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Evaluation of the MADELAINE demonstrator - An analysis of the efficiency and interoperability of a dynamically distributed DC charging system

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Executive Summary

Installing N conventional DC electric vehicle charging stations (DC-EVCS) to serve N electric vehicles (EVs) can be costly and inflexible, particularly in large parking facilities with long parking duration. To address this challenge, MADELAINE demonstrator introduces an alternative modular charging system for EVs that facilitates DC charging at multiple distributed charge points through a reduced number M<N of centralized AC/DC converters. By implementing an adaptive DC switch matrix, each charge point can be dynamically connected to any combination of converts. The convert's DC output can operate in parallel, enabling prioritized charging of individual slots. Simultaneous charging of as many vehicles as there are converters available is possible as well as various other configurations. To evaluate this approach, field test results of the MADELAINE demonstrator are presented and analysed. In conclusion, the economic and modular benefits of the proposed system have the potential to accelerate the deployment of modern EV charging infrastructure.

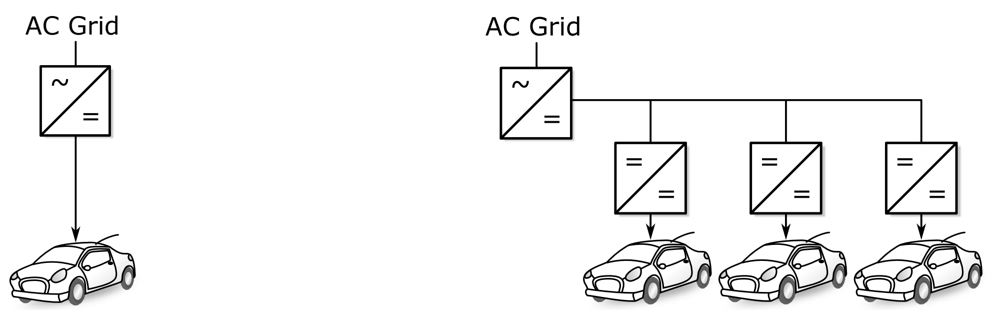
Keywords: Smart charging, Smart grid integration and grid management, Fast and Megawatt charging infrastructure, Power Electronic systems, Energy management

1 Introduction

The electrification of transportation is accelerating across Europe, creating high demand for efficient charging solutions. As of 2025 Q1, the EU hosts over 933,000 publicly accessible EV charge points, 151,000 of which are DC fast chargers. The present power distribution of the DC charge points is as follows: $6.7\,\%$ offer less than $50\,\mathrm{kW}$, $34.9\,\%$ range between $50\,\mathrm{kW}$ and $150\,\mathrm{kW}$, $42.1\,\%$ fall between

150 kW and 350 kW, and the remaining 16.3 % provide 350 kW or more [1]. These numbers will continuously increase, as the International Energy Agency's Global EV Outlook report estimates [2].
To deploy EV charging infrastructure across Europe consistently, the Alternative Fuels Infrastructure Regulation (AFIR) requires EU member states to provide public charge points with at least 1.3 kW of aggregated power output per registered EV and 0.8 kW per registered plug-in hybrid EV [3]. The regulation also defines mandatory roll-out targets for public fast chargers at European motorways. The enforcement of international and national policies helps meeting the growing demand for EV charging adequately.
Typical DC fast charging stations contain power electronics to convert electrical energy from the AC grid voltage level to the EV battery DC voltage level. Although their entire system is designed to provide the maximum charging capacity any time, the actual charging power demand is often far below the provided maximum. Frequently, no charging power is consumed at all due to EVs parking significantly longer than charging, leaving the available charging capacity unused.
This is particularly the case for typical commuter parking areas, like the installation site of the MADELAINE demonstrator, where people park their EV for an entire work day. In most of these situations, it is common to use slow AC chargers instead. However, AC charging is limited in power and requires drivers to relocate their car to a DC charge point if they need a fully charged battery earlier than planned. Conventional DC charging stations, on the other hand, are more expensive and require more space then AC charger, if they are located at each parking lot of a car park. These limitations can be mitigated by using distributed DC charging approaches where the power electronics is installed in a central unit, and space-saving DC dispenser units are placed at the individual parking lots. Hence, the available power electronics can be used for different charge points simultaneously, consecutively or both, depending on the charging demand. A potential system design for a distributed DC charging system is outlined in the US patent US7256516B2 [4]. Recently, several distributed DC systems have been presented for ultra-fast charging use-cases such as heavy-duty vehicle charging at motorways [5][6][7].
As outlined above, the question arises whether a distributed DC charging approach can also make sense for typical slow-charging applications, but with the additional option for high-power charging at each charge point. The MADELAINE research project has investigated this issue, and a demonstrator was developed and constructed at a work facility of the Austrian wind park operator WEB AG. Section 2 presents the installed and operational system and results from the project's first months of operation.

