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ESCALATE project: megawatt charging and its impacts on waste heat recovery and noise

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Executive summary

Megawatt charging is an important factor in the development of electric heavy-duty vehicle (HDV) fleets. In the ESCALATE project we have studied and developed megawatt charging system (MCS) infrastructure including standardisation, WHR (waste heat recovery), and NVH (noise, vibration, and harshness). MCS standardisation is being mostly finalized in 2025, and this will expand the MCS availability. In addition to basic charging functionality, such as power transfer and interoperability, there are other important factors that are becoming more apparent when the absolute power levels increase with MCS. They include the generation of the waste heat and thus also noise from the cooling systems, both from charging equipment and a vehicle. Our studies have shown the importance of thermal management for MCS, both with the vehicle and charging systems, as well as the possible ways to mitigate charging related noise.

Keywords: heavy duty electric vehicles and buses, standardisation, fast and megawatt charging infrastructure, noise-vibration-harshness (NVH), waste heat recovery

1 Introduction

ESCALATE Horizon Europe project aims to significantly reduce the carbon footprint of the freight industry. [1] This is achieved by making zero-emission heavy duty pilot vehicles (HDV) and by studying and developing hydrogen refuelling and high-power charging (HPC), especially megawatt charging system (MCS) infrastructure. While EV (electric vehicle) powertrains are more efficient than conventional powertrains, the recharge time is an issue in widespread adoption. High-power charging delivers substantial power in a short time. The development of MCS has been followed and influenced by both pre-normative and standardisation work in ESCALATE. When the implications of the MCS widespread use have been studied, two interesting topics have emerged: waste heat generation with possibilities to recover heat energy, and HPC related noise and the possibilities to reduce it and understand the scopes of NVH (noise, vibration, and harshness). [2]

2 Megawatt charging system (MCS)

2.1 MCS development in ESCALATE

The need for the megawatt charging system arises from the limitations of the CCS (combined charging system) DC charging power levels. The usual limitation is 350 kW, and especially long-haul heavy-duty vehicles (HDV) require more charging power for their large capacity batteries.

For ESCALATE project, a megawatt charging system as an extension of existing product portfolio, has been developed during the project. [3]

The megawatt charging system is based on CCS DC technology. The system consists of two parallel 600 kW power units, a newly developed satellite dispenser, and software capable of controlling them. The system overview is shown in Figure 1.

A proof of concept (PoC) system was used to demonstrate multiple cabinets in parallel. PoC was used to test cable cooling concepts and for investigating MCS cable thermal behavior. The implementation of IEC 15118 MCS communication protocol was an important part of the project.

High currents of MCS charging causes high losses in the system. Charging cable introduces considerable heat loss causing challenges in satellite cooling. Under the scope of this project the prototype cooling system relies on internal water cooling but on a system level the heat is dissipated directly to air through liquid-to-air heat exchanger. The selected cooling method causes noise at the dispenser and therefore, achieving set noise levels is difficult. The cooling method requires further development to reduce noise and the physical size of the dispenser. High cable losses also require the design to minimize cable length into a few meters. Short cable lengths must be considered when charging sites are designed.

Charging cable handling is also a crucial design aspect. MCS cable with integrated coolant channels is stiff and heavy to lift. Also, the design should make sure neither the cable nor the connector stays on the ground in between charging sessions. Then the cable will not get run over by a truck, and water, snow or dust will not get into the connector due to severe weather conditions.

Figure 1: Power unit cabinet on the left and MCS satellite on the right. [3]

2.2 MCS standardisation

MCS development and standardisation have progressed relatively slowly during the last few years, but the pace has increased during this year. Both technology and standardisation are now making the high-power charging possible.

CharIN organization outlined the requirements for MCS in 2022. [4] The requirements have been converted into standards during 2022 - 2025, and the work continues. The roadmap for the most important MCS standards is presented in Figure 2.

The vehicle standard ISO 5474-3 has been already released in 2024 (as a star in the figure). It covers the vehicle parts of the charging. The communication standards ISO 15118-10 was released in March 2025. The US SAE standard SAE J3271 was released as well in March 2025. The 2 remaining main standards for the connector and the EVSE system are in the process of being published in 2025 or at the latest 2026.

The relationships among the standards and the EVSE-vehicle combination are presented in Figure 3. Standards are partly overlapping. SAE J3271 with the parts 1 – 5 cover all these parts, at least to a certain level.

