changes the way that we use the electricity grid. Growth in the demand for electricity is happening faster than the speed at which grid operators can expand the grid. This means we will face capacity shortages and imbalance in the coming years. Managing electricity supply and demand is crucial to solving this.

While mobility and the power grid had virtually nothing to do with each other in the past, they are now becoming inextricably linked due to the rise of electric driving. The EV poses not only a major challenge from a grid perspective but is also an important part of the solution: EVs are basically big batteries on wheels, with the added benefit of being able to schedule their charging. Compared to combustion engine vehicles, charging is more flexible than refueling: there would never be a situation in which *all* gasoline-powered cars would be charged at the same time—there would be queues at the gas station. With EVs, not everyone needs to plug in to charge every day, much like not everyone visits the gas station every day. However, we *are* capable of charging simultaneously, if that's needed, due to a high supply of energy. Similarly, we can reduce charging speeds if desirable. Finally, we don't need to worry about wasting time waiting for power to become available, even when there's a huge charging demand: the system will make sure the car is recharged. If smart charging becomes the standard way of charging, we can make optimal use of the power grid while simultaneously accelerating the transition to (local) sustainable power from sun and wind.

Technical background
Of about eight million electricity connections in the Netherlands, the majority are households with a connection of 1x25, 1x35, or 3x25 Amps. Although the technical capacity of these connections ranges from 5.8 to 17.3 kW, these are all in the same tariff from the grid perspective. The expected simultaneous peak load of all connections is considered in the design or electricity grids. Until recently, an average peak power demand of between 1 and 1.5 kW per household was used for the calculation of actual required grid capacity. To allow for occasional short-term simultaneity, a margin of around 100% of the sum of average peaks was added for the actual grid design. With the arrival of EVs, the actual peak demand per household connection has changed drastically.

Most public charging points (and households with a charging point) have a 3x25 Amp connection. Depending on the type of onboard converter in the vehicle and (in the case of public chargers) the occupancy of the sockets on the charger, an EV takes 3.7 to 16 kW of power from a charging point (on average, this is a factor of ten times more power than a household).

By 2030, we expect a larger portion of cars in a neighborhood to be electric—if everyone would charge immediately after coming home from work without smart charging, the increase in simultaneous peak load on the low-voltage grid will exceed the capacity of the existing grid.

EVs are flexibility champions

Smart charging balances the effects of simultaneity. EVs have the potential to make a huge contribution to flexibility and restoring balance in supply and demand. With an average driving distance per day of only 35 kms, and batteries easily capable of driving ten times this distance, the amount of energy required for daily trips is very manageable for most drivers.

An average EV requires as much energy annually as an average (Dutch) household, and a full battery can store as much energy as is used by a household over a ten-day period. Additionally, EVs can charge with much higher peak power demands than other electrical devices in or around homes. Considering all of these factors, charging EVs can be a champion in providing flexibility in the demand for household power—and the only change needed is to switch from charging to *smart* charging!

Grid-friendly charging is a specialization of smart charging

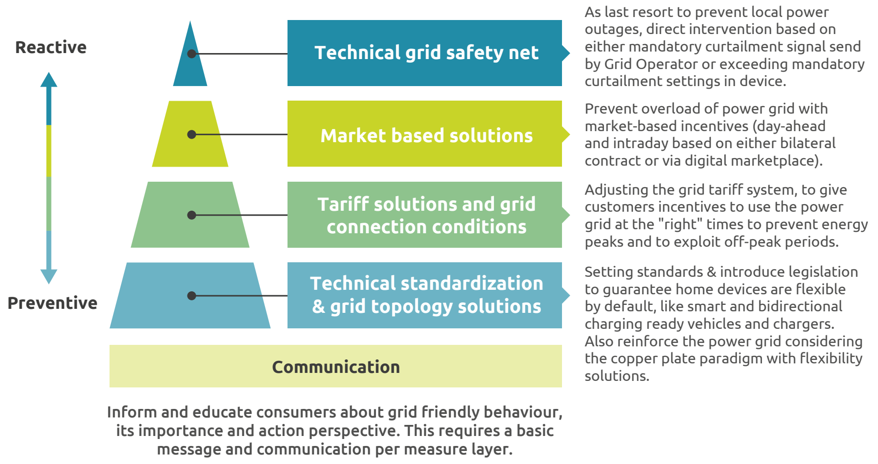
The European Electricity Act suggests that grid operators utilize demand control in addition to grid reinforcement. Unlocking flexibility through demand control allows for proper management of peak loads, thus preventing overloads. This efficient use of the grid results in lower investment costs because it avoids the needs for grid reinforcements. Moreover, demand control can also prevent potential interruptions.

Grid-friendly charging ensures the smooth integration of EVs into our electricity grid; it enables the successful roll-out of charging infrastructure, while simultaneously avoiding local grid overload. Grid operators aim to find an optimal social balance that justifies the reliability, affordability, and sustainability of the electricity supply. There are various ways to affect user choices in charging behavior, to ensure that the total costs of the electricity system are as low as possible, without compromising its performance level.

The basic idea of grid-friendly charging is to give maximum grid access when possible and minimal restrictions when necessary. Measures are applied to temporarily supply less capacity for charging cars *only* when charging sessions take place in a grid section that is technically at its limit (e.g., if the neighborhood transformer becomes overloaded). Charging can also be delayed as a result of grid-friendly charging.

Flex Pyramid of grid protection mechanisms

Charging EVs is a free market, so smart charging must be attractive to end-users. The grid operator has a range of instruments that can be used to stimulate and activate grid-friendly charging, also known as the Flex Pyramid of grid protection mechanisms. At the base of the pyramid, adjustments in charging behavior are primarily based on voluntary incentives, such as network tariffs or market-based rewards. If there is occasionally excessive electricity transport, the grid operator has a legal duty to act in the public interest. In that case, the incentive for smart charging can temporarily become mandatory. In the smart charging four-layer model this relates to layer 4 (legal): the grid contract, a B2B contract and legal conditions.



A more elaborate explanation of the Flex Pyramid is provided as an appendix.

National program Smart Charging for All

The “Smart Charging for All” program works on a broadly supported approach in which smart charging takes place with a guaranteed X kilowatt-hours in Y hours of charging time. As a starting point, the value of 30kWh in six hours was chosen. With this, drivers have charging certainty, whilst charge point operators receive ‘flexibility’ to develop competitive charging propositions. For example, charge point operators can respond to differences in purchase prices, participate in energy markets, and anticipate the availability of local sustainable electricity. The choices made (when considering the charging certainty for the user) lead to a charging profile for a specific charging session. The driver benefits from this charging profile by charging the car at times when electricity is cheaper, and/or when more sustainable generation is available, whilst enabling new business opportunities by making more efficient use of the available grid and power production. The program is also known as grid-friendly charging.

As smart charging is beneficial for electric drivers, it offers opportunities for new businesses. Smart charging is rapidly becoming proven technology, and the logical next step is to transform it into customer propositions. The Netherlands is setting the new precedent in this regard: it is now considered commonplace that a user can just “charge” their car in a “smart” way—it is now the default.
The ambition of the “Smart Charging for All” program is to make every charging session in a destination location “smart” the default way to charge in 2025. Destination locations are defined as places in which EVs are parked for a longer period of time (several hours), such as at home, at work, or at public charging points near homes or workplaces. The Ministries of Infrastructure and Water Management and of Climate Policy and Green Growth oversee the implementation of this program. All stakeholders in the charging chain are expected to contribute actively.

During the execution of the “Smart Charging for All” program, RAI Vereniging (which represents the vehicle importers and the industry behind them) and DOET (which represents the charging infrastructure industry) raised concerns about the technical feasibility of smart charging, based on experiences in earlier pilots and initial sprints. It was also noted that there is no formal standardization or legislation prescribing technical smart charging requirements for vehicles and chargers. As such, the Ministry of Infrastructure and Water Management responded by defining two actions:

- Lobby for EU legislation prescribing technical smart charging requirements for vehicles and chargers;
- Verify the technical feasibility of smart charging across a broad range of vehicles and charging stations currently available on the Dutch market.

Assignment - Verify the technical feasibility of smart charging

As part of the "Smart Charging for All" program, ElaadNL was tasked with the second aforementioned action point: performing smart charging tests on the full-electric and plug-in EVs present in the Dutch market.

The primary aim of the assignment was to verify the technical feasibility of smart charging across a broad range of vehicles and charging stations currently available on the Dutch market. The results include a positive user experience as well as an increase in manufacturers and dealer confidence. The anonymized results presented in this report provide crucial insights into the compatibility and behavior of EVs and charging stations during smart charging scenarios.

Together with the project board, tests were designed to represent customer scenarios as well as power grid scenarios, which are based on: 1) challenging versions of those found in the real world, 2) knowledge gathered from previous test experiences at the ElaadNL Test Lab, and 3) possible limitations derived from the vehicle-charging station communication and Dutch grid standards. The tests will be used to research the charging behavior of vehicles during such scenarios, aiming at increasing insights into the impact of smart charging on both the customer and the grid, and to learn about considerations for successfully integrating smart charging into the EV ecosystem.

By proactively testing vehicle compatibility, this project supports the reliable, large-scale implementation of smart charging, reinforces consumer and industry confidence, and helps to future-proof the EV ecosystem. The findings serve not only national ambitions but also offer valuable input for international developments in smart mobility.

Chapter 2

Test methodology

Scope

The primary aim of the tests in the "Smart Charging for All" program, was to verify the technical feasibility of smart charging across a broad range of vehicles and charging stations that are currently available on the Dutch market. As stated in the previous chapter, the ambition of the action program "Smart Charging for All" is to make smart charging the default for all charging sessions at destination locations in 2025. Destination locations are defined as places in which EVs are parked for a longer period of time, such as at home, at work, or at public charging points near homes or workplaces.

Given the concentration and charging load that is put on destination locations, the technical tests are limited to AC chargers, which is the main technology used at home and in parking lots. DC charging is usually used solely for fast charging, which does not reach a sufficiently long parking duration to perform smart charging (which is a prerequisite). In addition, during AC charging, the vehicle itself has a larger role in the charging process than during DC charging, where the vehicle batteries are charged directly by the charger (bypassing the onboard AC/DC-transformer).

With the participation of both established automotive brands and newcomers to the EV market, a broad and representative sample was formed to illustrate the current state of smart charging integration in the Netherlands. A wide range of electric models was tested, from compact city cars to luxury EVs—and everything in between. This sample totaled 142 models, each of which was represented by one vehicle. The following brands, in alphabetic order, participated in the tests: Audi, Aiways, BMW, BYD, Citroën, Cupra, Dacia, DS, Fiat, Ford, Honda, Hyundai, Jaguar, Jeep, Kia, KGM, Lancia, Land Rover, Leapmotor, Lexus, Lynk&Co, Maxus, Mazda, Mercedes-Benz, MG, Mini, Mitsubishi, Nio, Nissan, Opel, Peugeot, Polestar, Porsche, Renault, Seat, Skoda, Smart, Subaru, Tesla, Toyota, Volkswagen, Volvo, Xpeng and Zeekr. In the interpretation of test results, the scores have been calculated in comparison to the total size of the test group, as well as for the market share (using the data from the Dutch EV fleet distribution of 31-12-2024). The 142 models represent a market share of 77.1%, based on the number of sold units (see Appendix C).

For the charging stations, a selection was made based on the components most common in charging stations in The Netherlands: this selection was validated and approved by the project board. The following brands, in alphabetic order, were used in the tests: Alfen, Easee, Enovates, EVbox, Schneider Electric, Smappee, WeDriveSolar and Zaptec.

Governance

As previously mentioned, the test program was commissioned by the Ministry of Infrastructure and Water Management as part of the national initiative "Smart Charging for All". The governance structure for this test program was based on the governance model of the "Smart Charging for All" program, ensuring alignment in decision-making and stakeholder representation. The project board, responsible for the strategic direction and oversight of the program, consisted of four organizations: The Ministry of Infrastructure and Water Management represented the societal perspective, RAI Vereniging represented the vehicle industry, DOET represented the charging infrastructure industry, and ElaadNL represented the grid operators. As such, technical, commercial, societal, and infrastructural interests were all taken into account.

In addition to the project board, a stakeholder group was involved to reflect on the broader interests from the field. This group includes: the Vereniging Elektrische Rijders (VER), which represented the customer perspective, local and regional authorities, which represented the interests surrounding public charging infrastructure, and individual organizations from both the vehicle and charging infrastructure sectors, providing valuable input based on their expertise and operational experience.

The testing itself was carried out by a dedicated team of five specialists from ElaadNL. This team was responsible for planning, executing, and evaluating all tests within the program. In preparation of the actual testing phase, several key documents and procedural arrangements were jointly established. A standardized test protocol was developed in close collaboration with market participants and validated and approved by the project board. To test smart charging, the control signal in all test scenarios originated from the charger. The control of smart charging can also originate from the car (see layer 2 of the smart charging four-Layer model), which was not part of the test scenarios. The results provided in this report thereby primarily reflect the capabilities of the onboard charger in the car. A wish list regarding the vehicles and charging stations that would be tested was then drafted. This selection was made in close collaboration with market participants and was validated and approved by the project board. The main selection criteria were: the (expected) market share of vehicles and chargers, specific combinations of chargers and cars (asked for by market participants) and chargers with commonly used components. After all preparations, a Test Lab Agreement (TLA) was drafted, which was signed between ElaadNL and each of the participating vehicle manufacturers. According to the agreed-upon procedure, each vehicle was made available at the ElaadNL Test Lab for a period of 48 to 72 hours. Following the vehicle's availability, some tests were adjusted to fit in the timeframe.

Individual test results were shared exclusively with the respective manufacturer through a standardized reporting format. Intermediate results were discussed in a closed committee under strict confidentiality, ensuring that sensitive data were protected during the testing phase. Only aggregated and anonymized test results are shared publicly, in order to contribute to broader industry transparency without compromising the commercial interests of individual stakeholders.

This structured governance and execution framework ensured the program maintained technical rigour, neutrality, and relevance for all involved parties, while supporting the broader goal of advancing smart charging adoption in the Netherlands.

Test protocol

Comply with existing standards

The development of the test protocol was guided by the principle of aligning to existing international standards as closely as possible. The foundation for smart charging tests is primarily based on IEC 61851-1 (2019), which outlines the general requirements for conductive charging systems for EVs. This standard includes definitions for Mode 3 communication, which is the protocol that facilitates smart charging by enabling direct communication between the vehicle and the charging station.

Although IEC 61851-1 provides a comprehensive technical framework, it is not sufficient on its own to fully evaluate the performance of smart charging. True assessment requires the inclusion of dynamic, user-oriented scenarios that exceed everyday charging situations in the current market. Extended pauses, frequent disconnections, brief charging sessions, and delayed charging are some of the more extreme scenarios envisioned. These scenarios are not covered by the existing standard, and thus, ElaadNL's Test Lab has developed a set of supplementary test cases. These additional tests simulate possible future scenarios and are essential for understanding how vehicles interact with smart charging infrastructure in realistic settings.

In addition to communication and behavioral testing, the program also assessed how vehicles and charging equipment respond to common power quality variations on the grid. The following standards were used for this:

- Article 2.27 of the Dutch "Netcode Elektriciteit" stipulates that the power factor of electrical installations must be at least 0.85 for voltages up to 50 kV. This requirement helps ensure efficient energy use and grid stability;
- IEC 50160 defines the acceptable voltage quality levels on public electricity networks. In the Netherlands, this means the grid voltage is allowed to fluctuate between +10% and -15% of 230V. Devices connected to the grid are expected to function reliably within this voltage range;
- IEC 61000-4-11 and IEC 61000-4-34 were the basis for the Voltage Dip Test. During this test, the voltage was abruptly lowered from 230V to 161V (70%) for 25 iterations, equivalent to 0.5 seconds at 50 Hz;
- IEC 61000-3-2 and IEC 61000-3-12 define the allowable levels of harmonic currents produced by devices connected to the grid;
- NEN 3140, the Dutch safety standard for low-voltage installations, specifies a safety limit of 50V AC on non-powered phases, ensuring user and equipment safety.

High-level overview of tests:

Perspective	Test	Details
Customer	Smart charging Interoperability	Validating interoperability of smart charging by testing each vehicle against a representative series of charging stations, for both uncontrolled (regular) and controlled (smart) charging.
	Smart charging Profile and Mode 3 Compliance	Each vehicle was tested for its ability to respond promptly and correctly to both major and minor changes in charging speed. A correct response means that the vehicle does not exceed the allowed maximum at any charging speed.
	Low-Speed Charging Capability	The ability of the vehicle to charge at the lowest permissible current level was evaluated. This included ensuring that the power factor remained within defined limits and checking for overcurrent issues.
	Response to Charging Pauses	Vehicles were tested on their ability to pause for short (20 minutes) and long (6 hours) periods and on their response to "intermittent charging" (a subsequent number of iterations of pause/resume, which can be applied at charging plazas due to limited power availability).
	Response to Increased Charging Speed	To test dynamic responsiveness, vehicles were charged at a constant low speed (6A) for three hours, after which the charging station instructed the vehicle to increase the charging speed.
	User Notifications Via Vehicle App	Tests were conducted to verify whether the vehicle's companion app provided users with accurate information regarding charging speed. It was also assessed how many push notifications were sent when the charging session was repeatedly paused and resumed.

Perspective	Test	Details
Grid PQ Immunity	Voltage deviations	Each vehicle was tested under voltage deviations that remained within regulatory limits. The objective was to ensure that the vehicle continued to charge and that it complied with smart charging-defined current limits. This test was performed using the maximum number of supported phases at the lowest charging speed (6A).
	Harmonic Distortions	Tests were conducted with harmonic distortions present in the voltage (within permitted limits) to evaluate whether the vehicle continued charging correctly and stayed within the smart charging current limits. This test was performed using the maximum number of supported phases at the lowest charging speed (6A).
	Phase Switching	The vehicle's capability to switch between single-phase and three-phase charging modes was tested.
	Voltage on Non-Powered Phases	It was verified whether no high voltage (>50V ac) was present on inactive phases.
Grid PQ Emissions	Harmonic Emissions	Vehicles were assessed for compliance to standards with respect to harmonic emissions, both at nominal charging power and at lower charging speeds.
	Supraharmonics	Data on supraharmonic emissions (2 kHz to 150 kHz) was collected while charging at various speeds, to serve as input for future standardization efforts.
	Power Factor	The power factor was evaluated to ensure that the reactive power component remained within acceptable boundaries. Since smart charging often results in lower charging speeds, power factor measurements were taken at both high and low speeds to assess performance under varying conditions.

Contractual arrangements

A Test Lab Agreement (TLA) was established between ElaadNL and each vehicle manufacturer prior to the testing process. This agreement outlined the conditions under which the tests were conducted and how the data would be handled.

All individual test results are treated as confidential and have only been shared with the respective manufacturer. If any issues were identified during testing and subsequently corrected by the manufacturer, a retest was possible upon request or when deemed necessary.

In addition to individual reports, aggregated and anonymized test results are shared publicly. These results provide insights into the general compatibility of EVs with smart charging infrastructure, without revealing the identity of any specific manufacturer.

During the testing process, the ElaadNL Test Lab collected data related to vehicle and charging performance. This data is stored securely on protected servers and has been used for the analysis and preparation of test reports for each manufacturer. In situations in which measurement data was particularly noteworthy, it is included—anonymized—in public summary reports to highlight broader trends or findings. Under no circumstances will any data be disclosed in a manner that could allow the identification of individual manufacturers. Each manufacturer retains the right to request access to their own test data at any time.

ElaadNL is allowed to retain the test data after the project is completed to support potential future research.

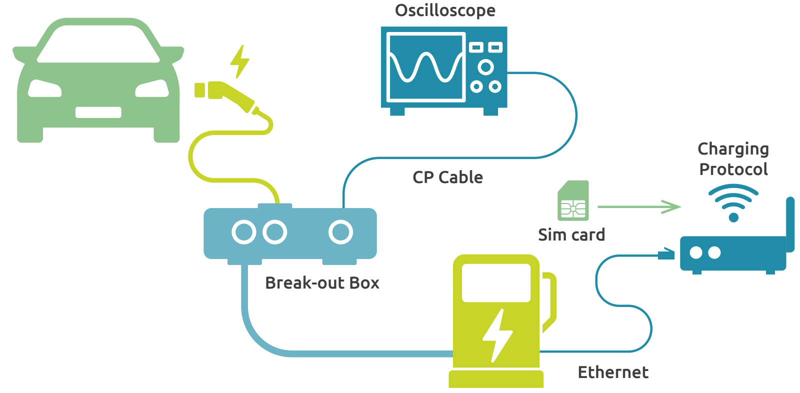
Physical Test set-up

All tests were conducted using an automated test program to ensure consistent and reproducible results across different vehicles and conditions. The data captured during these tests were stored for subsequent analysis and reporting.

Three distinct physical test setups were used to cover the full scope of the test protocol. Each vehicle was tested on all three set-ups to ensure comprehensive assessment across various smart charging scenarios.

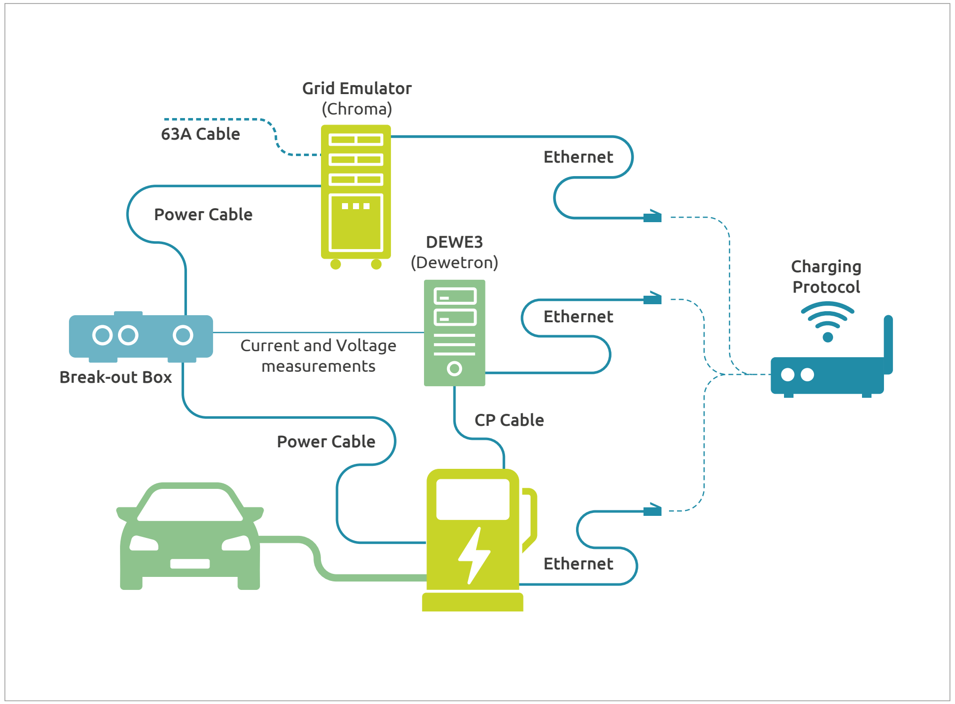
First test set-up

Test Set-up 1 focused on evaluating the interoperability of smart charging between vehicles and different types of charging stations. This set-up included a Dewetron DEWE3 measuring computer for data acquisition, measuring coils to capture current measurements on all three phases, as well as the earth and neutral conductors, and a selection of ten commonly used charging stations in the Netherlands.



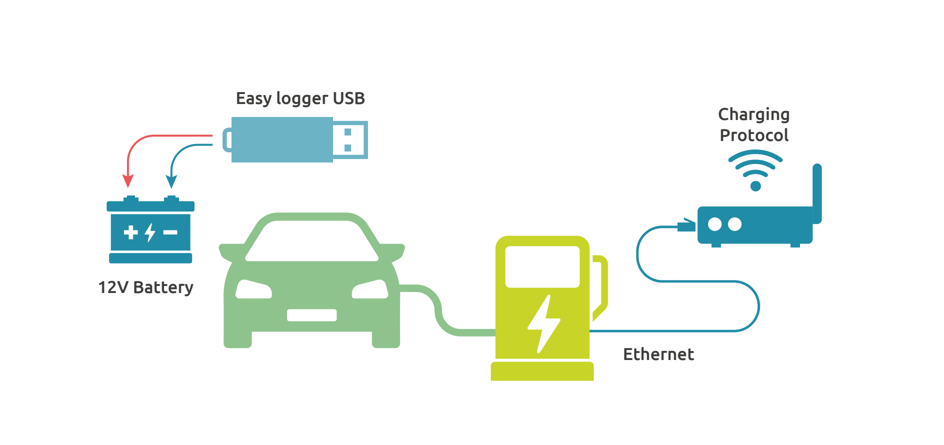
Second test set-up

Test Set-up 2 was designed to simulate extended smart charging scenarios, including variable grid voltage conditions. It also used a Dewetron DEWE3 measuring computer and measuring coils (highly accurate current transducers with a high sampling rate), in addition to a reference AC charging station that was compliant with smart charging protocols, and a Chroma 61830 grid emulator capable of emulating customizable grid conditions.



Third test set-up

Test Set-up 3 focused on endurance testing, including delayed and paused charging, as well as the ability of the system to adjust charging speed after extended idle periods. This set-up consisted of a charging station and a 12-volt data logger for monitoring the vehicle's battery voltage during the tests.



To accurately measure communication signals and the electrical current drawn by each vehicle, detailed measurements were taken using a Dewetron DEWE-800 measuring computer, combined with LEM IT65-S current transducers. The DEWE-800 offered a 1 mega-sample per second sampling rate and 16-bit resolution, allowing high-resolution analysis of all voltages and currents in the three-phase power grid. This capability enabled precise detection of subtle changes in power flow and vehicle behavior. The LEM IT65-S transducers, with a 600 kHz bandwidth, were specifically selected for their high accuracy and excellent linearity, making them suitable for advanced power quality analysis.

Presentation of results

Grouping of test cases

The different tests are presented in three chapters:

- **Customer perspective** - test cases for situations that can have a direct, tangible effect for the driver;
- **Power Quality immunity** - test cases to verify if the vehicle's capability to handle fluctuations in power quality, within specified thresholds;
- **Power Quality emissions** - test cases to examine if the vehicle itself is polluting the power quality.

Structure of each test case

Each test case description begins with a summary table that summarizes the goal, key outcomes, and any relevant remarks. After each table, the method of the test case is explained, including a description of the test set-up and criteria. Finally, the results are presented in detail. For each test, the results are presented in three different ways:

- Number of successful tests / total number of tests;
- Percentage of successful tests in relation to the total number of tests;
- Percentage of successful tests in relation to the market share of the successful tests.