2 Methodology



(a) Singular EVSE with AC/DC converter

(b) Central power unit with several satellite charge points connected by a common DC bus

Figure 1: Power converter conceptual schematic of conventional EVSEs

To explain the MADELAINE demonstrator's concept, Figure 1 shows the basic setup of conventional DC charging solutions. With a single charge point per EVSE, see Figure 1a, the required cost per charging service is relatively high. To increase the utilisation ratio and to reduce the infrastructure costs per charge point, satellite systems can be used. They consist of a central power electronics unit and locally distributed dispensers. These dispenser systems typically use a grid-connected AC/DC converter to create a static DC bus, with DC-DC converters supplying regulated voltages to each charge point, see [9] and Figure 1b. The DC/DC converts are usually also contained in the central unit and can often be operated in parallel.
Instead of using a centralized AC/DC converter and individual DC/DC converters, the MADELAINE demonstrator utilises five AC/DC power converters, which can operate in parallel if needed, to supply ten locally distributed charge points. These charge points are installed in pairs of two at five charge posts, see blue cabinets in Figure 3, outfitted with individual Combined Charging System (CCS 2) interfaces. Figure 2 provides an overview of the concept.

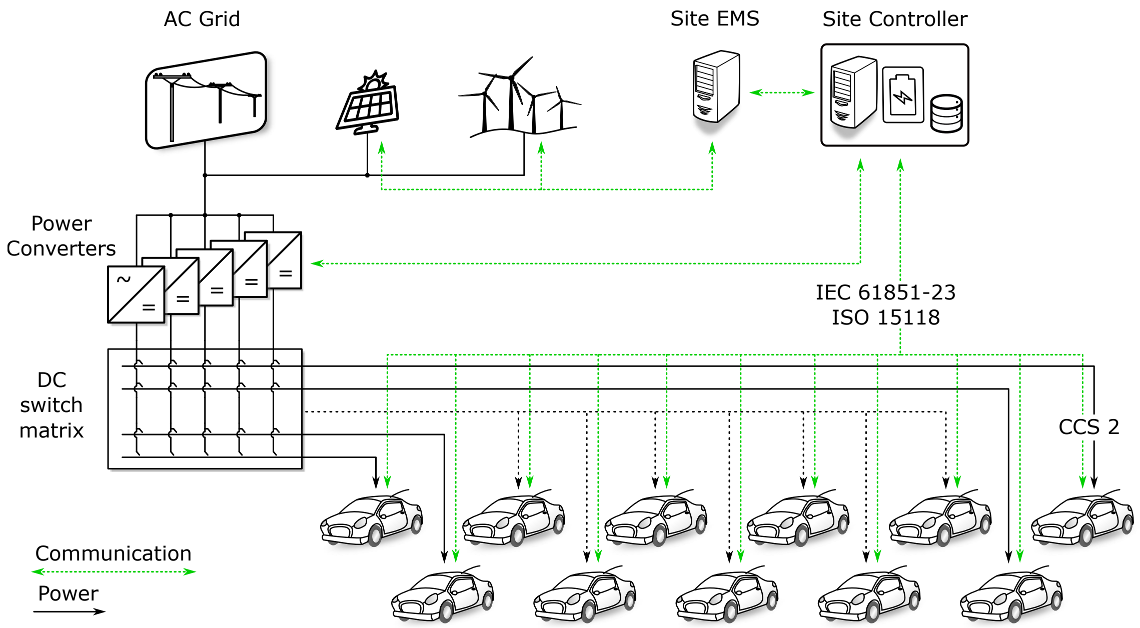


Figure 2: MADELAINE diagrammatic concept

The system's locally distributed charge posts are devoid of the usual power electronics, making them cost efficient. Only a small subset of components (CCS 2 connectors, fuses, and the charge-cable assembly) required. In the central unit, an adaptive DC switch matrix provides dynamically switchable routes for electrical DC current to flow from each converter to any charge point. This allows switching the power from one EV being charged to another EV, without any interaction at the parking EVs. By utilizing converter technology that allows for parallel operation, a single charge point can receive the combined power of 1 to M converters, where M is the total number of operational converters. The DC switch matrix brings increased complexity to the system. A substantial number of additional switches must be introduced to provide all permutations P(M,N) of system states, where N is the number of provided charge points. Power flow and control software was developed and extensively tested to avoid any short circuits or other catastrophic failures. To interact and communicate with the vehicles at each charge point, standard communication protocols IEC 61851 and ISO 15118 were implemented. As the system is intrinsically distributed in its functions and requirements, a complex communication, software and supervisory concept was implemented. Each charge point is a standalone digital communication system with certain privileges and responsibilities, managed by a central site controller. It's functions are to oversee all the charge point nodes, the converter control, and the switching of the DC switch matrix. The site controller and site EMS determine the charging strategy of the system, which ultimately decides which of the connected EVs get charged by which power converters at any time.

Figure 3: Aerial photo of the finished MADELAINE demonstrator; the power converters and adaptive DC switch matrix are located in the grey container on the top left of the photo, the charge points 1 - 10 are located in the blue cabinets

Typically, DC charging is used for high-power use cases. In MADELAINE, however, both slow and fast DC charging are possible at each charge point. Figure 3 shows the finished MADELAINE demonstrator at the WEB parking area in Pfaffenschlag, Austria (geolocation in open street map).

