# Electric vehicle charging measurements in the Nordic environment - charging profile dependence on ambient temperature

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**DOI:** 10.1049/icp.2023.0873

# ELECTRIC VEHICLE CHARGING MEASUREMENTS IN THE NORDIC ENVIRONMENT—CHARGING PROFILE DEPENDENCE ON AMBIENT TEMPERATURE

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## *ABSTRACT*

*This paper aims at providing further understanding of electric vehicle (EV) charging in a cold environment by providing an overview of laboratory tests conducted for several EVs. The paper describes the laboratory test process and the main findings of the laboratory measurements. The measurement results and stochastic load modeling show that the energy demand increases significantly over wintertime charging sessions. The increased energy demand also increases peak loads in the distribution networks. In Nordic distribution grids, EV charging peak loads often overlap baseload peaks, creating incentives to manage charging in a smart way. The increased energy content and additional preheating power cause a need to rethink smart charging applications. As the main outcome of the paper, the laboratory routine is described with the measurement results of four EVs and one plug-in hybrid electric vehicle (PHEV). As the main result, the study shows that the temperature dependence is among the key variables to be added to the stochastic EV charging load modeling in cold environment areas.*

## INTRODUCTION

Electric mobility is taking an increasing role in the private and public transportation. EU directives, national legislation, and energy policy are the key driving forces behind the rapid change of the private transportation sector. An attitude change can also be seen in the press releases of many car manufacturers, indicating a greater focus on full electric powertrains. While the public attitude toward EVs is also changing, EV sales are rapidly increasing in pace in the Nordic countries and all over the world. In practice, this means that scenarios are about to become reality, and distribution grids are already facing new loads. Countries with cold climate conditions need to pay special attention to the temperature dependence of EV charging loads as it is likely to cause additional needs for distribution grid reinforcement. The measurement results and stochastic load modeling show that the energy demand increases significantly over wintertime charging sessions. The increased energy also increases peak loads in distribution networks. In Nordic distribution grids, charging peak loads often overlap baseload peaks, creating incentives to manage charging in a smart way. The increased energy content and additional preheating power cause a need to rethink smart charging applications. Cutting the charging power too low is likely to compromise the charging event as charging energy per heating energy ratio leans strongly on heating energy, and as a result, the charging time window may run out.

The strategic planning of the electricity distribution is a multivariable optimization problem, which involves masses of variables describing various technical properties, economic aspects, and forecasts. Many of the variables related to EVs, such as kilometers driven per day or arrival time, can be estimated based on national traffic surveys or site-specific surveys. Vehicle stack or fleet properties can be queried from public or semipublic registers. In the Nordic climate conditions, the energy consumption and charging capabilities of vehicles in a cold climate play a significant role in the electricity system planning. Thus, it is important to study how a charging event changes when the ambient temperature drops below zero. Some studies [1, 2] have raised similar issues and partially answered these questions. In addition, efforts have been made by the press [3, 4] and associations in the field [5], but more research and measurement of the real-life operating conditions are needed.

This paper aims at providing further understanding of electric vehicle (EV) charging in a cold environment by giving an overview of laboratory tests conducted for several EVs, but also by showing how to apply results to stochastic load modeling. The paper describes the laboratory test process and the main findings of the laboratory measurements.

As the main outcome of the paper, a brief summary of the laboratory routine is provided with the measurement results of four EVs and one plug-in hybrid electric vehicle (PHEV). All cars were tested at temperatures of 20°C, 0°C, -10°C, and -20°C, reflecting typical outdoor temperatures in the Nordic countries. The measurement report describes the test setup, the measuring routine, and results


Fig. 1: Cold environment vehicle testing laboratory with the test subject car attached to a four-wheel dynamometer

in detail [6], and the raw data are also publicly available [7]. The measurements were conducted in a large temperature-controlled vehicle technology laboratory (Fig. 1), and the charging measurements were logged from a three-phase power analyzer. In the worst-case scenario, the charging energy demand may even double compared with charging in standard conditions (+20°C). In the testing, all the cars equipped with a battery heater showed an increasing energy demand. The car without an auxiliary battery heater was not able to charge fully when the temperature was decreased below -10°C. The results benefit EV charging modeling and EV uptake scenario analysis of the distribution grids in cold climate countries.

