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Building a Virtual Power Plant: Lessons from Europe's largest EV smart charging deployment

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Executive Summary

This paper explores a scalable smart charging solution using EVs as a Virtual Power Plant (VPP) to help stabilise renewable energy supply. It shares lessons learned from an active deployment of almost 16,000 charging points (8,000 stations) in the Rotterdam region – the largest smart-charging site in Europe, potentially the world. Developed and managed by Equans and Engie Laborelec, the VPP uses a cloud network and bespoke software to manage the charge speed in response to fluctuations of renewable energy. At peak times, the VPP has the capacity to release around 7.5 MW of flexible power, the equivalent of the rated capacity of over 20,000 solar panels [1]. As demonstrated by our large deployment, smart charging can contribute to grid stability and is commercially viable on a large scale. However, to fully harness its potential, coordinated efforts across technological, regulatory, and behavioural dimensions are essential, as this paper aims to demonstrate.

Keywords: S*mart Charging, Energy Management, Smart grid integration and grid management, Electric Vehicles, Sustainable Energy.*

1 The smart charging vision

Transitioning to electric vehicles (EVs) is widely accepted as an essential step in the efforts to decarbonise transport and contribute to crucial climate goals. For a successful transition, adequate public charging infrastructure is needed: having fast, connected, and reliable charging points in rural and urban areas incentivises the greater population to embrace electric vehicle ownership. The number of global charging points is expected to exceed 15 million by 2030 – a four-fold increase compared to the four million that were in operation in 2023 [2]. Yet, standard methods of home and curb-side EV charging (typically AC charging) are inflexible: the charge starts when the vehicle is connected and ends when the battery is full or when the user disconnects. On average, EVs are only charging for one-third of the time they are connected to an AC charging point (see Fig. 1).

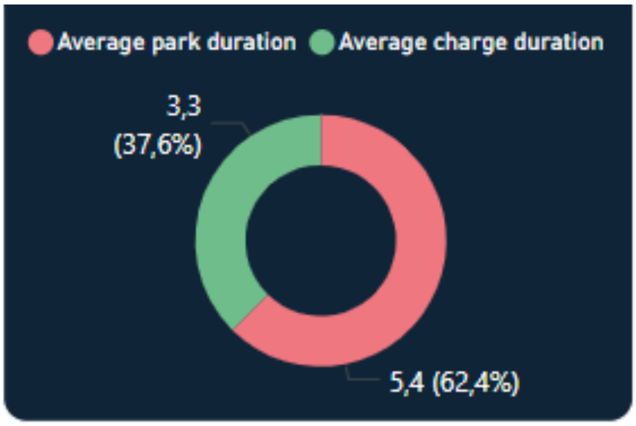

Figure 1. Distribution of session duration (in hours)

This represents a significant opportunity for smart charging. By integrating EV charging with energy market mechanisms, smart charging provides a crucial means of achieving flexibility, enabling dynamic adjustments to charging schedules based on real-time grid conditions and market incentives. In essence, through smart charging, EVs become a Virtual Power Plant (VPP) to more effectively manage the intermittent and uncontrollable nature of renewable energy. This is essential as the penetration of renewable energy sources on the grid increases and grid stability becomes a more significant challenge. By leveraging advanced data analytics, real-time communication, and intelligent energy distribution, smart EV charging can help reduce peak demand pressures on the grid and help accelerate the green energy transition.

Demand for smart charging solutions from consumers and public authorities in the Netherlands is growing. According to a survey conducted in the Netherlands in 2024 by the RVO (Netherlands Enterprise Agency) alongside other organisations [3], 23% of the 2,851 EV drivers surveyed (those that submitted full responses) said they use smart charging at public stations – up from 14% in 2023. The trend is also reflected in public charging tenders, as indicated in Fig. 2. The graph depicts tenders graded on price elements and quality elements. Under quality evaluations of tenders, smart charging has risen from around 8% of quality points in 2020 to 30% in 2024. It should be noted that the drop in total points for smart charging from 21% in 2023 to 12% in 2024 was due to the higher focus of tenders on price rather than quality in that year and therefore does not represent an absolute drop in smart charging tenders.

