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Testing 150 vehicles on Smart Charging capabilities

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Executive Summary

ElaadNL is concluding a research commissioned under the "Smart Charging for All" initiative to evaluate the compatibility of 150 electric vehicles (EVs) with smart charging technologies. The project focuses on testing EV interoperability on a range of charging stations, examining their behavior under fluctuating charging profiles, and assessing resilience to power quality disturbances. For example, tests involve varying grid voltage levels and simulating intermittent charging conditions, which are increasingly common in real-world scenarios. The results offer valuable insights into EV behavior during smart charging and contribute to both national and international efforts to future-proof electric mobility and charging infrastructure.

Given the timing of EVS 38 in June 2025, we expect to be able to share the results of the testing program in the conference. As the results are not yet available at the submission date of this paper, this paper will examine the importance of interoperability, smart charging and the approach and methodology of the testing program.

Keywords: Electric Vehicles, Standardization, Smart Charging, Smart Grid integration and grid management, Energy management

1 Introduction

Smart charging—the intelligent coordination of when and how electric vehicles (EVs) are charged—is essential for a sustainable mobility and energy system. To enable reliable large-scale implementation, technical compatibility between EVs and charging infrastructure must be ensured. From May 2024 to April 2025, ElaadNL conducted the largest smart charging test to date, commissioned by the Dutch Ministry of Infrastructure and Water Management. A wide range of EVs and charge points were tested. The results offer valuable insights into EV behavior during smart charging and contribute to both national and international efforts to future-proof electric mobility and charging infrastructure.

The test data gathered will be analyzed in May and June and results will be shared at EVS38. As the results are not available at the time of publication of this paper, this paper primarily focusses on the benefits of smart charging, the test approach and methodology and the intended impact of this project.

2 Objectives

Electric transport is considered a great opportunity for the energy transition. Given the increase of supply of wind and solar energy, electric vehicles can assist in balancing the energy system. Moreover, smart charging technology can be applied by drivers to charge cheaper and more sustainable. Electric vehicles are potentially electric power stations on wheels. For example, they store sustainable energy when the sun is shining and – in the near future – can supply the energy when you need it at home in the evening.

As smart charging is beneficial for electric drivers it offers opportunities for new businesses. Smart charging is rapidly becoming proven technology and commonsense next step is to transform this technology into customer propositions. Given the accelerated uptake of electric vehicles and capacity boundaries of the power grid, smart charging is a must have. So, let’s stop pretending smart charging is something special. The Netherlands is setting the new yardstick that you just “charge” your car which is, of course!, always done by default in a smart manner. You wouldn’t expect anything else in the 21st century, right?

The ambition of the action program "Smart charging for all" is to make every charge session on a destination location smart by default in 2025. To ensure that smart charging is both effective and user-friendly, it is essential that electric vehicles (EVs) and charging infrastructure are fully compatible with smart charging technologies. From May 2024 to April 2025, ElaadNL conducted the 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.”

The primary aim of this 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 provide crucial insights into the compatibility and behavior of EVs and charging stations during smart charging scenarios.

The primary objectives of the test project are:

1. To test EV interoperability with a range of charging stations, including common and uniquely behaving models.

2. To evaluate EV behavior under dynamic charging conditions, such as fluctuating charging profiles and delayed charging scenarios.

3. To assess EV resilience to power quality disturbances, such as voltage sags, overvoltage, and harmonic distortions.

3 Methodology

3.1 Scope

As stated in the previous chapter, the ambition of the action program "Smart charging for all" is to make every charge session on a destination location smart by default in 2025. Destination location refers to places where electric vehicles 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 on destination locations, the tests are limited to AC chargers. AC charging is the main technology used at home and in parking lots. DC charging is usually used only for fast charging. In addition, during AC charging the vehicle itself has a larger role and therefore more problems with smart charging can arise from the vehicle. During DC charging, the vehicle batteries are charged directly by the charger and the vehicle therefore has a smaller role in this area.

With the participation of both established automotive brands and newcomers to the EV market, a broad and representative picture was formed of the state of smart charging integration in the Netherlands. A wide range of electric models was tested, from compact city cars to luxury electric vehicles and everything in between. 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.

