DC V2G Exploring, potential in marine applications

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Executive Summary

With the transition to electromobility, all vehicles, including vessels, become a potential resource as soon as they are connected to a charger. It is about the battery, which can act as a distributed energy storage, eg supporting grid stability and peak shaving. This means the battery becomes an asset that can generate revenue and then lower the total cost of ownership (TCO). The technology that makes this possible is called vehicle-to-grid (V2G).

In this white paper you will learn about V2G in a marine setting, high level information about the ecosystem, and what is required to generate revenue. The results are generic and not limited to marine. Revenue is linked to the time connected to a charger, eg distribution trucks, are often parked 16 hours a day and weekends.

Brief overview of V2G concept in marine applications

In marine applications, this concept extends to all electric and hybrid vessels, commercial and leisure boats. These vessels will often have larger batteries than electric cars, making them ideal candidates for grid services. Larger batteries translate to higher power; therefore, this paper focuses on DC V2G.

Marine V2G in certain areas offers unique advantages:

Leisure vessels have the potential to be connected to chargers for a large part of the year. This applies on the quay, on land and on a trailer on your driveway.

Many commercial applications follow a schedule like ferries or are seasonal such as fishing vessels.

How to lower TCO

When connected to a V2G capable charger the vessel will act as a Battery Energy Storage System (BESS). A BESS is continuously connected to grid and can perform many services, back-up power, peak shaving, arbitrage and different flexibility services. Some of these services can reduce costs like power tariffs, and some generate revenue. Additionally, with V2G smart charging can be applied, meaning that charging can be done when electricity is cheapest.

In this paper we show that our DC V2G setup can fulfill FCR-N and FCR-D, reaching 86% of requested power by 7.5 seconds. This is one of the toughest requirements.

System stability and efficiency

To qualify for commercial flex services the system must be stable and demonstrate a reasonable system efficiency. We have demonstrated the following:

End to end charging session from aggregator to vessel lasting more than 7 days.

An average round-trip system efficiency of 20 kW charger is 86 % and for 80 kW charger is 84 %..

In coming pages, we will share details related to:

1. The ecosystem and considerations
2. The battery saving cost and generating revenue
3. Fulfilling FCR requirements
4. Some data - System efficiency.

V2G Ecosystem Overview

The marine V2G ecosystem in this project consists of an on-board domain installed on the vessel and a shore-side domain connected to the grid and the aggregator. Together, these parts enable bidirectional power transfer, coordinated control, and secure communication between the vessel and the external control system. The architecture is designed so that the vessel battery system can be used both for marine operation and for grid-interactive services when connected to shore power.

Main Components

The main components of the system are shown in figure below and can be grouped into 4 functional parts:

Boat/Onboard system

The vessel includes two battery packs, each with nominal energy of 90 kWh. The on-board control system includes a Vehicle Control Unit (VCU), an Electric Vehicle Communication Controller (EVCC) which is responsible for all communications between boat side and charger side, and a display unit for local monitoring and operation.

DC/DC charger

Both Charger and Inverter in this project are from Ferroamp. The charger is between the boat and the AC/DC Inverter. It performs the DC/DC stage, which is responsible for matching the voltage of the charger with the voltage of the battery according to charging or discharging. It includes an Electric Vehicle Supply Equipment (EVSE) communication interface, and power electronics for controlled charging and discharging of the battery system.

AC/DC Inverter

The inverter connects the charger to the AC side of the system. It enables the conversion between AC and DC power.

Aggregator / external control

The external control actor in this project is Varberg Energi, acting as the aggregator. It sends power requests and operating commands to the charger and is responsible for the higher-level control of charging and discharging actions.

Communication between components is specified in Figure 1.