## BACKGROUND INFORMATION

The main motivation for the further testing of electric vehicle (EV) charging was to acquire more detailed knowledge of how the charging power and energy can vary under different climate conditions, especially in the cold Nordic climate. The hypothesis based on the public discussion and basic physics is that EVs consume more energy when operating in cold climate conditions. The increase in the consumption can mainly be explained by the additional heating energy required to maintain a comfortable cabin temperature while driving. In reality, it is obvious that there are multiple factors that impact the total energy demand. Several scientific publications support the hypothesis, yet not many focus on the effect that the increased demand may cause on the distribution grid infrastructure.

The main interest of the measurements lies in low-temperature charging events as they set the parameters for the worst-case scenario in the Nordic climate conditions. The worst-case scenarios cannot be overlooked when designing and dimensioning the EV charging infrastructure. The rationale behind the time-consuming laboratory testing is that there is clear evidence that lithium-ion-based battery technologies face challenges in cold climate conditions. Issues are related, for instance, to accelerated battery degradation [8], cold climate fast charging capabilities [9], or cold climate charging capabilities in general [10]. The root cause for challenges in lithium-ion battery charging at subambient (below 20°C ambient temperature) temperatures is often dendrite growth [11] that potentially causes

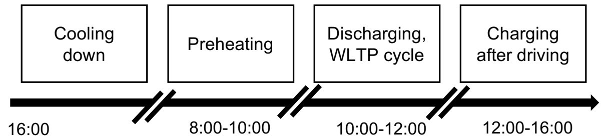


Fig. 2: Full-day testing routine divided into four main parts.

an internal short-circuit. Therefore, it is required to maintain a certain operating temperature during the charging event. Active temperature control requires energy, which is then shown as an additional demand on the distribution grid side. The cold climate charging power curve is often very different compared with charging events executed in close proximity of the battery manufacturer's recommended nominal operating temperature. Real-world laboratory or field tests can be seen to bring high added value, because modeling the car operation in varying conditions is likely to require many simplifications and contain a large number of very uncertain input variables, which affects the modeling results. Moreover, charging tests can be used to validate charging models to enhance the reliability of the results and even further encourage engineers to exploit the modeled results.

## TEST SETUP AND ROUTINE

In the design process of the testing routine, the main challenges are related to the selection of the cars and setting up a sufficient charging routine. The car selection can be considered to have a major impact on the results, as car manufacturers use distinct technologies for the powertrains and batteries of the cars. Often, models that fall into the premium full-size class are better equipped. A premium car can, for instance, be equipped with better battery temperature management to ensure a good charging experience regardless of the ambient temperature. The current sales figures in Finland were used as a guideline in the selection of the test cars; a detailed description is available in the measurement report [6]. The main goal of the test routine was to mimic a typical or average car usage. Fig. 2 illustrates the four stages of the charging routine. First, the car is cooled to the target temperature. The cooling cycle continues over night to ensure that also the battery has reached the target temperature. Secondly, in the morning, the discharge cycle begins with preheating of the car cabin. The preheating mimics typical operation of cars in winter conditions in the Nordic countries. The car is operated at the test bed according to the worldwide harmonized light vehicle test procedure (WLTP) test cycle to mimic the real-world driving as closely as possible. The operation continues until the battery state-of-charge (SoC) has discharged to 70%. The fourth and last stage is the charging stage. After the driving stage, the car is immediately plugged into the charger and charged to the full SoC.