For each test, one or more relevant visualizations are included.

If a test was not successful, a qualification of the severity of the issue is given, based on the following mapping:

Colour	Severity	Description
Red	Critical	An error that affects a significant portion of the functionality, resulting in the improper functioning of smart charging. Because this error may terminate the charging session, smart charging has a severe impact on the user experience or business operations.
Orange	Major	A significant error that affects multiple smart charging or power quality scenarios; there is a chance charging will be affected.
Yellow	Minor	A small error that affects stringent smart charging scenarios or rare power quality scenarios; in most cases, charging will not be affected.
Green	Trivial	Very small error, such as app behavior or small aesthetic problems that have little to no impact on functionality.
Gray	Enhancement	Not an error, but a suggestion for an improvement or new functionality to make smart charging more user-friendly or efficient.

CHAPTER 3

Results: Customer perspective

This chapter illustrates the results of test cases that were designed for situations that could potentially have a direct, tangible effect on a customers' user experience.

Test 1 - Smart Charging Interoperability

Summary

Goal	To validate interoperability of smart charging between the vehicle and a representative series of charging stations.
Description	All vehicles were tested on a representative series of ten different charging stations. The charging stations were chosen based on market share and unique behavior. The test consisted of two parts: • Test of uncontrolled interoperability by validating that a vehicle can charge at each charging station; • Test of smart charging interoperability by validating that a vehicle can follow a typical smart charging profile on each charge station. The typical smart charging profile contains various charging speeds and pauses.
Key outcomes	Of all tested vehicle/charging station combinations: • 99.8% (1.413/1.416) support basic uncontrolled charging. • This is representative of 99.96% of the tested market share; • 92.7% (1.173/1.265) support smart charging. • This is representative of 97.1% of the tested market share.
Remarks	In the percentages presented in the key outcomes, one charging station is excluded. This charging station, which is not produced anymore, deviates from standard smart charging settings by using an error state (as stated in the standard) to pause charging. Nevertheless, this charging station was included in the test because a small number of installed charging stations are still using this error state for pausing. In total, 19 vehicles out of the total group (142 vehicles) did not restart charging when this alternative error state (for pausing) was used.

Introduction

For a seamless charging experience for customers, each combination of vehicles and charging stations should (in principle) support smart charging. Since many different technical components are used in both vehicles and charging stations, it is important to test the mutual compatibility (interoperability).

During the smart charging interoperability test, vehicles were tested on both uncontrolled charging interoperability and smart charging interoperability. This test is an important indicator on smart charging efficacy (i.e., whether smart charging will introduce any new issues compared to uncontrolled charging).

The charging stations that were selected for this test are the most commonly installed charging stations (both public and private) in the Netherlands combined with charging stations with specific behavior. The goal of this test is to validate smart charging interoperability.

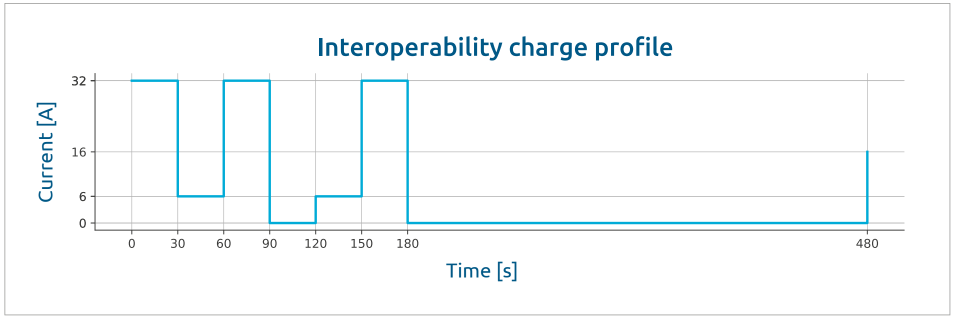
Method

Test set-up

The charging stations that were used for the interoperability tests are listed in the table below, in alphabetical order. This selection was made based on the most common components in charging stations in the Netherlands, which ensures that the selection is representative for the entire array of charging station brands and models used in the country.

Brand	Model	Brand	Model
Alfen	Twin 4XL	Evbox	ML
Alfen	Twin XL	Schneider Electric	EVLink
Easee	Home	Smappee	EVbase
Enovates	Pro22	WeDriveSolar	WDS-0001
EVbox	Liviqo	Zaptec	Pro

All charging stations were tested consecutively for each vehicle. The charging profile used for the smart charging interoperability test consists of alternating between the maximum and minimum charging speeds, a short 30-second pause and a five-minute pause. For the pause state, 9V/100% PWM is given. A visual representation of the charging profile is shown below:



During testing, two signals were monitored:

- The Control Pilot signal (which is the signal for communication between the charging station and vehicle), observed by using an oscilloscope connected to a breakout box (to intercept the Control Pilot signal);
- The current through the connection to the charging station, to monitor whether the vehicle changes the drawn current according to the charging profile.

The test setup used for this test is the first test set-up, which can be found in the Test Methodology chapter under physical test set-up.

Test criteria

Uncontrolled charging interoperability	
Pass	Each combination of vehicle/charging station that successfully starts to charge.
Fail	Each combination of vehicle/charging station that does NOT start to charge.

Smart charging interoperability	
Pass	Each combination of vehicle/charging station that successfully follows the charging profile.
Fail	Each combination of vehicle/charging station that only performs a part of the charging profile and then stops charging.

Results in detail

Uncontrolled charging interoperability

In total, 142 vehicles were available to be tested, which results in a total of 10x142=1,420 possible charger-vehicle combinations.

	Percentage passed	Market share
Able to charge	99.8% (1.413/1.416)	99.96%

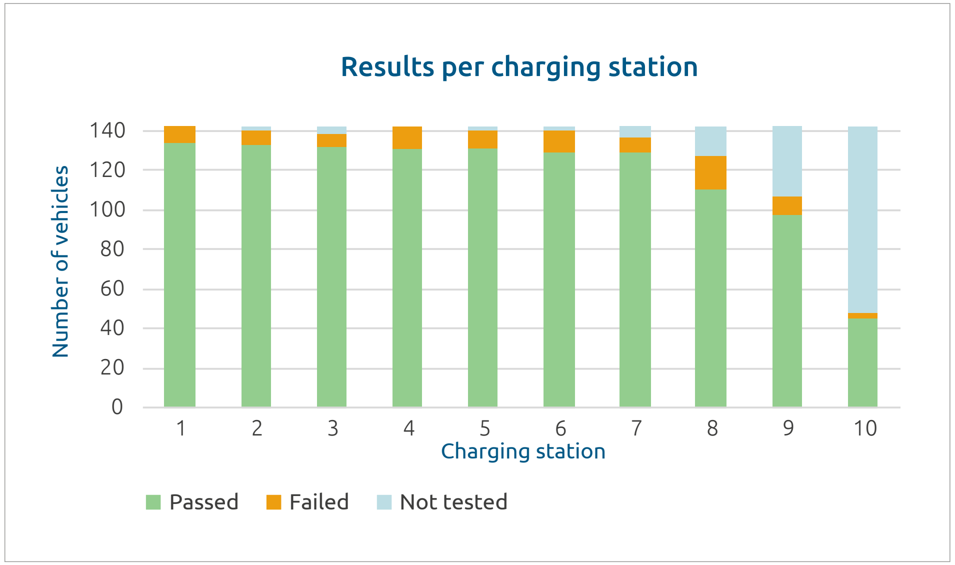
Four combinations could not be tested. In three cases, a charging station was temporarily unavailable; in the fourth case, the vehicle could not be connected to the fixed cable charging station because it only had a CHAdeMO charging port.

Of the remaining 1.416 combinations, 1.413 combinations were able to charge, a score of 99.8%. This is representative of a market share of 99.96%.

Smart charging interoperability

	Percentage passed	Market share
Able to smart charge	92.7% (1.173/1.265)	97.1%

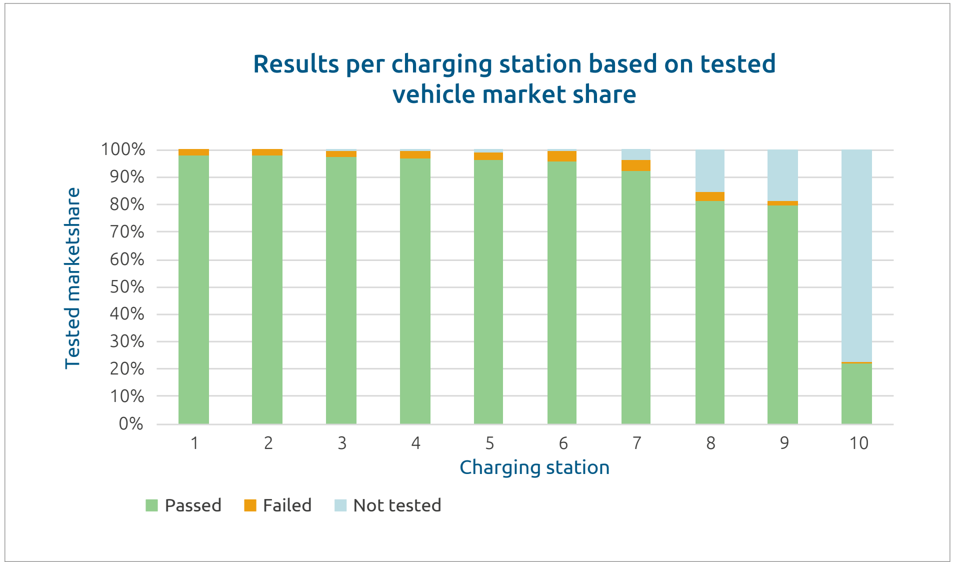
Due to the temporary unavailability of charging stations, 148 combinations could unfortunately not be tested. Out of the (1413 – 148 =) 1,265 combinations tested, 1,173 completed the full charging profile successfully. The image below, “results per charging station”, shows the results for each charging station, sorted by amount that PASSED.



The most important and interesting reasons for the cases of incomplete charging profiles can be tracked back to nine different vehicle models (which is important for the interpretation of the 92 FAILED tests). For three vehicle models, the manufacturers have reported that the issue has been solved with a firmware update. This is yet to be confirmed with a retest. Two models were not able to pause for less than one minute, which led them to fail the 30-second pause in this test. This is not considered a serious failure, since such short pauses are not representative of everyday charging. Four models showed irregular behavior with respect to restarting charging after a pause.

In the interoperability test, one charge station was tested (not included in the graphs) which uses an (incorrect) deviating pause state. Nineteen models, representing 8.7% of the tested market share, did not restart charging after a pause with the charging station with this deviating pause state (-12V/0%PWM). This result shows the importance for charging station manufacturers to comply to the standard.

The successful smart charging interoperability combinations represent a market share in the Netherlands of 97.1%. The figure below shows the success rate (in percentage) per charging station weighed by market share of the vehicles, sorted by the percentage passed.



Test 2 - Smart Charging profile/compliance to Mode 3 charging

Summary

Goal	To validate compliance of vehicles to different thresholds as defined in the standard IEC 61851-1 (2019).
Description	*This test validates multiple aspects of the standard:* • That the vehicle does not create an **overcurrent** in relation to the set charging limit; • The **response time** of the vehicle to adapt to changes in charging speeds; • That the vehicle does not **overshoot** the charging limit temporarily. The tests are performed both on one-phase and three-phase, when supported by the vehicle.
Key outcomes	*Of all the tested vehicles:* • 91.2% (103/113) comply to the set max current limit, on three-phase charging. This represents 99.0% of the tested market share; • 95.1% (135/142) comply to one-phase charging. This represents 99.4% of the tested market share; • 85.0% (96/113) respond (in time) to changes in charging speed, on three-phase charging. This represents 97.6% of the tested market share; • 81.0% (115/142) respond (in time) on one-phase charging. This represents 90.8% of the tested market share; • 86.7% (98/113) stay within the current limit when increasing the charging speed, on three-phase charging; this is 83.9% of the tested market share; • 77.5% (110/142) stay within the current limit when increasing the charging speed, on one-phase charging. This represents 91.6% of the tested market share. Overshoots only occurred at 6, 7 and 8A, on both three-phase and one-phase charging.
Remarks	None.

Introduction

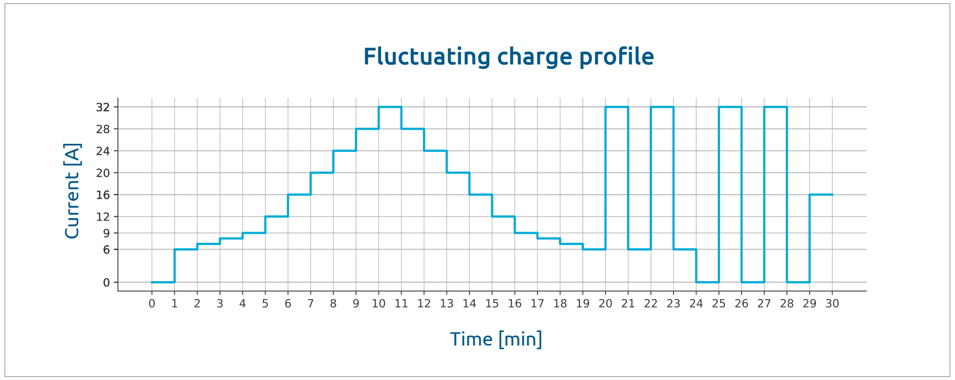
The previous test showed that, of the tested market share, 97.1% of the vehicle/charging station combinations can perform smart charging, with respect to changing charging speeds and complying to pauses imposed by the charging profile. However, that test does not monitor whether the vehicles comply to the charging standard that describes how the vehicle should behave during charging. The following test validates the vehicles' compliance to this standard on three aspects (explained in the methods section) and is therefore an important indicator for the efficacy of smart charging (i.e., whether smart charging at the limits of the standard will introduce any issues).

Method

Test set-up

During the in-depth smart charging profile test, the vehicles had to follow a charging profile that was designed to test different thresholds as defined in standard IEC 61851-1 (2019). To examine the behavior of the vehicle, a charging station is needed that does not stop charging as a result of an overshoot or overcurrent by the vehicle, since this would obscure the test results. The charging station chosen for this test continues charging until a 10% overcurrent is reached.

The vehicle was connected to the reference charging station which performed the smart charging profile displayed in the figure below.



The charging profile fluctuated from the minimum to the maximum charging speed of the vehicle (and various charging speeds in between) to test for overcurrent. The changes in charging speed are in both incremental steps and sudden leaps, to test for overshoots and response times. The test was performed on both one-phase charging and, if applicable, three-phase charging.

The test set-up used is the second test set-up, which can be found in the Test Methodology chapter under physical test set-up.

During testing, the currents (between the 'grid' and the charging station) and Control Pilot socket (PWM signal indicating the charging limit) were recorded using the Dewetron measurement computer for analysis.

Test criteria

Overcurrent - the condition in which the current of the vehicle structurally exceeds the set charging limit.	
Pass	The drawn current does not exceed 110% of the current limit indicated by the charging station, on any of the three phases.
Fail	Current exceeds 110% of the current limit indicated by the charging station on one or more phases for longer than one second.

Overshoot - the condition in which the current of the vehicle temporarily exceeds the set charging limit.	
Pass	The drawn current does not exceed 110% of the current limit indicated by the charging station. Note: when a vehicle FAILED the overcurrent test, the result of this test was marked as PASSED in the statistics, because the anomaly was not an overshoot but an overcurrent.
Fail	The drawn current exceeds 110% of the current limit after the limit increased but decreases below 110% of the limit within one second.

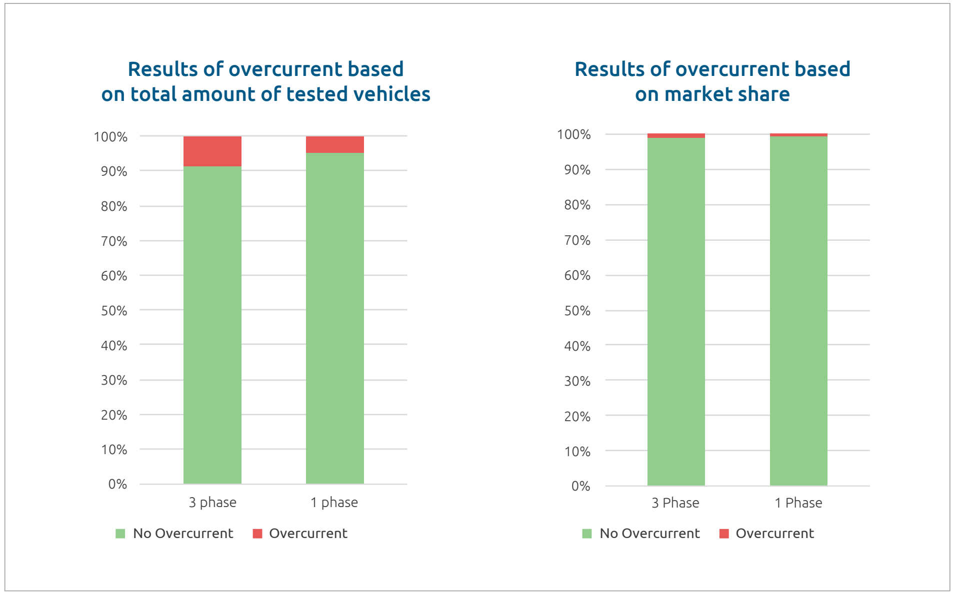
Response time - decrease in charging speed:	
Pass	The vehicle adjusts the drawn current equal to or below the maximum current indicated by the charging station within five seconds after the limit decreases.
Fail	The vehicle adjusts the drawn current equal to or below the maximum current indicated by the charging station later than five seconds after the limit decreases.

Response time - pause:	
Pass	*The vehicle complies to both situations below:* • Decrease of the current under 1A within three seconds after the limit is decreased to 0A; • After the current goes below 1A, the vehicle communicates that it stopped charging by opening the S2 switch to the charging station within three seconds.
Fail	*The vehicle:* • Does not decrease the current under 1A within three seconds after the limit is decreased to 0A; • Or does not communicate to the charging station that it stopped charging within three seconds; • Or communicates it stopped charging while the drawn current is still above 1A.

Results in detail

The results per category are shown in the table below:

	Three phase		One phase	
	Percentage passed	Market share	Percentage passed	Market share
Overcurrent	91.2% (103/113)	99.0%	95.1% (135/142)	99.4%
Response time	85.0% (96/113)	97.6%	81.0% (115/142)	90.8%
Overshoot	86.7% (98/109)	83.9%	77.5% (110/142)	91.6%



Note: Since some vehicles are only capable of one-phase charging, not all vehicles were tested on three-phase charging.

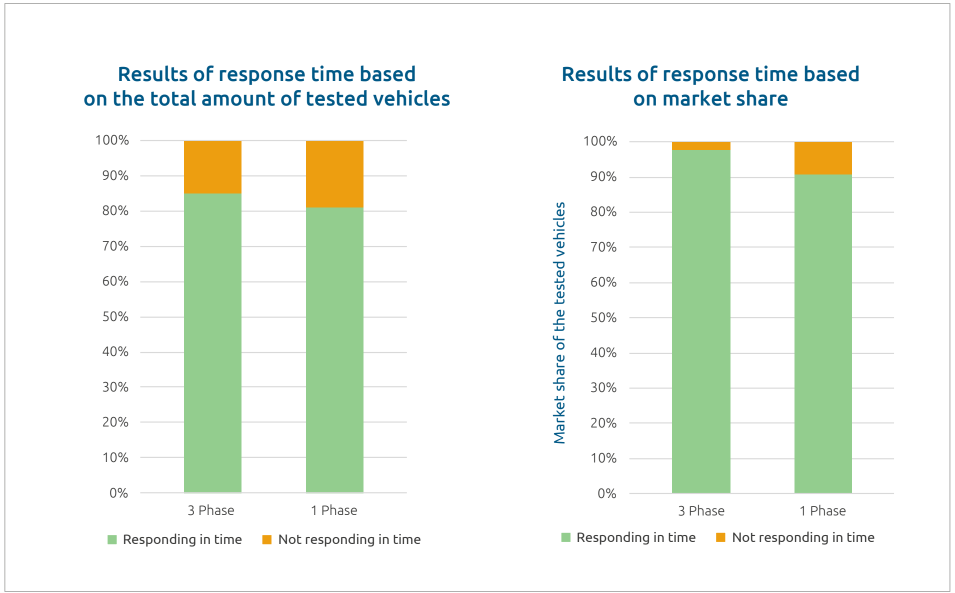
Overcurrent

For three-phase charging, 91.2% (103/113) and for one-phase charging 95.1% (135/142) PASSED the overcurrent test, representing 99.0% of the tested market share on three-phase charging and 99.4% on one-phase charging.

The tested vehicles that FAILED the *Overcurrent test*, failed at only one charging speed, with the exception of two vehicles, which was either at 6A or 7A. The two vehicles that failed on multiple charging speeds did so only during three-phase charging, at 6A, 7A and 8A.

Charging stations may stop charging due to overcurrent, and therefore this 1% is marked as a major error. Charging at low charging speeds (considering the overcurrent found in this test) is discussed further in Test 3 – Low speed charging capability.

Response time



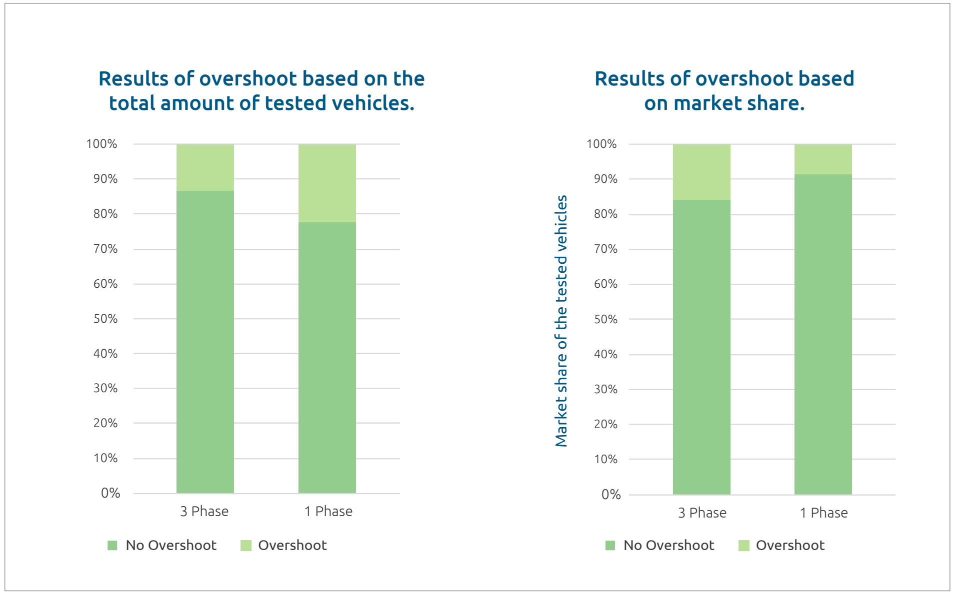
For three-phase charging of the tested vehicles, 85.0% (96/113) responded in time when the current limit decreased, representing 97.6% of the tested market share. For one-phase charging, this number was 81.0% (115/142) of tested vehicles (90.8% of the tested market share).

This large difference between three-phase and one-phase charging can be explained by the significant market share of vehicles only capable of one-phase charging that did not pass this test. However, the charging sessions were not terminated due to poor response times, and as such the error is only considered minor.

Overshoot

Of the vehicles that were tested on phase three-phase charging, 86.7% (98/109) did not overshoot the current limit (with a margin of 10%) in situations that increased the charging limit during the in-depth smart charging profile—this represented 83.9% of the tested market share. For one-phase charging, 77.5% (110/142) of tested vehicles did not overshoot the current limit with a margin of 10%, representing 91.6% of the market share.

Since an overshoot rarely causes charging station to terminate charging, the vehicles that had an overshoot were marked as a minor error.



Test 3 – Low-speed charging capability

Summary

Goal	To find the lower charging speed limit, considering the overcurrent and power factor, to find the charging speed accepted by the vehicles.
Description	Compare the charging behavior at different charging speeds.
Key outcomes	At the lowest charging speed of 6A, 91.2% (103/113) of the vehicles can charge correctly at three phases, representing 95.8% of the tested market share. During one-phase charging, 95.1% (135/142) of the vehicles charges correctly at 6A, representing 99.4% of the tested market share.
Remarks	Charging correctly is defined as follows: current within 110% of limit, and power factor >= 0.85.

Introduction

For a seamless charging experience by customers, it is important to validate that vehicles can charge correctly at lower charging speeds. When smart charging is implemented, lower charging speeds will be used more often. Since the vehicles are usually only tested at their nominal (maximum) charging speed, this test is performed to identify the minimum charging speed for each vehicle, according to defined rules.

Method

In this test, the lowest possible charging speed of vehicles is found by first defining two rules regarding how the vehicle should charge, in order to decide whether the vehicle is charging with or without issues. These rules are explained and defined as outlined below.

Overcurrent

If a vehicle draws more current than allowed, charging might be terminated due to mechanical overcurrent protection in the charging station or at the connection level. Because of this, charging stations monitor the current that is being drawn by the vehicle, to check if it is below the limit. This way, the charging station can stop the charging session before the mechanical overcurrent protection intervenes. The threshold at which a charging station stops charging may vary per charging station, both with respect to duration and amount of overcurrent. From ElaadNL's experience, most charging stations keep charging when the vehicle stays below 110% of the limit indicated by the charging station. Therefore, the threshold of 110% is used to determine how a vehicle can charge without issue, for each charging speed. However, ElaadNL always advises the vehicle manufacturers to stay below the allowed (100%) limit.

Power factor

At lower charging speeds, the on-board charger may use the capacity of the grid less effectively. This is measured by the power factor. According to the Dutch grid code (Article 2.27), the power factor should have a value between 0.85 and 1, which is therefore considered the baseline to define whether a vehicle is charging correctly or not, for each charging speed.

For this test, the measurement data recorded during the in-depth smart charging profile is used.

Test set-up

The test set-up used for this test is the second test set-up, which can be found in the Test Methodology chapter under physical test set-up.