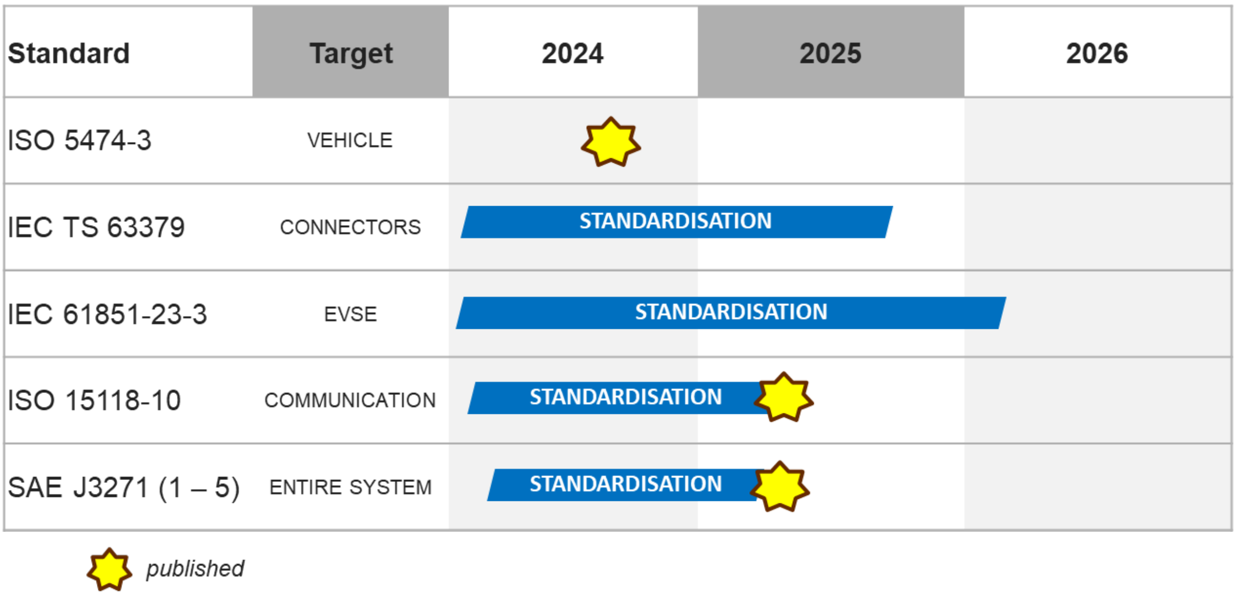

Figure 2: Schedule for main MCS standards. Adapted from CharIN MCS update [5] and recent announcements of the published standards.

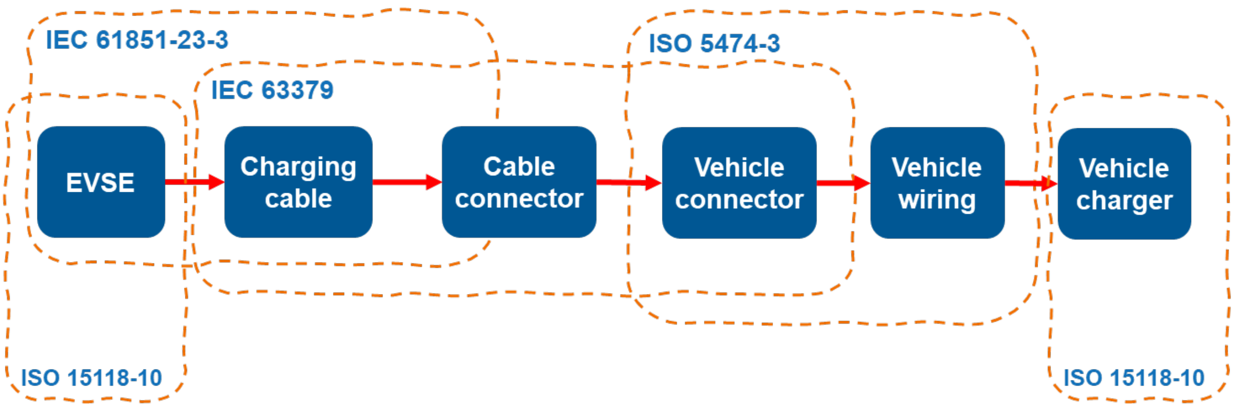

Figure 3: Relationships of the standards to the EVSE-vehicle combination.

Table 1: Possible use cases for waste heat recovery.

Use case	Temperature level (°C)	Heat pump needed (y/n)
Tap water heating	70 °C	y
Public pool heating	40-60 °C	y/n
Low temp. floor heating	30-35 °C	n
Ground heating	30-35 °C	n
3rd gen district heating system, supply line	100-85 °C	y
4th gen district heating system, supply line	50-65 °C	y

3 MCS waste heat and its recovery

Waste heat recovery (WHR) will lower the carbon footprint and increase the overall efficiency of charging hubs, especially with multiple EVSEs on one site. With 5 % - 7 % losses of 1 MW charging, heat generation of 50 kW - 70 kW will occur. This heat is often dissipated with convective cooling. Instead, waste heat could be recovered, either directly via a heat exchanger, or with the help of a thermodynamic cycle to overcome a temperature difference between heat source and sink. For WHR, the heat losses fall into three categories: high temperature (above 400°C), medium temperature (100°C - 400°C), and low temperature grade heat (below 100°C). For each category, different types of WHR systems can be employed. Since power electronics within EVSE should not be exposed to temperatures higher than 65°C, WHR produces low-grade heat. Low grade WH is the hardest to recover cost effectively. Only vapor compression heat pumps (VCHP) are considered as a viable option for MCS WHR. [6] Using EVSE as a heat source for the HP, system brings a significant increase in COP (coefficient of performance) compared to ground or ambient air as a heat source. Table 1 shows some use cases for waste heat recovery from MCS.