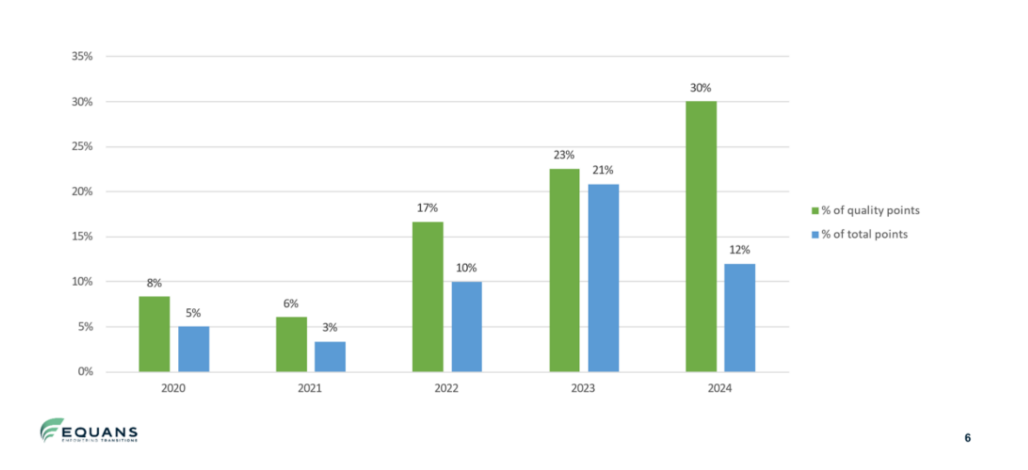

Figure 2. Smart charging trends in public charging infrastructure tenders in the Netherlands

2 The large-scale VPP deployment in the Rotterdam region

To harness the potential of smart charging, the VPP deployment was established in the Rotterdam region in 2022, and now consists of almost 16,000 cloud-connected, public, smart charging points, supplying 100% renewable, locally generated electricity across 30 municipalities in the surrounding region. The VPP leverages the imbalance mechanism – a system by which the transmission system operator (TSO) incentivises Balance Responsible Parties (BRPs) – often energy suppliers – to maintain the balance between energy supply and demand. A BRP has a cost associated with how imbalanced its energy portfolio is compared to the grid state. Smart charging can be used as a way to temporarily reduce the demand in electricity when the imbalance is high (i.e., supply is lower than demand) by adjusting the charging speed of EVs for a maximum duration of 15 minutes (known as 'activations').

Each charging station of the VPP deployment has two charging points, delivering 16A of current when one of the points is in use and 12.5A when both points are in use (outside of activations). The charging sessions are modulated based on real-time grid imbalance and peak demand data. If the grid reaches a certain specified level of imbalance, the charge speed of the stations is lowered (to a minimum current of 8A) to effectively 'release' power back into the grid. Fig. 2 shows the effect of a balancing activation and the related power reduction (MW) during the session. The graph does not show the full flexible capacity across the entire network, rather, it represents one subset of charging points.

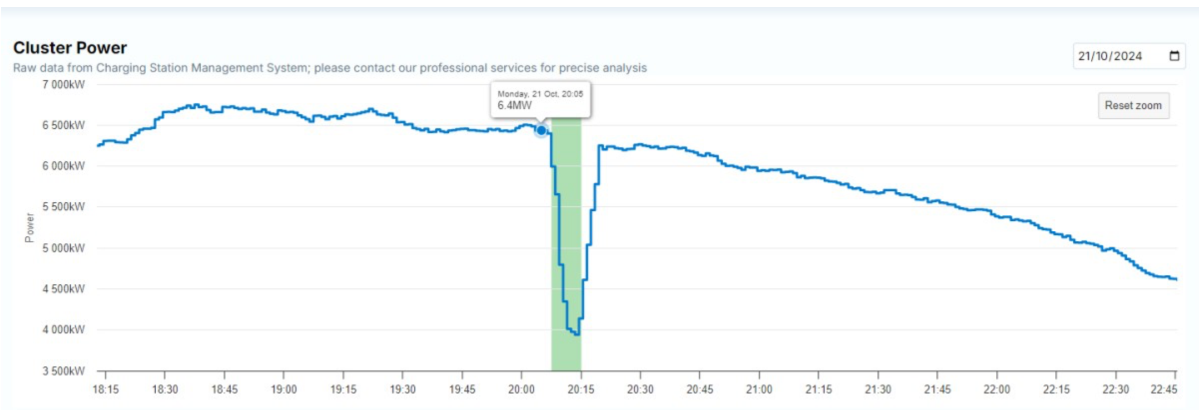

Figure 3. Power reduction during a balancing activation

2.1 Parties involved in the communication chain

The VPP communication chain comprises multiple parties: the transmission system operator (TSO); the energy supplier which signals the energy imbalance (Engie GEMS); the Charge Point Operator (Equans); the SMATCH software developed by Engie Laborelec; and the Charging Station Management System operator (Last Mile Solutions). The development of uniform communication protocols to ensure seamless interaction between EVs, chargers, and grid operators was essential for this project, as was the development of predictive and adaptive algorithms that optimise charging schedules while respecting user preferences and grid constraints. These are explored in more detail in section 3. It should be noted that having the Charging Point Operator (CPO) in the middle of the chain ensures that the impact on the EV driver is managed at all times: the CPO decides whether to relay a signal or not to the SMATCH software and therefore remains in control of the service.