Test criteria

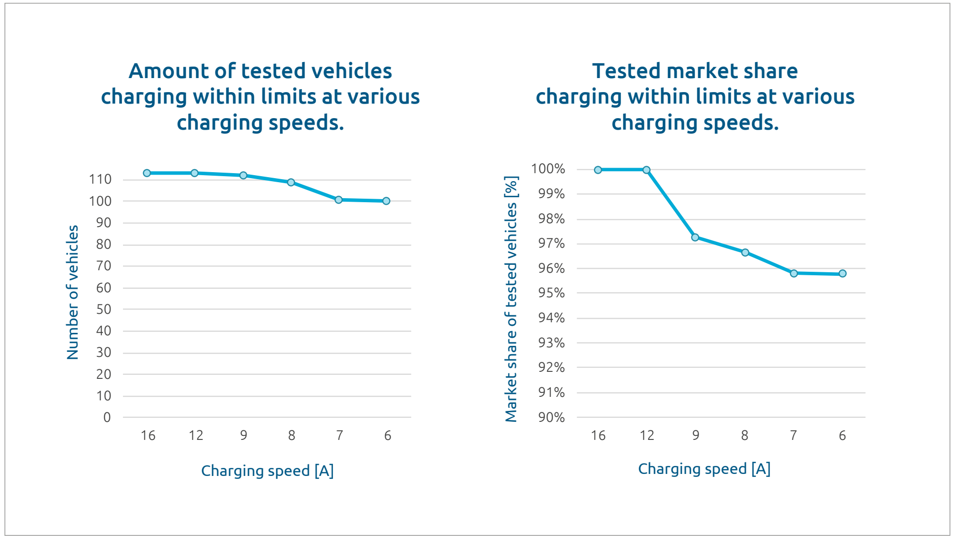
Lowest charging speed: Tested charging speed between 6A and 16A.	
Pass	At this charging speed, the vehicle does not exceed 110% of the current limit, and charges with a power factor of 0.85 or higher.
Fail	At this charging speed, the vehicle either exceeds 110% of the current limit, or charges with a power factor lower than 0.85.

Results in detail

	Three phase		One phase	
	Percentage passed	Market share	Percentage passed	Market share
Low speed charging (6A)	91.2% (103/113)	95.8%	95.1% (135/142)	99.4%
Nominal speed charging (16A)	100% (113/113)	100%	100% (142/142)	100%

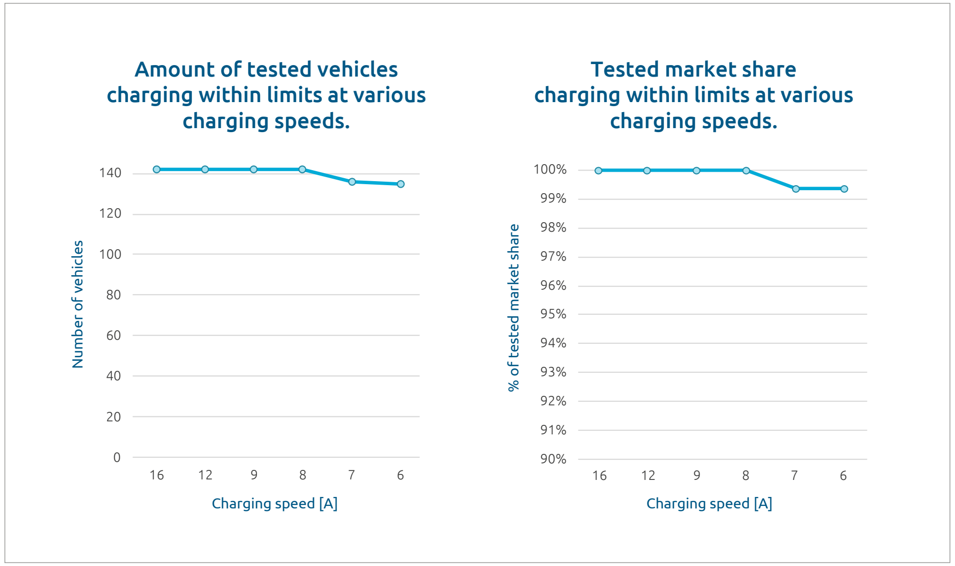
3 Phase charging

Of the 113 tested vehicles on three-phase charging, 91.2% (103/113) charged at 6A without 10% overcurrent and a power factor >= 0.85, representing 95.8% of the tested market share of the tested vehicles. For higher charging speeds and the corresponding number of vehicles and market shares, see the figures below.



One-phase charging

Of the 142 vehicles tested on one-phase charging, 95.1% (135/142) charged at 6A without 10% overcurrent and a power factor >= 0.85, representing 99.4% of the tested market share of the tested vehicles. For higher charging speeds and the corresponding number of vehicles and market shares, see the figures below.



Test 4 – Response to charging pauses

Summary

Goal	To validating the behavior of vehicles during various paused and delayed smart charging scenarios. To validate whether the 12V battery stays sufficiently charged so the vehicle is able to start after the overnight test.
Description	Several tests were performed with respect to the behavior of the vehicle during smart charging scenarios where the charging is paused, with respect to the following capabilities of the vehicle: • Whether the vehicle is able to continue charging properly after alternating between starting and stopping charging multiple times; • Whether the vehicle is able to resume charging after being paused for 20 minutes; • Whether the vehicle can charge properly after the charging was postponed and after paused for six hours. An additional test was performed in this process with six-hour pauses or delays, to validate that the 12V battery of the vehicle would stay sufficiently charged so the vehicle would be able to start.
Key outcomes	*Of the total amount of tested vehicles:* • 81.4% (92/113) were able to pause and resume charging 25 subsequent times on three- phase charging. Representing 90.0% of the tested market share. This was 76.8% (109/142) on one-phase charging, which represents 81.4% of the tested market share. • 91.5% (130/142) was able to resume charging after being paused for 20 minutes, which represents 95,3% of the tested market share. • 96.3% (130/135) was able to start charging after a six-hour delay, which represents 94.6% of the tested market share. • 96.4% (133/138), was able to resume charging, after the charging was paused for six hours, which represents 97.7% of the tested market share. • 100% (129/129) of the tested vehicles were able to start up after the overnight test, meaning the 12V battery had a sufficient charge for the vehicle to start. These vehicles logically represent 100% of the tested market share.
Remarks	The intermittent charging test consists of 25 iterations of one-minute charging at 6A followed by a one-minute pause. The goal of this specific test was to validate the maximum supported iterations and does not represent an everyday charging situation. The choice for pauses of one minute additionally does not reflect an everyday charging situation and was chosen due to time constraints for testing. In retrospect, this test represents an extreme theoretic charging situation (perhaps too extreme) and therefore the results of this test must be interpreted with caution. In the future, this test will be executed with pause/resume iterations of 15 minutes and the number of iterations will be reduced to 15 iterations. This altered test scenario better reflects the situation of alternate charging of vehicles, for example, on a (virtual) charging hub, and corresponds with a time period of 7.5 hours.

Introduction

For a seamless charging experience for customers, vehicles should be able to perform charging sessions that allow for pauses or postponement (delays), particularly because scenarios in which this is needed are becoming increasingly relevant. For example, when charging by solar energy on a partly cloudy day, charging may be paused frequently to prevent the use of grid power. Alternatively, when charging at a charging hub, power is often alternated between vehicles by pausing charging at intervals of 15 minutes, to keep the total charge demand within grid limits. Pauses can also occur during grid congestion. In this case, it might be better to postpone or pause charging for a longer period, and restart charging when the congested period is over.

Method

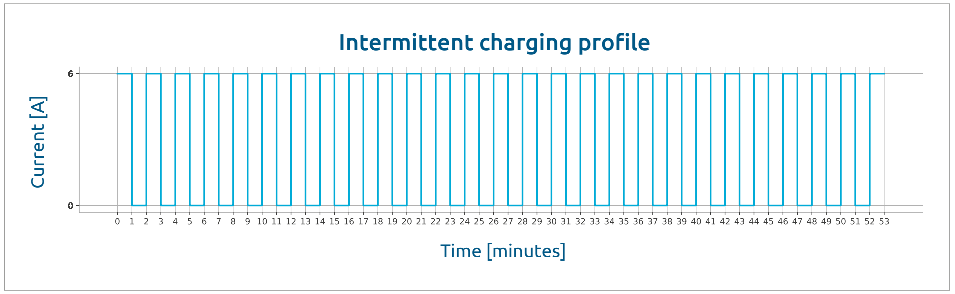
To validate that the vehicle can handle the aforementioned scenarios, several tests were designed.

The scenarios that include shorter pauses are merged into two tests: 1) an extreme test in which charging is paused 25 times for one minute, with only one minute of charging in between, and 2) a more realistic test in which charging is paused for 20 minutes. The scenario with 25 consecutive pauses reflects a charging session with frequent pauses due to limited power availability (e.g., during a solar energy charge on a partly cloudy day, or at a charging hub where power is divided between vehicles). The 20-minute pause test reflects one interval at a charging hub.

To validate that the vehicles can charge correctly during the scenarios regarding longer postponements and paused charging, a long-stretched test is performed where charging is postponed and then paused for six hours consecutively.

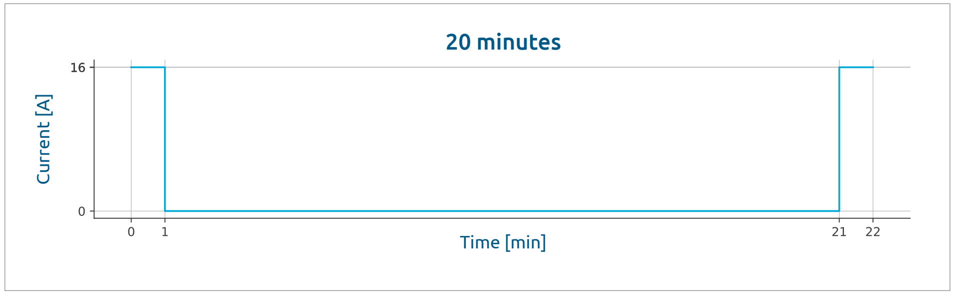
Intermittent charging test

During the intermittent charging test, the vehicle was connected to a charging station, which performed a charging profile consisting of 25 iterations of one-minute charging at 6A, and a one-minute pause. This test was performed on both one-phase charging and, if applicable, three-phase charging. The intermittent charging profile that was used for this test can be found below.



20-minute paused test

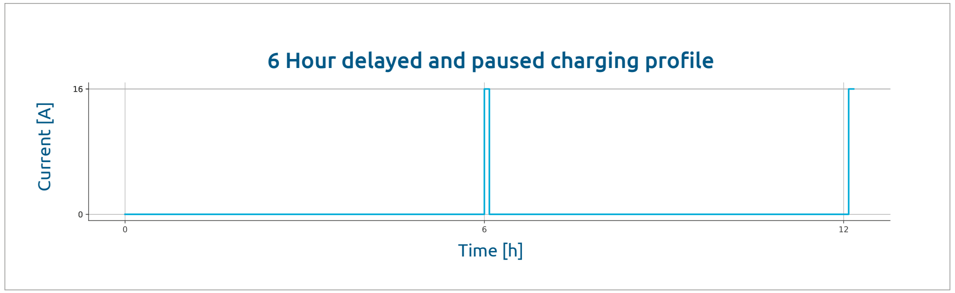
For the 20-minute paused charging test, the EV was first allowed to charge for a short period, after which charging was paused for 20 minutes. After the 20-minute break, the charging station indicated that the vehicle could resume charging. The 20-minute paused charging profile that was used for this test can be found below.



Overnight test (six-hour delay and six-hour pause test)

During the overnight test, the vehicle was connected to a charging station that used state B1 when no energy was available (i.e., the charge profile goes to 0A).

Afterwards, a charging session was performed on one-phase, with a charging profile (shown below) loaded onto the charging station. The charging profile can be described as follows: at first, the charging was delayed for six hours. After the delay, the vehicle should charge at 16A. Then, after charging at 16A for five minutes, the charging was paused for six hours, after which the vehicle should charge again.



12V battery test

After the overnight test, the vehicle was started up in order test whether the 12V battery was still sufficiently charged (enough to start the vehicle). A voltage logger (Lascar EL-USB-3 Voltage Data Logger) was connected to the 12V battery, to monitor the voltage during the overnight test. The data of the voltage logger will be shared with the manufacturer of the vehicle.

Test set-up

For the intermittent charging and 20-minute delay charging tests, the second test set-up is used, which can be found in the Test Methodology chapter under physical test set-up.

As for the six-hour pause/delay tests, the third test set-up was used, which can be found in the same chapter.

Test criteria

Intermittent charging	
Pass	The vehicle was able to pause and resume charging 25 times consecutively.
Fail	The vehicle was unable to resume charging every iteration.

20-minute paused charging	
Pass	The vehicle was able to resume charging, after the charging was paused for 20 minutes.
Fail	The vehicle is unable to resume charging, after being paused for 20 minutes.

Six-hour delayed charging	
Pass	The vehicle was able to start charging, after the charging was delayed for six hours.
Fail	The vehicle is unable to resume charging, after the charging was paused for six hours.

Six-hour paused charging	
Pass	The vehicle was able to resume charging, after the charging was paused for six hours.
Fail	The vehicle is unable to resume charging, after the charging was paused for six hours.

12V battery test	
Pass	The vehicle is able to start up after paused and/or delayed charging of six hours.
Fail	The vehicle is not able to start up after paused and/or delayed charging of six hours.

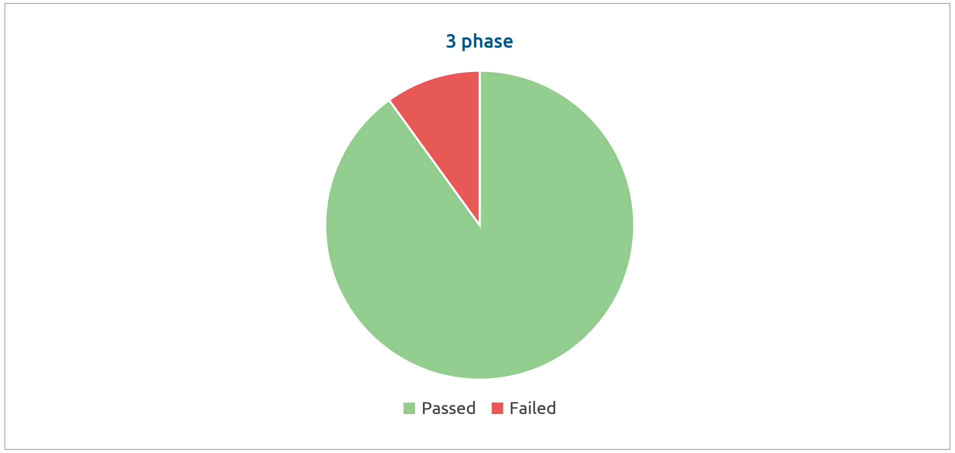
Results in detail

Intermittent charging

	Three phase		One phase	
Charging status	Percentage passed	Tested market share	Percentage passed	Tested market share
Continues charging throughout the entire test	81.4% (92/113)	90%	76.8% (109/142)	81.4%

Three-phase charging

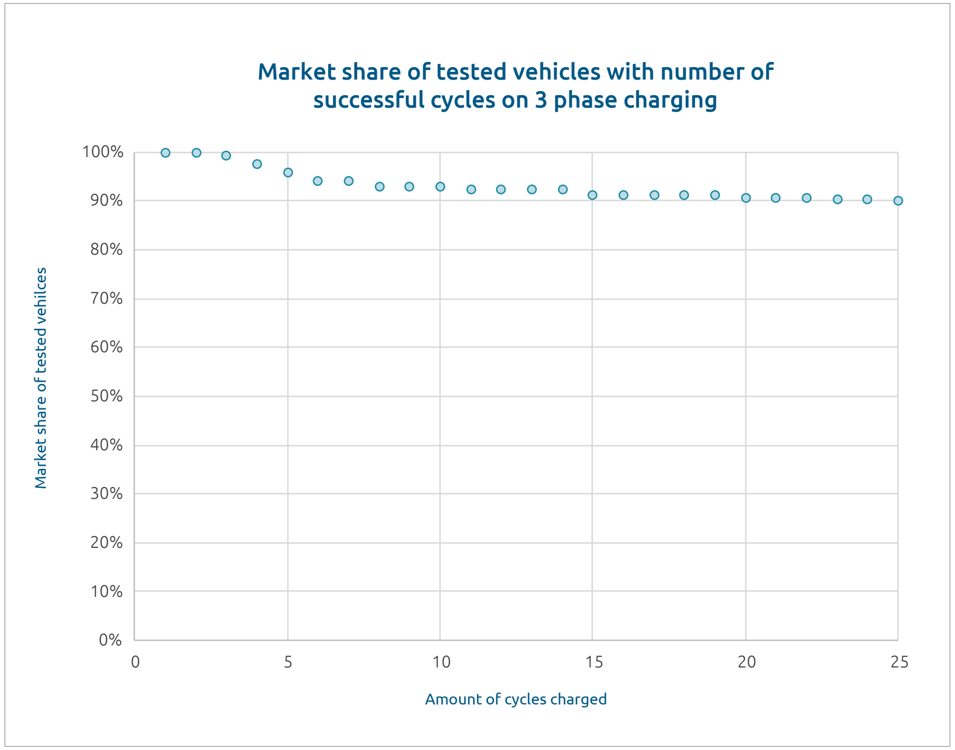
Each vehicle that was capable of charging on three phases was tested on three-phase intermittent charging.



Of the tested vehicles, 81.4% (92/113) were able to pause and resume charging 25 times consecutively on three phases, representing 90% of the tested market share.

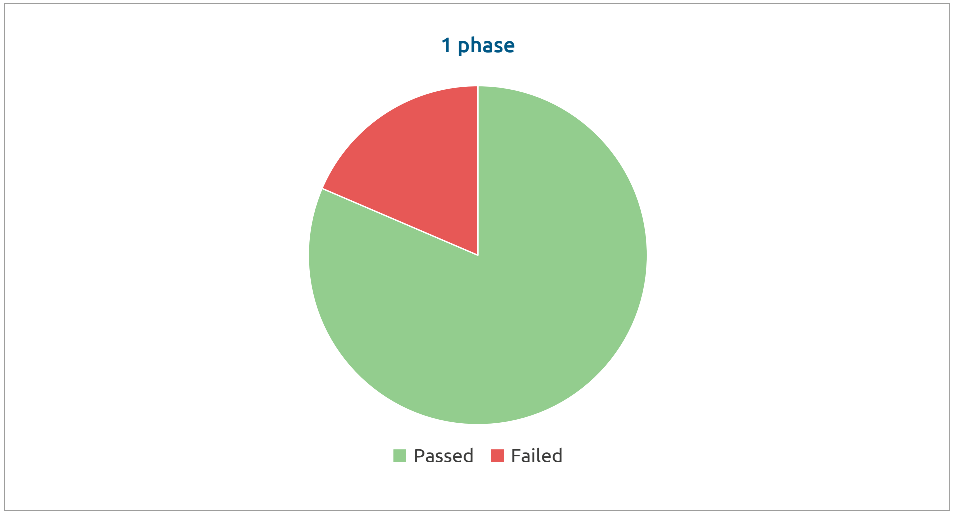
Of the FAILED vehicles, 90% (weighed by market share) stopped charging completely. The remaining 10% of the FAILED vehicles skipped iterations but restarted charging afterwards.

The market share of all tested vehicles (both the PASS and FAIL) with the corresponding number of successful iterations during this test can be found in the figure below. As can be seen, 100% of all vehicles tested can handle two full iterations of one-minute charging plus one-minute pause and 90% can handle all 25 iterations successfully.



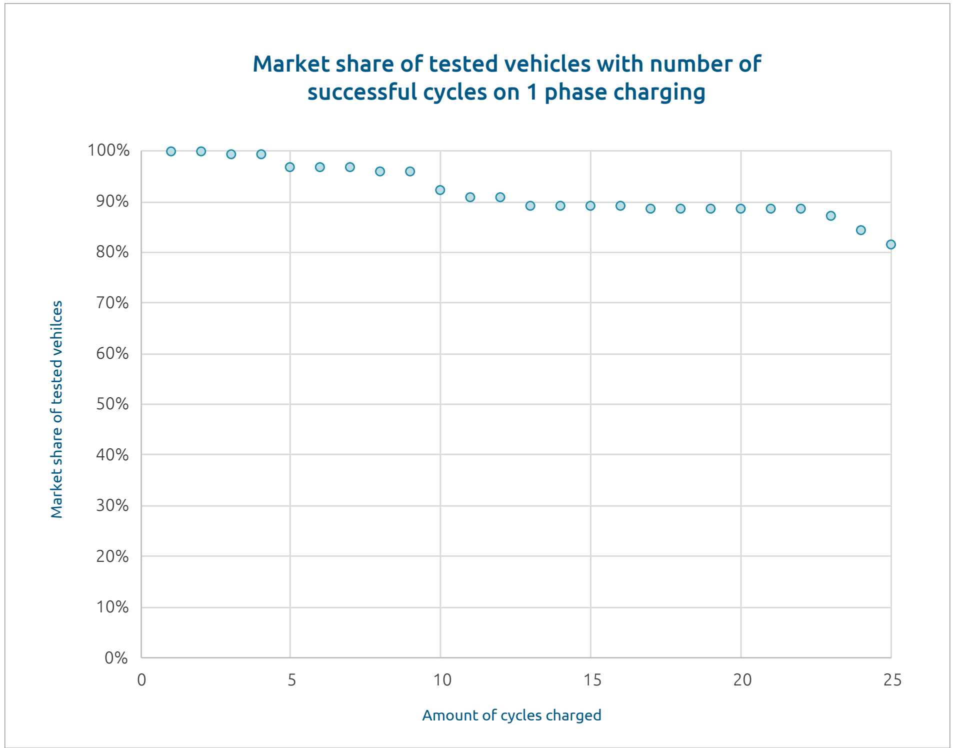
One-phase charging

Each vehicle was tested on one-phase intermittent charging.



Of the tested vehicles, 76.8% (109/142) were able to pause and resume charging 25 times consecutively on one-phase, representing 81.4% of the tested market share. Of the vehicles that were unable to resume charging within a minute for all 25 iterations, 49% skipped some charging iterations and resumed charging later during the session. The other 51% were unable to continue charging after being paused a certain number of times.

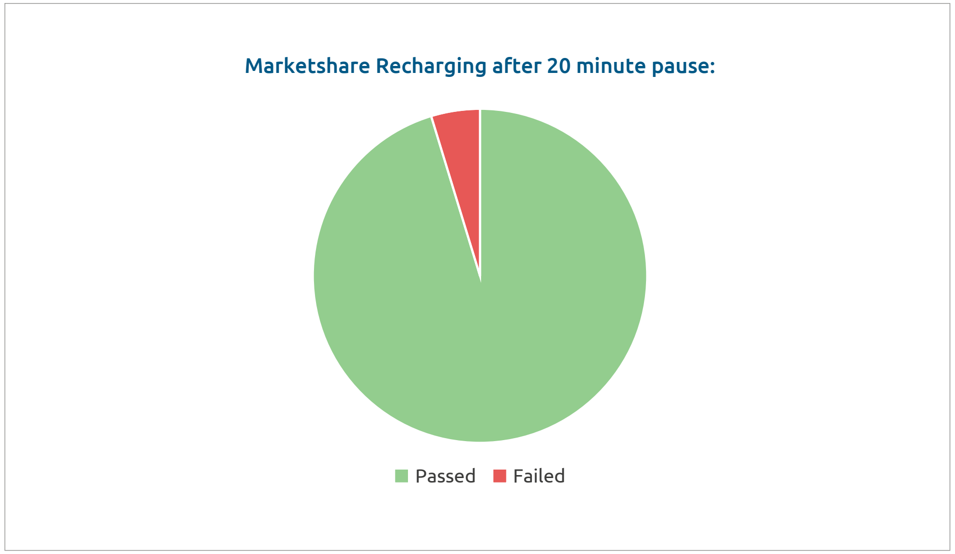
The market share of all tested vehicles (both the PASS and the FAIL) with the corresponding number of successful iterations during this test can be found in the figure below. As can be seen, 100% of all vehicles tested can handle two full iterations of one-minute charging plus one-minute pause, and 82% can handle all 25 iterations successfully.



20-minute paused

Charging status	Percentage passed	Tested market share
Resumes charging	91.5% (130/142)	95.3%

Each vehicle was tested on 20-minute paused charging.



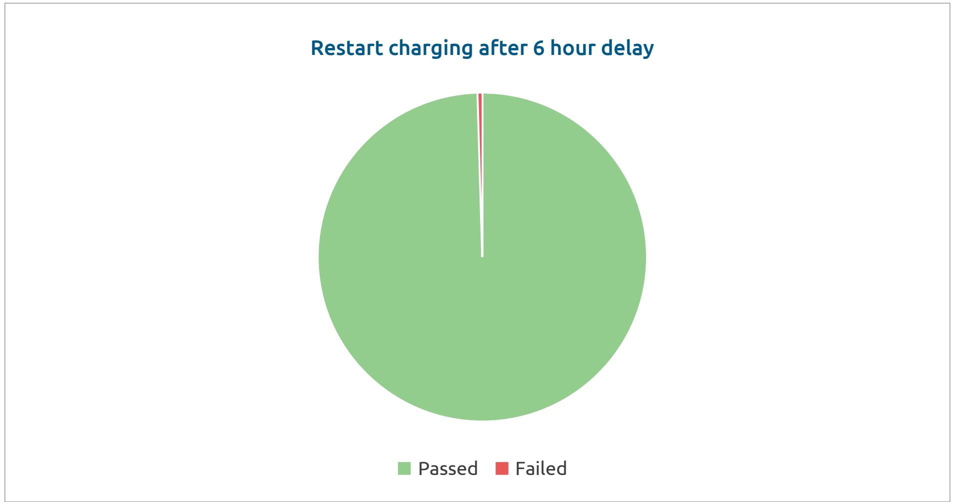
Of the tested vehicles, 91.5% (130/142) were able to pause and resume after being paused for 20 minutes, representing 95.3% of the tested market share.
With respect to the failed tests, a limited number of models from one vehicle manufacturer represent 64% of the total. This has been communicated to the vehicle manufacturer and the vehicle manufacturer is researching this behavior. Retests will be scheduled in due time.