3.1 Possible architecture

Figure 4 shows a system architecture for WHR streams from the charging cable and the power electronics (PE). WH coming from the air-cooled PE is collected by means of a standard air-coolant heat exchanger (HX) in an air duct where all the exhaust air from the charger is passing through. Waste heat from the charging cable is collected by means of an oil-coolant plate heat exchanger (PHX). The primary coolant circuit (yellow) collects the total waste heat coming from the charger. A secondary coolant circuit (shown in blue) delivers the collected waste heat to the heat sink. The heat sink can be another simple coolant loop, if the waste heat collected is at a temperature level which is significantly higher than the temperature level of the sink. If the temperature level in the primary coolant circuit is lower than the temperature of the heat sink, the heat collected can be elevated to a certain temperature level by means of a heat pump.

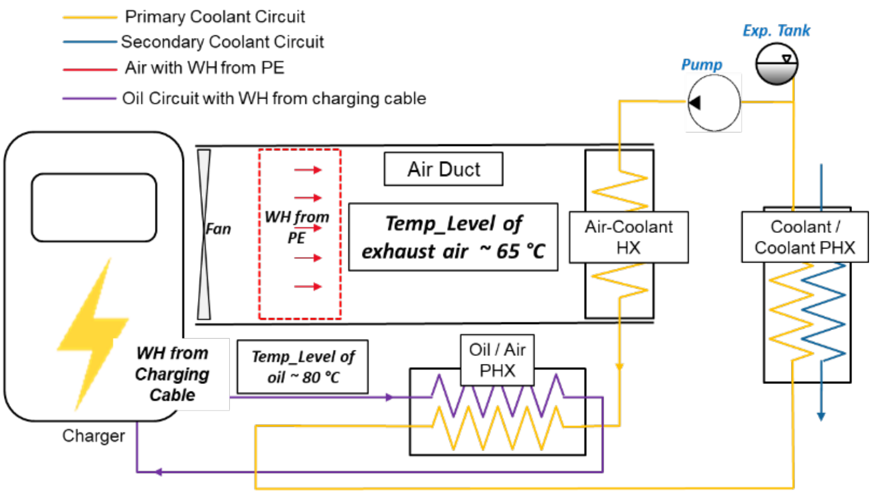

Figure 4: Possible system architecture is shown, facilitating the recovery of both, waste heat streams coming from the charging cable and the PE.

Table 2: Assumptions for heat generation during the 1 MW charging process.

Heat source	Heat generated (kW)	Share of heat generation (%)	Temperature (°C)
charging cable	8	16	80
power electronics	42	84	60

3.2 Possibilities of district heating

If temperature levels are higher than the specific heat sink, waste heat from MCS can be used directly. A possibility is the usage of district heating (DH) networks as a heat sink. From the 1st to the 3rd generation DH networks, supply and return temperatures have successively been lowered, to make them more efficient and create the possibility to include a wide variety of heat sources. By lowering operational temperatures, it became possible to start the decarbonization of DH networks by including different renewable sources such as geothermal, large scale solar plants and industrial waste heat. With the 4th generation of DH, possibilities for decarbonization will increase with the possibility of including low temperature grade waste heat sources as well, such as BEV charging stations. Where 3rd generation DH networks usually have supply temperatures between 85°C and 100 C, 4th generation DH networks are aimed at supply temperatures between 50°C and 65°C. This would make the integration of low temperature WH more efficient and feasible. [7], [8]

3.3 WHR simulation setup

To quantify the available WH from MCS, some assumptions must be made for the charger power electronics and the charging cable. Both emit heat at different temperature levels. According to assumptions made by EVSE manufacturer, at the maximum charging capacity of one megawatt charger (1500 A at 800 V) about 8 kW of heat must be dissipated from the charging cable. It is carried out by oil cooling via an oil to air heat exchanger. This results in feed oil temperature of 52°C for cooling and return temperature of 80°C (at 40°C ambient) with an oil volume flow of 10 l/min. Unlike the charging cable, power electronics are air cooled. With a maximum efficiency of 95 % during charging, a charging load of 1 MW would generate 50 kW of heat, 8 kW originating from the charging cable, and 42 kW originating from the power electronics. So, the PE is contributing 84 % to the total heat generated while the charging cable contributes 16 % (Table 2).

To investigate the potential of feeding waste heat recovered from one megawatt charger into a 4th generation district heating network supply line by means of a heat pump, a simulation model was built up in Matlab Simulink (v2023b) using various Simscape Toolboxes (Figure 5). The model consists of two heat sources, a WHR coolant loop that collects the rejected heat, a heat pump circuit that lifts the collected heat to the temperature level of the DH network and another coolant loop representing the DH network which acts as the heat sink. While the charging cable is oil cooled, in the simulation model a propylene glycol and water mixture was chosen due to the lack of a suitable thermal oil choice. Heat losses to ambient were considered in all coolant and air circuits.