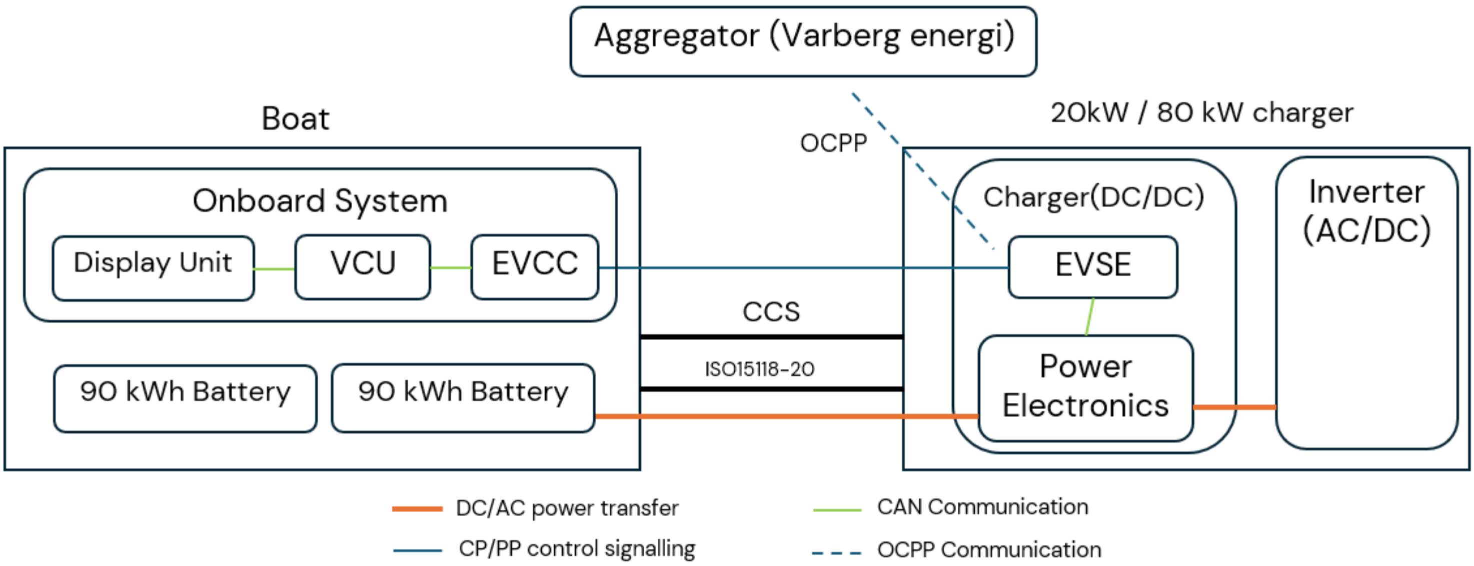


Figure 1. System architecture and components

Unlocking Value from V2G Systems

When connected to the grid, marine battery systems can create value by providing flexibility services and by enabling smarter energy use. The same technical capabilities can be used across different applications, allowing the battery system to act as a flexible energy asset in addition to its primary role for vessel operation.

Value Creation Mechanisms

Frequency Containment Reserve (FCR)

The battery supports grid frequency stability by responding rapidly to power requests. A key requirement is the ability to reach at least 86% of the requested power within 7.5 seconds, making fast response and reliable control essential. Battery systems are well suited for this service due to their short reaction time.

Manual Frequency Restoration Reserve (mFRR)

The battery can be activated on request to support grid balancing during larger system imbalances. Compared to FCR, mFRR typically allows slower activation but requires availability and sufficient power capacity when called.

Energy arbitrage

The battery can be charged during periods of low electricity prices and discharged during high-price periods. Value is created from the price difference over time, and performance depends on market volatility and charging/discharging efficiency.

Peak shaving

Discharging during short peak demand periods reduces grid power draw. This can lower peak-related tariffs and improve the overall load profile at the connection point.

Local flexibility services

In some cases, the battery can support local grid needs such as congestion management or site-level balancing, depending on grid conditions and contractual arrangements.

FCR Activation and Measurement Principle

How FCR Works in the Marine V2G Setup

Frequency Containment Reserve (FCR) is used to support grid stability when the grid frequency moves away from its nominal value. In Sweden, the nominal frequency is 50 Hz.

In this project, the frequency is measured locally at the test facility. When a frequency deviation is detected, Varberg Energi decides the required power response:

If frequency is below 50 Hz, the battery should be discharged to support the grid. If frequency is above 50 Hz, the battery should charge to absorb power.

Based on this decision, a power setpoint is sent from Varberg Energi to the charger. The charger then processes the command, activates the power electronics, and ramps the current toward the requested power level.

The key FCR response target used in this evaluation is to reach 86% of the requested power within 7.5 seconds.

Response-Time Measurement

The start time is taken from the Varberg Energi server, where the command timestamp is recorded when the setpoint is issued. The current response is measured from the charger through the MQTT broker.

The response time is calculated as:

> Response time = time when measured current reaches 86% of target - command timestamp

This gives an end-to-end measurement of the full response chain, including communication, charger processing, power electronics activation, and current ramping.