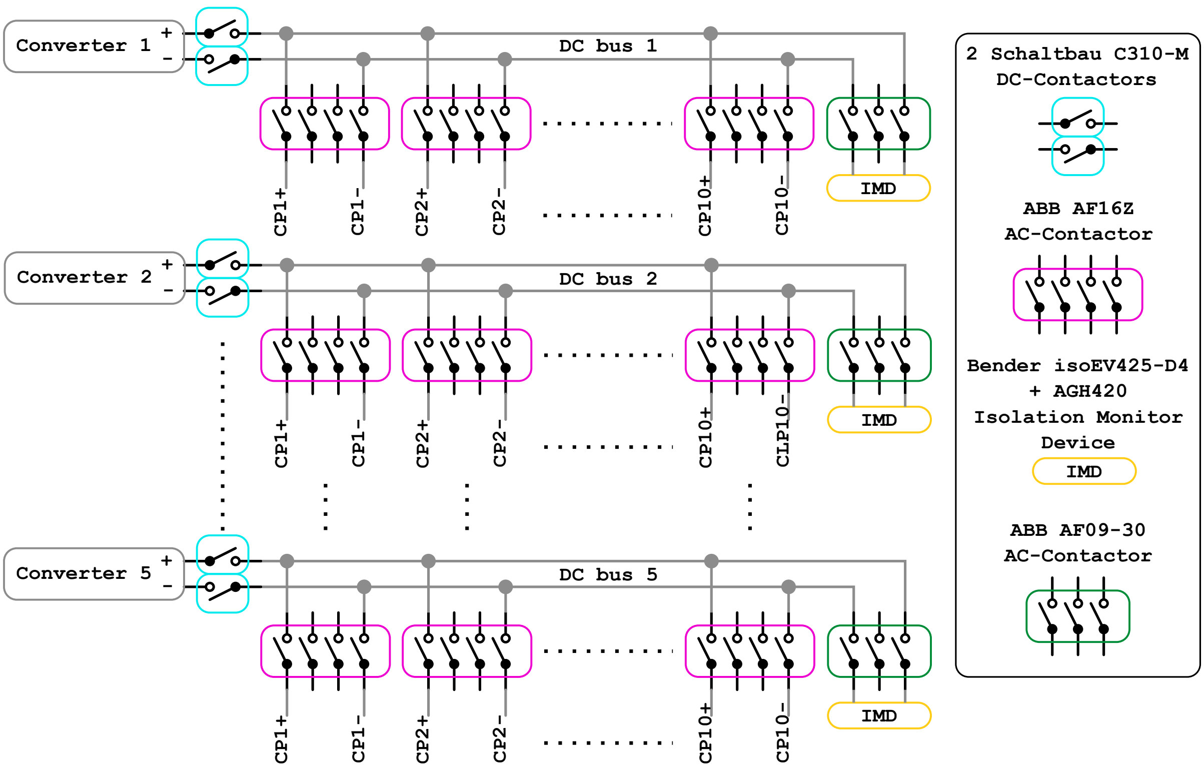


Figure 4: Schematic of the adaptive DC switch matrix, used in the MADELAINE demonstrator

Figure 4 shows the schematic concept of the DC switch matrix of the MADELAINE demonstrator. The DC switch matrix is used to dynamically and safely route each active CP to it's currently supplying AC/DC converter or multiple converters. To provide a route for DC+ and DC- from each converter to each CP, ten double-pole contactors per converter are required. Ideally, each of these 50 configuration-contactors is capable of making and breaking the maximum DC current at the maximum dc voltage of the entire system. Since the costs for such DC contactors are much higher than for the equivalent AC counterparts, an alternative solution for the demonstrator was investigated and found. The installed DC switch matrix utilises ABB AF16Z AC contactors for the 50 configuration-contactors. Of these four-pole devices, two and two switches are wired in series to increase the switching capabilities, see Figure 5. In this configuration, these AC contactors are allowed for operation in DC applications, as long as they are switched at 0 A. The obvious downside of using these AC contactors for the DC switch matrix is the lack of DC make and break capability. Therefore, Schaltbau C310-M DC contactors were used per DC+ and DC- pole, to safely connect and disconnect each AC/DC converter to it's corresponding DC bus. A safety programmable logic controller (safety PLC) is used to reconfigure the AC contactors whenever needed and only after the related DC contactors were switched to break the affected routes, ensuring the current is 0 A. By doing so, the amount of required DC contactors was reduced from 100 to 10 pieces at the cost of 50 additional AC contactors. Five additional ABB AF09-30 AC contactors were necessary to connect and disconnect the isolation monitor devices (IMD) depending on the current configuration of the DC switch matrix.