Overnight

Charging status	Percentage passed	Tested market share
Starts charging 6 hours delay	96.3% (130/135)	99.5%
Resumes charging 6 hours pause	96.4% (133/138)	99.5%
12V battery	100% (129/129)	100%

Six-hour delayed charging test

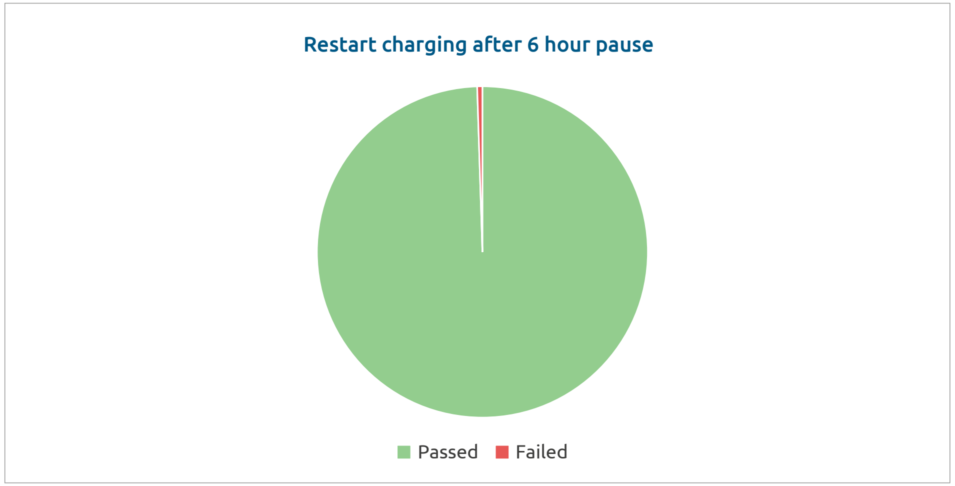
135 vehicles were tested on six-hour delayed charging.



Of the tested vehicles, 96.3% (130/135) were able to start charging after the charging was delayed for six hours, representing 99.5% of the tested market share. Seven vehicles were unable to be tested, one of which was due to the occurrence of a faulty test. Another test failure was the result of the incorrect configuration of a charging station. Due to this, the other five vehicles could not be tested on this aspect (there was not enough testing time for the six-hour charge delay)

Six-hour paused charging test

Each vehicle was tested on six-hour paused charging.



Of the tested vehicles, 96.4% (133/138) were able to start charging after the charging was paused for six hours, representing 99.5% of the tested market share.
Four vehicles were unable to be tested, one of which was due to an error in the test itself. In the case of another failed test (which occurred during the beginning of the project) the respective charging station was not configured correctly. The remaining two vehicles were not tested because there was not enough testing time available to pause the vehicle for six hours.

12-volt battery test

100% (129/129) of the tested vehicles were able to start up after the overnight test, meaning the 12V battery had sufficient charge for the vehicle to start. Logically, these vehicles represent 100% of the tested market share.

Test 5 – Response to increasing charging speed after three hours of constant charging speed

Summary

Goal	To validate whether the vehicles are still responding to changes in charging speed after a long period of time.
Description	The test increased the allowed charging speed after three hours of consistent charging speed.
Key outcomes	100% (129/129) of all the tested vehicles were able to change the charging current after charging for three hours, which represents 100% of the tested market share.
Remarks	If the six-hour pause or delay test failed, this test was executed separately. In the case of time constraints, the test was unfortunately not executed.

Introduction

For a seamless customer experience with charging, vehicles should be able to follow changes in the speed limits of charging, even after the limit has been constant for three hours. In the past, the ElaadNL Test Lab has experienced cases in which a vehicle was not able to change its charging speed after it had been consistent over a significant time. This test was performed to analyze the EV's response after three hours of charging at a consistent speed.

Method

The vehicle was placed on a charger where 1) the six-hour delayed charging test, 2) the six-hour paused charging test (mentioned in "Test 4 – Response to charging pauses") and 3) the three-hour low charging speed test were performed consecutively. After the six-hour delayed and paused charging tests, the vehicle was charging at 6A on one-phase for three hours. After three hours had passed, the charging current was changed to 16A.

It is important to note that– the tests were performed consecutively in order to save time. If the three-hour test was not successful (due to the vehicle not charging after the six-hour paused test), the test was performed again separately, time allowing.

Test set-up

For this test the third test set-up was used, which is mentioned in Test Methodology chapter under physical test set-up.

Test criteria

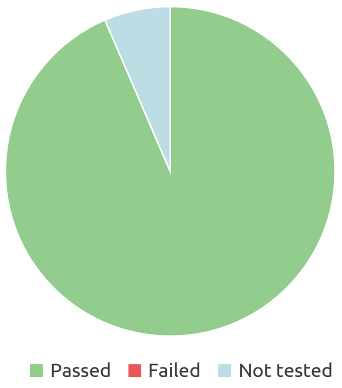
Increasing charging speed after three hours constant charging	
Pass	The vehicle changes the charging speed when the current limit changes after three hours.
Fail	The vehicle does not change the charging speed when the current limit changes after three hours.

Results in detail

Below are the results of the three-hour slow-speed charging test:

Charging status	Percentage passed	Tested market share
Continues to charge	100% (129/129)	100%

Increase charging speed after 3 hours of slow charging



100% (129/129) of the tested vehicles were able to increase the charging speed when the current limit changed after three hours.

9.2% (13/142) of the vehicles in the sample size were not tested (representing 6.5% of the tested market share) because they were not behaving correctly during the six-hour paused or delayed charging tests (mentioned in “Test 4 – Response to charging pauses”) that were performed prior to this test. Because of this, the charging session could not begin, and, due to time constraints, a separate test could not be executed. Considering that 100% of the other vehicles (which were tested) passed the test, it is unlikely that the vehicles that could not be tested on this aspect would have failed.

Test 6 - User notifications through vehicle app

Summary

Goal	To delineate push notifications sent to the customer by a vehicle app during smart charging.
Description	During a smart charging session, the push notifications sent by the vehicle app are monitored on three aspects: • Latency • Information about charge speed • Information about start, stop, pause and resume
Key outcomes	Of the vehicle apps that were tested and able to connect: • 28.6% (22/77) were able to send notifications whenever the vehicle started or stopped charging, or when the charging was being paused. This represents 47.6% of the tested market share; • 24.7% (19/77) were sending messages every charging iteration, which represents 15.5% of the tested market share; • 37.3% (28/75) were able to display the charging speed of the vehicle, which represents 30% of the tested market share.
Remarks	11.3% (16/142) of the total amount of tested vehicles have not been tested on the app because they provided no information.

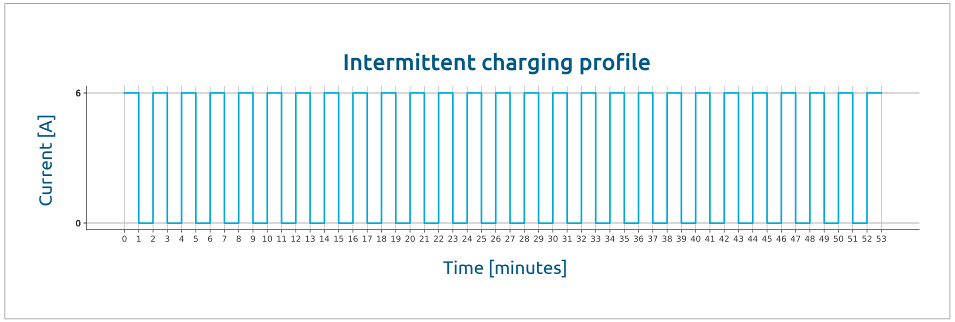
Introduction

A mobile application that comes with a vehicle is a great way provide the customer with status updates, such as battery and charging state. With the introduction of smart charging, the need for information is likely to change. In this test, we examine the information provided to the customer through the associated vehicle app during a typical smart charging session. The results of this test are not qualified as pass or fail, but rather this test provides insights into current vehicle apps, and how they inform the customer during a smart charging session.

Method

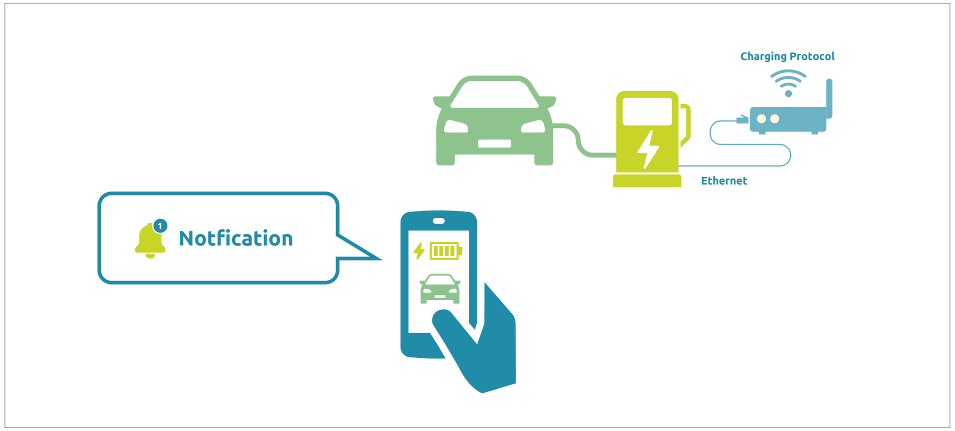
When available, the vehicle app was connected to the tested vehicle. After a successful connection, the notifications and charging status of the vehicle were enabled in the app.

After a successful connection, the app was monitored during the intermittent charging test, which is displayed in the image below.



Test set-up

For the app test, the following test set-up was used:



Test criteria

Since this was an observational test, no pass/fail criteria are defined. During a smart charging session, the notifications sent by the vehicle app are monitored on two aspects:

- Information about charge speed
- Information about start, stop, pause and resume

The test could only be executed when a vehicle app was available and could be successfully connected with the test vehicle.

Results in detail

Available apps

In total, there were 43 brands tested of vehicles that had an app available. One of the tested brands did not have an app available. Of the total amount of available apps, 33 brand apps have been tested. The untested apps were not included because no information was provided regarding which apps to use during the testing of the vehicles.

Apps able to connect to vehicle

App status	Percentage passed	Market share
Vehicle apps able to connect	61.1% (77/126)	57.6%

Of the total amount of tested vehicles, 88.7% (126/142) were tested to see if the app could connect to the vehicle.

61.1% (77/126) of the total amount of tested vehicles could connect to the app. Representing 57.6% of the tested market share.

The procedure for connecting the vehicle app to the tested vehicle could not always be completed. The main reasons for a failed connection were:

- Only the main user could connect, and their login information was not available, or an account had to be removed in order to become the main user;
- Two keys were required to connect and the second key was not available.

Tested vehicle apps that were sending messages

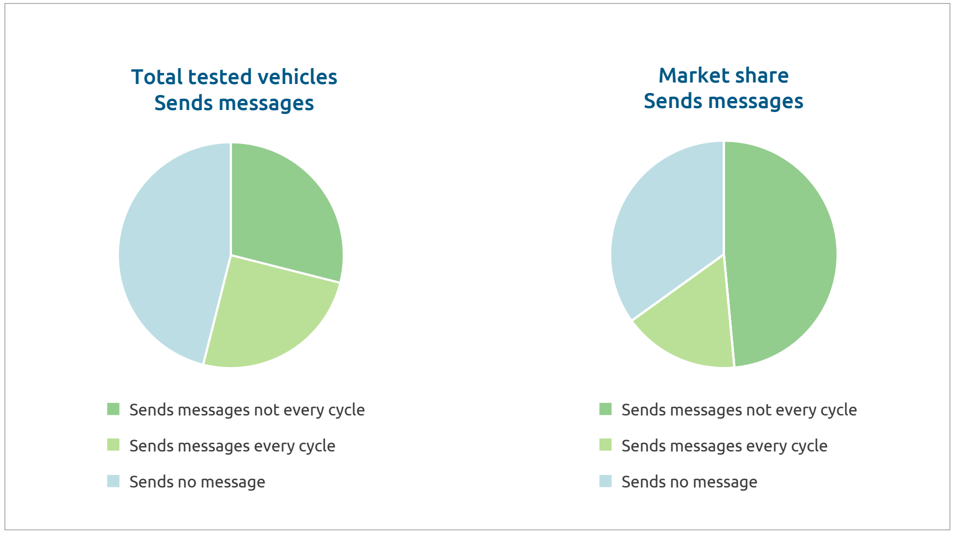
App status	Percentage passed	Market share
Does not send messages every iteration	28.6% (22/77)	47.6%
Sends messages every iteration	24.7% (19/77)	15.5%

Of the total amount of app-vehicle combinations that were tested, 28,6% (22/77) resulted in messages about the charging status of the vehicle, but not at every charging iteration of the tested charging session (see "intermittent charging profile" in methods above). This represents 47.6% of the tested market share.

The app sent messages at every charging iterations of the tested charging iteration in 24.7% (19/77) of cases of the total amount of tested app-vehicle combinations. This represents 15.5% of the tested market share.

In 46.8% (36/77) of the total amount of tested app-vehicle combinations, the app did not send messages when the charging status of the vehicle changed. This represents 36.9% of the tested market share.

Tested vehicle apps that were displaying the charging status

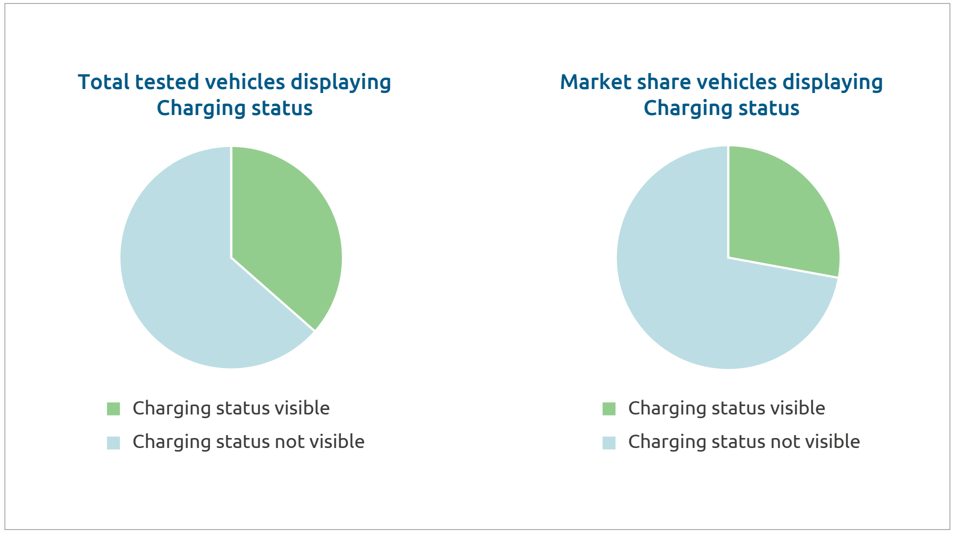


App status	Percentage passed	Market share
Showing charging Status	37.3% (28/75)	30%

Note: due to specific circumstances, two app-vehicle combinations were not tested on the charging status test.

Of the total amount of tested app-vehicle combinations, 37.3% (28/75) were able to display the charging status of the vehicle. This represents 30% of the tested market share.

For 62.7% (47/75), the app did not display the charging status of the vehicle. This represents 70% of the tested market share.



CHAPTER 4

Results: Power Quality immunity

Due to the ongoing energy transition, greater variability in grid Power Quality is anticipated. This chapter presents tests that were conducted to verify the vehicle's capacity to handle fluctuations in power quality within the specified regulatory thresholds.

Test 7 - Voltage deviations

Summary

Goal	To validate the compliance of the vehicles during changes of the voltage on the grid, according to the IEC 50160.
Description	Several tests were performed, in which the grid voltage was changed. The tests include two tests in which voltage was slowly increased and decreased, and one test including a large jump in voltage.
Key outcomes	*Of the tested vehicles:* • 100% (142/142) kept charging on both the maximum charging speed and 100% (141/141) at 6A, when the voltage of the grid was above the lower limit (higher than 196V). This represents 100% of the tested market share. • 97.9% (139/142) continued charging at the maximum charging speed, and 94.3% (133/141) at 6A during the entire overvoltage test, and was charging below 110% of the allowed charging current. This represents 97.3% of the tested market share at the maximum charging speed, and 96.8% at 6A. • 97.2% (138/142) continued charging at the maximum charging speed, and 99.3% (138/139) at 6A, after the voltage dip, representing 99.2% of the tested market share at the maximum charging speed, and 98.7% at 6A.
Remarks	None

Introduction

There are several power quality scenarios that can happen on the grid, to which a device should be immune. For instance, the voltage in the grid can deviate from its standard 230V per phase. If the demand is higher than the supply, the voltage can decrease, and vice versa. Furthermore, if there is a sudden change that results in a high amount of current being drawn because of inrush current or a short circuit, the voltage can drop suddenly. Because of this, the voltage on the grid can change (sometimes quite dramatically) during a charging session. It is important to know how the vehicles will respond to deviations of the grid voltage, as well as how they respond when the voltage returns to 230V.

Method

For each of the following tests, the vehicle was charging at the maximum phase number. Each test was performed at the maximum charging current and at 6A. During the tests, the grid voltage always began and ended at 230V. Tests always ended with at least 30 seconds at 230V, so that the vehicles had time to restart charging, if charging was stopped. During tests, the charging status and drawn current was monitored.

Undervoltage

In the Netherlands, the voltage on the grid is allowed to fluctuate within +10% and -15% of 230V (253V & 196V), as stated in the IEC 50160. This value is based on a 10-minute average, meaning the grid voltage may exceed the limit for a short time, as long as the 10-minute average threshold is within limits.

To test the immunity of vehicles to undervoltage deviations, the grid voltage was lowered by 2V every second until it reached 180V, after which it was returned to 230V with similar 2V steps. During this test, the vehicle continued charging when the voltage was at least 196V (-15%) or higher. If the voltage is below 196V, a vehicle is allowed to stop charging, but it should restart when the voltage is back within limits. The vehicle should not increase the current.

Overvoltage

To check the overvoltage limits, the grid voltage was increased by 2V every second until it reached 260V, and then decreased back to 230V with similar 2V steps. During this charging period, the vehicle should at least continue charging until the voltage is 253V, but charging is allowed during the whole test.

Since 253V is often reached due to the local production of solar energy, it is beneficial for the grid if vehicles keep charging on this voltage with a slight top margin, as long as this is within specifications of the power converter in the vehicle.

Voltage dip

During the voltage dip test, the grid voltage was immediately lowered from 230V to 161V (70%), for 25 iterations (0.5 s at 50Hz). This corresponds to the voltage dip from the IEC 61000-4-11 standard, which can be found in the table below. The vehicles should be immune to this voltage dip, meaning that they should continue charging during the dip, or else resume charging when the voltage is back to 230V.

A voltage dip might be caused by a high load on the grid. When the voltage lowers, vehicles might take in more current to compensate for constant power. This puts an extra load on the grid while it is already stressed, especially when many vehicles are connected. From a grid operator’s perspective, it is better that vehicles do not (temporarily) increase the current during the dip, so as not to further load the grid while it is under high load.

At the start of the project, this test was performed with a dip to 100V (40%) for 30 cycles (0.6s at 50Hz); this test was based on the Dutch grid code Article 7.3.2.e. 41. Vehicles were tested with the old version of the test, then the test was changed to follow the IEC standard. Two of the 41 vehicles tested with the old procedures failed—and for those two cases, a retest will be offered.

Classes[a]	Test levels and durations for voltage dips (t_s) (50 Hz/60 Hz)				
Class 1	Case-by-case according to the equipment requirements				
Class 2	0% during ½ cycle	0% during 1 cycle	70% during 25/30[c] cycles		
Class 3	0% during ½ cycle	0% during 1 cycle	40% during 10/12[c] cycles	70% during 25/30[c] cycles	80% during 250/300[c] cycles
Class X[b]	X	X	X	X	X

[a] Classes as per IEC 61000-2-4; see Annex B.

[b] To be defined by product committee. For equipment connected directly or indirectly to the public network, the levels shall not be less severe than class 2.

[c] "25/30 cycles" means "25 cycles for 50 Hz test" and "30 cycles for 60 Hz test". "10/12 cycles" means "10 cycles for 50 Hz test" and "12 cycles for 60 Hz test" and "250/300 cycles" means "250 cycles for 50 Hz test" and "300 cycles for 60Hz test".

[d] May be replaced by product committee with a test level of 50% for equipment that is intended primarily for 200 V or 208 V nominal operation.

Test set-up

The test set-up used is the second test set-up, which can be found in the Test Methodology chapter under physical test set-up.

Test criteria

Undervoltage test	
Pass	The vehicle continues charging at 196V or above. The vehicle is charging below 110% of the permissible charging current.
Fail	The vehicle stops charging before the voltage was lowered to 196V, or it was charging at 110% or more of the permissible charging current.

Overvoltage test	
Pass	The vehicle continues charging at 255V or lower. The vehicle is charging below 110% of the permissible charging current.
Fail	The vehicle stops charging before the voltage was increased to 255V, or it was charging at 110% or more of the permissible charging current.

Voltage dip	
Pass	The vehicle stopped charging when the voltage was lowered from 230V to 161V and resumed charging when the voltage was rising back to 230V. The vehicle is charging below 110% of the permissible charging current.
Fail	The vehicle did not stop charging during the voltage dip, or it did not resume charging after the voltage was rising back to 230V, or it was charging at 110% or more of the permissible charging current.

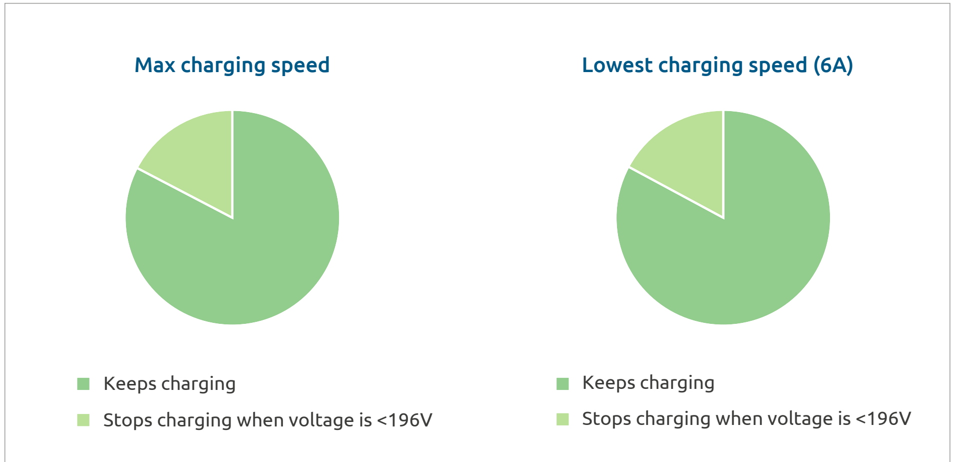
Results in detail

Undervoltage

Each vehicle's behavior was tested during undervoltage, on both the maximum and low charging current.

Charging status	Max speed percentage passed	Max speed market share	6A percentage passed	6A market share
Continues charging	95.1% (135/142)	82.7%	96.5% (136/141)	82.8%
Stops charging when voltage is 196 or lower	4.9% (7/142)	17.3%	3.5% (5/141)	17.2%

Note: due to time constraints, one of the vehicles could not be tested on 6A for the undervoltage test.



100% (142/142) of the tested vehicles continued charging under both conditions when the voltage on the grid was within limits (higher than 196V).

At the maximum charging speed, 95.1% (135/142) of the tested vehicles continued charging during the entire undervoltage test, and at 6A this was 96.5% (136/141) of the vehicles—this represents 82.7% and 82.8%, respectively of the tested market share.
Of the tested vehicles, 4.9% (7/142) and 3.5% (5/141) stopped charging when the voltage of the grid was below 196V, at the maximum charging speed and 6A respectively. These vehicles represent 17.3% of the tested market share at the maximum charging speed and 17.2% at 6A. Considering that the lower limit of the grid is 195.5V, this behavior is marked as a trivial error.
None of the vehicles increased the drawn current to compensate for constant power.

Of the tested vehicles, four did not restart charging after stopping charging during undervoltage. These results have been shared with the corresponding vehicle manufacturers; they will research this behavior, and the vehicles will be retested in due time.

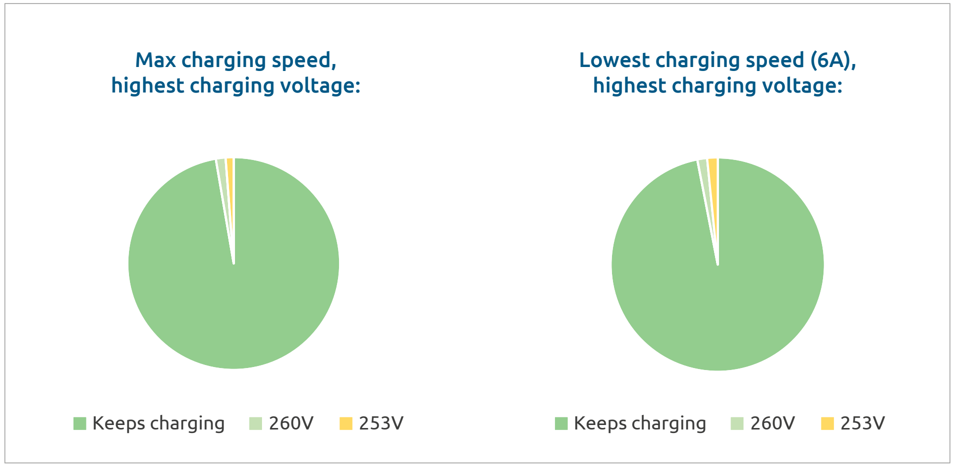
Overvoltage

Each vehicle was tested on its behavior during overvoltage, on both the maximum charging current and low charging current.

Charging status	Max speed percentage passed	Max speed market share	6A percentage passed	6A market share
Continues charging	97.9% (139/142)	97.3%	94.3% (133/141)	96.8%
Stops at 253V	1.4% (2/142)	1.2%	4.3% (6/141)	1.6%
Stops at >= 260V	0.7% (1/142)	1.5%	1.4% (2/141)	1.5%

Note: due to time constraints, one vehicle could not be tested at 6A for the overvoltage test.

At the maximum charging speed, 97.9% (139/142)—and at 6A, 94.3% (133/141)—of the vehicles continued charging during the entire overvoltage test and was charging below 110% of the allowed charging current. This represents 97.3% of the tested market share at the maximum charging speed, and 96.8% at 6A.



At the maximum charging speed, 1.4% (2/142)—and at 6A, 4.3% (6/141)—of the vehicles stopped charging when the vehicle was charging at 253V. This represents 1.2% of the tested market share at the maximum charging speed, and 1.6% at 6A. Since this can cause charging to stop in a stringent power quality scenario, these results are marked as a minor error.

0.7% (1/142) of the vehicles stopped charging at the maximum charging speed—and 1,4% (2/141) at 6A—when the vehicle was charging at 260V or higher. This represents 1.5% of the tested market share at the maximum charging speed and 1.5% of the tested market share 6A. Considering that 260V is above the limits, this is marked as trivial.