The testing took place in the laboratory of Metropolia University of Applied Sciences in Helsinki, Finland. The test cycles were monitored and logged in data logs to be

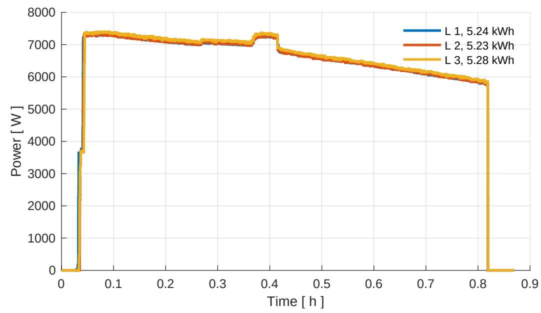


Fig. 3: Power curve of three phases at 20°C ambient temperature in the car A charging test.

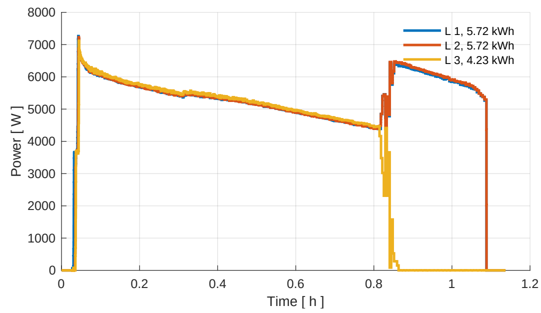


Fig. 4: Power curve of the three phases at -10°C ambient temperature in the car A charging test.

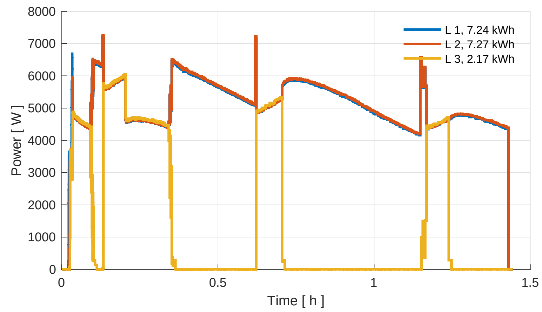


Fig. 5: Power curve of the three phases at -20 °C ambient temperature in the car A charging test.

examined later. An Ensto EVF100W-BSAC [12] charging pole was used to provide mode 3 charging support. The charging power was measured by using a Carlo Gavazzi EM340 [13] power analyzer. Data were then logged by using the Modbus interface of the power analyzer by a Modbus logger [14] and further uploaded to a long-term storage [7].

## LABORATORY MEASUREMENT RESULTS

The tests conducted in the laboratory revealed substantial changes in the power and energy demand of the EVs. In the following, highlights of the power curves recorded at the testing event are provided, and changes in the total charging energy demand are summarized. The testing of the cars was highly time consuming, taking a full working week per a car tested. The first test for each car was a reference test, where the car charging was tested at the ambient temperature of 20°C. Fig. 3 shows that the total energy of the charging event is 15.7 kWh. The charging begins with the rated power and continues at the full power for a few minutes before the battery cell voltages begin to limit the charging current.

The second test at 0°C showed a similar power curve compared with the +20°C testing case. All cars followed a similar pattern between the first two tests. The reference and 0°C curves varied slightly between the cars depending on how close to the actual full capacity the battery was reaching at the 100% SoC observed by the user. The cars with smaller safety tolerances showed a typical lithium-ion charging curve, where the end of the charging period has a concave-shaped end caused by the decreasing charging current (to not exceed the maximum allowed cell voltage).

The third test at -10°C changes the setting dramatically with the test conducted to car A (Fig. 4). The total energy of the charging event stays almost the same as in the reference case. The charging event begins with the rated power and quickly drops by about 1 kW per phase. The charging continues at a steadily decreasing charging current until the car reduces the third-phase power to zero and increases the power of the two other phases. The total charging time increased by about 35%, and the shape of the power curve changed slightly. Furthermore, it is noteworthy that in the last part of the charging event, the three-phase load is asymmetrical as the car has dropped the power of one phase to zero.