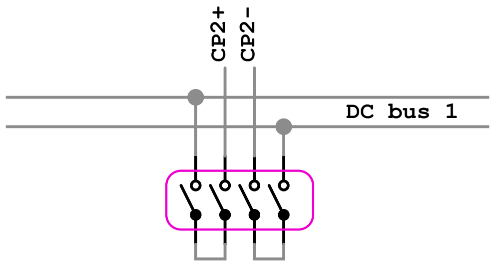


Figure 5: Schematic of the AC contactor wiring

3 Results

The MADELAINE demonstrator started its operation in March 2024 and serves ten charge points. Since then, relevant parameters of these charging processes were monitored and logged. These parameters for each connected EV and charge point are:

- state of charge (*SoC*),
- maximum available current at each CP (*EVSE Max Current*),
- actual current at each CP (*EVSE Present Current*),
- actual DC voltage of each CP (*EVSE Present Voltage*)
- total AC input power
- total DC output power

The *SoC* and *EVSE Max Current* of each connected EV and CP are communicated according to ISO 15118 and logged by an additional industrial PC, dedicated for capturing and visualising data.
EVSE Present Current and the *EVSE Present Voltage* are measured by each of the supplying power converters and the currents are summed up if more than one power converter is providing power to a specific CP. For the entire MADELAINE demonstrator, the total AC input power was measured at the AC power meter of the container and the total DC output power was measured by the individual power converters and added up. These parameters were logged in 5 s intervals by the industrial PC.

3.1 Analysis of charging processes

For this paper, the gathered data was analyzed and specific days were identified to show findings, derived from the recent months of operation. Significant charging parameters for each charge point are compared in Figure 6. These parameters are the *SoC* of the currently connected EV battery, the *EVSE Max Current* per charge point, and the *EVSE Present Current* per charge point. On this specific day in March 2025, all charge points except CP 7 and CP 10 were active at some time.
The chronology of the charging processes in Figure 6 shows how the MADELAINE demonstrator balances its available charging capacity between connected EVs. The implemented core principles are equal shares if possible, and if not possible, prioritisation of EVs with lower SoC over EVs with higher SoC.