Vehicles charging with a power factor close to zero (pure reactive power) at 6A are drawing current only passively. This means that the current will naturally increase as the voltage increases. These vehicles have also been tested at higher charging speeds with a power factor >=0.85. These results have been shared with the manufacturers; however, in order to investigate the vehicles' response during overvoltage at a low charging speed (6A) the results in this report *only* include the tests at 6A.

At 16A, all vehicles continued charging after the overvoltage test. At 6A, 136/137 vehicles continued charging after the overvoltage test, meaning that one vehicle did not restart charging. This was one of the vehicles that was drawing 100% passive power (power factor close to 0, see Test 13 - power factor), inherently resulting in an increase in current when the voltage increases. Therefore, in this situation the overcurrent protection of the charging station caused the charging station to stop the charging session.

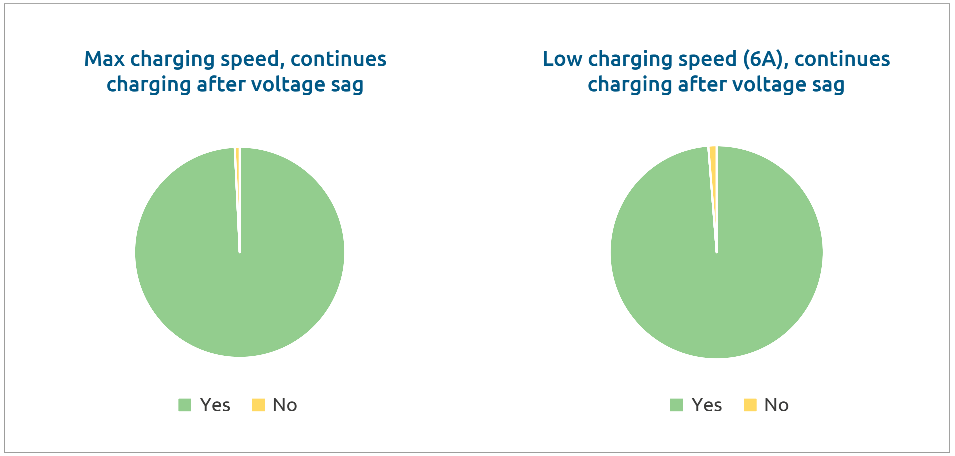
Voltage dip

Each vehicle's behavior was tested during a voltage dip, on both the maximum and low charging currents.

Charging status	Max speed percentage passed	Max speed market share	6A percentage passed	6A market share
Continues charging after dip	97.2% (138/142)	99.2%	99.3% (138/139)	98.7%

Note: due to time constraints, three vehicles could not be tested at 6A for the voltage dip test.

At the maximum charging speed, 97.2% (138/142) of the tested vehicles—and at 6A, 99.3% (138/139)—continued charging after the voltage dip, representing 99.2% of the tested market share at the maximum charging speed, and 98.7% at 6A.



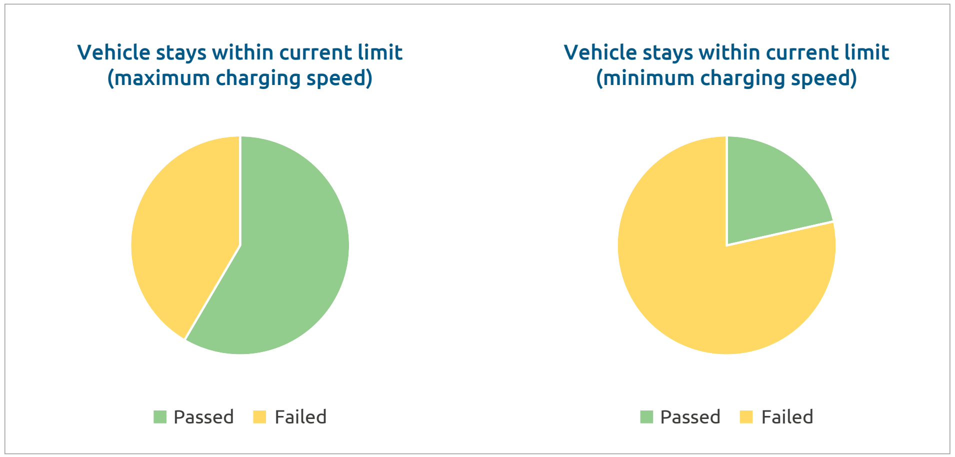
Of the tested vehicles, 2.8% (4/142) at the maximum charging speed and 0.7% (1/139) at 6A respectively, did not continue charging after the voltage dip, representing 0.8% of the tested market share at the maximum charging speed, and 1.3% at 6A. Since this may cause charging sessions to stop only during stringent power quality scenarios, this was marked as a minor error.

Finally, the behavior of the vehicles during the voltage dip was monitored.

Current limit	Max speed percentage passed	Max speed market share	6A percentage passed	6A market share
Stays within current limit	57.4% (81/141)	58.5%	25.2% (35/139)	21.5%

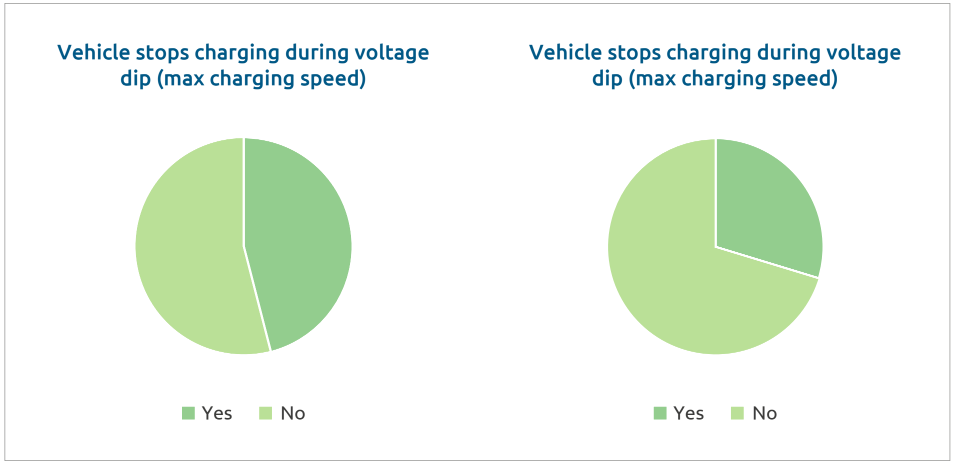
Note: due to time constraints, one vehicle could not be tested at the maximum charging current, and three vehicles at 6A, for current limit test during the voltage dip.

Of all the tested vehicles, 57.4% (81/141) at the maximum charging current—and 25.2% (35/139) at 6A—did not exceed the current limit during the voltage dip, which represents 58.5% of the tested market share on the maximum charging speed and 21.5% at 6A. Since this overshoot may impact the grid during a voltage dip—but a voltage dip is a rare scenario—this is marked as a minor failure.



	Max speed percentage passed	Max speed market share	6A Percentage passed	6A market share
Stops charging during voltage dip	56.3 (80/142)	46.0%	41.7% (58/139)	29.7%

56.3% (80/142) of vehicles at the maximum charging speed and 41.7% (58/139) at 6A stopped charging during the voltage dip, representing 46.0% of the tested market share at the maximum charging speed. and 29.7% at 6A, respectively.



Since charging during the voltage dip is not causing problems to the vehicles or charging station, this was marked as a trivial error. However, from a grid operator's perspective, it is desirable that vehicles stop charging during a voltage dip, resulting in a lower load on the grid.

Test 8 – Harmonic distortions

Summary

Goal	To validate the behavior of vehicles when they charge on a grid with harmonic distortions.
Description	Harmonic distortions were simulated up to 2000Hz, when the vehicles were charging.
Key outcomes	Of the tested vehicles, 83.7% (118/141) continued charging when harmonic distortions were added, which represents 86.2% of the tested market share.
Remarks	There were several moments in which the charging of the vehicle was paused due to overcurrent.

Introduction

It is possible that so-called harmonic and interharmonic distortions appear on the grid. These distortions could change the charging behavior of the vehicle. For example, the vehicle might stop charging, or the vehicle might draw too much current. In order to see if the vehicles are still behaving correctly during these distortions, a Meister curve harmonic distortion test is performed.

Method

During the Meister curve harmonics test, the vehicle charged at its minimum charging current, on the maximum number of phases. Afterwards, harmonic distortions were added to the grid to emulate a distorted grid. The added frequencies went from 16,5Hz to 2000Hz, which can be found in the table below with the corresponding intensity.

	Block 1	Block 2	Block 3	Block 4
From	16.5Hz	100Hz	500Hz	1000Hz
To	100Hz	500Hz	1000Hz	2000Hz
Intensity	3%	9%	(4500/current frequency) %	(4500/current frequency) %

If the vehicle continued charging during the entire Meister curve harmonics test, the vehicle passed the test. If the vehicle was unable to charge during part of the Meister curve harmonics test, or if there were unexpected changes during the charging session, the vehicle failed the test.

Test set-up

The test set-up used is the second test set-up, which can be found in chapter Test Methodology chapter under physical test set-up.

Test criteria

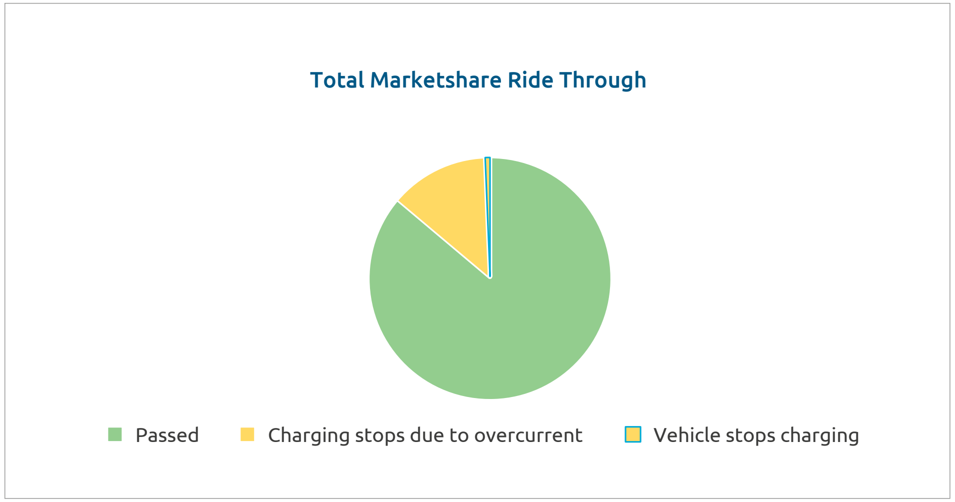
Meister Curve Harmonics distortions	
Pass	The vehicle was able to continue charging when distortions were present on the grid.
Fail	The vehicle failed the test if it stopped charging when distortions were added to the grid.

Results in detail

Each vehicle was tested on its ability to keep charging during the Meister curve test.

Meister curve results	Percentage passed	Market share
Continues charging/ride through	83.7% (118/141)	86.1%
Charging station stops due to overcurrent	13.5% (19/141)	13.2%
Vehicle stops charging itself	2.8% (4/141)	0.6%

Note: due to time constraints, one vehicle could not be tested for the Meister curve harmonics test.



Of the tested vehicles, 83.7% (118/141) continued charging during the entire Meister curve harmonics test, representing 86.1% of the tested market share.
13.5% (19/141) of the tested vehicles increased the current intake when distortions were added, causing the charging station to stop charging due to overcurrent protection. These vehicles represent 13.2% of the tested market share. Considering that the charging station is the cause of stopping the charging session, this was marked as a minor error.

Of the tested vehicles, 2.8% (4/142) stopped charging by themselves during the Meister curve test, representing 0.6% of the tested market share. These vehicles were unable to carry out the entire Meister curve test.

Test 9 - Phase Switching

Summary

Goal	To validate whether the vehicles are capable of switching between one- and three-phase charging.
Description	Vehicles that were capable of three-phase charging will switch between charging on one phase to charging on three phases.
Key outcomes	97.3% (109/112) of the tested vehicles were capable of switching from one-phase charging to three-phase charging. These vehicles represent 98.4% of the tested market share.
Remarks	If more than 50V was detected during the Voltage on non-powered phases (see "Test 10 – Voltage on non-powered phases") test, this test was not performed. However, this report also contains the behavior during smart charging with a charging station that switches between phases, which was done in order to test whether a vehicle is able to switch between one- and three-phase charging.

Introduction

Several charging stations exist that can switch between one-phase charging and three-phase charging. This has various advantages: it can be used for load balancing, or to charge only on the phase in which solar energy is available. To validate if vehicles are capable of switching from three-phase to one-phase charging and back, a phase switch charging test was performed.

Method

During this test, a charging session was started on three phases. The charging was then paused (Control Pilot signal 100% PWM) and phase two and phase three were switched off in the breakout box (see figure below). Afterwards, charging was restarted from the charging station side (Control Pilot signal 53% PWM, current limit = 32A). After the vehicle started charging on one phase, the charging was again paused, and phase two and phase three were switched back on in the breakout box. Finally, charging was started from the charging station (Control Pilot signal 27%, current limit = 16A) once again. Then, the vehicle should start charging on three phases.

Test set-up

The test set-up used is the second test set-up, which can be found in Test Methodology chapter under physical test setup.

Test criteria

Phase switching	
Pass	The vehicle is charging on three phases after charging on one phase, during the same charging session.
Fail	The vehicle is not able to charge on three phases after charging on one phase, during the same charging session.

Results in detail

Each vehicle that was capable of charging on three phases was tested on its ability to switch between one-phase charging to three-phase charging.

Switching phases results	Percentage passed	Market share
Able to switch from one-phase charging to three-phase charging	97.3% (109/112)	98.4%

Of all the tested vehicles, 97.3% (109/112) were capable of charging on three phases after charging on one phase, during the same charging session. This represents 98.4% of the tested market share.

Test 10 - Voltage on non-powered phases

Summary

Goal	To research how many vehicles have a high voltage (>50V (AC) on non-active phases. To validate if the none-powered phases of the vehicle could cause problems.
Description	The voltage on the three phases was measured while two phases were disconnected during a charging session.
Key outcomes	Of the tested vehicles, 87.9% (94/107) had Phase 2 and Phase 3 stay below 50V while charging on one-phase, Representing 88.1% of the tested market share.
Remarks	None.

Introduction

In ElaadNL's experience, it is known that voltage might be present on non-live phases during one-phase charging at the charging port of a three-phase vehicle. This might be due to the phases being internally connected, for instance, to connect two inverters to charge at a higher current. In an extreme case, this could result in the vehicle directly connecting one phase with another. This might pose a risk for a short-circuit during phase switching (see "Test 9 – Phase Switching") or for an electrical shock during maintenance on a phase in the connected installation that is deemed to be inactive.

Method

Based on NEN-EN-IEC 61140, we defined the safe limit on non-live phases at 50V (AC). This voltage is deemed safe to touch, without any electrical protection needed.
The test started by charging the vehicle on all three phases. The charging was paused, and Phase 2 and Phase 3 were disconnected, with the aim to measure the voltage that the vehicle applies to its L2 and L3 contactor. From this moment, there should be less then 50V (AC) provided from the vehicle to Phase 2 and Phase 3.
If the voltage stayed below 50V, the test continued and the vehicle could start charging on one-phase only. The voltage measurement was repeated once.

Test set-up

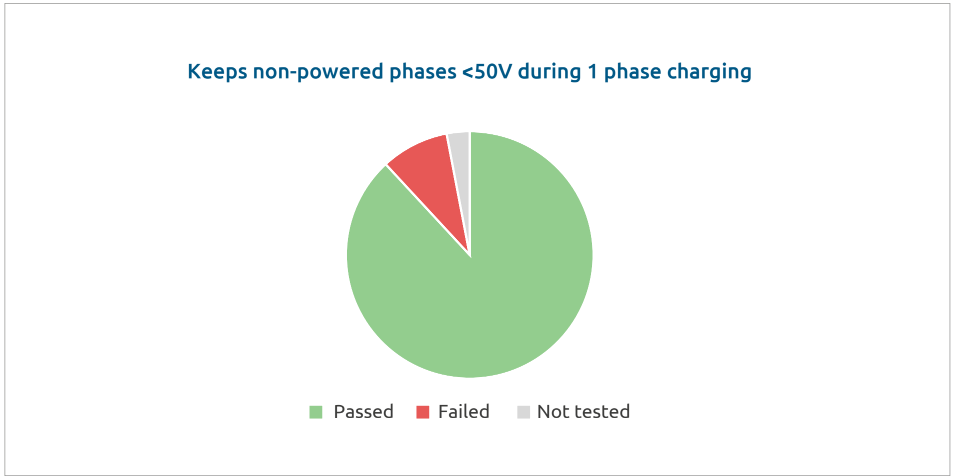
The test set-up used is the second test set-up, which can be found in Test Methodology chapter under physical test set-up.

Test criteria

Voltage on non-powered phases	
Pass	The voltage on phase 2 and phase 3 stayed below 50V, during the entire time phase 2 and phase 3 were disconnected from the grid.
Fail	The voltage on phase 2 and/or phase 3 was 50V or higher when the phases were disconnected from the grid.

Results in detail

Power on phases results	Percentage passed	Market share
Stays below 50V	87.9% (94/107)	88.1%



Of the tested vehicles, 87.9% (94/107) of vehicles passed the test that kept the voltage on two phase and three phase below 50V while charging on one-phase. This is equal to 88.1% of the tested market share.

Of all the vehicles capable of three-phase charging, 5.3% (6/113) were not tested. This was due to the fact that the test in which the vehicles switched from one-phase charging to three-phase charging was not yet properly set up during the early stages of the project—it was not due to the behavior of the charger or vehicle during the test.

For 12.1% (13/107) of all tested vehicles, a voltage of >50V would be present when the vehicle was charging on one phase. Sometimes this lasted less than a second, and in some cases the exact sine of 230V of L1 was visible on L2 and L3. The risk does exist that a short-circuit could occur during a phase switch, or an electric shock during maintenance. Thus, the issue was reported to the corresponding vehicle manufacturers.

CHAPTER 5

Results: Power Quality emissions

The car itself can be the origin for fluctuations in power quality. This chapter presents tests that were conducted to verify that the vehicle is not polluting the power quality.

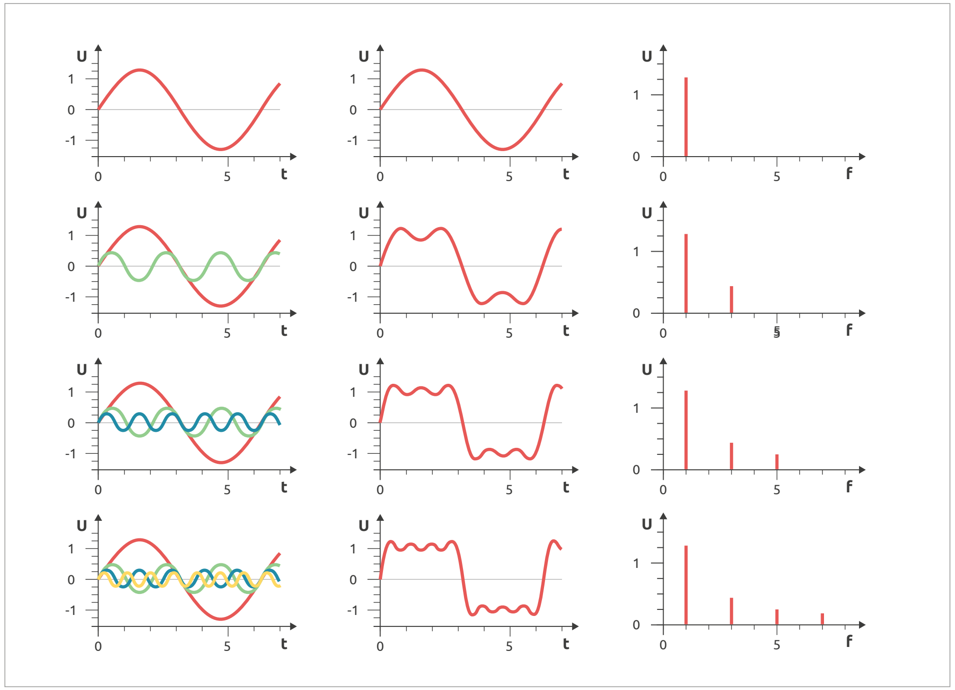
Test 11 – Harmonic emissions

Summary

Goal	To validate whether or not vehicles comply with the standards defining acceptable harmonic limits—not only on nominal power, but also while charging at lower charging speeds.
Description	This measures the emissions of single harmonic currents (current emissions with frequencies of multiples of 50 Hz) and the Total Harmonic Current while charging at various charging speeds.
Key outcomes	• Of all vehicles, 100% (113/113) stayed within the allowed harmonics limits on all the charging speeds, on three-phase smart charging. • Of all vehicles, 95.8% (136/142) stayed within the allowed harmonics limits on all the charging speeds, on one-phase smart charging. This was 97.8% of the tested market share.
Remarks	None

Introduction

A harmonic current is one that has a frequency that is an integer multiplication of the fundamental frequency of the grid (50Hz). This means that the 2nd harmonic is at 100 Hz, the 3rd harmonic is at 150 Hz, etc. Some examples can be seen in the graphs below, where the first graph shows a clean sinus wave, and furthermore in the graphs below, that an extra harmonic is added in each consecutive graph. At the left, the separate frequencies are shown; in the middle, the resulting wave pattern, and at the right a so-called FFT diagram, which shows the amplitude of each harmonic frequency.



For the first 40 harmonics, there are limits to which devices up to 16A must comply. For devices with a power rating between 16 and 75A, there are limits for the first 13 harmonics and for the Total Harmonic Current (THC).

However, compliance to these limits is only tested at nominal power (so the highest charging speed), not a limited lower charging speed. To research the effect of charging at lower speeds on the harmonic emissions, the amplitude of the 40 harmonic currents that are present and the THC will be measured at various charging speeds and analysed according to the relevant limit, to the corresponding charging speed.

Method

To gather data for this test, the amplitudes of the different harmonic currents that were present were measured during the in-depth smart charging profile test during which the vehicles were charged at different charging speeds (see "Test 2 smart charging profile/compliance to Mode 3 charging").

A python analysis tool then compared the recorded emissions to the emission limits defined by standards IEC 61000-3-2 and IEC61000-3-12. The IEC 61000-3-2 is an international standard that limits main voltage distortion by prescribing the maximum value for harmonic currents from the second harmonic up to and including the 40th harmonic current. IEC 61000-3-2 applies to equipment with a rated current up to 16A. The 61000-3-12 prescribes the maximum value for harmonic currents from the second harmonic up to and including the 13th harmonic current and for the Total Harmonic Current (THC). This standard applies to equipment with a rated current between 16 and 75A. The limits can be found in Appendix E – Harmonic emission limits.

For each vehicle the results were summarized in a list of limit crossings per harmonic and charging speed, if any. These were shared with the manufacturers only. The overall results were plotted in an anonymized and aggregated heatmap (see "Test 12 - Supraharmonics").

Test set-up

The test set up used can be found in the Physical Test set-up, under second test set-up.

During testing, the currents (between the 'grid' and the charging station) and Control Pilot socket (PWM signal indicating the charging limit) were recorded by using the Dewetron measurement computer for analysis.

In order to examine the behavior of the vehicle, a charging station is needed that does not stop charging as a result of an overshoot of overcurrent by the vehicle, since this would obscure the test results. The charging station chosen for this test continues charging until 10% overcurrent.

Test criteria

Harmonic emissions	
Pass	The combination between the harmonic currents and charging speeds stayed within the limits, stated in the standards IEC 61000-3-2 and IEC61000-3-12.
Fail	The combination between the harmonic currents and charging speeds exceeded the limits, stated in the standards IEC 61000-3-2 and IEC61000-3-12.

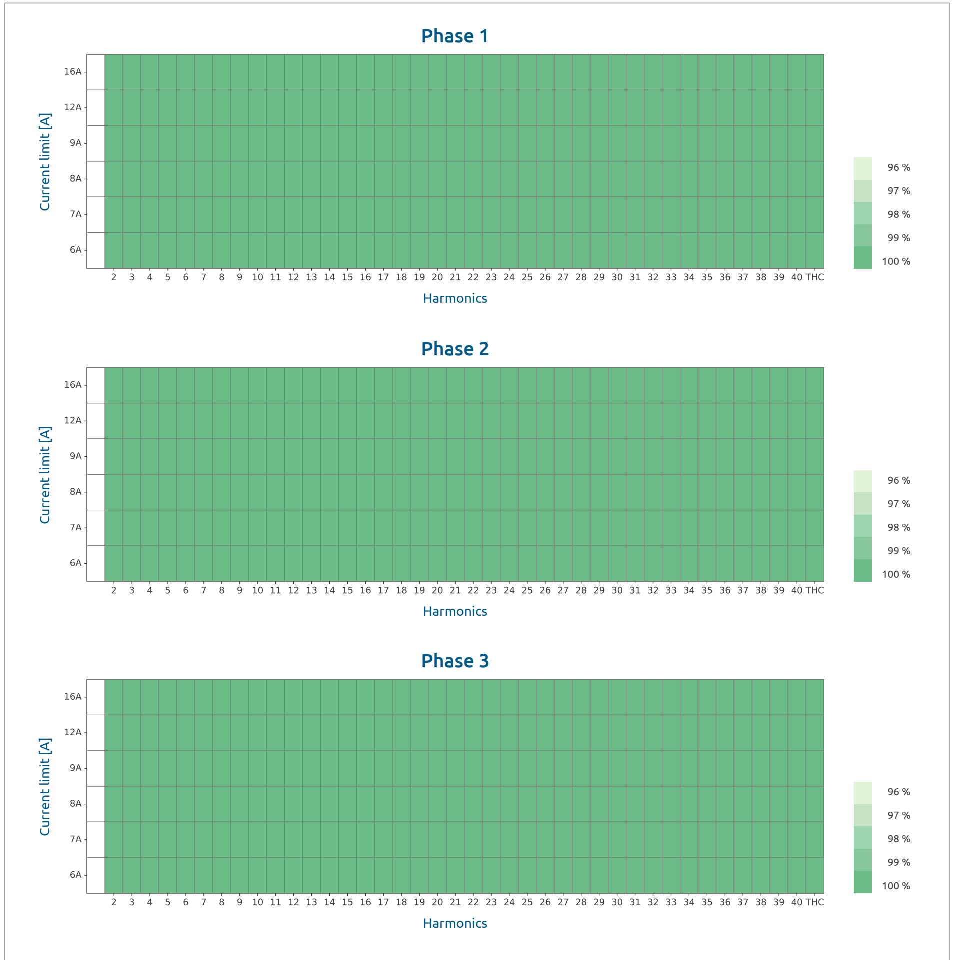
Results in detail

Below, heatmaps are presented that display the results in percentages—they indicate how many of the vehicles' currents stayed within the harmonics limits.