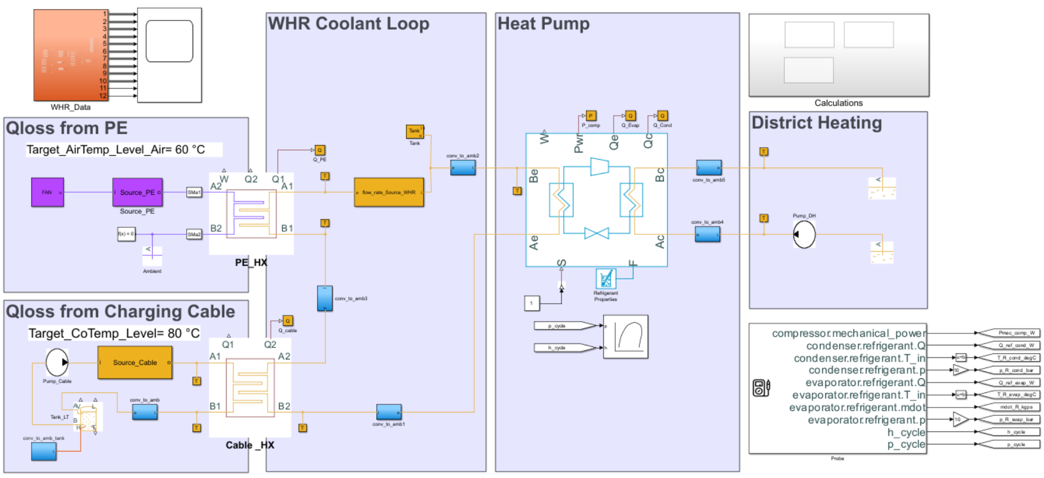

Figure 5: Simulation model of feeding waste heat from a megawatt charger into a 4th generation district heating network.

Table 3: Temperature setpoints.

Control variable	Temperature signal	Temperature setpoint (°C)
pump_cable_cooling_rpm	T_Cable_HeatExchanger_in	80
pump_WHR_loop_rpm	T_evaporator_in	DH_Temperature_Level-15 K
pump_DH_network_rpm	T_condenser_out	DH_Temperature_Level+10 K
fan_PE_rpm	T_PE_ HeatExchanger _in	60

Since the COP (coefficient of performance) of a heat pump is directly related to how close together the temperature levels of the heat source (evaporator) and heat sink (condenser) are, it is important to control coolant pumps and the fan for certain target temperature. Table 3 shows control variables and temperature set points.

The refrigerant circuit was parametrized to a design point with a heat transfer rate at the evaporator of 50 kW, a condensation temperature of 60°C, an evaporation temperature of 45°C, a compressor with volumetric and mechanical efficiency of 95 % and a $COP_{heating}$ of 5.5 for the given boundary conditions (Figure 6). The refrigerant in use is R134a. For the layout of the design point, the open-source software CoolPack was used. [9]

3.4 WHR Simulation Results

As input for the simulation model, it was assumed that one megawatt charger is operating at its peak load (1 MW) for as long as it takes to charge a battery with 936 kWh from a start SOC (state of charge) of 10 % to a final SOC of 100 %. A charger efficiency of 95 % was assumed. The shares of heat generated from the PE and the cable are as shown in Table 2.

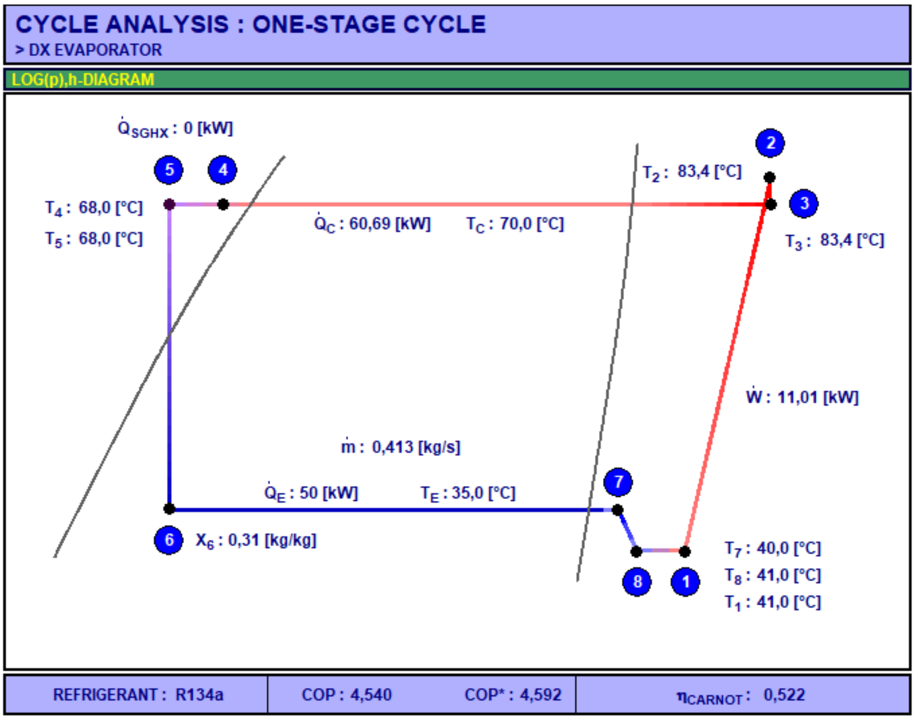

Figure 6: Design point of the refrigerant circuit. [9]