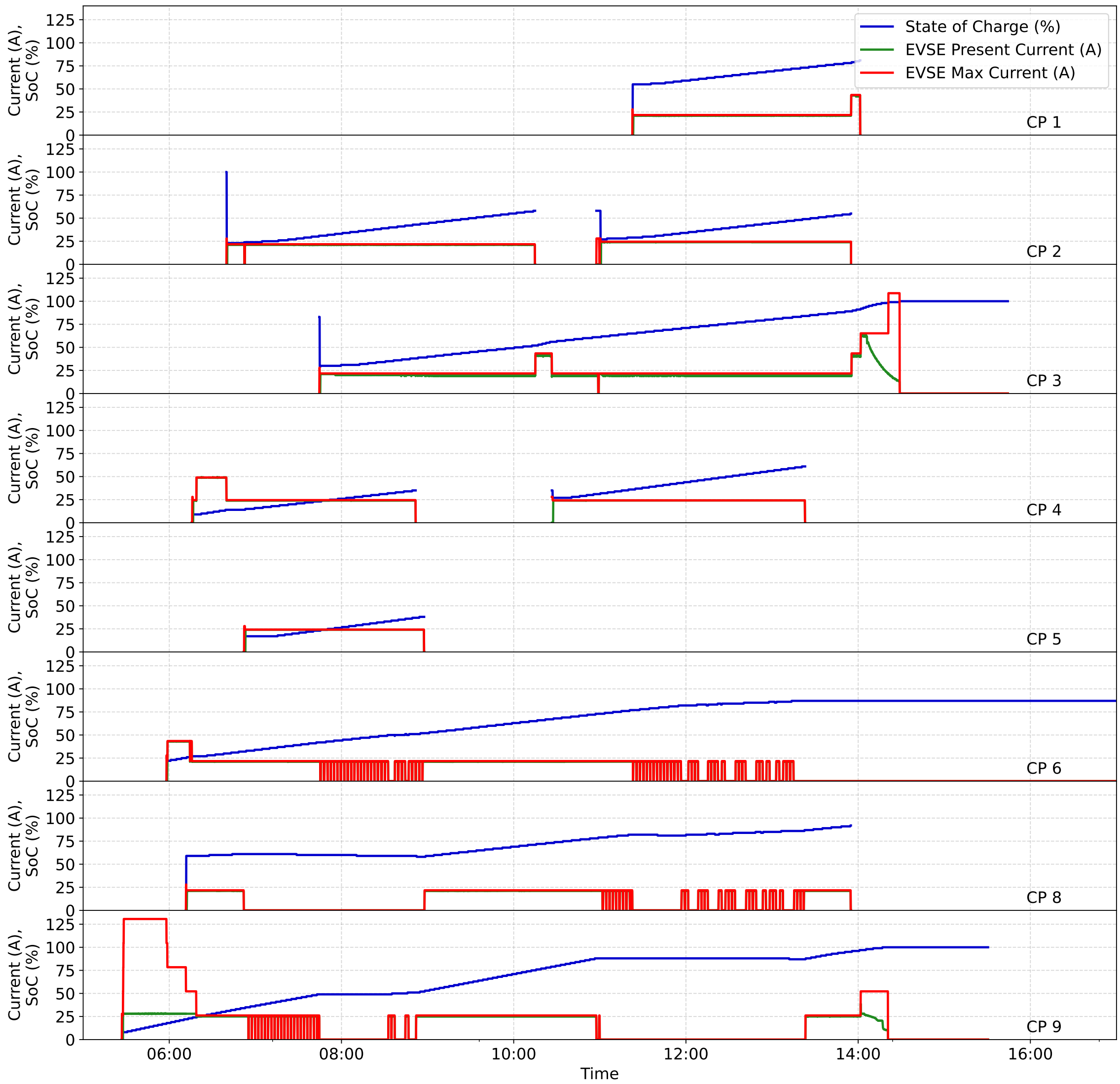


Figure 6: Charging processes on all active charge points during March 31, 2025

Around 05:30 the first EV is connected to CP 9 and would be allowed to draw from all five power converters in parallel, but only consumes power equal to one. Another EV arrives at 06:00 at CP 6. Subsequently, the EMS switches two of five converters from CP 9 to CP 6. The EV at CP 9 is allowed a higher share of power converters due to it's lower SoC. Shortly afterwards, around 06:15, the third EV and the forth EV arrive at CP 8 and CP 4. Facing the challenge of sharing five power converters on four EVs, the EMS prioritises the most recent arrived EV, again, because of the lowest SoC at this vehicle.

When a fifth EV arrives around 06:45, the EMS now provides one power converter per connected EV equally and independent of SoC.
The charging curve of the EV at CP 9 between 05:30 and 06:15 shows room for optimisation of the MADELAINE demonstrator's EMS strategy. The EV at CP 9 would be allowed to draw from five, then three, and two power converters, but constantly consumes only the capacity of one power unit. As soon as the second EV arrives at CP 6, the EMS balances the entire capacity $\frac{3}{2}$ between CP 9 and CP 6, although the EV at CP 9 clearly does not make use of two of it's available three units. In such cases, the EMS could, after a short waiting period, reduce the share of the EV at CP 9 to one power converter and offer the additional capacity to the EV at CP 6, thus increasing the likelihood of raising utilisation from $\frac{3}{5}$ to 1.
Another example of the sharing strategy was observed from 11:00 until 14:15. During this time, up to 7 EVs are connected to the demonstrator and the EMS cuts several EVs down to 0 A for various amount of time during this phase. The longest pause period becomes effective for the EV at CP 9, because if it's already high SoC compared to the other connected EVs. The EVs at CP 6 and CP 8 exchange one power converter several times during this period, because their SoC is in an equal range. As soon as the one EV charging reaches a higher SoC, power is switched to the EV with the lower SoC until this EV reaches a higher SoC and power is switched back. The other EVs at CPs 1-4 draw power constantly from one unit each due to their lower SoC compared to the EVs at CP 6 and CP 8 during this period.