2.2 Minimising driver impact while creating value for the grid

Measures are utilised to ensure driver satisfaction – which is often the main priority for municipalities awarding new charging infrastructure contracts. The VPP steering is highly conservative: reduced charging is activated for just seven minutes on average (activations can last for up to 15 minutes however this is rare). This conservative steering presents a notable advantage over other modes of smart charging which often require postponing the charge for multiple hours – significantly impacting drivers who are only parked for short durations and expect to leave on a full charge. The steering utilised by the VPP is therefore highly suitable for situations where departure time is unknown as it requires only short and minimally intrusive balancing actions, resulting in minimal impact to the driver. Due to this conservative steering, currently 81% of sessions do not get activated at all. Further controls to minimise driver impact include a strict limit on the activations per session: no more than 30 minutes of decreased charge speed is allowed in a four-hour period.

2.3 Rapid scaling of the VPP

The VPP scaled rapidly since the first charging points were installed in October 2022 (see Fig. 4). This is important for maximising performance and benefits for the energy grid, and for a successful energy transition in general, which is dependent on vast amounts of flexibility in the grid. The more charging stations added to the VPP, the greater the controllable capacity and therefore the greater the CO2 reduction. And as more flexibility is created in the grid through smart charging (and other measures), more renewable energy sources can be connected to the grid, further expediting the energy transition.

Improvements are continuously made to the algorithm as further scaling occurs, enabling the VPP to respond faster and smarter to shortages on the electricity market while maintaining an optimal user experience. User satisfaction is determined by the number of users terminating their sessions early (‘hot plug-outs’). This is closely monitored and to date, there has been no significant variance in hot plug-outs when comparing the non-smart charging stations with the VPP.

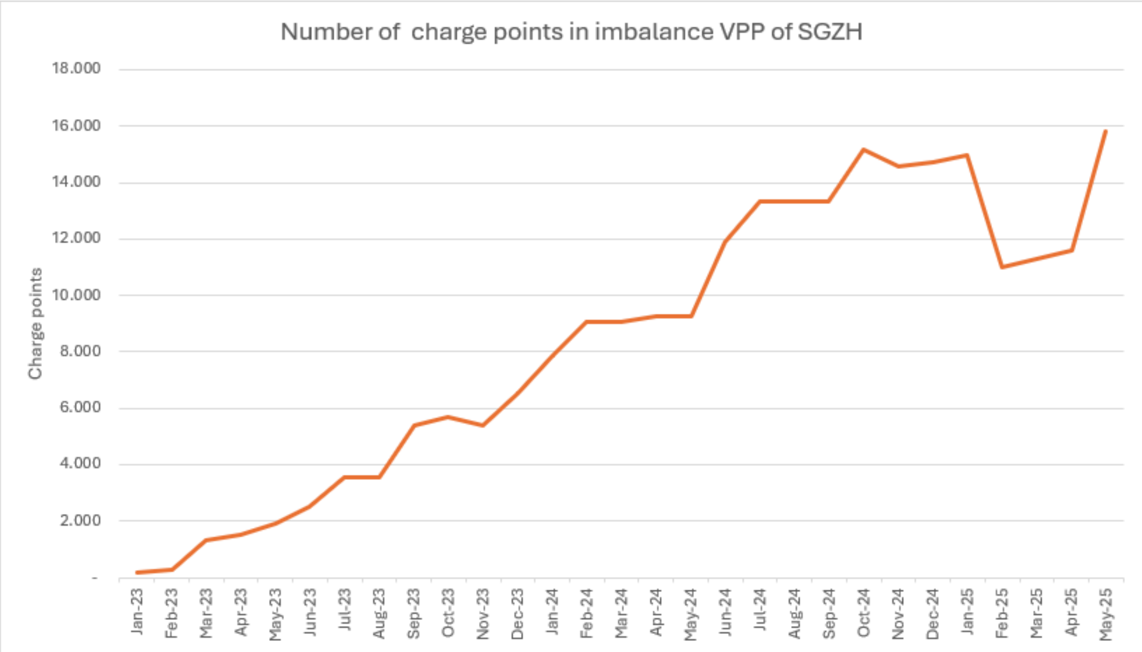

Figure 4. Project expansion since January 2023

3 Measuring flexibility gains

Accurate measurements are essential for disaggregating the imbalance cost reduction resulting from smart charging from the global portfolio of the BRP. They are also a crucial enabler of scaling, particularly as we are now targeting ancillary services, such as mFRR (manual frequency restoration reserve) and aFRR (automatic frequency restoration reserve). These markets play a vital role in maintaining grid stability by ensuring that real-time deviations between electricity supply and demand are corrected efficiently. The advantages of using such ancillary services for the VPP over passive imbalance measures are threefold:

Faster imbalance correction: While passive participation (on which the VPP was originally based) helps smooth net load on the grid, mFRR and aFRR provide dispatchable capacity within minutes (mFRR) or seconds (aFRR). This rapid response stabilises grid frequency more effectively, reducing the risk of under- or over-frequency events as the use of variable renewables grows.

Enabling higher renewable penetration: By offering a stable and controllable reserve of electricity, the VPP becomes a reliable counterweight to solar and wind variability. This accelerates the transition to a zero-carbon grid: system operators can confidently integrate more renewables knowing that the VPP will help to balance out the inevitable peaks and troughs.