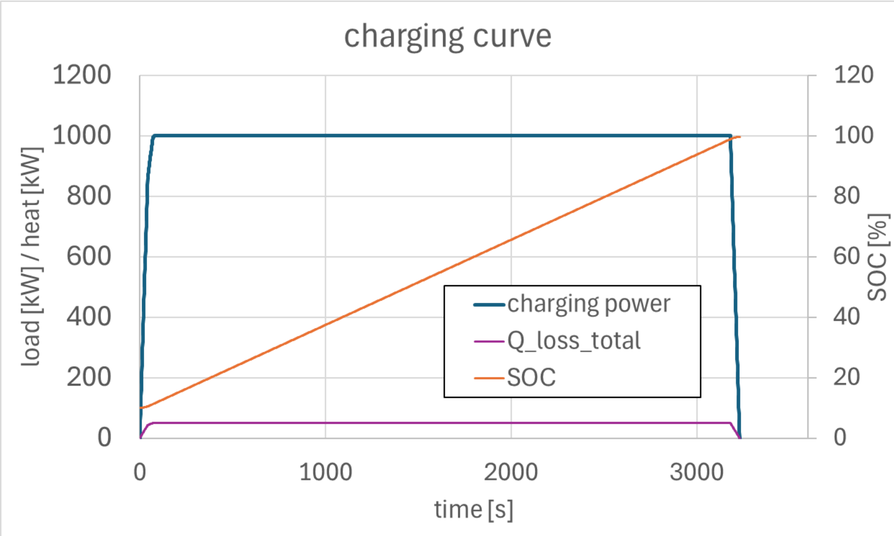

Figure 7: Load curve for WHR simulation.

The resulting load curve, associated total heat loss, and SOC curve are shown in Figure 7. The system was simulated with 0°C and 45°C ambient temperatures, with DH network supply temperatures of 50°C and 65°C. Results indicate the benefit of lowering the DH supply temperature in terms of COP, for both ambient conditions. Lower supply temperatures in general lead to less energy consumed by the compressor which results in higher COPs. In general, it can be said that COP and total waste heat collected at the evaporator decrease with decreasing ambient temperature and increasing DH supply line temperature. While an increase in supply temperature always leads to an increase in compressor work and mostly effects system COP, a decline in ambient temperature leads to a decline in WH recovered at the PE air-to-coolant heat exchanger, since a significant portion of the heat generated within the PE only heats up ambient air without the possibility of recovery. For all coolant loops (WHR, cable, DH) the increase in heat losses towards lower ambient temperatures does not play a big role, assuming proper insulation of all necessary parts. With the simulation results and the assumption of eight megawatt chargers per charging site, each charger completing ten charging cycles per day as simulated, seven days out of the week the following projections could be made (Table 4). Assuming a heat demand of 7000 kWh/a for one household (100 m² with 70 kWh/m²/a), the WHR potential, in the case of 65°C DH supply and 0°C ambient temperature, equates to the yearly heating demand for ~113 households.

The simulation results show the energetic potential for waste heat recovery executed for a charging site with multiple megawatt chargers while feeding waste heat recovered into a 4th generation district heating network by means of a heat pump. A system architecture for waste heat recovery was proposed and simulated for various ambient temperatures and district heating supply temperatures. With the simulation results and certain assumptions made, it was shown that for a charging site with 8 MW chargers the yearly heating demand of 137 to 228 households could be met, depending on ambient and DH supply temperatures. In conjunction with using renewable energy sources to meet the total work demand for the heat pump process, the decarbonization of district heating networks could take a big leap forward considering the scale of future waste heat potential originating from charging stations, not just for heavy duty trucks, but from charging stations of all sorts of electric vehicles.

Table 4: Yearly projections of waste heat recovered.

T_ambient (°C)	DH supply temperature (°C)	WH recovered (MWh)	WH fed into DH (MWh)	total work (MWh)	household equivalents
65	45	1095.0	1305.2	271.6	186.5
50	45	1445.4	1600.2	210.2	228.6
65	0	613.2	794.2	268.6	113.5
50	0	805.9	963.6	239.4	137.7

4 Noise modelling and noise reduction methods for MCS

4.1 Charging noise of current electric trucks: quantification & source separation

Publicly available data, including technical datasheets and system layouts of current BETs (Battery Electric Trucks), provide insights into potential noise sources in MCS. They primarily relate to cooling systems that ensure that the battery and charging infrastructure remain at safe operational temperatures. This information was used to strategically target measuring devices at known and suspected sources of noise to record their acoustic footprint and measure the contribution of each source to the overall noise levels.

NVH measurements were performed on two different models of commercially available BETs to quantify their noise sources during high-power charging. The measurements showed that both vehicles had similar noise profiles. Therefore, this paper only presents results obtained with one of these trucks, illustrating the more general trends observed.