The fourth test at -20°C shows major changes in the shape of the charging load power curve and in the total energy. The total energy increased by about 1 kWh, but the power demand was very intermittent and the car switched multiple times between two-phase and three-phase charging. The charging curve shows clearly that the car uses the battery heating element to reach temperature levels where charging can be continued. Fig. 5 demonstrates the intermittence of the charging curve characteristics. The total charging time was also prolonged significantly compared with the reference test, by almost 80%.

Tables 1 and 2 summarize the total preheating and charging energies of each car under test. Absolute values are car-specific and should not be compared, as the reference charging energy varies according to the car under test. The relative change in the charging energy varies between a 100 % increase and a -36 % decrease. The cars that showed a decreasing energy content were not equipped with battery heaters, and thus, the total energy charged to the battery was lower than it would have been in the reference operating temperature. In low (below 0°C) temperatures, it is possible that battery is not capable of storing the full energy capacity (see car B in Table 1). The cars that showed an increasing total energy in low-temperature charging were equipped with battery heaters. Most of the additional charging energy was due to battery heating.

Table 1: Total charging energy of the tested cars. *Battery charging was terminated before reaching the 100% SOC. **Worst-case scenario, the car parked overnight with a discharged battery. Preheating energy not included.

| Car | Testing temperature | | | | |
|---|---|---|---|---|---|
| | 20°C kWh | 0°C kWh | -10°C kWh | -20°C kWh | -20°C** kWh |
| Car A | 15.7 | 15.6 | 15.7 | 16.7 | 23.6 |
| Car B | 20.3 | 17.8 | 18.3 | 15.3 | 15.6* |
| Car C | 13.0 | 12.4 | 12.6 | 12.6 | 15.0 |
| Car D | 23.3 | 23.0 | 25.5 | 24.3 | 27.5 |
| Car F | 10.3 | 10.2 | 10.0 | 9.7 | 7.6* |

Table 2: Total preheating energy of the tested cars.

| Car | Testing temperature | | |
|---|---|---|---|
| | 0°C kWh | -10°C kWh | -20°C kWh |
| Car A | 5.5 | 7.9 | 12.3 |
| Car B | 0.7 | 3.1 | 3.1 |
| Car C | 1.6 | 2.9 | 2.4 |
| Car D | 1.4 | 0.5 | 2.5 |
| Car F | 0.3 | 0.5 | 0.4 |

In addition to charging tests, the cars were preheated before driving, and the data were recorded. The total energy content of preheating is highly dependent on the ambient conditions, technical boundaries, and most importantly, also on the user preferences. Table 2 shows that the total energy content of preheating can be compared with the total charging energy content. The cars equipped with heat pumps had a much lower energy impact.

## NETWORK EFFECTS

The results of the cold climate charging tests were applied to stochastic EV charging load modeling to reveal the dependence of the peak load and the stochastic load curve on the ambient temperature. The stochastic model used in the analysis is described in more detail in [15]. To obtain the overall effect of the ambient temperature in the modeling, the relation of the car's energy consumption to the ambient temperature has to be incorporated in the model. Fig. 6 shows how the consumption depends on the ambient temperature. The data are gathered from various sources and include tens of cars in different car sizes and type classes [3–5]. When the temperature drops below 0°C, the consumption starts to increase dramatically. It is pointed out that the tests are not conducted scientifically, but can still be used to build a good starting ground for the stochastic model. It is also important to note that driving cycles, the driver's driving style, and other personal preferences have a major impact on the EV's energy consumption in cold climate conditions.
The stochastic model is a relatively simple Monte Carlo simulation, but the parameter tuning requires skill, experience, and fine-tuning. The model is fed with distributions