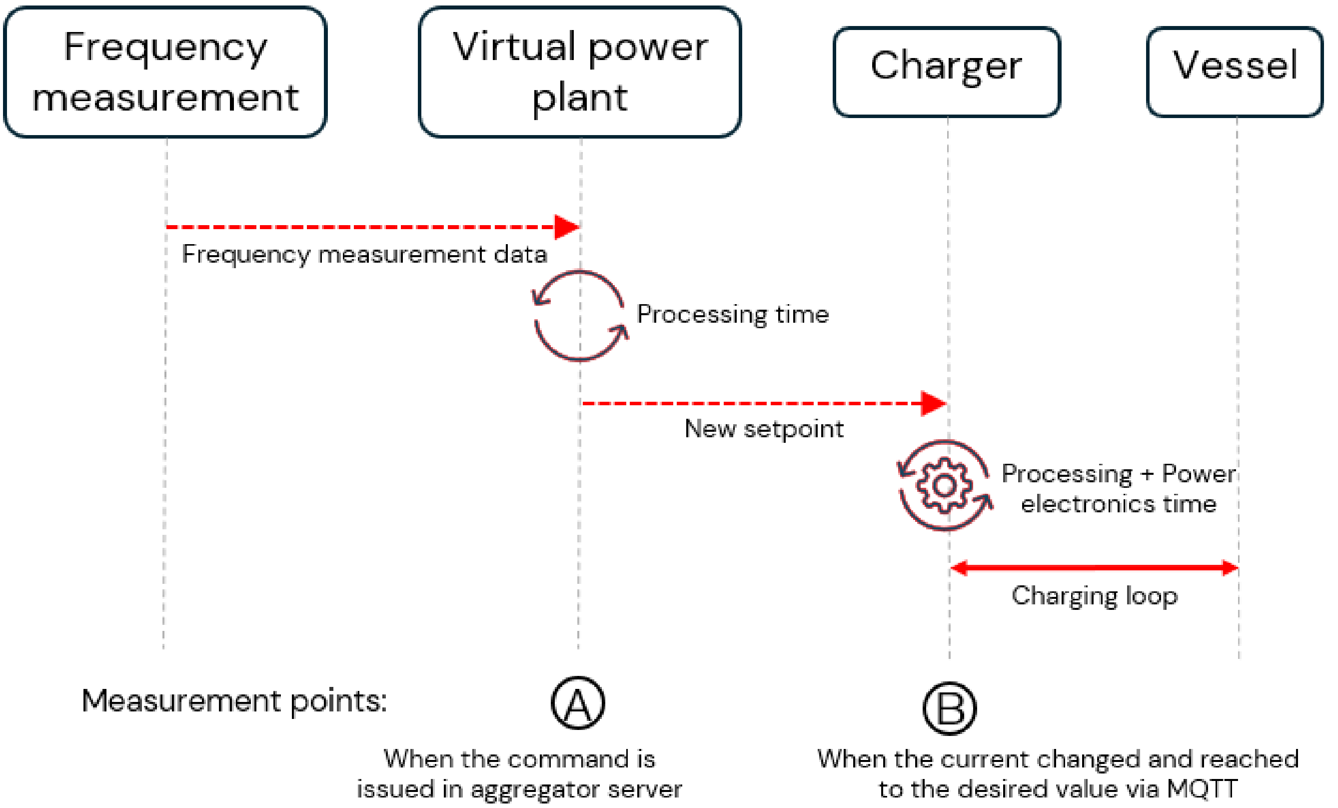


Figure 2. Delays in between system components

Reaching the FCR Requirement

Final Response-Time Performance

The final response-time tests show that the marine V2G setup meets the FCR response requirement for both charger configurations: the 20 kW charger and the 80 kW charger.

The FCR requirement used in this evaluation is to reach 86% of the requested power within 7.5 seconds. Final tests were performed for both charging and discharging, and the measured current response was compared against this limit.