To present the situation with the highest expected noise levels, the boundary conditions for measuring the charging noise were defined accordingly. This scenario encompassed a low state of charge (SOC) under 20 %, increased truck and battery temperatures after prolonged highway driving, ambient summer temperatures of approximately 30°C, and high-power DC charging in an industrial zone during the late afternoon. A truck charging at a high-power station after a long highway run on a warm afternoon serves as an example of this scenario. These conditions were selected to capture the peak noise emissions of fast charging in realistic and demanding operating environments.

Figure 8 shows the noise levels recorded during charging, using microphones placed outside the truck and inside the driver's cabin. As per the defined boundary conditions, the near-field A-weighted levels measured 1 meter away from the vehicle varied between 73 dB and 88 dB. Noise levels inside the cabin, near the driver's ears, ranged from about 43 dB to 76 dB. For comparison: background noise measurements without taking charging noise into account resulted in 55 dB outside and 37 dB inside the cabin.

The in-cabin A-weighted noise levels surpass the regulatory recommended EU target values for sleeping conditions, which are set at 30 dB – 40 dB. This finding shows that the charging process not only affects acoustic comfort but also potentially important legal standards and guidelines. Considering that the charging power of the two tested trucks was below 150 kW during the measurements, the planned increase in charging power by an order of magnitude to the megawatt range means that an even higher cooling requirement for the battery components will be necessary. Consequently, noise emissions from high-power charging may pose difficulties in meeting established acoustic guidelines. This highlights the need for noise mitigation strategies in the design of BETs and their infrastructure when long-range electric trucks come into play. In the worst charging case, vibrations transmitted through the structure led to a high level of structure-born noise in the cabin badly disturbing a driver. This highlights the possibility of significant acoustic discomfort during HPC, especially when drivers might be resting in their vehicles.

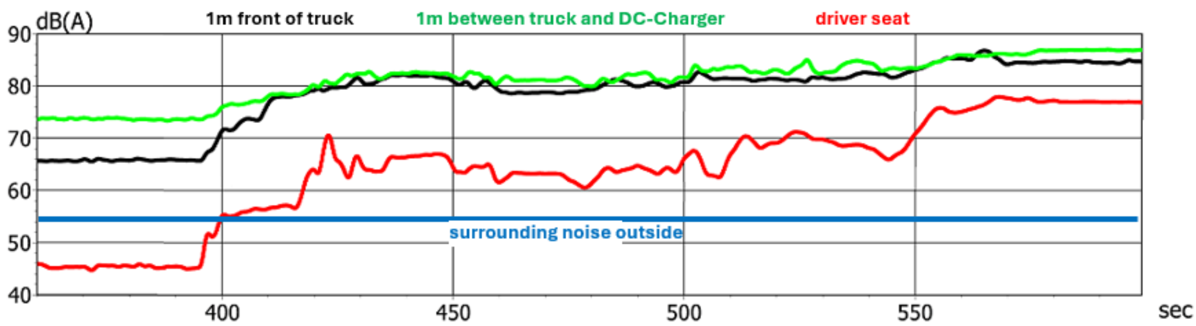

Figure 8: Overall noise levels of a current-production electric truck during high power DC charging. Boundary conditions: (SOC) below 20%, elevated truck & battery temperatures following extended highway driving, ambient temperature 30°C, 100kW charging power.

A detailed analysis of the measurements illustrated in Figure 9 reveals three main sources of noise emission, all related to the cooling of components and batteries:

1. the AC compressor, which cools the batteries and the cabin while charging,
2. the truck cooling fan, which eliminates waste heat, and
3. the cooling fans in the DC charging station

The current design of most BETs and DC charging stations is based on a similar architecture, so these findings are generally applicable. Most electric trucks make use of a standard scroll-type AC compressor along with a one- or two-stage cooling fan. On the other hand, DC charging stations usually incorporate multiple small cooling fans arranged in a standardized manner.

During the majority of the charging process (before 400 seconds in Figure 8 and Figure 9), the fans inside the DC charger were responsible for the largest contribution to the ambient noise level, generating about 73 dB(A) at the external noise microphone located between the BET and the charging station. Considering the vehicle insulation in the tested truck, this results in a 43 dB(A) noise level inside the cabin, which is suitable for short breaks or work but too high for restful sleep.

When the battery warms up, the AC compressor and the two cooling fans of the truck switch on (beginning around 400 seconds in Figure 8 and Figure 9), contributing to a greater acoustic complexity:

- Contribution of cooling fan: The activation of the two cooling fans generates a broadband flow noise above 300 Hz, accompanied by distinct tonal components from the harmonics of the fan blades. Acoustic beats are observed in the first order of the fan blades (with eleven blades per fan) when the two identical fans operate at the same speed (indicated by a dotted order line on the left side of Figure 9, labeled "1st order truck cooling fan").
- AC compressor contribution: Further acoustic contributions from the harmonic orders associated with the AC compressor.

These two sources combined increase the noise level to 88 dB(A) outdoors and 76 dB(A) within the cabin. Regarding acoustic behavior, it is crucial to distinguish between noise emissions from outside and noise and vibrations inside the cabin. In the interior, decoupling the vibrations from the air conditioning compressor is essential for airborne sound insulation.