Enhancing grid resilience: Active reserve participation creates a distributed ‘shock absorber’. Instead of relying solely on large central plants, thousands of EV chargers collectively deliver reserve services, lowering the chance of large-scale disturbances.

mFRR and aFRR markets have more stringent access requirements compared to passive imbalance steering; for example, they require certification from the grid operator, proof of high reaction times and highly accurate steering. This is where the challenge lies: accurately measuring the energy savings achieved during a flexibility activation is a complex process. Traditional metering systems such as those used by Equans’ charging stations in the Rotterdam region provide energy consumption data at 15-minute intervals. This granularity is insufficient for capturing the precise power reductions and subsequent recoveries that occur during short flexibility activations. To overcome this limitation, we utilise a more refined dataset – relying on OCPI status updates recorded every five minutes – allowing us to track session-level energy consumption and instantaneous currents. By applying interpolation techniques and edge detection methods, we reconstruct power trends with high accuracy, enabling us to compute the exact energy shaved during a flexibility activation, as described in section 3.4.

3.2 Demand-response flexibility

When the energy supplier (Engie) is in an imbalance position, it sends a signal to the operator (Equans) who then decides whether to relay the signal to EV chargers through SMATCH. Once received, SMATCH automatically sets all the charging sessions to the minimum possible power. Power is restored either at the end of the imbalance settlement period (the end of the 15-minute intervals – i.e., on HH:00, HH:15, HH:30, HH:45) or on a specific time given with the activation signal. The typical duration of the flex period is around seven minutes.

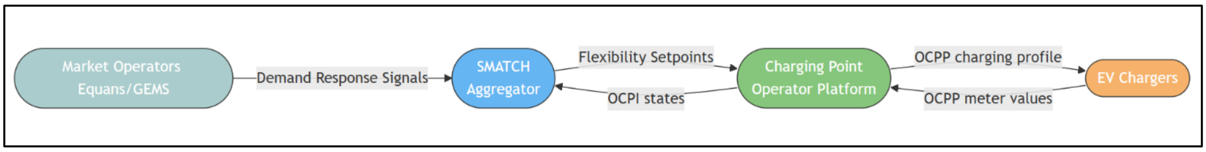

Figure 5. High level architecture of the demand-response feature in SMATCH

Fig. 5 represents a high-level architecture of the demand-response feature in SMATCH. The software communicates to the charging point through a CPO platform in the Open Charge Point Interface (OCPI) protocol. The CPO communicates to the charging points via the OCPP protocol.

When a charging session is active, SMATCH receives a state every five minutes. This state contains a timestamp, the amount of energy consumed up to this time, the instantaneous current on each phase at this time, as well as supplementary information related to the session (start time, charging point id, number of phases status, …). Imbalance positions are settled every 15 minutes; therefore, we need to know the exact consumption data on these intervals to determine the energy shaved. Since the charging points are equipped with smart meters, the operator knows the consumption of charging points in 15 minutes intervals. This granularity and the lack of real time information about currents makes it difficult to accurately compute the displaced energy.

3.3 The sampling challenge

A comparison between the energy measured by the power meter and the energy received in the SMATCH states for a particular charging station is shown in Fig. 6. The station consists of two charging points, and the power measures the sum of the two charging points. The curve from the power meter is depicted in blue, the curve reconstructed from the SMATCH states is depicted in red. We see that there is a close alignment between the curves. For the period for which the power meter data was made available, the discrepancy in energy at the end is around 1%. It can also be noted that even when there are no active charging sessions, there is slight consumption reported by the power meter. This consumption is around 4 to 5 W and should correspond to the consumption of the electronic circuits inside the charging station when it is idle. Once we correct for this small passive consumption, the difference between the power meters and the SMATCH states drops to 0.8%.

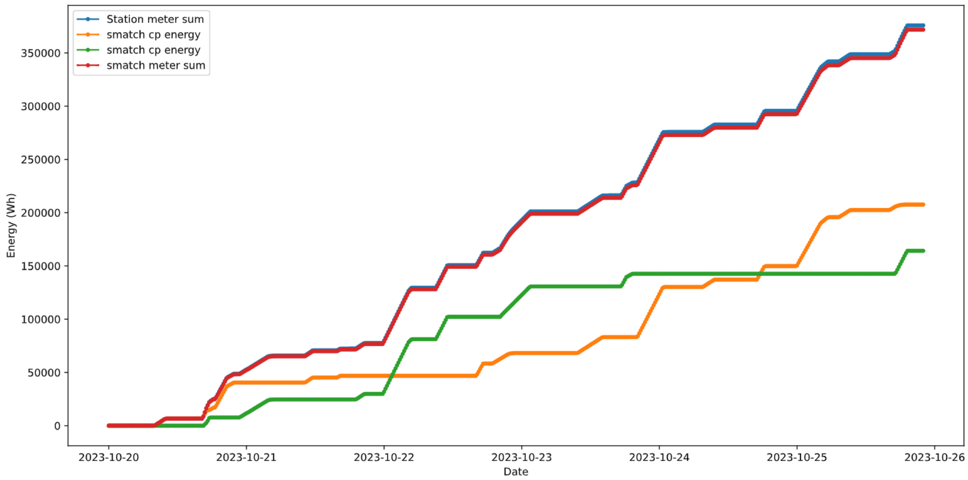

Figure 6. Comparison between power meter energy readings and SMATCH states. Power meter consumption is in blue, a station consists of two charging points, show in green and orange, and their sum in red.