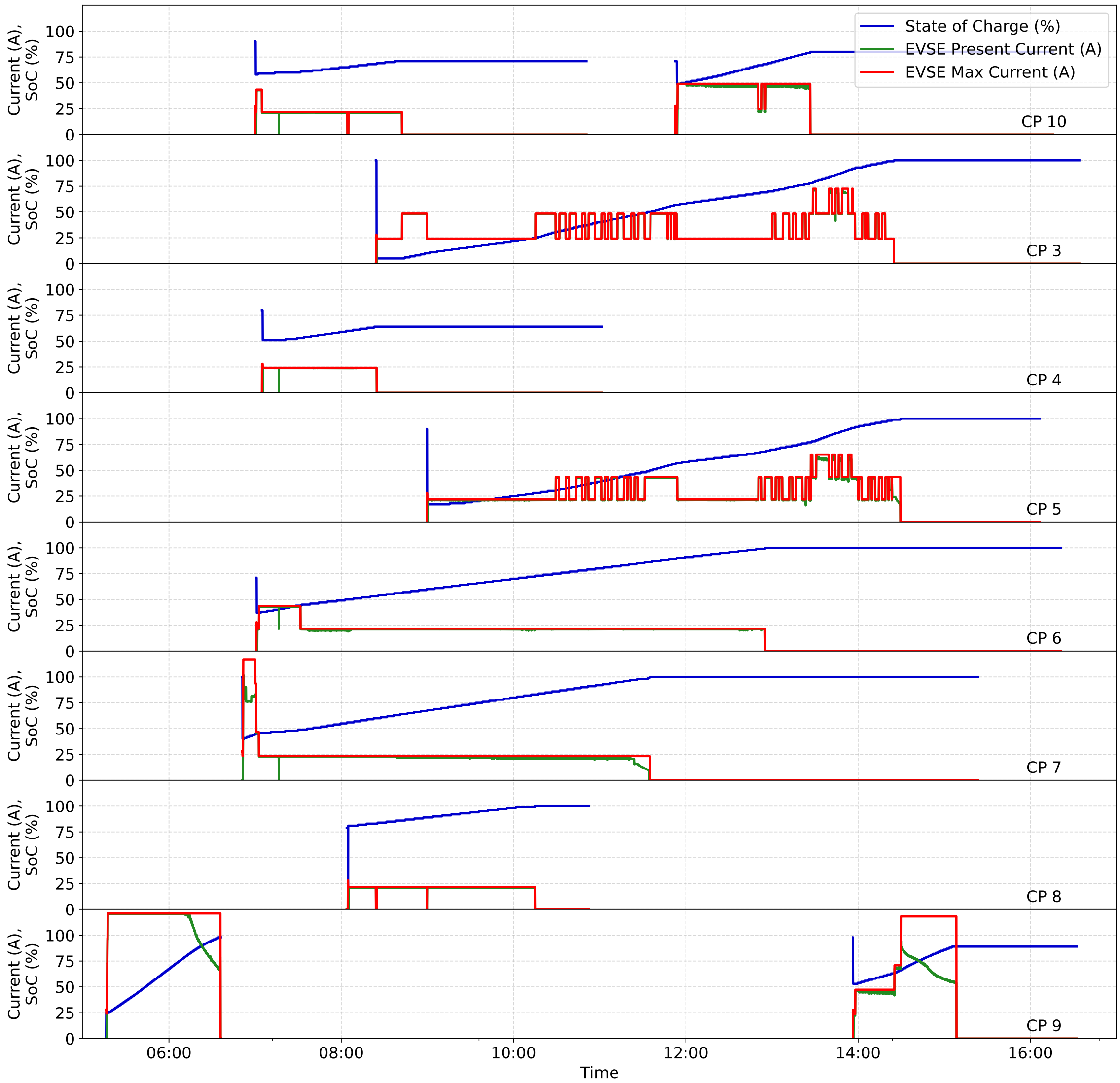


Figure 7: Charging processes on all active charge points during January 29, 2025

Figure 7 shows the same overview of charging processes for January 29, 2025, where all charge points except CP 1 and CP 2 were active. Here, again, exchange of available capacity is happening frequently between EVs at CP 3 and CP 5, due to their SoC in the same range. This day also shows an example of a very typical fast charging curve of an EV at the maximum capacity of the MADELAINE demonstrator in the early morning hours between 05:15 and 06:30. A longer period of constant current (CC) charging is followed by constant voltage (CV) charging due the EV's battery management system (BMS). While analysing the gathered data, some specific charging processes stood out in terms of abnormal behaviour. Some of these charging processes are displayed in Figure 8, which were all captured on January 10, 2025.

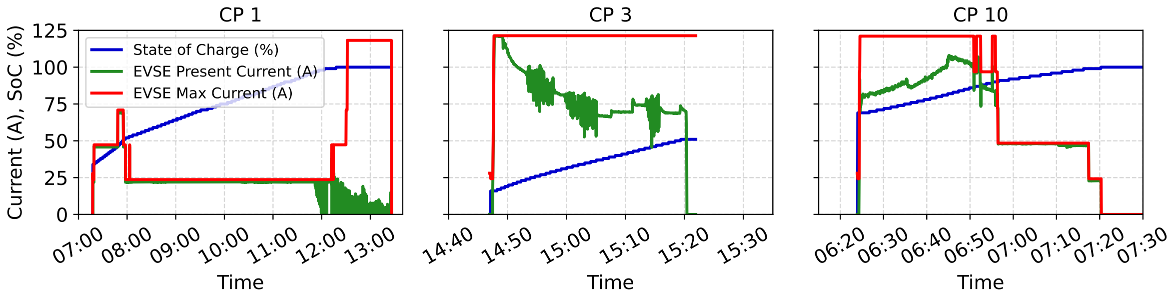


Figure 8: Detail of charging processes at specific charge points during January 10, 2025

A specific Tesla Model 3 of an WEB employee is known to have issues when reaching a SoC close to $100\,\%$. An example of this issues is given in Figure 8 at CP 1. As soon as the SoC reaches $97\,\%$, the measured charging current starts fluctuating every several seconds because the EV repeatedly requests different charging currents by means of the ISO 15118 communication. The reason for this behaviour is unknown.
A similar behaviour was observed at CP 3 where a Renault Zoe was charging in a lower SoC range of $25\,\%$ to $50\,\%$. The fluctuating current is induced by the EV repeatedly requesting different target currents and the demonstrators power converters fulfill these requests each time. The fluctuations occur three times during the recorded charging process and last roughly $20\,\mathrm{min}$.
Another incident with an EV requesting less target current than the demonstrator provides is shown in Figure 8 at CP 10. This EV was a Skoda Enyaq, which started charging at $78\,\mathrm{A}$ while $125\,\mathrm{A}$ would have been available. In this case, the temperature of the EV battery was too low for the maximum allowed charging current and the current continuously increased as soon as the internal losses heated up the battery.

3.2 Power, energy consumption, and efficiency

Because the MADELAINE demonstrator is the result of a research project, designed to investigate the concept of the DC switching matrix specifically, some other aspects are open for optimization. Examples are the amount of required space inside the central container with the subsequent necessity for heating and cooling as well as the optimal ratio of maximum charging capacity per AC/DC converter to the amount of charge points. Hence, an increased energy consumption, especially in standby was expected. To assess the demonstrator in these regards, the energy efficiency of the entire system was calculated. Figure 9 and Figure 10 show two exemplary days.