Heatmap 3 phase charging

Harmonics distortions	Percentage passed	Market share
Number of vehicles that had no harmonics distortions during 3 phase charging	100% (113/113)	100%

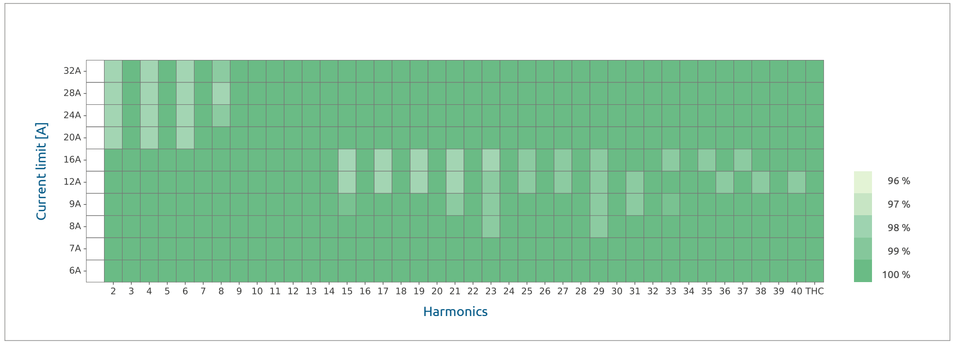
As can be observed from the image below, all combinations of harmonic currents and charging speeds stayed within limits, as stated in the standards IEC 61000-3-2 and IEC61000-3-12. This was true for all vehicles during three-phase charging.



Heatmap 1 phase charging

Harmonics distortions	Percentage passed	Market share
Number of vehicles that had no harmonics distortions	95.8% (136/142)	97.8%

Of the total amount of tested vehicles, 95.8% (136/142) stayed within the harmonics limits (stated in the standards IEC 61000-3-2 and IEC61000-3-12) on one-phase charging. This represents 97.8% of the tested market share. Additionally, no vehicle exceeded the harmonics limit on the THC.



Test 12 - Supraharmonics

Summary

Goal	To gather data on supraharmonic distortions by vehicles, which can be used for further research and as input for standardization.
Description	This measured supraharmonic distortions (2kHz-150kHz) while charging at various charging speeds.
Key outcomes	Around 22% (one phase) and 25% (three phase) of the vehicles exceeds the CISPR supraharmonic distortion limit.
Remarks	This is merely an indicative test; for a proper research program, a different test set-up is needed. However, this test has been included to show that distortions are present, and that more research is needed regarding this range of distortions.

Introduction

During the harmonic analysis in test 11, the current harmonics (up to the 40^{th} harmonic) have been evaluated. As these are multiples of the base frequency of 50Hz, this adds up to frequencies of 2kHz. Higher frequencies should also be investigated. Modern AC/DC convertors have high frequency switching components which can create current emissions above 2kHz, which are known as supraharmonic or low frequency conducted distortions. The supraharmonic distortions range is defined by the 2 to 150kHz frequency band. As of now, current distortions in this frequency spectrum are not regulated for EV or charging stations. However, since this might be regulated in the future and does have an impact (which is explained below), the supraharmonic distortions test is included in this report.

Just like harmonic distortions, supraharmonic distortions can cause a temperature increase in grid assets and can influence the grid voltage; this may lead to the failure of grid assets, charging stations, electronic devices, EVs themselves, and other grid-connected devices. It is therefore good practice to keep the supraharmonics as low as possible. As there are no applicable standards for the supraharmonic range yet, there are no current limits available. Therefore, ElaadNL used the limits created within the TEPQEV[1] project (a research project led by ElaadNL, which focuses on learning about the impact of these distortions) which preliminarily put forth limits. The analysis of the supraharmonics is therefore done by comparing the distortion to these preliminary limits. This data will anonymously be used in further research on supraharmonic distortions and as input for the standardization activities.

Method

To gather data for this test, supraharmonic emissions were recorded during the in-depth smart charging profile test, during which the vehicles were charged at different charging speeds (see “Test 2 smart charging profile/compliance to Mode 3 charging”).

Test set-up

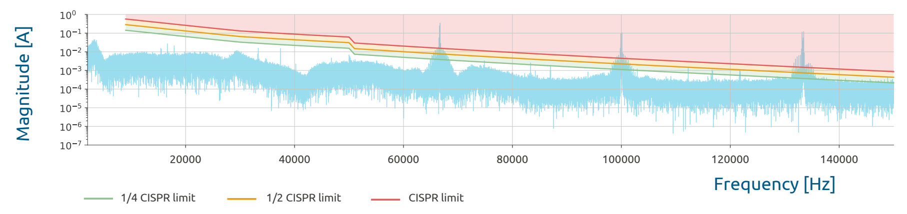
The test set-up used can be found in the physical test set-up section under the second test set-up.

Thanks to the high sampling rate and to the highly accurate current transducers, the measurement set-up was able to measure these high frequency and low amplitude currents. However, since this test was not part of the original test protocol, the test set-up was not designed with this test in mind. Therefore, distortion peaks were already present during the measurement. During analysis, the peaks that are naturally present in this test set-up have been ignored, to only include the distortions that are clearly coming from the vehicle.

The measurements have been analysed using a python analysis tool, which compares the frequency plot (as seen in the image “Frequency Spectrum” below) with limits suggested by T. Slangen in the TEPQEV project. These frequency plots show the frequency up to 150 kHz on the x-axis, and the logarithmic amplitude in current on the y-axis.

1 https://elaad.nl/en/projects/tepqev/

As illustrated below, multiple limit lines have been drawn in the graph. These are based on the differences in grid impedance and the way distortions add up. The amount of distortion and the effect on voltage was influenced by the impedance of the grid which can differ per location. Furthermore, the TEPQEV research concluded that when multiple devices with AC/DC converters (like EVs) were connected, the distortions were increased initially and then decrease once more. The distortions roughly doubled at the highest point, which is visualized here as three lines. The more the distortions remain below the lowest of these lines, the better. This test does not produce pass/fail results but gives an indication of the lowest limit to which the vehicle complies. This was measured at all charging speeds.



Example of a supraharmonic analysis: the peaks present in the test set-up are visible at 66, 100, and 133 kHz, along with small exceedances of the limits at other frequencies.

Results in detail

The colours in the table below do not represent a colour severity used in the rest of the report but correspond to the colours found in the graph found in methods.

#phases	Current	Exceeds CISPR	Exceeds ½ CISPR	Exceeds ¼ CISPR
One phase	6A	21.5% (26/121)	95% (115/121)	100% (121/121)
	32A	22.3% (27/121)	81.8% (102/121)	100% (121/121)
Three phase	6A	24.2% (24/99)	94.5% (94/99)	100% (99/99)
	16A	26.3% (26/99)	88.9% (90/99)	100% (99/99)

As the test set-up used was not optimized to measure supraharmonics, these results only give an indication and cannot be used to draw conclusions.

Test 13 - Power factor

Summary

Goal	To see if the reactive current does not become too big when charging speed is decreasing.
Description	The power factor was measured at different charging speeds. The power factor indicates how efficiently the grid capacity is used.
Key outcomes	Of the market share all the tested vehicles: • The power factor decreased by 4.5% when comparing the highest and lowest charging speed, on three-phase charging. • The power factor decreased by 1.5% when comparing the highest and lowest charging speed, on one-phase charging.
Remarks	None.

Introduction

The power factor is the ratio between real, usable, current and the reactive, unusable currents. Reactive currents are currents that are transported but are out of phase when compared to the voltage. This means they cannot be used to generate power or, in this case, to charge the vehicle. The lesser the reactive currents, the higher the power factor.

Because of certain components in the on-board charger of EVs, they may take in a certain amount of reactive current. As the charging station only indicates the current limit, which the vehicle needs to stay below, any reactive current will mean a lower usable current. Therefore, charging becomes less effective. Furthermore, the reactive current needs to be transported as well, and therefore takes capacity of the grid. The Dutch DSOs therefore demand that the power factor of an installation must be at least 0.85 (see article 2.27 from the Dutch “Netcode Elektriciteit”) at voltage up to 50kV at a scale from zero to one. When this threshold is respected, the grid capacity will be used more efficiently and vehicles will be charged faster.

Reactive currents are commonly created by passive components in electronic devices, which are always “on” when connected. Because of this, it is important to measure and analyze the power factor to see if the reactive part of power consumption does not become too large. Since smart charging involves vehicles that charge at varying speeds, the power factor is measured both at higher and lower charging speeds.

Method

To gather data for this test, the power factor was recorded during the in-depth smart charging profile test (see “Test 2 smart charging profile/compliance to Mode 3 charging”), during which the vehicles were charging at different charging speeds. The power factor is manually analysed by taking the average power factor over a period in which the vehicle was charging at a constant speed, at 6, 7, 8, 9, 12, and 16A. Since most vehicles were only charging at up to 16A on three phases, the power factor at 32A was only measured during one-phase charging.

Test set-up

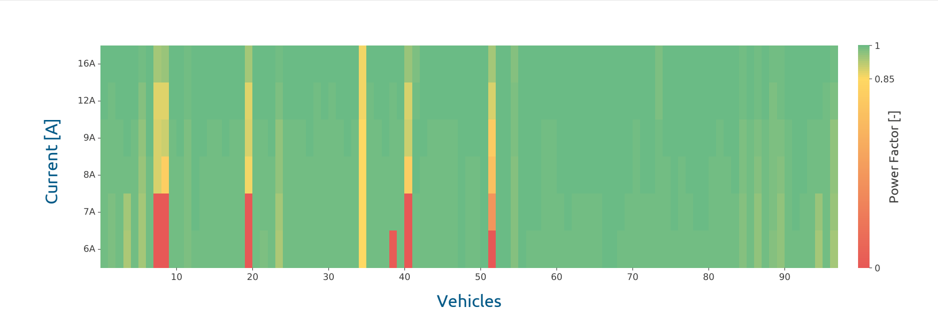
The test set-up used is the second test set-up, which can be found in the Test Methodology chapter under physical test set-up.

Test criteria

Power factor	
Pass	The power factor is equal or above 0.85 for all charging speeds.
Fail	The power factor is lower than 0.85.

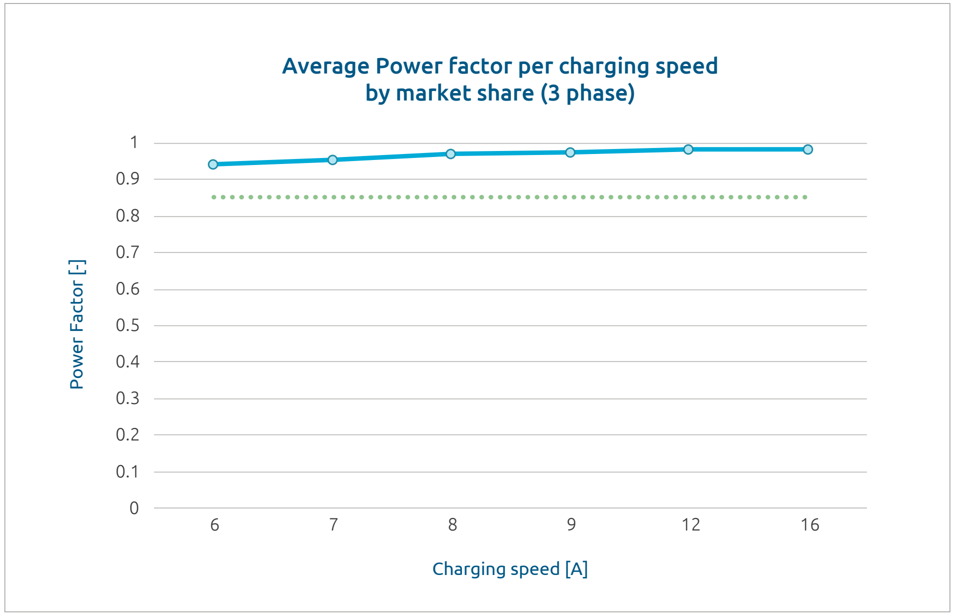
Results in detail

Three-phase charging



The market share of vehicles charging with a power factor of close to zero at the lower charging speeds amounts to 2% (see the image above).

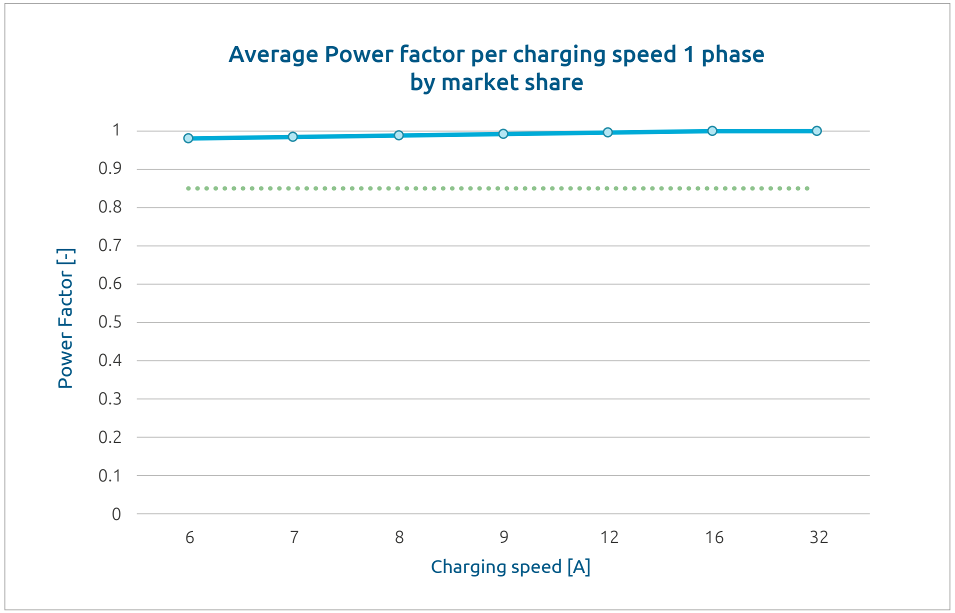
When accounting for the market share, the average power factor decreased by 4.2% when compared with the highest (PF=0,985) and lowest (PF=0,941) charging speeds. This can be observed in the image below.



One-phase charging

The heatmap of the vehicles tested at one-phase charging (found below) gives a good overview of how the power factor changed when the charging speed was decreased. The market share of vehicles charging with a power factor of close to zero at the lower charging speeds amounts to 0.01%.

When taking the market share into account, the average power factor decreased by 1.9% when compared with the highest (PF=0.985) and lowest (PF=0.941) charging speed. This can be observed in the image below.



CHAPTER 6

Summary of Results

This chapter presents an overview of the collected results. In the majority of tests, over 95% of the market share passed. The exceptions to this are summarized after the general results.

General results

Customer perspective:

- Over 97% of the tested market share successfully passed the smart charging interoperability test.
- Over 99% of the tested vehicle market share supports a typical smart charging profile.
- Over 95% of the tested market share supports low-speed charging at 6A.
- Over 95% of the tested market share supports six-hour delayed charging as well as pauses of 20 minutes and six hours.
- Over 90% of the tested market share supports intermittent charging up to 15 iterations of one- minute pause/resume.
- 100% of the tested market share responds to changes in charging speed after long periods of uninterrupted charging.
- For 54% of all tested vehicles, a vehicle app was successfully used by the test team. About 30% of the tested market share of apps show the charging status. When charging is repeatedly paused/resumed, 16% of the tested market share does notify this at every pause/resume iteration and 48% sends irregular notifications.

Grid perspective:

- Over 97% of the tested market share is immune to undervoltage, overvoltage, and voltage dips.
- Over 86% of the tested market share can charge when harmonic distortions are present on the supplied power, which is a positive result.
- Over 98% of the tested market share successfully executed the phase-switching test
- Over 90% of the tested market share stays within safety voltage limit (< 50 Volt) on inactive phases.
- Over 97% of the tested market share does not inject harmonic distortion into the grid.
- Around 78% (one phase) and 75% (three phase) of the vehicles do not exceed the CISPR supraharmonic distortion limit.
- Over 95% of the tested market share has a power factor of at least 0.98 (single-phase vehicles) and at least 0.92 (three-phase vehicles), which is well above the threshold of 0.85.

Low-speed charging, Pauses and Intermittent charging

Over 95% of the tested market share supports low-speed charging. About half a dozen of vehicles had a power factor of below 0.85 when the charging limit was set below 8A. This results in less or no energy transfer. This issue is marked as critical, as it has a direct effect on the driver.

About a dozen vehicles structurally exceeded the charging limit (overcurrent) when the charging speed was set below 8A. This behavior is not noticeable to the driver. However, from a grid perspective, overcurrent is marked as a major issue. There were also some (minor and trivial) issues were found in response times and overshoots.

Over 95% of the tested market share supports delayed charging as well as pauses of 20 minutes and six hours. About 40 vehicles did not fully pass the extreme intermittent charging test, consisting of 25 consecutive charge and pause actions in 50 minutes. 100% of all vehicles tested can handle two full iterations of a one-minute charge plus one-minute pause, and 90% can handle all 25 iterations successfully. Well over 90% of the tested market share supports intermittent charging up to 15 iterations of one-minute pause/resume. As intermittent charging is not defined in the standard, the number of pause/resume iteration to be supported is still undecided. From a safety perspective, some manufacturers limit the number of pause/resume iterations allowed, which resulted in some dropouts for this test.

The (extreme) intermittent charging test consisted of 25 iterations of one-minute charging at 6A followed by a one-minute pause. The goal of this specific test was to validate the maximum number of supported iterations, and it does not represent an everyday charging situation. The choice for pauses of one minute is extreme and was only chosen due to time constraints for testing. In retrospect, this test represents a charging situation that is too extreme and theoretic—therefore, the results need to be interpreted with caution, and ElaadNL has already drafted an improved test set-up. In the future, intermittent charging will be tested with pause/resume iteration of 15 minutes. This altered test scenario is more like the situation of alternate charging of vehicles, for example on a (virtual) charging hub.

Although the test itself does not reflect an everyday charging situation, not supporting intermittent charging is marked as a critical issue because it has a direct effect on the driver.

Power quality immunity

In the case of undervoltage, overvoltage or voltage dips in the power grid, a handful of vehicles temporarily stopped charging but resumed after the grid voltage was restored to regular levels. On the outer voltage limits (or when exceeding the outer voltage limits), a handful of vehicles stopped charging and did not resume. These issues are marked as minor and major.

In the case of harmonic distortions, a handful of vehicles stopped charging by themselves and about 20 vehicles activated the overcurrent protection in the charging station in order to stop charging. This issue is marked as major.

Power quality emissions

A handful of vehicles exceeded the harmonic emission limits. This issue is marked as minor.

Multiple vehicles exceed the CISPR supraharmonic distortion limit. This is just an indicative test but shows that more research into this range of distortions is needed.

Vehicle apps

All tested car brands except one could support a vehicle app. Connecting the vehicle app to the test vehicle proved to be challenging for different reasons, resulting in only 77 successful connections. About 30% of the tested market share (of all the tested vehicles) show the charging status in the vehicle app. When charging is repeatedly paused/resumed, about 16% of the tested market share (of all the tested vehicles) notifies this at every pause/resume iteration, and about 48% sends irregular notifications.

In general, the existing vehicle apps have limited functionality and cannot be customized by the end-user. A distinction is usually not made between a pause and a stop in charging. In the case of intermittent charging, this can result in bothersome push notifications which cannot be turned off.

CHAPTER 7

Discussion and recommendations

This chapter reflects on the outcomes of the smart charging tests, in relation to the large scale and unified implementation of smart charging. It also provides practical recommendations for the scaling up of smart charging.

Performance of vehicles and chargers

The tests performed in this program range from current procedures to hypothetical extremities. In general, vehicles and chargers performed as should be expected within normal smart charging operations. When confronted with extreme fluctuations in charging speeds or very low power limits, some vehicles showed undesirable behavior. In some cases, deviations were mitigated easily by the vehicle manufacturer, due to their involvement during testing. Other vehicle manufacturers are internally assessing and prioritizing the identified issues and may also be able to solve these issues through firmware updates. This shows the value of performing tests at an independent facility—in collaboration with vehicle manufacturers - as was done in this study. It is expected that some vehicle manufacturers can only mitigate the issues by replacing hardware elements, which is not guaranteed to happen.

Safety

A dozen vehicles did not comply to the safety requirements of a voltage limit (< 50 Volt) on inactive phases. This issue is marked as critical, and applicable vehicle manufacturers have been urged to solve this safety issue as soon as possible.

Low-speed charging, Pauses and Intermittent charging

Although 95% of the tested market share complied to the low-speed charging threshold of 6A (as described in the IEC 61851-1 standard), about half a dozen vehicles did not comply to this threshold; in most cases, this was because they were produced before 2019. About a dozen vehicles also structurally exceeded the charging limit (overcurrent) when the charging speed was set below 8A. Applicable vehicle manufacturers have been called upon to resolve these issues or to actively inform drivers. Additionally, when possible, CPOs are advised to refrain charging below 8A to be safe, to minimize impact on the group of customers that could be affected (<5% of current market share) and to maintain the power quality of the grid.

Over 95% of the tested market share supported delayed charging, as well as pauses of 20 minutes and six hours. Longer delayed or paused charging sessions are possible as well for example, when the vehicle is plugged into a charger at an airport, and charging is postponed for several days; or, the vehicle is already full and still connected to the charging station. It is advisable to test whether the vehicle will drain the 12V battery in these situations, and, if possible, to charge the 12V battery with the high voltage battery when needed.

Over 90% of the tested market share supported intermittent charging up to 15 iterations of one-minute pause/resume. About 40 vehicles did not fully pass this extreme (25 iterations) intermittent charging test. As a precaution, some vehicle manufacturers have limited the number of pause/resume iterations. As intermittent charging is not defined in the IEC 61851-1 standard, the number of pause/resume iterations that can be supported is still undecided. Vehicle and charger manufacturers are advised to agree on the number of iterations that will be supported, as well as on a minimum pause time; both of these decisions should be included in an updated version of the standard. In the meantime, applicable vehicle manufacturers are called upon to increase the number of supported pause/resume iterations to at least 15. When possible, CPOs are advised to refrain from extreme intermittent charging and/or to pause for minimum of 15 minutes in order to reduce the number of pause/resume iterations. These two recommendations make it possible to bridge a period of 7.5 hours (15 pause/resume iterations of 15 minutes).

While mobility and the power grid have had virtually nothing to do with each other in the past, they are now becoming inextricably linked due to the rise of electric driving.

Grid-friendly charging ensures the smooth integration of EVs into our electricity grid, enabling charging infrastructure to be scaled without restriction, while simultaneously avoiding local grid overload. Regardless of the issues found, it is essential that the grid operators (DSOs) can change (or lower) the charging speed of all vehicles to a minimum of 6A—or charging can be delayed or paused as described in the IEC 61851-1 standard—in the case that the grid is facing direct capacity restraints and a power failure is eminent.

Power quality

Although the issues regarding power quality are marked as minor and trivial, applicable vehicle manufacturers are advised to select components which are more resilient to voltage deviations and which operate within harmonic emission limits.

Update standards

The smart charging tests performed are based primarily on principles from IEC 61851-1 (2019). Although IEC 61851-1 provides a comprehensive technical framework, it is not sufficient on its own to fully evaluate the performance of smart charging. True assessment requires the inclusion of dynamic, user-oriented scenarios that represent everyday charging situations in the current market. Extended pauses, frequent disconnections, brief charging sessions, and delayed charging initiations are some of the scenarios that are missing in the current version of the standard. It is recommended that the IEC 61851-1 standard is updated, based on the findings of this test report. It is also recommended that a guideline is established for conformity assessments, to ensure reliability.

In addition to the IEC 61851-1 standard, the NEN-EN-ISO 15118-20 standard has been developed and specifies the communication between the EV, including both battery electric vehicles (BEV) and plug-in hybrid electric vehicles (PHEV), and the electric vehicle supply equipment (EVSE). The NEN-EN-ISO 15118-20 standard supports higher-level communication protocols (such as IP-based communication), whereas the IEC 61851-1 controls the charging with PWM-signal only. The IP-based communication extensively enhances the information to be exchanged between the vehicle and charger. It also enables additional functionalities such as:

- Data security both on the transport layer and the application layer;
- Distinctions between two main situations: (a) the EV is in charge of ensuring the mobility needs (scheduled control mode), or (b) ensuring the mobility needs is delegated to an off-board system, which is the charging station (dynamic control mode);
- Bidirectional power transfer (BPT); and,
- Plug and Charge (PnC).

In the coming 15 to 20 years, it is likely the IEC 61851-1 standard and the NEN-EN-ISO 15118-20 standard will coexist, with a gradual phase-out of the IEC 61851-1 standard. Given this timeframe, it is recommended to formally update both standards regularly. Vehicle and charge point manufacturers are advised to regularly update their products accordingly.

Make smart charging obligatory for both vehicles and chargers

The smart charging standards currently available are not mandatory and are adopted by the market itself. As a result, compliance to these standards is voluntary. The test program in this report provides a contribution to market adoption and compliance but identifies and solves issues afterwards (reactively) instead of beforehand (preventively). In this test program, only one vehicle was tested for each model of vehicle and charger. Moreover, each vehicle was tested with only one firmware version, in which it was asked to install the most recent version. Although we believe the results in this report give a realistic perspective on the technical smart charging capabilities, it should be noted that the tests are based on these unique characteristics. Due to the fact that, in some cases, slightly older versions of vehicles were tested, some of the vehicles that failed tests may have been legacy vehicles with typical charging issues that might have been resolved in a more recent version. However, this hypothesis has not been checked with retesting of newer versions of those vehicles. It may be valuable to organise such retests in the future.

It is recommended that smart charging standards become mandatory. The obligation for technical smart charging standards/protocols in vehicles can be mandated through UNECE type approvals and/or EU Whole Vehicle Type Approval (WVTA) under Regulation (EU) 2018/858. The obligation for technical smart charging standards and protocols can be included through, for example, an implementing act or delegated act under European regulations such as the Alternative Fuels Infrastructure Regulation (AFIR), Energy Performance of Buildings Directive (EPBD), Renewable Energy Directive (RED), or Energy Efficiency Directive (EFD).

Continuation of smart charging testing at Elaad Testlab

Although many current EV models with a large market share have been tested in this research, it is recommended to monitor the charging behavior of EVs and how they deal with smart charging in daily practice and consumer experience. New models are coming onto the market and software updates can also have consequences.