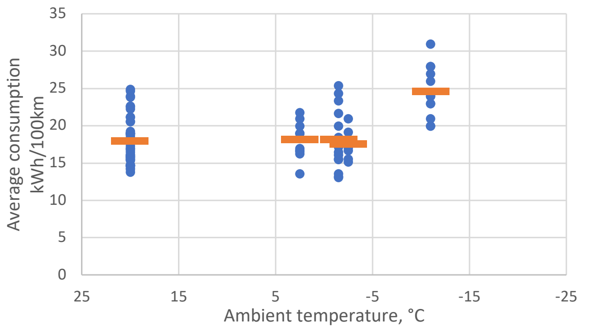


Fig. 6: Car power consumption estimates in different temperatures. Data compiled from various sources.[3–5, 15]

of arrival time, departure time, number of trips, total kilometers driven, vehicle consumption, battery size area efficiency, and user preferences. In addition, there is a large number of parameters that allow to adapt the model for various environmental conditions. Fig. 7 shows an example of the model results in the case of an apartment house parking area with a total of 20 charging spots equipped with 11 kW chargers. The effect of cold ambient temperature can be seen as an increased peak load, but also as a secondary consumption peak in the morning hours. The secondary peak is caused solely by the preheating of the cars, and it is typically very difficult to estimate accurately. The primary peak power increases by approximately 25%, which is a substantial increase considering the grid planning. The model captures the stochastic properties of the EV charging load, because even a low number of cars often results in a peak power, which is a product of the charger power and the number of cars. Fig. 8 illustrates the model properties as a function of the number of cars. The model also provides a capability to estimate smart charging, which aims at the lowest possible peak power by shifting individual charging events to a later time. Dynamic charging coordination or peak shifting can be very beneficial especially in cold climate conditions, where peak loads are likely to increase when the ambient temperature drops below zero. Based on the simulation, uncontrolled charging at +20°C ambient temperature results in high peak loads as does the dynamically controlled charging at -20°C ambient temperature.

## CONCLUSION

The study summarized testing of four EVs and one plug-in hybrid electric vehicle (PHEV). The results show that the subambient temperature has a substantial effect on the EV charging power, energy, and total charging time. The absolute magnitude of changes is highly dependent on multiple variables, such as battery temperature, battery heating equipment, the car manufacturer's preferences for cold climate operation, battery chemistry, and probably also battery age. As the main result, it is shown that EV charging has a significant temperature dependence. In respect of grid planning, it is recognized that cold climate

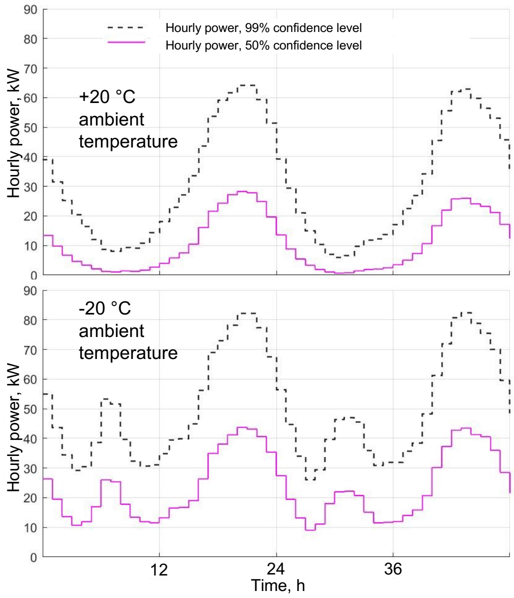


Fig. 7: Comparison of +20°C and -20°C ambient temperature charging events. The upper graph shows the charging load profile simulated for +20°C ambient temperature and the lower graph the same result graph when the temperature parameter is changed to -20°C.