A similar comparison can be made with the power, as shown in Fig. 7. For smart meter data, the power was computed simply as the difference of energy between two measurement points of 15 minutes, whereas for the SMATCH system, the instantaneous current was used. Here again, the alignment is close.

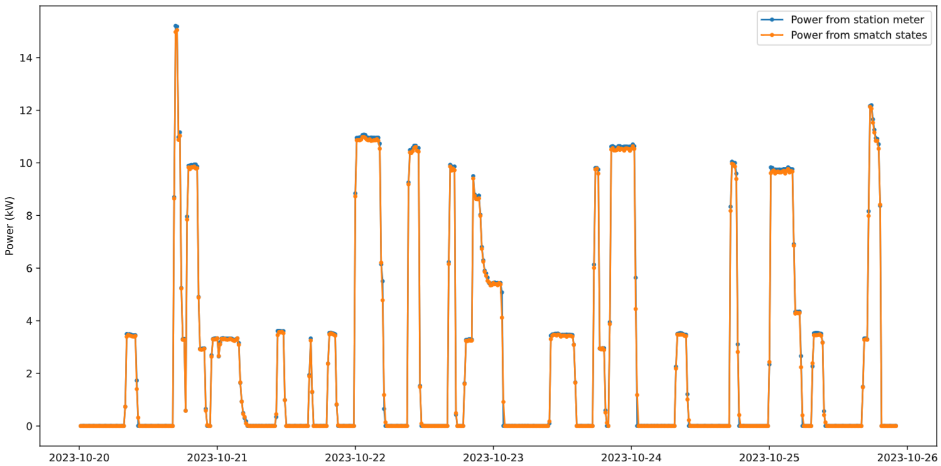

Figure 7. Comparison of instantaneous power between power meter and SMATCH states

In order to be able to compute the amount of energy that has been shifted, two components are needed: the amount of energy that was actually consumed, and the amount of energy that would have been consumed if nothing was done.