The response performance depends on the complete system chain:

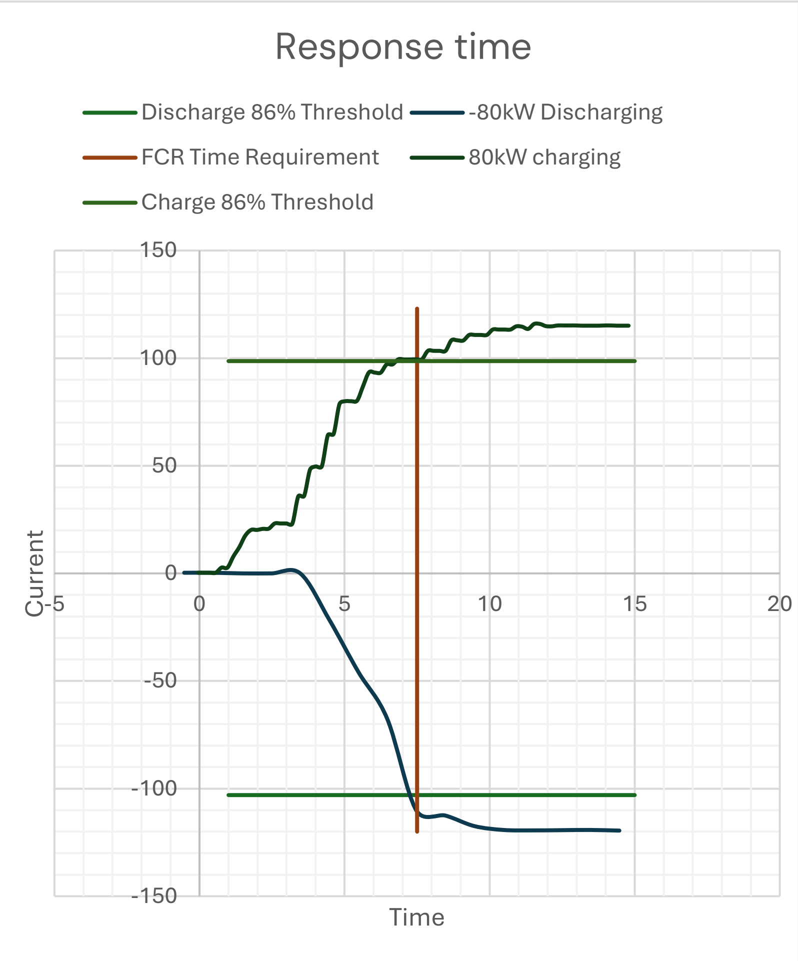
- command and control communication,
- charger processing time,
- activation of power electronics,
- current ramping in the charger and inverter.

For discharging from standby, the charger must also change operating direction before negative current can start. This makes discharging more demanding than charging, where the charger is already in charging mode at 0 kW.

The results show that both charger configurations reach the required response area for charging and discharging. The 20 kW and 80 kW charger results are shown in Figure 3.

Main Result

The test results confirm that FCR-level response is achievable for the marine V2G setup. Both the 20 kW and 80 kW charger configurations reached 86% of requested power within 7.5 seconds, demonstrating that the system can meet the required response performance after control optimization.