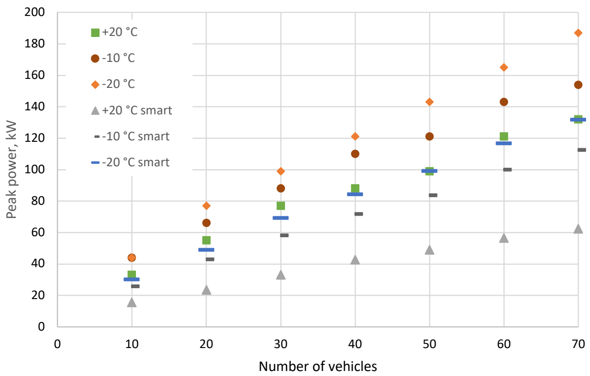


Fig. 8: EV charging peak power as a function of the number of cars. In the legend, "smart" refers to dynamic load control (peak shifting or valley filling). Peak powers are presented at a 99% confidence level.

not only increases the peak power of the EV charging but also impacts the energy demand and the shape of the charging profile. When charging takes place at a below-zero temperature, the load curve is introduced with a secondary power peak, which is mainly caused by preheating of the cars. The primary peak of the load curve increases by 25–30%. The energy demand in the winter season also increases significantly, up to double.

## REFERENCES

[1] P. Huang, S. Liu, Y. Zhang, Y. Ou, G. Zeng, J. Zhou, and Z. Bai. Assessment of Electric Vehicle Charging Scenarios in China Under Different-temperature Conditions. Journal of Energy Storage, 41:102859, 2021.

[2] X. Hao, H. Wang, Z. Lin, and M. Ouyang. Seasonal effects on electric vehicle energy consumption and driving range: A case study on personal, taxi, and ridesharing vehicles. Journal of Cleaner Production, 249:119403, 2020.

[3] Talvisähköauto 2019 [in Finnish]. Tekniikan Maailma (TM), 5:23–40, 2019.

[4] Talviauto 2021 [in Finnish]. Tekniikan Maailma (TM), 5:26–50, 2021.

[5] Norges Automobil-Forbund. 20 popular EVs tested in Norwegian winter conditions. URL: https://www.naf.no/elbil/aktuelt/elbiltest/ev-winter-range-test-2020, 2020.

[6] V. Tikka, J. Kalenius, O. Raisanen, and J. Lassila. Technical report: Measurements of cold climate EV charging. Technical report, LUT University, Lappeenranta, Finland, 2021.

[7] V. Tikka and T. Laine. Measurements of cold climate EV charging. URL: http://urn.fi/urn:nbn:fi:att:1ac935ce-fbb9-422e-9081-9a8db3c53399, 2021.

[8] K. Darcovich, S. Recoskie, H. Ribberink, and C. Michelet. The impact of V2X service under local climatic conditions within Canada on EV durability. eTransportation, 9:100124, 2021.

[9] Y. Motoaki, W. Yi, and S. Salisbury. Empirical analysis of electric vehicle fast charging under cold temperatures. Energy Policy, 122:162–168, 2018.

[10] J. Jaguemont, L. Boulon, and Y. Dubé. A comprehensive review of lithium-ion batteries used in hybrid and electric vehicles at cold temperatures. Applied Energy, 164:99–114, 2016.

[11] R. Akolkar. Modeling dendrite growth during lithium electrodeposition at sub-ambient temperature. Journal of Power Sources, 246:84–89, 2014.

[12] Charging station EVF100W-B4B. URL: https://www.ensto.com/fi/tuotteet/sahkoauton-lataus/julkinen-lataus/pro/evf100w-b4b/, 2021.

[13] Carlo Gavazzi EM340. URL: https://carlogavazzi.com, 2020.

[14] CAN Bus and CAN FD Interfaces and Analyzers. URL: https://dewesoft.com/products/interfaces-and-sensors/can-interfaces, 2020.

[15] V. Tikka, J. Kalenius, O. Raisanen, and J. Lassila. Loppuraportti: Sähköautojen latauksen muodostama kuormitus- ja mitoitusteho erilaisissa toimintaympäristöissä [in Finnish]. Technical report, LUT University, Lappeenranta, Finland, 2021.