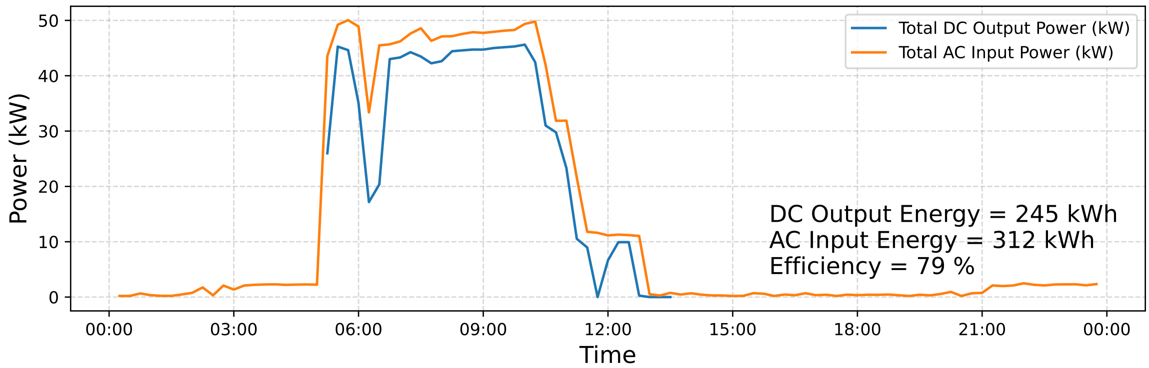


Figure 9: Power consumption AC and delivery DC of the entire MADELAINE demonstrator during January 17, 2025

Figure 9 shows increased standby AC power consumption from 02:00 until the first charging process in the morning around 05:00 as well as in the evening, starting from 21:00. During these hours, the central container and the charge point cabinets required additional heating to keep temperatures above the freezing point.
Figure 10 demonstrates how the installed capacity of 50 kW is utilised very effectively during a business day, which is the intended advantage of the MADELAINE concept. Overall, the first evaluation period showed that the installed charge points are used frequently. Moreover, they are sufficiently powered to provide enough charging capacity for employees during business days, while keeping the required installed capacity of the entire system lower than comparable solutions with ten individual DC-EVCS. Subsequently, the costs for the installed EVSE and the required electrical connection to the local AC grid were reduced.

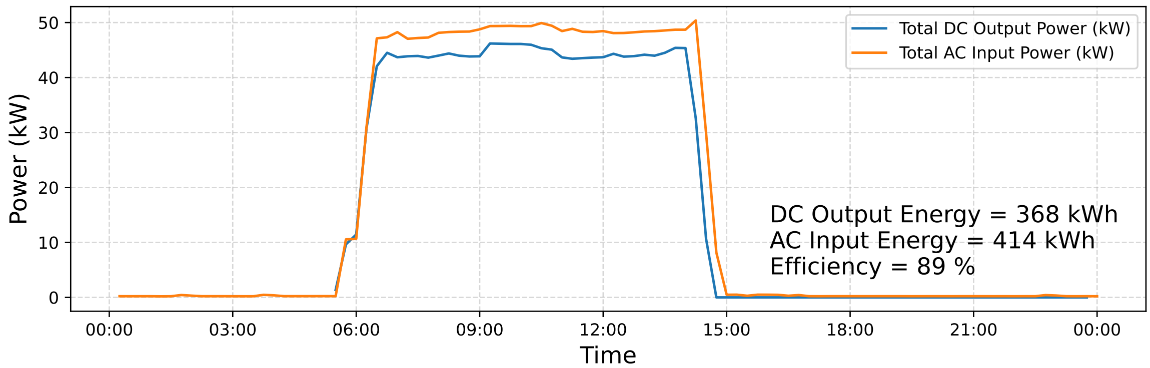


Figure 10: Power consumption AC and delivery DC of the entire MADELAINE demonstrator during March 31, 2025

Figure 11 shows the monthly energy balance of the MADELAINE demonstrator from September 2024 to March 2025. The AC input energy was recorded at the AC grid connection of the demonstrator, located in the container. The DC output energy was measured by the power converters and added up by in monitoring data post processing. The gathered data shows that the demonstrator operates with an efficiency between 83 % and 90 % during the given period. Unfortunately, some data was lost in the month of December 2024 and thus no meaningful conclusions were possible for the energy balance of the entire month. In November 2024, the cooling concept of container unit was changed. The changes were reverted in the same month because, contrary to the expectations, they led to a higher energy consumption, possibly a reason for the reduced efficiency compared to the other months. Because the MADELAINE demonstrator was constructed as part of a research project. To accommodate personnel for testing, the container is much larger than actually required for the given charging capacity. Additionally, a split unit cooling system is used to control the temperature inside the container. Replacing the container by a properly sized cabinet with a cooling system, which ventilates outside air via filters through the system, would reduce the energy consumption of the entire system and improve efficiency.