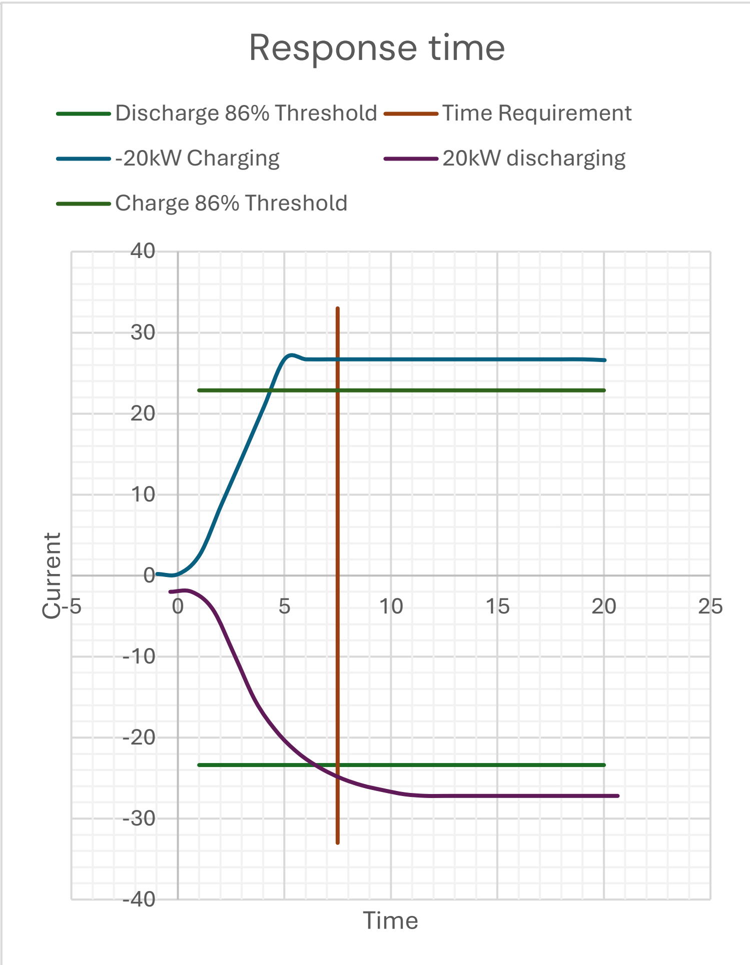


Figure 3. Response-time performance for the 80 kW and 20 kW charger

What Round-Trip Efficiency Captures

RTE: Full-Cycle Energy Performance

Round-trip efficiency (RTE) describes how much of the charged energy can be returned during discharge. In this project, RTE is measured over one complete charging and discharging cycle, using the same SoC window and the same power level.

$$RTE = \frac{E_{Discharged}}{E_{Charged}} \times 100$$

The energy is measured at the same measurement boundary for both charging and discharging. In the test setup, the main RTE measurement point is on the AC side before the inverter. This gives system-level efficiency value and reduces uncertainty from using different measurement points.

As shown in Figure 4, the energy passes through the inverter, DC/DC charger, and battery during charging. While discharging, the energy flows back through the same path in the opposite direction. Therefore, the measured RTE includes the main loss areas in both directions:

- Power electronics losses during charging
- Power electronics losses during discharging
- Battery internal losses during charging + discharging

The figure also shows two measurement points. Point A represents the AC-side measurement boundary used for RTE calculation. Point B represents the DC-side measurement point, used as supporting information from the charger/battery side. The RTE value reported in this white paper is based on point A measurement boundary for energy charged and energy discharged.

Measurement notes: The RTE tests are performed within defined SoC windows. Since SoC is estimated by the battery management system and may include some uncertainty, especially around window boundaries, small variations in the actual tested energy window can occur. To reduce this effect, the same SoC window, same power level, and same measurement boundary is used for each charge/discharge cycle, and results are reported as repeated-test averages.