For the charge station, a selection was made based on the components most common in charge stations in The Netherlands. The following brands, in alphabetic order, participated in the tests: Alfen, Easee, Enovates, EVbox , Schneider Electric, Smappee, WeDriveSolar and Zaptec.

3.2 Governance

The governance structure for this test program was based on the governance model of the overarching Smart Charging for All program, ensuring alignment in decision-making and stakeholder representation.

The project board, was responsible for the strategic direction and oversight of the program, consists of four key parties. 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. Each of these organizations brings a unique and critical perspective to the governance of the project, ensuring that technical, commercial, societal, and infrastructural interests are all taken into account.

In addition to the project board, a stakeholder group was involved to reflect 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 for the actual testing phase, several key documents and procedural arrangements were jointly established. A standardized test protocol was developed, and priorities were set regarding which vehicles and charge stations would be tested. A standard Test Lab Agreement (TLA) was drafted and signed between ElaadNL and each participating vehicle manufacturer.

Individual test results were shared exclusively with the respective manufacturer through a standardized reporting format. In cases where issues were identified and subsequently corrected by the manufacturer, the vehicle could be retested to confirm resolution. Intermediate results were discussed in a closed committee under strict confidentiality, ensuring that sensitive data was protected during the testing phase. Only aggregated and anonymized test results will be shared publicly, in order to contribute to broader industry transparency without compromising the commercial interests of individual stakeholders.

3.3 **Test protocol**

The development of the test protocol was guided by the principle of aligning as closely as possible with existing international standards. The foundation for smart charging tests is primarily based on IEC 61851-1 (2019), which outlines the general requirements for conductive charging systems for electric vehicles. This standard includes definitions for Mode 3 communication, 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 real-world performance of smart charging systems. True assessment requires the inclusion of dynamic, user-oriented scenarios—such as extended pauses, frequent disconnections, brief charging sessions, and delayed charging initiations. These scenarios are not covered by the existing standard, and thus, ElaadNL's Testlab has developed a set of supplementary test cases based on practical experience. These additional tests simulate everyday behaviour and are essential for understanding how vehicles interact with smart charging infrastructure in realistic settings.

In addition to communication and behavioural 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 Sag Test. During this test, the voltage was abruptly lowered from 230V to 161V (70%) for 25 cycles, 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.

3.4 **High level overview of tests:**

Perspective	Test	Details
Customer	Smart Charging Interoperability	Testing each vehicle against a series of ten charging stations, including AC charge points in the Netherlands, covering public and private infrastructure. Evaluating EV's ability to charge flawlessly.
	Smart Charging Profile and Mode 3 Compliance	Testing vehicle's response to changes in charging speed, ensuring it does not exceed the allowed maximum.
	Low-Speed Charging Capability	Evaluating vehicle's ability to charge at the lowest permissible current level, checking for overcurrent issues and acceptable power factor.
	Response to Charging Pauses	Testing vehicle's ability to bridge peak load periods by pausing sessions or delaying new ones. Ensuring 12-volt battery remains charged during pauses. Assessing response to alternating charging strategies and session continuity.
	Response to Increased Charging Speed	Charging vehicles at constant speed (6A) for three hours, then increasing the rate to test dynamic responsiveness.
	User Notifications via Vehicle App	Verifying vehicle's app provides accurate charging speed information and assessing the number of push notifications sent during repeated start-stop cycles.
Grid	PQ Immunity - Voltage Variations	Testing vehicles under voltage deviations within regulatory limits, ensuring compliance with smart charging current limits at lowest charging speed (6A).
	PQ Immunity - Harmonics	Testing vehicles with harmonic distortions in voltage, ensuring correct charging and compliance with smart charging current limits at 6A.
	PQ Immunity - Phase Switching	Validating vehicle's capability to switch between single-phase and three-phase charging modes.
	PQ Immunity - Voltage on Non-Powered Phases	Verifying no high voltage (>50V AC) on inactive phases, ensuring safety.
	PQ Emissions - Harmonic Emissions	Assessing vehicles for compliance with standards regulating harmonic emissions during nominal and lower charging speeds.
	PQ Emissions - Supraharmonics	Collecting data on supraharmonic emissions (2 kHz to 150 kHz) at various charging speeds for future standardization efforts.
	PQ Emissions - Power Factor	Evaluating power factor to ensure reactive power component remains within acceptable boundaries at high and low charging speeds.