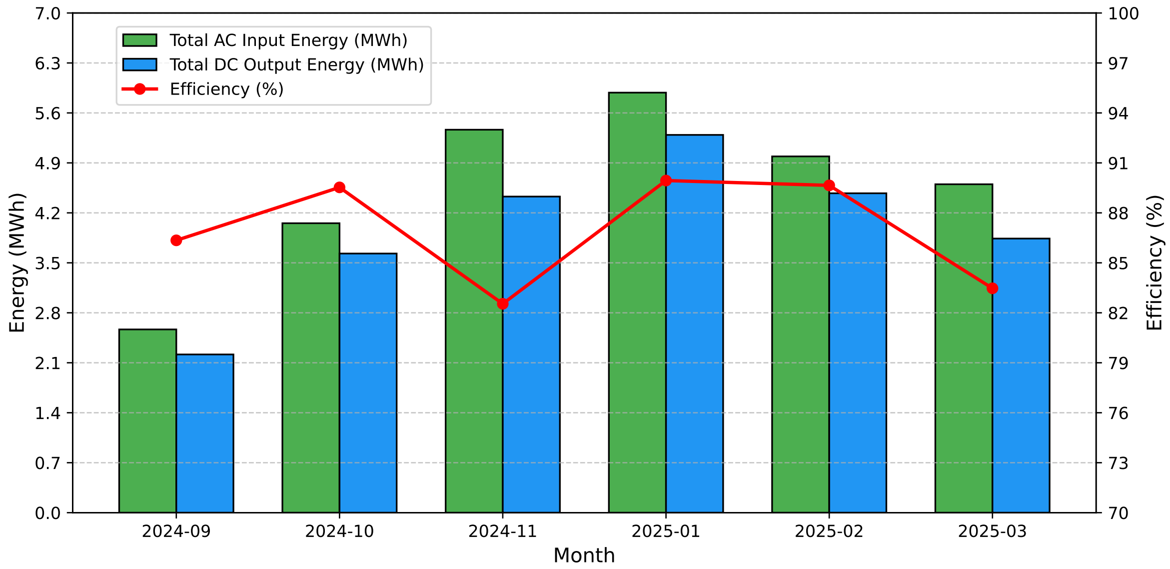


Figure 11: Energy consumption and delivery of the MADELAINE demonstrator from September 2024 to March 2025

4 Discussion and Conclusion

Overall, the first operation period of the MADELAINE demonstrator showed that the DC switch matrix works reliably and the implemented sharing strategy is sufficient for charging ten EVs during a working day by means of only five power converters. Additionally, fast charging can be used at every charging point, whenever free capacity is available. Nevertheless, detailed analysis of charging processes on individual days showed several potentials for improvement of the systems. Sometimes, prioritised charging capacity is offered by the demonstrator to the EV but the EV is consuming only a fraction of it. The current strategy of the MADELAINE demonstrator is to stick to this *EVSE Max Current* unless other EVs connect to the system. By doing so, available charging capacity is left unused, reducing the utilisation ratio of the entire EVSE. Future improvements to the EMS of the demonstrator will implement corrections to this behaviour and help increase the efficiency and further reduce the charging duration of connected EVs.

Acknowledgments

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References

[1] Infrastructure - European Alternative Fuels Observatory (2025). Available online at https://alternative-fuels-observatory.ec.europa.eu/transport-mode/road/european-union-eu27/infrastructure, checked on 4/24/2025.

[2] IEA (2024), Global EV Outlook 2024, IEA, Paris, Licence: CC BY 4.0. Available online at https://www.iea.org/reports/global-ev-outlook-2024, checked on 4/24/2025.

[3] Regulation - 2023/1804 - EN - EUR-Lex (2025). Available online at https://eur-lex.europa.eu/eli/reg/2023/1804/oj/eng, checked on 4/24/2025.

[4] W.D. Buchanan, J. F. Mohos, W. E. Rippel, 2003, Battery Charging System and Method, US Patent US7256516B2.

[5] Distributed Charging Systems - Kempower. Available online at https://kempower.com/solution/distributed-charging-systems/, checked on 4/24/2025.

[6] Liquid-Cooled Ultra-Fast Charging - Huawei. Available online at https://digitalpower.huawei.com/en/smart-charging-network/ultra-fast-charging.html, checked on 4/24/2025.

[7] HYC 1000 - Alpitronic. Available online at https://www.alpitronic.it/de/hypercharger/hyc-1000/, checked on 4/24/2025.

[8] *EVS30*, http://www.evs30.org, accessed on 2020-11-06.

[9] W. Khan et.al., *Fast EV charging station integration with grid ensuring optimal and quality power exchange*, Engineering Science and Technology, vol.22, issue 1, 2019, 143-152 https://doi.org/10.1016/j.jestch.2018.08.005.

Presenter Biography

Stephan Ledinger is a physicist (Technical University of Vienna) and energy engineer (University of Applied Sciences Upper Austria). He is a research engineer at AIT since 2013 and specialised in the field of grid integration of electric vehicle supply equipment as well as measurement technology. His main tasks are research projects involving charging stations for electric vehicles as well as testing services for EVSE at the AIT laboratories. Stephan Ledinger is participating in the EV TCP Task 53, CharIn, IEC TC 69 PT 61851-23-3, and OVE TSK GMT 69.