As long as smart charging standards are not mandatory and no formal conformity tests are available, ElaadNL will continue to test vehicles and chargers for free. All relevant parties are called upon to make use of these testing possibilities and/or to inform other relevant manufacturers.

The ambition is to further enhance smart charging tests to also include (amongst others): other routes for the control signal (car and energy management system), behavior in case of multiple conflicting control signals, bidirectional charging, EU grid codes, cybersecurity, interoperability and more advanced power quality tests.

Communication to end-users

The majority of tests scored over 95% of the tested marked share for both the customer and grid perspective. This provides a sound technical basis for the large-scale rollout of smart charging. Nevertheless, we do observe a small number of issues which might have a direct impact on a part of the end-user group. From a macro perspective, these issues are exceptions to the rule, but on a micro level it can have direct and noticeable impact on the driver. The good news is that relatively simple solutions can be implemented for nearly all issues in order to mitigate a specific end-user issue. It is recommended to implement solutions for the limited number of issues and to address them through proactive communication.

Uncontrolled charging already requires pro-active communication. Introducing smart charging on a large scale further increases the information needs of end-users. As part of the program “Smart Charging for All”, a simple opt-out possibility should be implemented for customers to refrain from smart charging for an individual charging session. Users wishing to start charging at maximum available capacity immediately after plug-in can make use of an opt-out function, overcoming cumbersome experiences. This functionality provides an action perspective for the limited number of vehicles that face issues with charging at 6A or intermittent pauses.

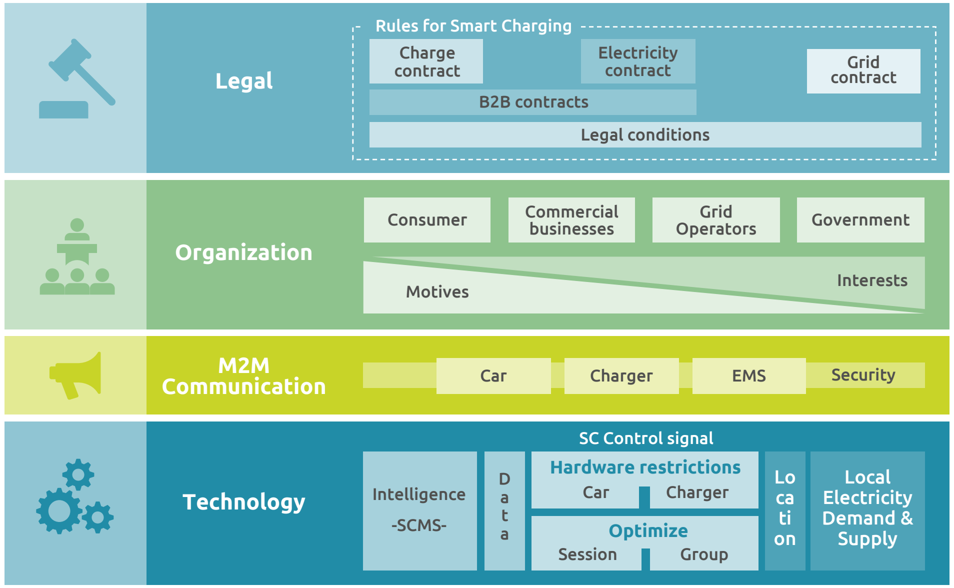
Enhancing functionalities in vehicle apps (e.g., a distinction between pause and stop of charging; the possibility to customize (at least) push notifications) can be other major contributions to improving end-user communication.

ElaadNL also received several suggestions to further improve customer communication from involved stakeholders, including: website with objective information about (smart) charging, information on charging points, the creation of a national helpdesk for charging (for both uncontrolled and controlled charging), training of roadside assistance providers—as well as to actively monitor the actual number of issues reported by drivers through different channels to supervise the unwanted nuisance.
It is up to the Dutch Ministry of Infrastructure and Water Management and all parties involved in the national program “Smart Charging for All” and the “Nationale Agenda Laadinfrastructuur” to discuss these suggestions. It is fundamental to further gain trust and/or create a smooth/effortless smart charging journey for those EV-drivers already active in the EV-scene, but first and foremost, to make it attractive for those contemplating the switch to EV.

APPENDIX A

Smart Charging four-layer model

To understand the different perspectives of smart charging, the smart charging four-layer model was developed by ElaadNL:



The **first layer**, technology, is about the components that make smart charging technically possible, the possibilities and limitations that technology provides, and the data. For example, somewhere in the smart charging ecosystem there must be components that send and receive a control signal. If there is no intelligence anywhere in the hardware, you could not charge smartly (other than by plugging in or plugging out at the right times). But beyond the fact that no one would want to plug in their car in the middle of the night in order to harvest the low-priced power from wind turbines, this isn't what we mean by smart charging. The device itself must contain smart components—be it the charging station and the car, or through another route, such as a home energy management system. The technology also determines the bandwidth within which smart charging is possible: the power used to charge the battery that enters the smart charging point from the grid can never be more than the maximum that is transmitted at every link in the chain.

The **second layer** is the that of communication between devices. This specifies which routes a smart charging control signal can follow and which languages ('ICT protocols') are required. The devices—charging station, car, or other route—must not only have components that can communicate with the outside world; they must also be able to 'talk' to each other in the same language so that they can understand one other. And because that communication must be secure, cybersecurity is a crucial feature in this layer.

The **third layer** is about how we organize it all. Who sends control signals, with which profiles, and with which strategies? And how do these all come together? How can we regulate this? Several parties have a stakeholder interest in smart charging: the motorist, the car manufacturer, the charging station operator, an Electric Mobility Service Provider, the municipality, the grid operator, the energy supplier, a possible 'aggregator', et cetera. These interests can sometimes run in parallel, but they can also be conflicting. As such, the system must be able to handle all stakeholder needs. In addition, a key aspect is that the system that actually controls charging makes intelligent combinations of the input from the diverse group of stakeholders. Intelligent and automated decision-making is needed to satisfy all stakeholders' needs.

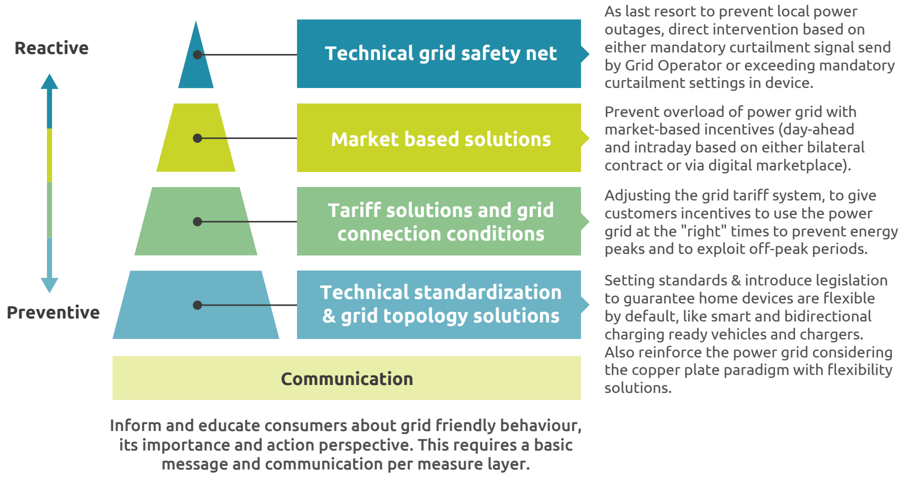
The **fourth layer** is the legal set of contracts, laws and regulations, i.e., the contracts that the parties draw up and the laws and regulations within which they operate. Smart charging starts with an agreement between the person who can provide flexibility (for example, charging an EV later or less quickly) and the person who needs this flexibility. Agreements can therefore vary from long-term (in the form of an annual contract) or be more flexible. It is worth noting here the issue of 'who plays which role'? What is available on the market, and what about public parties? Can grid operators, for example, pay for flexibility or offer other contracts (including flexibility), and can they intervene if there's a risk of overloading the grid? At the moment, the law provides room for experimentation, so we can gain experience with various forms of flexibility—e specially related to smart charging. However, structural solutions are still limited at this moment in time.

A full description of the smart charging four-layer model can be found in the Smart Charging Guide, which can be downloaded at https://elaad.nl/wp-content/uploads/2022/05/Smart-Charging-Guide-EN-single-page.pdf.

APPENDIX B

Flex pyramid of grid protection mechanisms

The Flex Pyramid of grid protection was developed to explain the range of instruments that a grid operator has to stimulate and activate for grid-aware:



The **first** instrument is network tariffs. In the 2019 EU electricity regulation, provisions were made for differentiated network tariffs, allowing for differentiation based on users' consumption profiles. These provisions provide the opportunity to introduce grid transport tariffs that incentivize users to participate in smart charging.

Dutch electricity connections are categorized based on the transport capacity of that connection. The connection and transport agreement is the basis for determining network tariffs. In tariff regulation, the cost causation principle is leading, which means that every connection pays a justifiable amount of the total grid costs for households; currently, this translates to every household paying the same grid tariff, regardless of how much power demand they put on it.

The consumption profile of a small consumption grid connection that regularly charges an EV is significantly different from traditional household use. This leads to reconsideration of the causation principle. Grid operators are investigating how to better distinguish between fixed and flexible access to the electricity grid. In general terms, a new network tariff should encourage consumers to charge when grid capacity is available, in addition to their regular, non-flexible power usage, which can be guaranteed at all times. This results in the more efficient use of the electricity grid and can prevent costly grid reinforcements for avoidable peak loads. From the electricity grid's perspective, it is beneficial to charge cars outside of its traditional peak hours. This means to primarily charge around midday and at night to avoid the peaks that occur in the morning and early evening.

The **second** instrument to manage grid issues is market assistance. When electricity demand exceeds grid capacity in a specific area, a congestion management system is activated. This system is a temporary solution, in which the grid operator asks market participants to adjust their electricity usage at certain times. Smart charging of EVs is one way for market participants to respond, and the grid operator compensates them for this adjustment.

Market assistance can be organized through contracts that guarantee flexibility when needed, such as with large charge point operators. Another option is a digital trading platform in which the grid operator requests flexibility, and market participants submit bids. Market participation platforms are still in early development because congestion management has only recently become a focus for regional grid operators.

The **third** instrument is direct intervention. Even with both previous instruments (network tariffs and market assistance) implemented, a scenario in which a critical grid situation arises must still be considered. In these emergency situations, the grid operator must intervene directly to prevent the electricity supply from failing.

Legislation already allows direct intervention with a legally determined fee. In practice, this would mean that charging EVs is adjusted based on the current grid situation through a signal from the grid operator. The signal for interventive smart charging is mandatory, regardless of the charging profiles that are established voluntarily. Since all charging points in the neighborhood temporarily reduce the charging speed in this scenario, the electricity demand decreases, thus preventing overload.

Technically, there are multiple options for implementation, which can be divided into central control (e.g., curtailment through the back office) and decentralized control (e.g., self-healing modules that are connected to the local grid transformer).

APPENDIX C

List of tested vehicles

Num	OEM	Model
1	Aiways	U5
2	Aiways	U5 (3phase)
3	Aiways	U5 (K810LG)
4	Audi	A3 e-tron
5	Audi	e-tron
6	Audi	Q3
7	Audi	Q6 e-tron
8	BMW	320e
9	BMW	550e
10	BMW	i3
11	BMW	i3s
12	BMW	i4
13	BMW	i5
14	BMW	i7
15	BMW	iX
16	BMW	iX1
17	BMW	iX2
18	BMW	iX3
19	BMW	X3 30e
20	BYD	Atto3
21	BYD	Dolphin
22	BYD	Seal
23	BYD	SealU
24	BYD	Tang
25	Citroen	e-C4
26	Cupra	Born
27	Cupra	Tavascan
28	Dacia	Spring
29	DS	3
30	Fiat	500e
31	Fiat	600e
32	Ford	Capri
33	Ford	E-Transit
34	Ford	Explorer
35	Ford	Kuga
36	Ford	Mach-E
37	Honda	e:Ny1
38	Hyundai	Ioniq 5
39	Hyundai	Ioniq 6
40	Hyundai	Kona
41	Hyundai	Santa Fe
42	Hyundai	Tucson
43	Jaguar	I-Pace
44	Jeep	Avenger
45	KGM	Torres EVX
46	Kia	EV3
47	Kia	EV6
48	Kia	EV9
49	Kia	Niro
50	Kia	Sorento
51	Lancia	Ypsilon
52	Land Rover	Range Rover
53	Land Rover	Range Rover Sport
54	Leapmotor	C10
55	Leapmotor	T03
56	Lynk&Co	E335
57	Maxus	eDeliver3
58	Maxus	eDeliver5
59	Maxus	eDeliver7
60	Maxus	T90
61	Mazda	CX-60
62	Mazda	CX-80
63	Mazda	MX-30
64	Mazda	MX-30 BEV
65	Mercedes	eCitan
66	Mercedes	EQA
67	Mercedes	EQC
68	Mercedes	EQE
69	Mercedes	EQS SUV
70	Mercedes	eSprinter
71	Mercedes	eVito
72	MG	4
73	MG	5
74	MG	Marvel R
75	MG	ZS
76	Mini	Cooper SE
77	Mini	Countryman E
78	Mitsubishi	Eclipse Cross
79	Mitsubishi	Outlander
80	Nio	ET5
81	Nissan	Ariya (1phase)
82	Nissan	Ariya (3phase)
83	Nissan	Leaf
84	Nissan	Townstar
85	Opel	Astra ST
86	Peugeot	e2008
87	Peugeot	e208
88	Peugeot	e3008
89	Polestar	2
90	Polestar	3
91	Polestar	4
92	Porsche	Cayenne Turbo e-hybrid
93	Porsche	Taycan
94	Renault	5
95	Renault	Kangoo
96	Renault	Megane
97	Renault	Scenic
98	Renault	Twingo
99	Renault	Zoe (2017)
100	Renault	Zoe (2022)
101	Seat	Leon
102	Seat	MII electric
103	Seres	3
104	Skoda	Citigo e-iV
105	Skoda	Kodiaq iV
106	Skoda	Octavia
107	Skoda	Superb
108	Smart	#1
109	Smart	#3
110	Smart	#5
111	Subaru	Solterra
112	Tesla	Model 3
113	Tesla	Model S
114	Tesla	Model X
115	Tesla	Model Y
116	Toyota	BZ4X
117	Toyota	C-HR
118	Toyota	Prius
119	Toyota	Proace
120	Toyota	Rav4
121	Volkswagen	eUp!
122	Volkswagen	Golf
123	Volkswagen	ID.3
124	Volkswagen	ID.4
125	Volkswagen	ID.5
126	Volkswagen	IDBuzz
127	Volkswagen	Passat
128	Volkswagen	Tiguan
129	Volvo	C40
130	Volvo	EC40
131	Volvo	EX30
132	Volvo	EX40
133	Volvo	EX90
134	Volvo	V60
135	Volvo	V90
136	Volvo	XC40
137	Volvo	XC40 (BEV)
138	Volvo	XC60
139	Volvo	XC90
140	Xpeng	G6
141	Xpeng	G9
142	Zeekr	Cx1E

Note: A limited number of models have not been tested by ElaadNL but the applicable vehicle manufacturer has formally stated to ElaadNL that these models are technically identical to other models that have been tested. The RAI association has independently validated the statements of the vehicle manufacturers and found that some claims are probably too generic and do not fully take into account the different technical variations of some models over time. Also, it was found that some technically identical models (probably by mistake) have not been mentioned by the vehicle manufacturer. As the list of vehicles is used to calculate the market share tested, the calculated percentage (77.1%) might not be fully accurate. However, based on all information available to ElaadNL, it has been concluded that the list of tested vehicles and the snapshot of the percentage of tested market share supports the statement that the sample group of 142 vehicles is broadly representative of the current (date: 31 December 2024) Dutch passenger car fleet. This is with a sidenote that first generation vehicles are under-represented.

APPENDIX D

Test protocol

This appendix describes the smart charging tests and the results for the project "Smart Charging for All" performed at the ElaadNL test site. The document consists of two parts: first, it describes all of the tests that are performed. Secondly, it shows the test results and, if needed, further explains them.

In general, these tests are performed to identify any issues concerning the integration of the EV with the charging infrastructure and the electricity grid. See the overview below for per subject specificity; several different tests are performed of which each has a specific purpose. These are explained in detail in the next sections.

- Interoperability tests: testing the EV's ability to charge flawlessly on the different charging stations during regular and smart charging.
- Smart charging laboratory tests: tests and measurements on how the EV reacts to changes in the PWM signal and different smart charging scenarios, like fluctuating charging speeds, intermittent and delayed charging.
- Power Quality immunity tests: test and measure the influence the quality of the grid itself has on the smart charging behavior of the EV.

During these tests, the mobile app of the vehicle (if applicable) will be monitored to check if and how the app communicates the changes in charging speed, or when the charging is halted to the consumer. Also, the auxiliary battery is monitored, specifically to check if the battery is drained during the six-hours pausing periods at the overnight test.

The Elaad Testlab performs more types of tests apart from these "Smart Charging for All" tests. If interested in testing your implementation of new standards and charging capabilities, like 15118-20 and bidirectional charging, the Elaad Testlab can be contacted via testlab@elaad.nl.

Mode 3 interoperability tests

During the interoperability test, the EV will be tested on its specific, per charging station, smart charging behavior. This test includes changing the maximum charging current offered by the stations and interrupting charging for five minutes. The stations that are selected for this test have specific behavior and/or are the most common in the Netherlands. The scope of this test is to find any smart charging or other interoperability issues between the charging stations and the vehicle. The tests will be performed using the charging stations at the ElaadNL testing ground.

Test set-up

During the test on the different station types, the following routine procedure is used to see how the vehicle responds in combination with the specific station:

- In between the charging cable and station connector, a break-out connector box is placed which makes it possible measure the CP (Communication Pilot) signal.
- An oscilloscope is connected to the CP cable in a break-out connector box to measure the mode 3 communication and the behavior of the PWM signal.
- A transaction is started using a regular RFID charging card.
- An OCPP 1.6 or 2.0.1 charging profile is sent to the station.

The station will change its PWM signal to match the different current levels defined in the charging profile. The following maximum allowed currents will apply during the test. These maximum currents might be lower depending on the capabilities of the station.

Start time (s)	0	30	60	90	120	150	180	480
Current (A)	32	6	32	0	6	32	0	16

- During the first minute, the current will fluctuate between maximum 32 (also depending on the station its capabilities) and 6A. This is done to test the vehicle's response to a "smart" charging session.
- After 90 seconds, the vehicle is tested on how it responds when the charging session is paused for a few seconds, and how it responds when the vehicle starts charging again after the interruption. It is worth noting that not all charging

stations pause a charging session the same way. Some stations pause by going to state B1 (9V, 100% PWM), others to state F (-12V, 0% PWM), and even others first go to state B1 and after a few seconds to state F.

- After three minutes, the session will be interrupted for five minutes in total. The purpose of this test is to check if the vehicle will not fall asleep after lowering the current to zero for a longer period of time. The vehicle will pass the test when it starts charging again after a five-minute interruption.

Interop testing procedure

The standard interop test shall begin by plugging the cable from the break-out connector box into the charging station. Then, one end of the charging cable from the car will be plugged in the break-out connector box, and the other end will be plugged into the car. After the cable is plugged in, a signal will be given so that the charging of the EV can begin. If the charging goes correctly, the oscilloscope will show the correct PWM value.

When it is shown that the EV can charge normally without any problems, the smart charging test can begin with the charging station. In this test, the charging profile (that will be sent to the charging station) shall be executed. During this test, there will be short interruptions during the charging process. Here it will be checked if the vehicle starts drawing current matching the PWM signal after the interruption.

Station overview

These tests will be performed on the selection of charging stations found in the table below.

Num	Station	Model	Pause state
1	Alfen	Twin XL	9V/100% PWM
2	Alfen	Twin 4XL	9V/100% PWM
3	Easee	Home	9V/100% PWM
4	Enovates	Pro22	9V/100% PWM
5	EVbox	ML	9V/100% PWM
6	GE	Durastation	-12V/0% PWM
7	Schneider Electric	EVLink	9V/100% PWM
8	Smappee	EVbase	9V/100% PWM
9	WeDriveSolar	WDS-0001	9V/100% PWM
10	Zaptec	Pro	9V/100% PWM
11	EVbox	Liviqo	9V/100% PWM

Smart charging laboratory tests

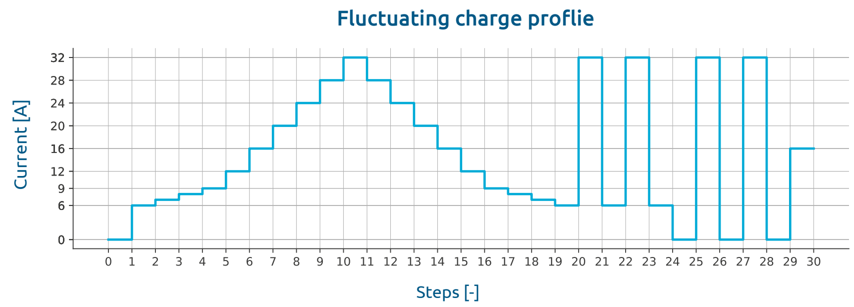
The following tests are meant to measure the time needed by the EV to adapt to PWM changes, to see what charging speeds are accepted and to perform a check on the ability of the EV to handle different smart charging scenarios. These tests will be executed on one reference charging station. These tests are performed using Mode 3 communication as described in the IEC 61851-1 (2019).

The IEC 61851-1 standard states the EV shall adjust its maximum current drawn to be equal or below the maximum current indicated by the PWM duty cycle within five seconds after the station signals the new maximum via the PWM signal. It also states that the vehicle needs to stop drawing current within three seconds after the station stops the PWM signal, after which the vehicle has three seconds to open its S2 switch. To measure the communication and current, the vehicle will be charged while the charger currents voltages, and the Mode 3 signal are being measured in detail using a Dewetron DEWE-800 which measures computer in combination with LEM IT65-S current transducers (see Figure 1). The Dewetron has a one mega-sample sampling rate with 16-bit resolution of all currents and voltages in the three-phase grid, which makes it able to measure in great detail, and will store all measured data for analyses. The current transducers have a 600 kHz bandwidth and are made for measuring with very high accuracy and linearity. The tests are performed using an automated test program, to ensure reproduceable tests.

Figure 1: Dewetron DEWE-800 and LEM IT65-S

Fluctuating charging profile

This test looks at the behavior of the vehicle to changes of different size in the allowed charging current, as well as the ability to effectively charge on different charge current levels. A check will be performed of the power factor at the lower charging speeds, which indicates the amount of power that the vehicle can actively use for charging and should not be below 0.85. The test will be performed on one phase and three phase, depending on capabilities of the vehicle.

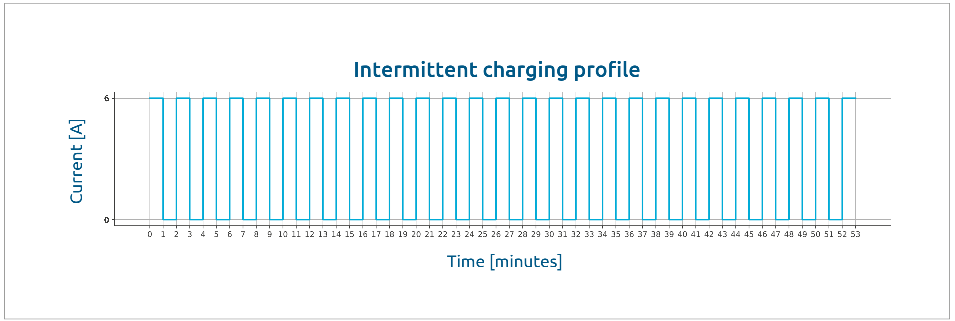


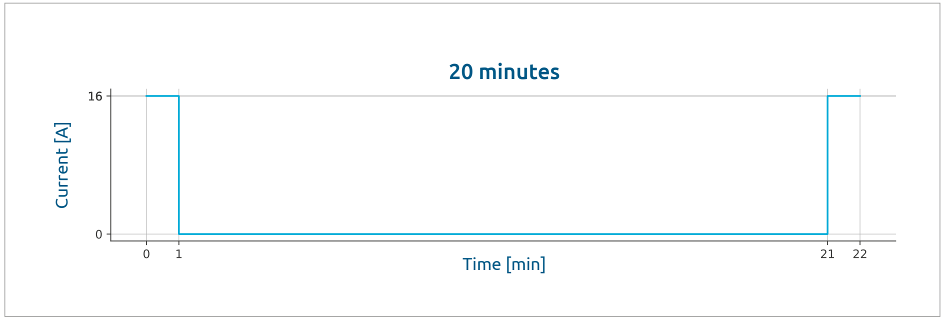
A special notice regarding one-phase charging; we test up to 32A, but as a general rule in the Netherlands (Dutch *Netcode elektriciteit* of 14-12-2021), any device taking in more than 5.75 kVA (~25A) should be connected via three phases to prevent voltage unbalance. In Germany, a similar but stricter rule applies (the VDE-AR 4100 standard), which states that the maximum connection power for single-phase loads is limited to <= 4.6 kVA (~20A) when connecting to the low-voltage grid of power utilities.

These limits might result in charging stations being limited in power for one phase vehicles to 25A or 20A. Because this further limits the total charging speed for the customer, and to prevent voltage unbalance in the grid, ElaadNL advises to use three phase on-board chargers.

Intermittent charging test

This test measures the response of the vehicle to intermittent charging, during which the charging session is paused multiple times. This can, for instance, be the case while charging on solar power or at a busy charging hub to balance the load. To perform this test, a charging profile containing frequent pausing periods is sent to the station. The interval between the changes is set to 60 seconds. A single test is performed that switches between 6A and 0A for 25 times. If the vehicle is not able to charge at 6A, a higher value will be selected.





Delayed and paused charging test

This test checks if an EV is able to restart charging when being delayed and paused for longer time periods. Two types of tests are performed: 1) delayed charging, during which the charging is delayed from the start of the transaction, and 2) paused charging, during which the vehicle is allowed to charge for a moment and then paused. Two time periods are used for these tests.
First, a 20-minute pause test is performed in the lab. Twenty minutes has been chosen to test if the vehicle can cope with a 15-minute pause as is commonly used during intermittent charging.