3.4 Measuring the amount of energy shifted (or shed)

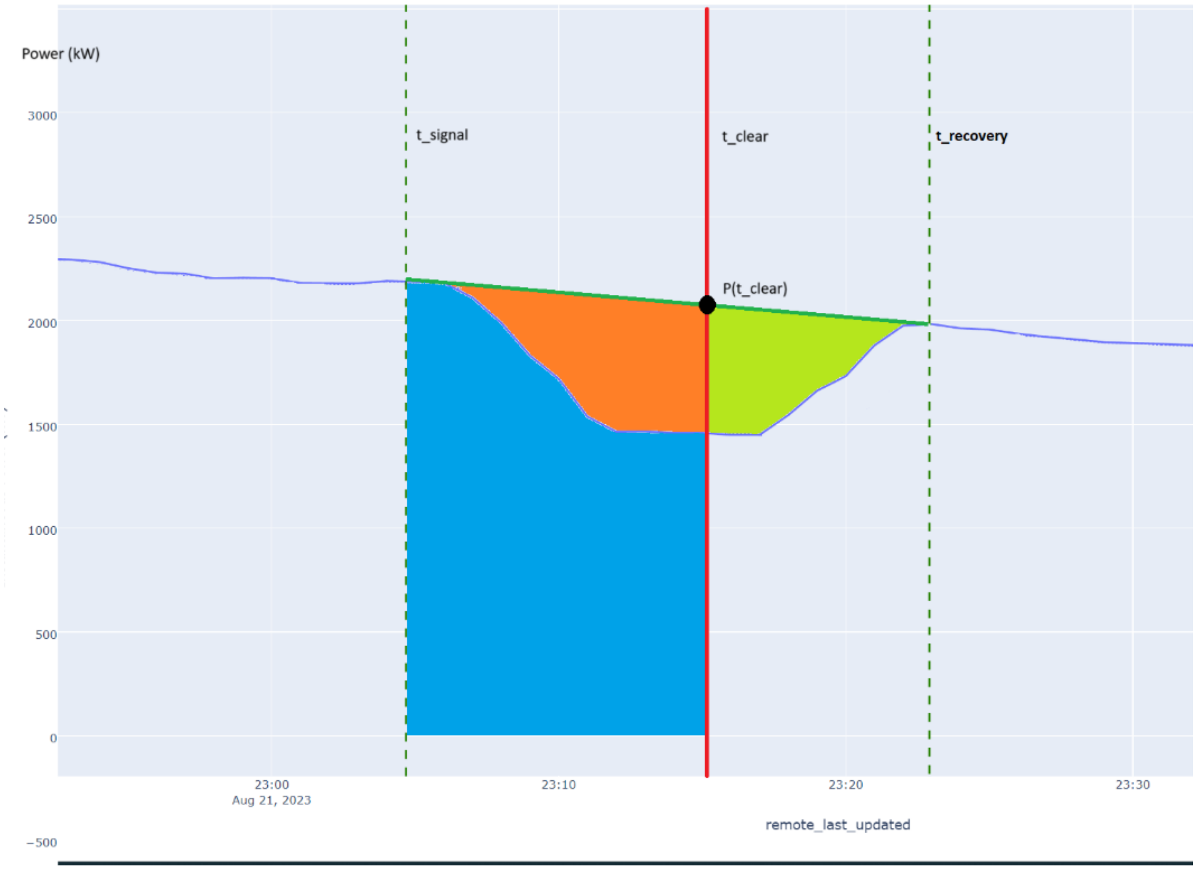

Figure 8. Measuring the amount of energy shifted

Imbalance prices are published in EUR/MWh for each Imbalance Settlement Periods (ISP) – the 15-minute intervals mentioned earlier (e.g., from 23:00 to 23:15). In Fig. 8, a demand-response signal happens at 23:04 (**t_signal**) and a clearing signal (**t_clear**) at 23:15. In order to estimate what value was generated by shifting the consumption to another time, we need to know how much energy was consumed between 23:04 and 23:15, and how much would have been consumed had the signal not been acted upon.

The quantity of energy that has actually been delivered in this timeframe is represented in blue in Fig. 8. It can be calculated by integrating the instantaneous power over the duration of the demand-response. We can precisely measure the amount of energy delivered at **t_clear** and **t_signal**, it is:

$$\sum_{i=0}^{N} E_i(t_{\text{clear}}) - E_i(t_{\text{signal}}) \qquad (1)$$

Where i runs over all active sessions between **t_clear** and **t_signal**, and is understood to be zero if the session i was not active at the time of $E_i(t_{\text{signal}})$.

What we are interested in is the value of the energy shifted or shed: the quantity of energy that was momentarily not delivered due to the demand-response, represented by the orange area in Fig. 8. The total energy that would have been delivered without steering is represented by the area of the trapezoid defined vertically by **t_clear** and **t_signal**, and horizontally by 0 and the green line on the graph.

The green line can be computed by applying an edge detection algorithm (by looking at the derivative) on the instantaneous power curve, before and after the demand-response. A linear interpolation is then performed for the power before the signal and the power after the signal. At **t_clear**, this gives us the **P(t_clear)** which is a credible and smooth estimation of what the power would have been without a demand-response. This interpolation captures the arrivals and departures during the duration of the demand-response.

The energy that would have been consumed without a demand response (orange + blue area) is: $P(t_{signal}) + P(t_{clear}) * \frac{(t_{clear} - t_{signal})}{2}$ (area of the trapezoid). (2)

After calculating this value, we subtract the previously computed blue area (representing the energy actually delivered) from it. The result is the orange area, which indicates the amount of energy that was either shifted or shed. This method is based on the real aggregated data and uses no hypothesis.

3.5 Performance monitoring: theoretical flexibility

By retroactively adjusting all sessions consuming more than the minimum intended charging rate (8A) and plotting the aggregate resulting power alongside the actual historical power, as illustrated in Fig. 9, we can assess the system's performance.

The gap between the historical power during a demand-response event and this theoretical minimum power helps the CPO identify misconfigured assets or anomalies resulting in suboptimal performance. This can also serve as a target to maximise the use case by highlighting where the actual ceiling is.

Figure 9. Assessing VPP performance by computing the theoretical minimum power along the historical power