3.5 Physical Test setup

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

Test Setup 1 focused on evaluating the interoperability of smart charging between vehicles and different types of charging stations. This setup 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.

Test Setup 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, in addition to a reference AC charging pole compliant with smart charging protocols, and a Chroma 61830 grid emulator capable of emulating customizable grid conditions.

Test Setup 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 setup consisted of two charging stations at the ElaadNL charging plaza 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.

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 was stored for subsequent analysis and reporting.

4 Expected Impact

The project aims to address critical challenges in EV charging:

- Ensuring that EVs can adapt to increasingly dynamic grid conditions.
- Enhancing interoperability across diverse charging stations.
- Identifying areas for improvement in current smart charging standards.

By providing actionable insights, the project will support the development of robust, sustainable EV charging systems that are scalable for widespread adoption. The findings of this test program highlight that addressing challenges in interoperability and power quality is more than just a matter of improving individual EV performance—it is a critical step toward the reliable, scalable, and sustainable development of the entire EV charging ecosystem. As electric mobility continues to expand, the implications of resolving these technical barriers stretch across infrastructure planning, grid management, user adoption, and the overall energy transition.

4.1 Reliability and User Confidence

Interoperability ensures that EVs can effectively communicate with various charging stations, regardless of brand or location. When vehicles fail to respond to smart charging commands or incorrectly interpret dynamic load signals, it results in failed or incomplete charging sessions. For drivers, this can lead to frustration, reduced confidence in the technology, and potential range anxiety.

Solving these issues significantly enhances the reliability of smart charging, ensuring that users receive the expected amount of energy within their preferred time frame. This reinforces trust among drivers, fleet operators, and leasing companies. In turn, a reliable and transparent charging experience can increase acceptance and usage of smart charging services, paving the way for smart charging to become the default mode of operation.

4.2 Operational Efficiency and Cost Reduction

From the perspective of charge point operators (CPOs) and mobility service providers (MSPs), technical compatibility reduces the volume of support calls, maintenance costs, and system downtime. Charging sessions that fail or perform below expectations often lead to manual interventions, service tickets, or compensation claims. These not only impact customer satisfaction but also add to operational expenditures.

Furthermore, a uniform and robust response from vehicles allows for simpler backend software development. Today, backend systems must often account for dozens of different EV behaviors and exceptions. Standardization through improved compatibility would reduce this complexity, resulting in lower software development and maintenance costs and enabling faster rollout of new features.

4.3 Grid Efficiency and Infrastructure Optimization

Power quality issues—such as non-compliant harmonic emissions or poor response to voltage variations—can pose a serious risk to grid stability, especially as EV adoption increases. Poorly behaved EVs can amplify grid imbalances, require additional grid-side filtering hardware, and in some cases even lead to unintentional load shedding.

Improving EV resilience to voltage disturbances and limiting harmonic emissions supports a more stable and efficient electricity grid. Smart charging that adapts reliably to available grid capacity helps to flatten peaks in demand, deferring or eliminating the need for costly grid reinforcements. This is particularly relevant in areas where distribution networks are nearing their capacity limits.

In the long term, solving power quality problems will enable the mass deployment of smart charging across neighborhoods, business parks, and apartment complexes without the need for expensive grid upgrades. This makes the smart charging infrastructure more scalable and future-proof.

4.4 Enabling Advanced Energy Services

High interoperability and grid compliance are also prerequisites for more advanced functionalities such as dynamic pricing, load balancing, and bi-directional energy transfer (Vehicle-to-Grid or V2G). These services rely on the accurate and timely exchange of information between EVs, charge points, and energy systems.

For instance, in a future energy market where electricity prices fluctuate on a hour basis, EVs must be capable of adjusting their charging rate within seconds to respond to pricing signals. Without consistent and reliable performance across all vehicle types, these advanced services will remain limited in scale or only available to a small subset of users.

By resolving compatibility issues today, we pave the way for energy innovation tomorrow. This also positions the Netherlands—and Europe more broadly—as a frontrunner in developing energy-smart mobility solutions.

4.5 Societal and Environmental Impact

The societal impact of resolving these technical challenges should not be underestimated. A seamless and robust smart charging system contributes directly to climate goals by enabling greater use of renewable energy and improving grid efficiency. Additionally, reducing the need for physical infrastructure upgrades translates into fewer construction projects, lower public spending, and less disruption for residents.