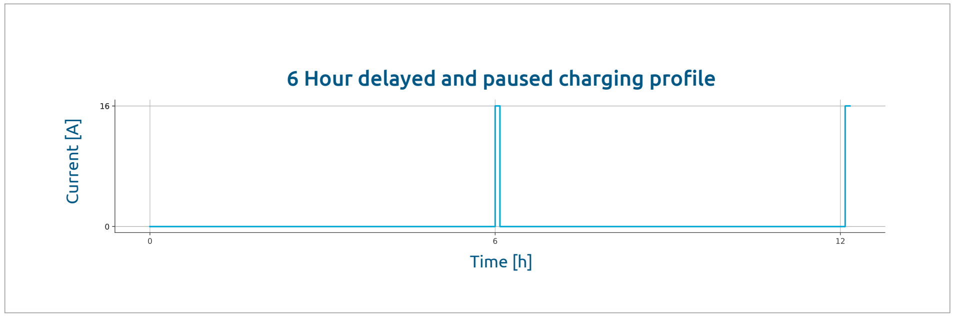
Paused charging 20 minutes

Start time (s)	0	60	1260
Current (A)	6	0	6

Secondly, if the vehicle performs well during the 20-minute test, a six-hour delayed and paused test is performed to see if the vehicle can cope with longer delays and pauses, such as being used for delaying or pausing the charging session until after the evening electricity usage peak. To perform these tests, an overnight test is set up using a charging station that uses state B1 when no energy is available. A charging profile is sent to the station that first delays the charging session for six hours, and then shortly starts charging at 16A for five minutes, and pauses the charging session again for six hours, after which charging is allowed again for five minutes.

Six-hour delayed and paused charging

Start time (s)	0	21600	21900	43500
Current (A)	0	6	0	6



Charging speed change after a long, stable charging speed

After charging for a longer period on a stable charging speed, it can be that a vehicle stops listening to the PWM signal and just assumes the charging speed will not change at all during the charging session. To test this, the vehicle is charged for three hours at 6A, after which the charging speed is changed to 16A. Afterwards, a check is performed to see if the vehicle increased the charging speed when allowed.

Three-hour low charging speed

Start time (s)	0	10800
Current (A)	6	16

Auxiliary battery test

When the charging is halted for long periods of time, it is important to make sure that the auxiliary battery's voltage is not getting below its normal operating range. In order to ensure that, the voltage of the battery shall be measured using an EasyLog USB voltage data logger during the six-hour delay, six-hour pause and three-hour low current charging tests.

Heating/cooling test

There are certain scenarios in which the heating or cooling functions of the car are turned on while the EV is charging. For example, if the owner wants to warm up the EV during the winter or cool down the EV during hot summer days before getting in, while the EV is charging. During such scenario, there is the possibility that the vehicle draws more current than allowed.

To see if the heating and cooling functions alter the charging behavior of the EV, the EV shall be charged normally. When the EV is being charged, the cooling functions and heating functions of the EV shall be turned on and off. During these moments, the current will be measured, to observe whether the vehicle's current intake exceeds the current limit.

Power quality immunity tests

There are several power quality scenarios that can happen on the grid, to which a device should be immune. These can be tested at the ElaadNL Test Lab by using a Chroma 61830 grid emulator (see Figure 2). This device is able to emulate a grid of predefined specifications and allows for changes to the voltage height and quality for all three phases separately during the tests. The tests described below are performed while the vehicle charges on its minimum and maximum current and at one- or three-phase charging (depending on the capabilities of the vehicle).

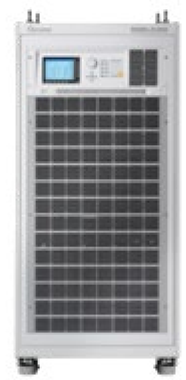


Figure 2: chroma 61830

Grid voltage tests

The grid is not always completely stable. It is possible that the voltage sometimes is lower or higher than 230V. The height of the grid voltage is brought down by the current drawn (e.g., by DC fast chargers) and brought up by the current produced (e.g., by solar panels). From a customer perspective, it would be preferable that the vehicle does not abort the charging and can continue when the voltage is within the allowed ten-minute average voltage deviations as stated in the IEC 50160 (within +10%/-15% of nominal voltage for 100% of the time). In Europe, this translates to a range of 196 – 253 Volts. If the voltage deviates from this range, the charging may be stopped.

Under voltage at max charging current and 6A

It is possible that the voltage is sometimes lower than desired. During this test, the voltage on the phases will be brought down linearly to 195 Volts and linearly back to 230 Volts. This tests analyses how the vehicle will respond when the voltage is lower, specifically if it will increase the current above the maximum allowed limit signalled by the charging station and if it stops charging at a certain level. This is tested on both the maximum charging current as on 6A.

Over voltage at max charging current and 6A

It is also possible that the voltage is sometimes higher than desired. During this test, the voltage is increased linearly to 260 Volts and linearly back to 230 Volts. This looks at how the vehicle will respond when the voltage is higher, specifically if it will increase the current above the maximum allowed limit signalled by the charging station and if it stops charging at a certain level (keeping into consideration what voltages are safe for charging). This is tested on both the maximum charging current as on 6A.

Voltage sag at max charging current and 6A

The voltage on the grid can also drop to low values (i.e., 100V) for a short amount of time. During this test, the voltage will be decreased to 161V for 25 cycles. It looks at how the vehicle will respond when a voltage sag occurs, specifically if it will increase the current above the maximum allowed limit signalled by the charging station and if it stops charging. This is tested on both the maximum charging current as on 6A.

Meister Curve Grid harmonic test

This is a standardized test of charging behavior when harmonics are added to the voltage according to the IEC 61000-4-13 standard. The EV is considered a Class 2 product (see description below in Figure 3). The ability of the vehicle to keep charging is tested (ride through) and the measurements are analysed for any unexpected changes in the charging currents due to the voltage harmonics. The definition of Class 2 equipment 61000-4-13 is that "this class applies to points of common coupling (PCCs for consumer systems) and in-plant points of common coupling (IPCs) in the industrial environment in general". The compatibility levels in this class are identical to those of public networks; therefore, components designed for application in public networks may be used in this class of industrial environment.

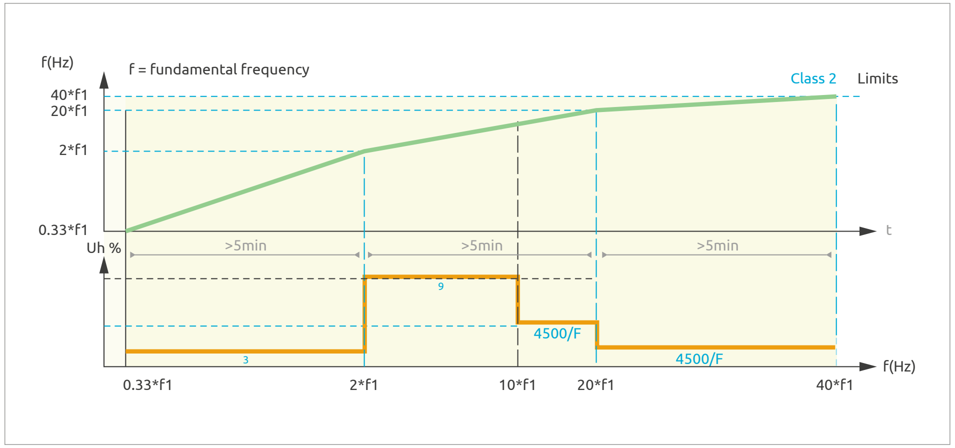


Figure 3

During the test, harmonic distortion is added over time with different frequencies and amplitudes. The picture and table below offer more information about the added distortions.

The power grid has a base frequency of 50Hz, which means the meister curve can be divided into four blocks. Below is a table that summarises the picture above (which shows the harmonics induced during this test).

	Block 1	Block 2	Block 3	Block 4
From	16.5Hz	100Hz	500Hz	1000Hz
To	100Hz	500Hz	1000Hz	2000Hz
Intensity	3%	9%	(4500/current frequency) %	(4500/current frequency) %

Phase independent absence of voltage at start transaction (switching one-phase to three- phase charging, only on multi-phase vehicles)

It is possible that, at the start of a transaction, one or more phases do not have any voltage, but that the voltage on these phases might return during the charging session. For instance, this can for happen when the electric installation is under maintenance, or when charging is happening on charging stations that have the ability to switch between one- and three-phase charging.

During this test, the vehicle's response is checked to an absence of voltage on one or more phases and how the vehicle behaves when voltage is brought back on the missing phases. Special attention is given to possible phase-linking when charging a multiple-phase vehicle on one-phase. During phase-linking, the voltage on the charging phase (L1) is returned on the other phase(s) (L2 and/or L3), which is not allowed and can cause a short circuit or a 230V electrical shock to a person. If a voltage larger than 50V is detected, the test is not continued.

Vehicle App test

A car's app (which is provided upon purchase) is a great way for the customer to get insights about the state of the car, e.g., the state of charge of the car, whether it is being charged and how fast, and if the car is locked or unlocked. However, with smart charging becoming more common, several smart charging situations can make the app behave differently than intended or desired. Therefore, we test the app on three topics:

Does the app notify the user every time the charging is halted?
While charging on solar energy on a partly cloudy day, charging may be halted every time there is no solar energy available. Similarly, at a charging hub, EVs are charged alternately to divide power between the vehicles. If the vehicle app sends a notification every time the charging is halted, this could become annoying to the user. By testing this, it becomes clearer what the effect of smart charging is on the behavior of the vehicle app.

Is the charging speed visible?
Since the charging speed during smart charging may vary from what is expected, it may be useful to be able to see the charging speed (in Amperes or kW) in the vehicle app. This will make the user aware of smart charging.

Is the information about charging real-time?
Since the charging speed can change quickly, having the information in the app change in real-time (or getting the notifications about charging in real-time) makes the information more reliable; after all, the vehicle app would show old data if it were not in real time.

How to interpret vehicle app test results

The results of this test are not necessarily good or bad, but an indication on how smart charging will change the way of using the app, or change the behavior of the app. The vehicle manufacturers themselves should research how the customer would like the app to behave during smart charging.

Reflection on test protocol

Introduction

The tests were performed according to the original test protocol for the smart charging capabilities of the vehicles. In hindsight, there are certain tests that could have been performed differently. This chapter will discuss how these could have been changed or added to the "Smart Charging for All" testing project.

12 Volt battery test

During the 12V battery test, the test was performed over a period of six hours for both the delayed and paused charging test. However, what if the battery starts to drain after a longer period of time? What if the charging was delayed or paused for a matter of 24 hours, or perhaps even for 48 hours or longer? Due to the short amount of time that the vehicles were present at the ElaadNL testing facility, a test of that duration could not be performed. Furthermore, the working voltage of such batteries varies per type, meaning that 12V for one battery might be too low already, while for another battery this still means that it is 40% full. If this information is known before the test, it is possible to know how much the battery drains during.

Vehicle-controlled charging

A t test could have been added to see if the charging schedules of the vehicles were overruling the charging schedules of the charging stations, and vice versa. Such a test could have been performed by implementing a charging schedule in the vehicle and the charging station, which start at different times.
Likewise, a test could be performed in which either the vehicle or the charging station pauses a charging session, while the other continues the charging session, as well as a test in which the vehicle and charging station are running a charging session on different charging speeds.

Paused charging

In some instances, during the in-depth smart charging tests and intermittent charging tests, a vehicle would not resume charging within a minute after being paused. However, during those moments it was not tested whether or not the vehicles would resume charging after a longer period of time.

25 times intermittent charging

The intermittent charging test consisted of 25 iterations of one minute charging at 6A followed by a one-minute pause. The goal of this specific test was to validate the maximum supported iterations and does not represent an everyday charging situation. The choice for pauses of one minute also doesn't reflect an everyday charging situation and was chosen given time constraints for testing. In retrospect, this test represents an extreme theoretical charging situation and therefore the results of this test must be interpreted with caution. In the future, this test will be executed with pause/ resume iterations of 15 minutes and the number of iterations will be reduced to 15. This altered test scenario better reflects the situation of alternate charging of vehicles, e.g., on a (virtual) charging hub, and corresponds with a time period of 7.5 hours.

Harmonic distortions on minimum phases

The harmonic distortion test was performed while charging on the maximum number of phases. All the vehicles that could only charge on one phase passed the test, meaning that the only instances of a failed test were during those on multiple phases.

Therefore, the vehicles that failed the test on multiple phases could have been tested once more, but rather on one-phase charging instead of the maximum number of phases. Considering that this test was not performed, there was no distinction being made on whether the vehicle was unable to handle the distortion indefinitely, or if the vehicle was unable to handle the distortions when charging on multiple phases.

Power quality

The Undervoltage, Overvoltage and Voltage dip tests were not always performed in the same way. In the beginning, the voltage was changing in steps of 5V during the Undervoltage and Overvoltage tests—however, later in the project, the voltage was changing in steps of 2V. Likewise, in the beginning the voltage was dropping to 100V during the Voltage dip test. Later in the project, the voltage was dropping to 160V instead.

Therefore, the vehicles that were tested at the beginning of the project underwent a slightly different Undervoltage, Overvoltage and Voltage dip test. Since those vehicles have not been retested, the vehicles should be retested.

APPENDIX E

Harmonic emission limits

According to the IEC-61000-3-2/12 standard, the following maxima (on the following page) are allowed per harmonic. There are different levels for currents under 16A, and currents between 16 and 75A. The vehicles are thus tested as equipment instead of balanced three-phase equipment. This goes for three-phased vehicles too, as three-phase converters are non-balanced devices.

Under 16A current input per phase

As defined in the IEC-61000-3-2, the maximum height of the different harmonic currents (up to the fortieth), is shown in the table below.

Even - Harmonic	Max current	Odd-Harmonic	Max current
2	1.08	3	2.3
4	0.43	5	1.14
6	0.3	7	0.77
8	0.23	9	0.4
10	0.18	11	0.33
12	0.15	13	0.21
14	0.13	15	0.15
16	0.12	17	0.13
18	0.1	19	0.12
20	0.09	21	0.11
22	0.08	23	0.1
24	0.08	25	0.09
26	0.07	27	0.08
28	0.07	29	0.08
30	0.06	31	0.07
32	0.06	33	0.07
34	0.05	35	0.06
36	0.05	37	0.06
38	0.05	39	0.06
40	0.05		

In between 16A and 75A current input per phase

As defined in the IEC-61000-3-12, the maximum height of the different harmonic currents (up to the thirteenth) and the Total Harmonic Current (THD), is shown in the table below.

Harmonic	Max percentage
2	8.0%
3	21.6%
4	4%
5	10.7%
6	2.67%
7	7.2%
8	2%
9	3.8%
10	1.6%
11	3.1%
12	1.33%
13	2%
THD	23%

APPENDIX F

Summary results

Perspective: Customer		
Test	**Short description**	**Key outcomes & issues**
Smart charging Interoperability	Validating interoperability of smart charging by testing each vehicle against a representative series charging stations, for both uncontrolled and controlled smart charging.	Of all tested vehicle/charging station combinations, over 97% of the tested market share support smart charging.
Smart charging Profile and Mode 3 Compliance	Each vehicle was tested for its ability to respond promptly and correctly to both major and minor changes in charging speed. It was verified that the vehicle did not exceed the allowed maximum at any charging speed.	Over 99% of the tested market share support a typical smart charging profile. About a dozen vehicles structurally exceed the charging limit (overcurrent) when set below 8A, however this is not noticeable to the driver. However, for a grid operator the overcurrent is marked as a major issue. Furthermore, some (minor and trivial) issues were found in response times and overshoots. Applicable vehicle manufacturers are called upon to resolve these issues to contribute to maintaining the power quality of the grid.
Low-Speed Charging Capability	The ability of the vehicle to charge at the lowest permissible current level was evaluated, without creating overcurrent and ensuring that the power factor remained within defined limits.	Over 95% of the tested market share supports low-speed charging. About half a dozen of vehicles have a power factor below 0.85 when the charging limit is set below 8A. This results in less or no energy transfer. This issue is marked as critical as it has a direct effect on the driver. Applicable vehicle manufacturers are called upon to resolve these issues or actively inform drivers. When possible, CPOs are advised to restrain charging below 8A to minimize customer impact.

Perspective: Customer		
Test	**Short description**	**Key outcomes & issues**
Response to Charging Pauses	Vehicles were tested on their ability pause for short (20 minutes) and long (six hours) periods. It was also assessed whether vehicles support "intermittent charging" (= 25 iterations of pause/ resume). Intermittent charging is commonly applied at charging plazas — and responds appropriately to frequent pauses due to limited power availability (e.g., during charging with local solar generation on a partly cloudy day).	Over 95% of the tested market share support delayed charging of six hours and pauses of 20 minutes and six hours. Over 81% (one-phase vehicles) and over 90% (three-phase vehicles) of the tested market share support intermittent charging. About 40 vehicles do not fully support intermittent charging. As intermittent charging is not defined in the standard, the number of pause/resume iterations that will be supported is still undecided. Out of safety considerations, some manufacturers have limited the number of pause/resume iterations. Not supporting intermittent charging is marked as a critical issue as it has a direct effect on the driver. Vehicle and charger manufacturers are advised to agree on the number of iterations that should be supported and to include this number in an updated standard. Applicable vehicle manufacturers are called upon to increase the number of supported pause/resume iterations. When possible, CPOs are advised to restrain from intermittent charging and/or pause for a minimum of 15 minutes to reduce the number of pause/resume iterations.
Response to Increased Charging Speed	To test responsiveness, vehicles were charged at a constant speed (6A) for three hours, after which the charging station instructed the vehicle to increase the charging speed.	100% of the tested market share responds to a change in charging speed after a long period of time.

Perspective: Customer		
Test	**Short description**	**Key outcomes & issues**
User Notifications Through Vehicle Apps	Tests were conducted to verify whether the vehicle's companion app provided users with accurate information regarding charging speed. It was also assessed how many notifications were sent when the charging session was repeatedly paused and resumed.	All brands (expect one) provide a companion vehicle app. Connecting the vehicle app to the test vehicle proved to be challenging for different reasons, resulting in only 77 successful connections. About 30% of the tested market share showed the charging status in the vehicle app. When charging is repeatedly paused/resumed, about 16% of the tested market share notifies this at every pause/resume iterations and about 48% sends irregular notifications.

Perspective: Grid PQ Immunity		
Test	**Short description**	**Key outcomes & issues**
Voltage deviations	Each vehicle was tested on voltage deviations in the power grid, both within and outside of regulatory limits.	Over 97% of the tested market share can successfully absorb undervoltage, overvoltage and voltage dips. A handful of vehicles temporarily stopped charging but resumed after the grid voltage was restored to regular levels. On the outer voltage limits or when exceeding the limits, a handful of vehicles stopped charging and did not resume. Although these issues are marked as minor and trivial, applicable vehicle manufacturers are advised to select components which are more resilient to voltage deviations.
Harmonic Distortions	Tests were conducted with harmonic distortions present in the voltage (within permitted limits) to evaluate whether the vehicle continued charging correctly and stayed within the smart charging current limits.	Over 86% of the tested market share can successfully absorb harmonic distortions. About five vehicles stopped charging themselves and about 20 vehicles activated the overcurrent protection in the charge point to stop charging. Applicable vehicle manufacturers are advised to select components which are more resilient to harmonic distortions.

Perspective: Grid PQ Immunity		
Test	**Short description**	**Key outcomes & issues**
Phase Switching	The vehicle's capability to switch between single-phase and three-phase charging modes was validated.	The phase switching test was executed successfully by all tested vehicles.
Voltage on Non-Powered Phases	It was verified if no high voltage (>50v ac) was present on inactive phases, in line with safety requirements.	Over 90% of the tested market share stayed within safety voltage limit (< 50V) on inactive phases. About a dozen vehicles did not comply to this safety requirement. This issue is marked as critical and applicable vehicle manufacturers are urged to solve this safety issue as soon as possible.

Perspective: Grid PQ Emissions		
Test	**Short description**	**Key outcomes & issues**
Harmonic Emissions	Vehicles were assessed for compliance with standards regulating acceptable harmonic emissions, not only during nominal charging power but also at lower charging speeds.	Over 97% of the tested market share do not inject harmonic distortion into the grid. A handful of vehicles exceeded the harmonic emission limits. This issue is marked as minor and applicable vehicle manufacturers are advised to select components which operate within harmonic emission limits.
Supraharmonics	Data on supraharmonic emissions (2 khz to 150 khz) were collected while charging at various speeds. These results will be used for further analysis and will serve as input for future standardization efforts.	Around 78% (one phase) and 75% (three phase) of the vehicles do not exceed the CISPR supraharmonic distortion limit.

Perspective: Grid PQ Emissions		
Test	**Short description**	**Key outcomes & issues**
Power Factor	The power factor was evaluated to ensure that the reactive power component remained within acceptable boundaries. Since smart charging often results in lower charging speeds, power factor measurements were taken at both high and low speeds to assess performance under varying conditions.	The power factor is minimal over 0.98 (one-phase) and over 0.92 (three-phase), well above the 0.85 threshold. Of the tested market share, the power factor decreased by 1.5% (one-phase) and 4.5% (three-phase) when comparing the highest and lowest charging speed. About half a dozen vehicles have a power factor of below 0.85 when the charging limit is set below 8A. This results in less or no energy transfer. This issue is marked as critical as it has a direct effect on the driver. Applicable vehicle manufacturers are called upon to resolve these issues or actively inform drivers. When possible, CPOs are advised to restrain charging below 8A to minimize customer impact.

APPENDIX G

Information about partners

Dutch Ministry of Infrastructure and Water Management

The Dutch Ministry of Infrastructure and Water Management is responsible for traffic and water management, spatial planning, and liveability. It is committed to a smooth flow of traffic in a well-designed, clean and safe environment. The Ministry works on effective connections by road, rail, water and air. It protects against flooding and promotes the quality of air and water.

The Ministry aims to promote a "more beautiful" Netherlands. Together, we ensure an accessible country with strong dikes, in which you can travel safely from point A to B. We ensure a country with clean air, clean soil and clean water. A country in which we are careful with raw materials and reuse as much as possible. One in which we travel sustainably. A country with room for possibilities. And this requires a ministry that connects not only places and ideas but especially connects people. Everything we do is for a more beautiful Netherlands.

National Charging Infrastructure Agenda (NAL)

Smart charging of EVs will make the energy system more flexible and is indispensable for the transition in sustainable mobility and energy in the Netherlands. Smart charging delivers significant advantages for our society, our EV drivers, and for our providers of charging services. As such, the National Charging Infrastructure Agenda (NAL) considers smart charging as fundamental. The NAL has elaborated a national upscaling program entitled 'Smart charging for All' (SLVI) aimed at improving the scaling-up process, in close collaboration with all stakeholders in the charging chain.

Our ambition is that by 2025, more than 60% of all charging sessions are smart. In order to achieve this goal, SLVI creates an attractive offering for users, a national rollout of grid-conscious charging and boosts overall awareness, knowledge and enthusiasm among users to adopt smart charging. The approach is focused on various aspects that will prove effective in the short term. In the elaboration and implementation stages, SLVI prefers to keep things simple, and will focus on what is currently achievable.

This is why testing EVs for smart charging compatibility is part of our action plan and is deemed essential for a smooth implementation of smart charging, providing an attractive user experience, promoting sustainability and increasing the confidence of (potential) owners, as well as vehicle manufacturers and dealers, and of EVs and their charging infrastructure. The testing program of a substantial number of EVs contributes to the development of reliable smart charging sessions of various EVs, ensuring a seamless cooperation between vehicles and smart charging infrastructure and, as a result, supports the transition to sustainable mobility systems that underpin the smooth integration of the EV—delivering our future-proof electricity system.

ElaadNL

The knowledge and innovation centre ElaadNL researches and tests smart charging of EVs. ElaadNL is an initiative of the joint Dutch grid operators. Through their involvement with ElaadNL, the grid operators are preparing for a future with electric driving and sustainable charging. The goal is to smoothly integrate EVs and charging infrastructure in the electricity grids. ElaadNL investigates the expected growth of various forms of electric transport, the associated charging infrastructure, and how to integrate this smartly into the power grid.

The ElaadNL Test Lab is a non-profit testing facility. Together with manufacturers from all over the world, we test e-Mobility products to identify necessary improvements on the products and the standards on which they are based. The test activities of the

Test Lab are pre-normative and pre-competitive in nature and will be transferred to commercial test organizations as soon as appropriate standards and legislation are in place. This way, the ElaadNL Test Lab fills the gaps identified by ElaadNL in the current testing processes, certifications, and type approvals. Together with manufacturers from around the world, they test the latest techniques for charging EVs, trucks, buses and construction machinery in the Test Lab in Arnhem.

RAI Association

The RAI Association represents the interests of over 700 manufacturers and importers of passenger cars and trucks, trailers and semi-trailers, bodies and special vehicles, motorcycles and scooters, mopeds and bicycles. The suppliers of parts and garage equipment are also affiliated with the RAI Association. The RAI Association is committed to sustainable, safe and affordable mobility. As an advocate for the mobility industry in the Netherlands, the RAI Association is the connecting link in the complex playing field of politics, government, consumers and business. The Netherlands is in full transition to sustainable mobility. The importers of passenger cars and light commercial vehicles in the Netherlands, united in the Passenger Cars and Light Commercial Vehicles Section of the RAI Association, fully support this effort.

RAI is closely involved in the development of charging infrastructure in the Netherlands and are a member of the working group “Smart Charging for All.” Together with our passenger car and light commercial vehicle members, we have advocated for testing how the vehicles of our members can handle various forms of smart charging. For the members of the RAI Association, it is important that the charging infrastructure does not hinder further electrification of the vehicle fleet. The user must be able to trust that they can always charge their car. By consuming less energy during peak times and, if possible, shifting this to times when sufficient energy is available, overloading our electricity network can be prevented as much as possible. RAI Association therefore supports the “Smart Charging for All” program on the condition that charging security is offered as much as possible.

Doet Association

As a member of the Dutch core team “Smart Charging for All” (SLVI) and a representative of the Dutch charging industry, the DOET Association was closely involved in the unique tests carried out by the ElaadNL in Arnhem.

Users of EVs must be able to count on a reliable charging network, even in times of grid congestion where flexible and smart charging is becoming increasingly important. The nearly 80 members of DOET Association are therefore happy to work constructively on making the Dutch charging network increasingly smarter by exchanging knowledge and offering smart charging infrastructure and smart charging services in the public and private domains.

With a view to this large-scale test, DOET Association actively asked its members and relations at the beginning of 2024 about specific points of attention from daily practice when charging electric passenger cars and vans. These points of attention and those from other parties, such as the automotive industry, have been incorporated into a professional test protocol with which ElaadNL was able to carry out a professional test that can be regarded as unique worldwide and in which DOET Association and its members were happy to participate.
DOET Association has been the Dutch industry association for parties active in the field of charging infrastructure and charging services since 2010. More information can be found at: www.doetdoet.nl


Elaadnl