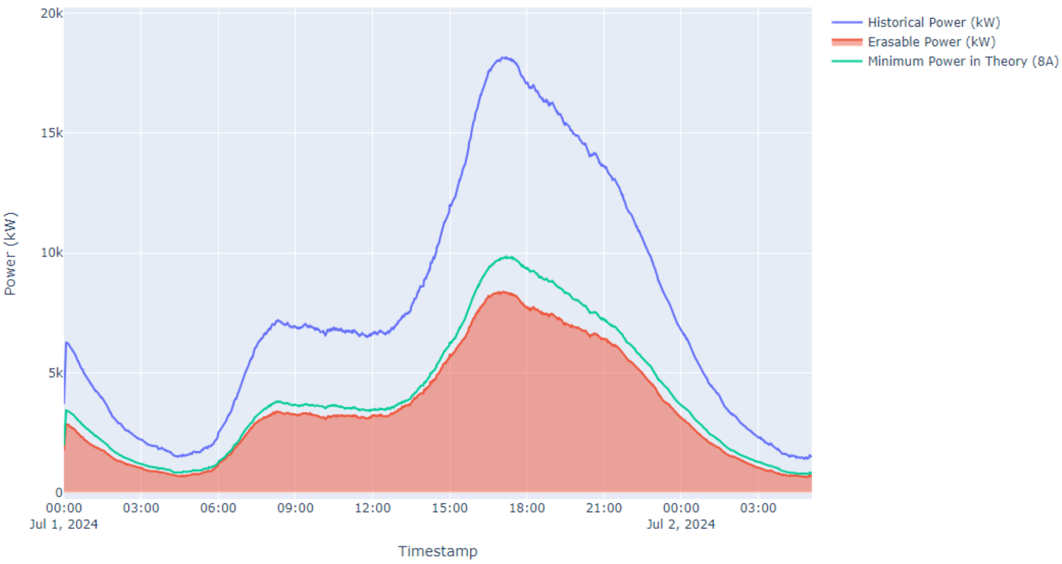

Figure 10. Computing erasable power based using minimum charging rate

This can also be used to assess the erasable power of an EV's VPP at various times of the day, as in Fig. 10. Understanding the characteristics of the asset's flexibility is required to integrate it into a flexible energy portfolio.

4 Key Challenges of the VPP

In this section we highlight some of the key challenges when developing the VPP and how they were addressed.

4.1 Standardisation of software and hardware

Owing to the innovative nature of the project, an initial challenge arose from the software and hardware which had not been designed for this method of responding in real time to green energy supply. Standardisation was a particular challenge, with eight different brands of chargers and around 80 different controller-firmware combinations. While they all use Open Charge Point Protocol (OCPP), there was still variance in the interpretation of that protocol that needed accounting for. This was resolved by testing and integrating each combination individually.

Communication challenges do still occur however, as experienced in March/April 2025 with around 2,000 chargers having communication failures with the Cloud software. This resulted in the breakdown of communications chains and a loss of data for this time period (indicated earlier in Fig. 4). The issue was fixed through close collaboration between Equans, LMS and the charge point manufacturer to improve OCPP compliancy.

A further hardware consideration relates the cars: some EVs cannot reconnect to power if the connection has been paused during the charge [5]. This means that exploiting the full flexibility potential of unidirectional charging (momentarily suspending every charging session) remains theoretical when we only communicate with the chargers and not the EVs (drivers), known as an EV supply equipment-centric approach. This is especially the case when scale is involved. In the long term, manufacturers (OEMs) need to ensure better conformity to the standards to avoid such issues altogether. In the short to medium term, we expect that capturing information about the individual EVs (either through car integrators or through drivers' preferences via mobility services providers) is needed to allow for the full potential of smart charging.

The independent nature of each charging station was a further challenge. Charging stations are configured to send meter values every five minutes during active sessions, but these readings are relative to the session's start time. Consequently, each charging point sends data at independent five-minute intervals. Up-sampling and interpolation relying on CPO data was used to address this; with the method validated by smart-meter readings as described in section 3.

4.2 Length of communications chain

Responding to grid changes in near-real time is essential for the smart charging solution employed by the VPP. Challenges of data quality and latency issues in the early stages of the project, stemming from the connection with the Charging Station Management System (CSMS) and the length of the communications chain in general, created a lengthy response time for the VPP. It was essential that this response time was lowered for the VPP to be effective, and following various process optimisations, the response time across the chain was reduced to less than one minute.

A further challenge of the communications chain is the current inability to remunerate the driver when conservative steering is deployed: with numerous actors in the chain, the value generated becomes almost negligible. As more user data is known, greater flexibility can be leveraged for more targeted steering, resulting in the delivery of greater economic value, to the point where all actors in the chain, including the EV driver, can be remunerated for the smart charging session. Options to increase driver engagement and gather driver preferences are currently being explored through a pilot project in Amsterdam (see section 4.4).

4.3 Managing the variation between VPP and local constraints

Initially, the smart charging software was designed with static load balancing to handle local grid connections efficiently. This was done by performing optimisations at a local level to properly balance between connectors of a station according to grid constraints (and drivers' predicted departure times).

As the project evolved, we introduced demand-response functionality for passive imbalance steering. Demand-response requires rapid reaction times, as described in section 3.2, which meant bypassing optimisation temporarily. However, background optimisations continued, ensuring that charging profiles resumed as "optimal ones" once the demand-response event was over.

Further enhancements led to the integration of grid-aware charging. This feature allows for congestion management at subcluster levels of various sizes, ensuring that charging sessions are optimised based on dynamic constraints. It considers factors such as available power, user preferences (predicted departure times and energy needs), and the DSO desired aggregate profiles for the day.

By incorporating these capabilities, the smart charging solutions are designed to handle multiple challenges simultaneously. This versatility enables us to address various use cases and stack value, ensuring a robust and adaptive charging infrastructure.