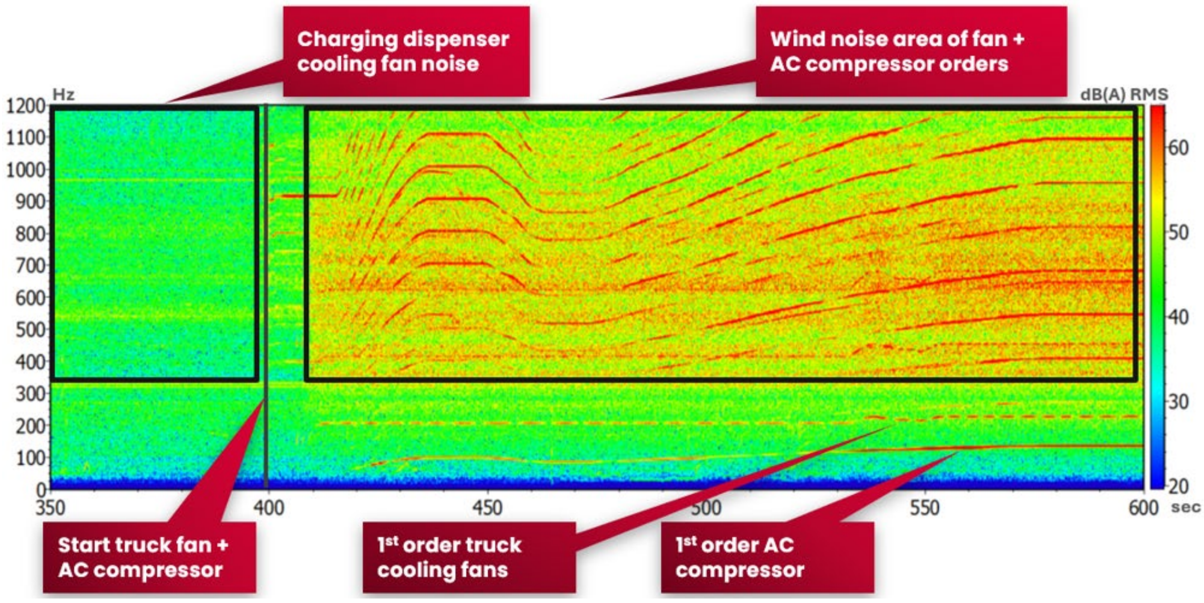

Figure 9: Campbell diagram to separate noise sources during high power DC charging of currently produced BET.

4.2 Exterior noise simulation of an electric truck charging hub

When planning a megawatt charging hub, noise emissions play a crucial role in site selection and approval by local authorities. This research used the data shown in Figures 8 and 9 to simulate noise emissions from a prospective megawatt truck charging station. As shown in Figure 10, a sample location is situated near the port of Gothenburg. [10] The site features several office buildings, industrial facilities, a cafe and a hotel. From an acoustics point of view, a challenging scenario is represented by long-haul trucks in which drivers sleep in the cabin while the truck is being charged. With high-power charging at night, taking advantage of excess renewable energy, the cooling systems may produce noise that can disturb drivers and residents.

The simulation was carried out following ISO 9613-1 and ISO 9613-2, which outline methods for calculating sound propagation in outdoor settings. This analysis used Noise Map the simulation tool, including the BET during high-power charging as an extra noise source in addition to the ambient highway noise. [11]

The sound emission of a single BET was estimated using two point-sources: one located at the front of the truck and another between the truck and the charging station (as shown in Figure 8). The sound power levels for these sources were calculated according to microphone measurements, with the assumption of a quarter-sphere radiation pattern (as it is the case over hard ground and against a reflective surface). This method produced third-octave sound power levels that were used in the simulation illustrated in Figure 10.

Other simulation boundary conditions included the configuration of the charging station, ambient noise levels, and reflective surfaces from adjacent structures. This example modeled five trucks that were charging in parallel. Ambient noise levels were obtained from the official noise map of the state of Sweden and are shown here as day and night levels. The results of the acoustic simulation showed that not only the truck drivers themselves but also the environment is affected. The A-weighted noise levels in the front outdoor area of the hotel, the café, and the offices increased up to 15 dB from approximately 45 dB to almost 60 dB.

Depending on the location and construction of the building, such an increase in noise can affect the noise level in work and guest rooms and impair sleep quality. Possible solutions could include expensive, site-specific noise reduction strategies or preferably a direct decrease in noise emissions.