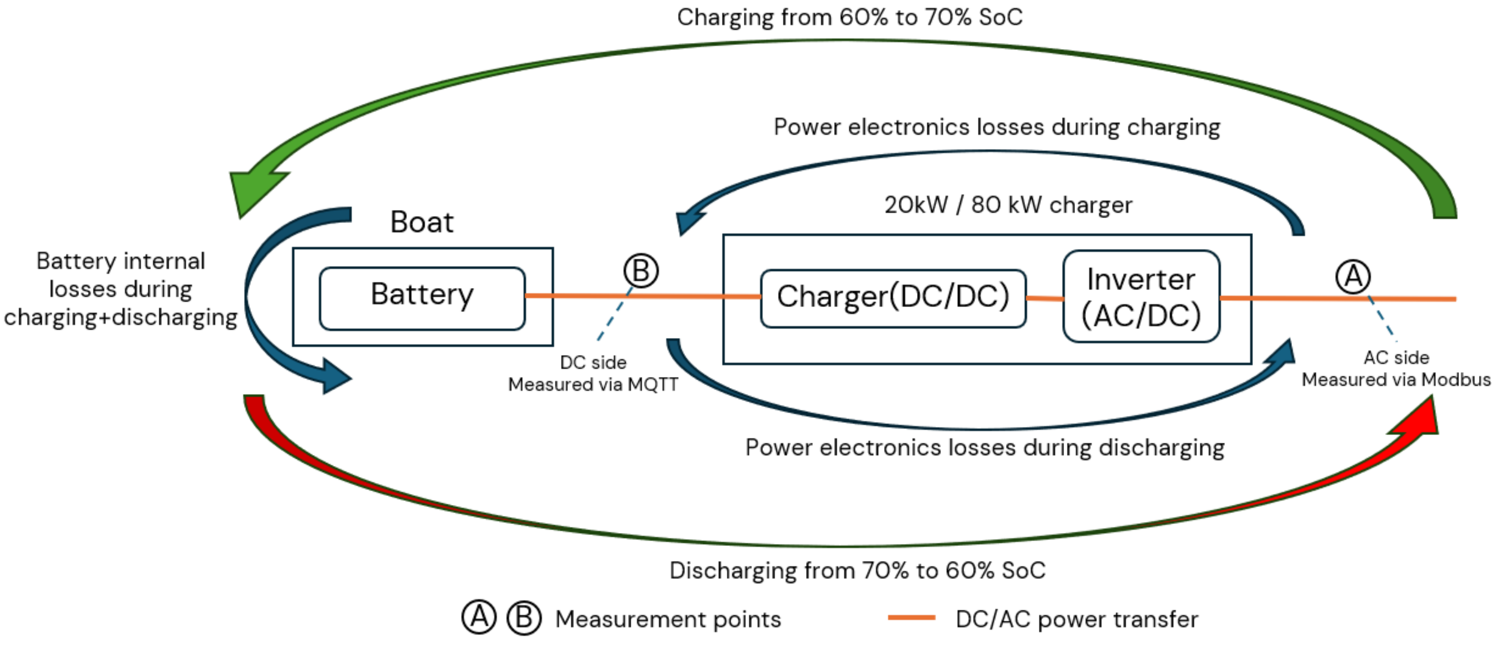


Figure 4. RTE measurement boundary and included loss areas

Efficiency Results from the Test Setup

Round-trip efficiency tests were performed in the 60–70% SoC window. For each power level, the full charge/discharge cycle was repeated five times, and the reported value is the average RTE across the five repetitions. This improves repeatability and reduces the impact of one-off measurement variation.

The project included both 20 kW chargers and 80 kW chargers. A main driver for increasing the power is that the revenue from many services, such as frequency regulation markets or peak shaving, is directly proportional to the available power. At the same time, the power level must not impact battery life or require increased grid capacity at the marina. Hence, 80 kW was considered a good fit for optimizing these requirements.

The total round-trip efficiency of the system includes the losses in the AC/DC inverter, the galvanically isolated DC/DC charger, cables, battery chemistry, and any support systems in the charger and boat-side energy system.

The results are shown in Figure 5, where RTE is plotted against power level for both charger configurations. The graph gives a direct comparison of how efficiency changes with operating power. The results show that RTE is strongly affected by power level, especially at lower power. At low power, fixed losses have a larger impact compared to the transferred energy. As power increases, efficiency improves and becomes more stable.

The loss breakdown indicates different behavior across components: battery internal losses increase with power, while charger/inverter losses during charging decrease at higher power levels. In discharging, charger/inverter losses remain relatively stable across the tested range.

The 80 kW inverter comprising 4 × 20 kW power modules that are switched in and out as needed to optimize the efficiency curve throughout the power range. Despite this, the 80 kW inverter has slightly higher losses than the 20 kW charger. This is partly due to the effect that the losses also include support systems such as an air-to-air heat exchanger in the charger, designed to protect the electronics in marine environments. The inverter was also over-dimensioned at 112 kW, contributing to slightly higher idle losses.

Detailed raw results from all five repetitions are not included in the main white paper but can be provided on request.