4.4 Variance in contract requirements when expanding to new regions

A further challenge of the project relates to variations in concession contracts. Each municipality has different requirements for issuing their charging contracts, which adds additional complexity when expanding nationally or internationally. For example, some municipalities prioritise balancing the grid and are not concerned about the length of time a vehicle is connected; others require a 'stop charging fee' when the charge ends or is paused and the driver needs to pay for regular parking. Some may require explicit consent from the driver in order to limit the charge, while others do not. The VPP system and model needs to be flexible enough to address all use cases and meet all regulations, but if it becomes too complex it becomes impractical. As the project expands internationally, different requirements will need to be managed, aligning the smart charging strategy to each one.

4.4 User data required for increasing the flexibility gains

Achieving sufficient user engagement and trust in the smart charging solution is critical for the long-term success of the VPP. According to the earlier-mentioned 2024 RVO survey, 70% of respondents expressed a desire for the ability to opt out of smart charging at public stations, possibly due to concerns about availability or slower charging speeds. And while many EV drivers said they would be willing to make adjustments to help balance the grid or take advantage of lower prices, 65% of respondents said they want full control over whether or not they charge smartly, with only 5% willing to let a third party, like a grid operator, make those decisions for them. In terms of pricing, 53% said they would be willing to pay more to charge during high-demand times, and 61% would accept slower charging during these periods to reduce grid stress. However, 43% are uncomfortable with public smart charging unless they can guarantee their car will reach a certain level of charge. This research indicates that communication, transparency, and maintaining an optimal user experience are key factors in the successful uptake of smart charging.

To increase driver engagement and obtain basic user data required for more targeted steering we are exploring options to connect the VPP with existing charge card platforms, with a pilot underway in Amsterdam. This will enable EV drivers to select the smart charging option through the charge card app they already have installed on their phone. The information they choose to share can then be used to optimise their charging session and remunerate them for their delivered flexibility.

5 Conclusions and future vision

As this paper aims to demonstrate, VPPs hold tremendous potential, when scaled successfully, to make significant contributions to grid flexibility and help expedite the transition to renewable energy. However, coordinated efforts across technological, regulatory, and behavioural dimensions such as EV driver engagement, are essential to fully realize this potential.

As well as integrating user data, a future consideration will be to integrate energy prices and weather forecasts into the algorithm to favour the recharge when the electricity prices are lower and to predict supply levels more accurately. It is also hoped that despite the challenges of expanding to different markets, municipalities and regions as mentioned in section 4.4, the VPP will extend within and beyond the Netherlands, leveraging significant scale to deliver greater flexibility for energy grids, and ultimately place the transition to green energy well within range.

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Presenter biographies

Bart Swens

After completing his bachelor degree in Mechanical Engineering at Delft University of Technology, Bart concluded his masters in Control Engineering by building a controller to schedule EV charging sessions using Vehicle-to-Grid, optimising on carbon intensity and day-ahead electricity prices at Jedlix. This ignited a passion for smart charging. Building on this experience, Bart joined Equans E-Mobility in 2022, where he has been dedicated to advancing innovative smart charging strategies. As of May 2023, Bart serves as the Product Owner for Smart Charging, leading efforts to enhance Equans' offerings and drive the energy transition forward.

Louis Sokal

Louis graduated in Bioscience Engineering in 2016 and has a passion for innovative solutions that support the renewable energy transition. Louis began his career as a consultant at Altran (Capgemini), gaining knowledge in the energy sector and digital industry. Since 2021, he has been with Engie Laborelec, a Research & Innovation center in Belgium, where he works as Product Owner for SMATCH smart charging solution.

Tommaso Difonzo

Tommaso, a dynamic energy and electric vehicle manager, started his journey in e-mobility with his 2011 thesis at the Polytechnic of Milan. After his studies, he joined Enel Group, where he held various roles in e-mobility, including functional analyst, tester of charging station and software solutions, project manager, and business developer. His experience at Enel's EU Affairs office, in charge of Enel's relationship with the European Parliament deepened his knowledge of electricity markets and EU clean energy legislation. During this period, he also attended a summer school at the Florence School of Regulation. In 2019, Tommaso joined ENGIE Laborelec as Business and Product Manager for SMATCH Smart Charging for EVs, and since June 2022, has been the Research Programme Manager on e-Mobility for the ENGIE Group, responsible for the Group's Research & Innovation activities on e-mobility.

Iris van Dam

Iris holds a Master degree in Psychology from Utrecht University and started her career at Equans in 2016 as a Market Research Analyst, followed by Consultant E-Mobility in 2021. She now serves as Marketing Manager E-Mobility at Equans Netherlands. In her role, she focuses on the development and promotion of sustainable and innovative charging solutions for electric vehicles. She bridges the gap between technological advancements, market needs, and public policy, aiming to accelerate the energy transition. Through her work, Iris contributes to initiatives that enhance grid stability and make electric mobility accessible to a wide range of stakeholders, including businesses, governments, and consumers.