Moreover, by ensuring that smart charging is inclusive and reliable across all vehicle types and use cases, the system becomes more equitable. Users in rural or lower-income areas, who may rely on less expensive vehicle models or have fewer charging options, will benefit equally from a well-functioning smart charging network.

5 Future Work

Results will be used to inform policy recommendations and contribute to global discussions on EV charging standardization. While the large-scale test campaign conducted by ElaadNL from May 2024 to April 2025 provides a solid foundation for understanding the current state of smart charging compatibility, it also reveals multiple opportunities for further research, development, and implementation. As smart charging evolves from pilot applications to standard practice, a structured follow-up is essential to address remaining gaps, operationalize findings, and support stakeholders in scaling up smart charging across Europe.

5.1 Data Analysis and Reporting

The most immediate priority following the conclusion of the test period is the detailed analysis of the data collected. This includes both quantitative measurements (e.g. voltage, current, harmonic content) and qualitative observations (e.g. user app feedback, recovery after paused sessions). Final results will be analyzed during May and June 2025 and presented at EVS38.

5.2 Expansion of the Test Scope

Given that this project focused primarily on AC destination charging, future efforts should expand to cover:

- DC fast charging scenarios, including interoperability at high-power charge points and behavior under grid-constrained conditions.
- Bidirectional charging (V2G) functionality, which requires entirely new test protocols to assess safety, communication reliability, and grid impact.
- Heavy-duty vehicles, such as electric trucks and buses, whose smart charging profiles and demands differ significantly from passenger vehicles.

These extensions will allow the findings to be generalized across a broader segment of the mobility landscape.

5.3 Validation in Field Conditions

While the controlled environment of the ElaadNL Testlab provides highly repeatable results, real-world environments introduce variables such as fluctuating user behavior, ambient temperature, network congestion, and renewable generation profiles. A follow-up pilot in operational field settings—for example at residential neighborhoods, workplace hubs, or shared charging plazas—will help validate test findings under realistic usage conditions.

Such pilots would provide valuable insight into:

- The long-term reliability of smart charging algorithms.
- User behavior in response to smart charging incentives.
- Grid effects at scale, including load shifting effectiveness.

5.4 International Collaboration and Harmonization

To ensure consistent vehicle and infrastructure behavior across borders, the results of this program will be shared with international standardization bodies, such as ISO and IEC. Close collaboration with European partners (e.g., through projects like SCALE and AFIR, EPDB and REDIII implementation frameworks) will be essential to harmonize communication protocols and compliance testing.

Additionally, a European interoperability test framework could be established based on this project's methodology, enabling other countries to replicate and contribute to a shared smart charging knowledge base.

5.5 Development of a Smart Charging Certification Scheme

One of the most impactful outcomes of this work would be the establishment of a voluntary or mandatory certification scheme for smart charging compatibility. Such a scheme would:

- Give consumers and fleet operators confidence when choosing vehicles and chargers.
- Encourage OEMs to prioritize compatibility and robustness.
- Reduce the burden on CPOs by minimizing interoperability issues.

The certification scheme could be implemented in collaboration with independent test labs and aligned with ongoing regulatory efforts in Europe.

5.6 Supporting Innovation and Market Development

Finally, the knowledge generated through this program can be used to support the development of new smart charging business models. This includes:

- Dynamic pricing services that reward off-peak charging behavior.
- Grid flexibility platforms, where EVs participate in local energy markets.
- Smart home integration, linking EV charging with rooftop solar and energy management systems.

To facilitate this, it will be important to continue knowledge sharing with software developers, utilities, municipalities, and consumer organizations.

By continuing this work across the technical, operational, and policy domains, we can ensure that smart charging moves from promising technology to widely trusted standard—one that supports the decarbonization of transport and the reliability of the electricity grid alike.

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Presenter Biography

Frank Geerts is director smart and bidirectional charging at ElaadNL leads a team of experts to accelerate the widespread market deployment of smart charging. Frank is member of the EC Smart Energy Expert Group, Project coordinator of EC project SCALE and Member of coordination team Dutch program Smart Charging for All. Frank has over 25 years' experience in the energy sector and nearly 15 years' experience in the eMobility sector. He is a regular speaker on international conferences.