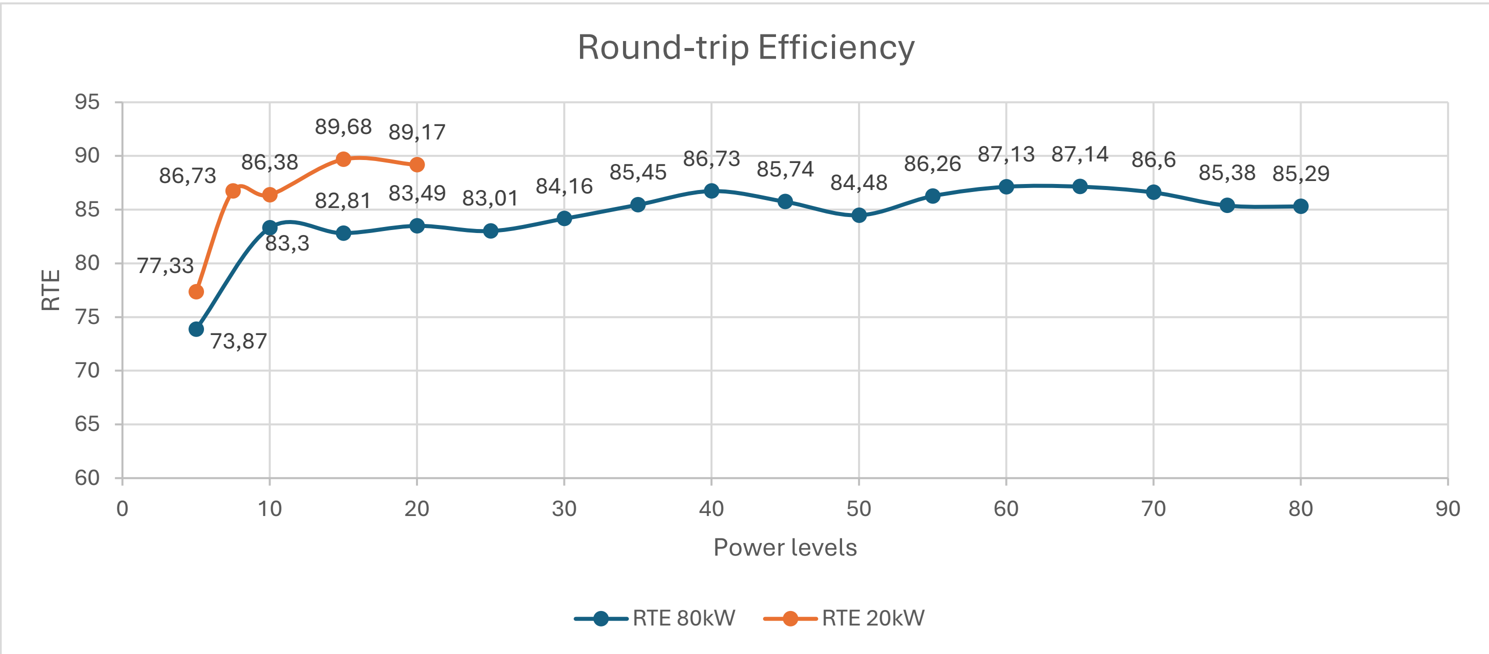


Figure 5. Round-trip efficiency results for both 20kW and 80kW chargers

References

[1] E. Apostolaki-Iosifidou, P. Codani, and W. Kempton, “Measurement of power loss during electric vehicle charging and discharging,” Energy, vol. 127, pp. 730–742, 2017.

[2] W. Schram, N. Brinkel, G. Smink, T. van Wijk, and W. van Sark, “Empirical Evaluation of V2G Round-trip Efficiency,” in Proc. International Conference on Smart Energy Systems and Technologies (SEST), 2020.

[3] P. Videgain Barranco and C. F. Covrig, Vehicle-to-Grid and/or Vehicle-to-Home Round-trip Efficiency: A Practical Case Study, Joint Research Centre, European Commission, 2021.

[4] K. Sevdari et al., “Efficiency of bidirectional EV charging: Key insights from implementing ISO 15118-20 CCS2 and CHAdeMO,” Sustainable Energy Technologies and Assessments, 2025.

[5] G. Pintér, A. Vincze, N. H. Baranyai, and H. Zsiborács, “Boat-to-Grid Electrical Energy Storage Potentials around the Largest Lake in Central Europe,” Applied Sciences, vol. 11, no. 16, 2021.

[6] U. Suryawanshi et al., “Enhancing the Performance of Distribution Network Using Ferry-to-Grid Technology,” in Proc. IEEE Conference, 2019.

[7] R. B. Roy, S. Alahakoon, and S. G. Jayasinghe, “Microgrid and Fleet to Grid Operation of a Hybrid Electric Ferry,” in Proc. AUPEC, 2021.

[8] Anam, A. Kersten, Y. Xu, and B. Ban, “Boat-to-Grid for Marine Leisure Drivelines: A Swedish Case Study on Evaluating Lifecycle CO_2-Equivalent Emissions and Profitability,” in Proc. IEEE Conference, 2025.

[9] Anam, A. Kersten, Y. Xu, B. Ban, and S. Stipetić, “Lifetime Assessment of Power Electronics for Propulsion and Charging in Marine Leisure Vessels with Boat-to-Grid Capability,” in Proc. IEEE Conference, 2025.

[10] Technical Requirements for Frequency Containment Reserve Provision in the Nordic Synchronous Area, Nordic TSOs / Svenska kraftnät, 2023.

[11] Test Program for Prequalification of FCR in the Nordic Synchronous Area, Nordic TSOs / Statnett, 2025.

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