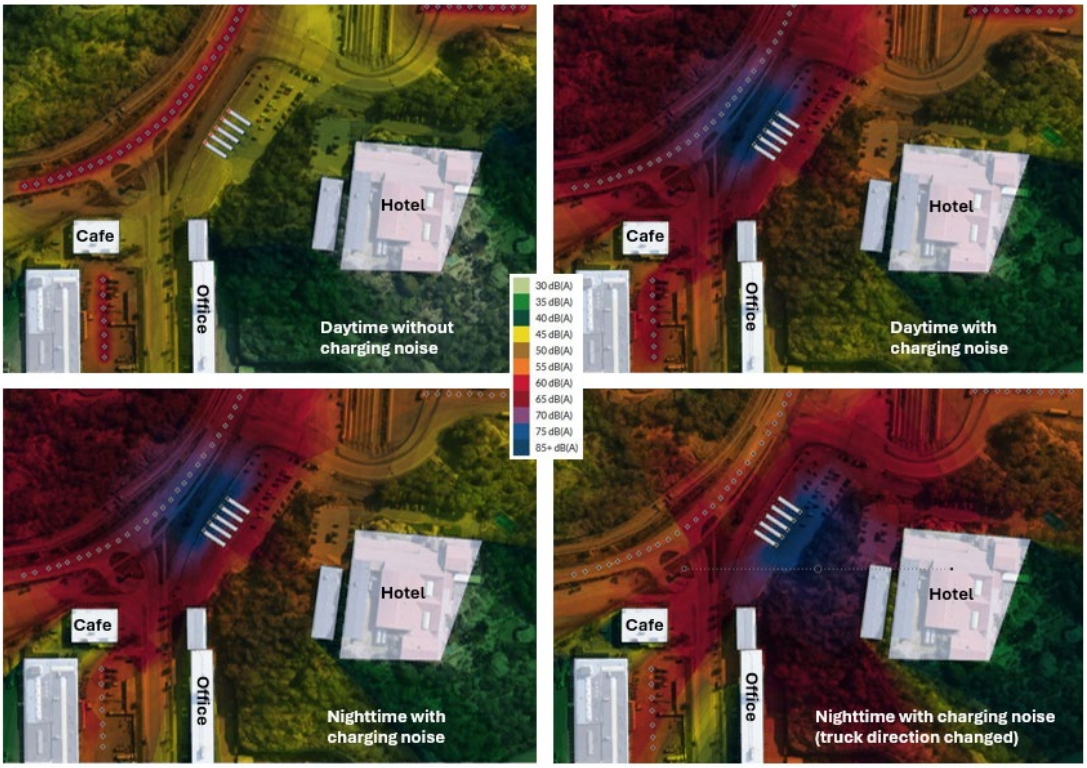

Figure 10: Simulation of the environmental noise impact of a high-power truck charging station at day and night at a sample location near the harbor of Gothenburg.

Table 5: Suggestions for truck OEMs.

Set acoustic targets	Cooling component optimization	Improved cabin insulation	Compressor & fan noise minimization
Focus on the most important noise sources (fans & compressors)	Hybrid NVH simulations in the early stages of design	Target for comfort & silence for the drivers	Reduce noise levels and improve sound quality by smartly regulating fan and compressor speeds
Cascade the overall noise objectives down to the transfer channels of individual noise sources.	Combine HE components into one unit linked only by refrigerant and electrical connections	Take into account the long charging breaks	Reduce tonal noise with fully enclosed compressors
	Layout optimization & reduction of airborne and structure-borne noise		Use low-noise compressor type

Table 6: Suggestions for charging infrastructure.

Charging station orientation and layout	High-noise components	Liquid-cooled dispensers
Position trucks with the noisiest fans and compressors close to the road and away from sensitive areas	Locate the cooling systems and power supplies in specific buildings or structures	Noise levels are considerably reduced by moving away from massive air-cooled units next to the vehicle

4.3 Noise mitigation strategies for quiet megawatt charging

The battery electric vehicles used in this investigation had very low cooling requirements and were primarily intended for urban deliveries. In contrast, long-haul BETs will require significantly more powerful cooling systems, which boost their heat dissipation capacity by one or two orders of magnitude. If not handled proactively, this increase in cooling requirements - caused by increased battery capacity and faster charging C-rates - could potentially result in noisier charging procedures. Suggestions for truck OEMs are presented in Table 5.

Achieving ambitious targets for electric freight transport requires a comprehensive high-power charging infrastructure, including the European Union's target of 50 % of BETs by 2030. There is a risk that charging station locations will seriously disturb residents and nearby cars if they are built without considering NVH criteria. The suggestions in Table 6 describe how charging station planners and vehicle OEMs can reduce charging noise at high-power charging levels.

5 Conclusions

MCS standards are being finalized soon, and this opens the road to megawatt level charging of EVs. Also, commercial MCS charging stations are becoming available.

Our studies have shown the importance of thermal management for MCS, both with vehicle and charging systems. There are several potential uses for the recovered heat energy, including heating of the buildings, boilers of the warm water, ground heating in charging hubs during the cold season, and district heating. Also, non-optimised thermal management causes unnecessary noise.

The noise control and mitigation become especially important, when large heavy-duty vehicle charging hubs become common, and their effects on the surroundings must be minimized. Not only the charging systems but vehicles can be significant noise sources, too. There are many effective way to reduce and mitigate noise.

The research continues is ESCALATE project to create a holistic view of the future MCS hubs, and ways to optimize their operation and simultaneously minimize their adverse effects.

6 Acknowledgements

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Presenter bibliography

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