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TECHNICAL REPORT: MEASUREMENTS OF COLD CLIMATE EV CHARGING

LUT-yliopisto
LUT School of Energy Systems
Tutkimusraportti 130
LUT University
LUT School of Energy Systems
Research report 130

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Technical report: Measurements of cold climate EV charging

LUT University
LUT School of Energy Systems
PL 20
35851 LAPPEENRANTA
ISBN 978-952-335-715-0
ISBN 978-952-335-715-0 (PDF)
ISSN-L 2243-3376
ISSN 2243-3376

Lappeenranta 2021

Preface

This report presents the key measurement observations of the project ”Sähköautojen lataamisen kuormitus- ja mitoitusteho erilaisissa toimintaympäristöissä” [”Peak load power and average load power of EV charging in different operating environments”] carried out at LUT University (LUT) and Metropolia University of Applied Sciences between November 2020 and September 2021. The members of the research group were associate professor Jukka Lassila, Ville Tikka, M.Sc., Otto Räisänen, M.Sc., Jani Kalenius, M.Sc., and laboratory engineer Teemu Laine (Metropolia). The research was funded by the Finnish Electricity Research Pool (ST-Pooli), the Promotion Centre for Electrical Safety (STEK), and Suomen Kiinteistöliitto ry.

The conclusions, results, and suggestions for future actions presented in this report are the authors' views only and do not tie the funding organizations in any way.

Lappeenranta September 2021

Authors

Abstract

This research project aimed at providing further understanding of electric vehicle (EV) charging in a cold environment. The report provides laboratory measurement results and acts as supporting documentation for the raw measurement data. The laboratory measurements were executed at a large temperature-controlled vehicle technology laboratory, and the charging measurements were logged from a three-phase power analyzer. The testing comprised four battery electric vehicles (BEVs) and a single plug-in hybrid electric vehicle (PHEV). All cars were tested at 20 °C, 0 °C, -10 °C, and -20 °C. The results describe the charging behavior of each vehicle under different ambient temperature operating conditions. The further analysis of the results is included in a separate research report [1].

Contents

Nomenclature

Acronyms

BEV	Battery electric vehicle
BMS	Battery management system
EV	Electric vehicle
ICE	Internal combustion engine
NTS	National Travel Survey
PHEV	Plug-in hybrid electric vehicle
SoC	State-of-charge
WLTP	Worldwide Harmonized Light Vehicle Test Procedure

1 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. The recent trend sets new requirements for the energy production and supply infrastructure. Traditional vehicles have relied on liquid fuels that can be transported and stored relatively easily. It has taken several decades for the infrastructure to develop into its present form. Novel powertrains such as the full electric powertrain require a supporting infrastructure for energy delivery as the current liquid fuel supply network has very little to offer for the electric vehicle (EV) charging infrastructure. Nevertheless, on the bright side, we may argue that the present power system, electricity transmission grid, and distribution grid are mostly sufficient for the job. On the other hand, however, the present infrastructure has been designed to support loads that are very different from electric vehicle charging. Issues can be seen at all levels of the electricity distribution infrastructure, but the lowest topology level plays the key role in setting the requirements for dimensioning of the grid. The electric systems of parking areas and buildings have to be planned and designed appropriately in order to support EV charging. Too extensive overdimensioning often leads to a poor power and capacity efficiency of the whole energy distribution system, whereas underdimensioning may jeopardize, for instance, the operation of an EV charging station, the electricity network of a building, or even the whole electricity distribution system.

The design of the electricity network of a building and charging area can be considered a multi-variable optimization problem. Many of the variables, 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 [2] [3] raise similar issues and partially answer these questions. In addition, efforts have been made by the press [4][5] and associations [6] on the field, but more research and measurement of the real-life operating conditions are needed.

The technical report on the cold climate charging of electric vehicles summarizes charging tests conducted in a controlled climate environment. The objective of the report is to provide detailed understanding of how the test setup was built and what the main assumptions and simplifications were in the testing of the power behavior of the charging event. The report describes the measured charging profiles and summarizes observations made on the charging events during the tests.

2 Background information

The main motivation for the further testing of EV charging was to acquire more detailed knowledge of how the charging power and energy can vary under different climatic conditions. The main interest lies in low-temperature charging events as they set the parameters for the worst-case scenario in the Nordic climatic conditions. The worst-case scenarios cannot be overlooked when designing and dimensioning the EV charging infrastructure. The scientific community and media have recognized the issue of the cold environment, but there is still very little research available on the topic. It is well recognized in the studies that most lithium-ion-based battery technologies face challenges in cold climatic conditions. Issues are related, for instance, to accelerated battery degradation [7], cold climate fast charging capabilities [8] or, in general, cold climate charging capabilities [9]. The root cause for challenges in lithium-ion battery charging at subambient (below 20 °C ambient temperature) temperatures is often dendrite growth [10] that potentially causes an internal short-circuit. Therefore, many car manufacturers use heating resistors to keep the batteries in operating temperatures.

The car operation in varying conditions can be modeled, but often, the model contains plenty of uncertainties and many simplifications, and therefore, real-world laboratory or field tests can be seen to bring a high added value. 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.

When designing the experiment, 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 varying technologies for the powertrains and batteries of the cars. Often, models that fall into the premium of full-size class are better equipped. A premium car can, for instance, be provided with better battery temperature management to ensure a good charging experience regardless of the climatic conditions. When selecting cars for testing, current sales figures were used as a guideline. In the design process of the charging routine, the main goal was to mimic a typical or average car usage. The following subsections describe the measurement setup and initial assumptions in detail.

2.1 Test routine

The test routine mimics a real-world average EV charging use case. The use case was carefully prepared to match most of the features of the real-life behavior affecting the charging event. Many of the assumptions can be justified by statistics of the current travel or transportation surveys. Some assumptions were made based on the assumed behavior patterns of the car operators. All assumptions were then reflected on the charging event to get an idea of their possible impacts on the results. This section describes the use case and assumptions related to the use case. The final test routine was then derived from the defined use cases.

The use case approach was taken to give a clear understanding of how a charging event is assumed to take place and what the main assumptions are in defining the test procedure. The description of the use case follows loosely the typical use case definitions described, for instance, in [11]. The main focus is on describing the charging event in typical operating (behavior) conditions. It is also assumed that charging takes place during the winter season. In practice, this means that cars are typically preheated for comfort prior to driving. The second use case addresses an exceptional use case, where the car is stored in a cold environment, and the charging event takes place after a cold storage period.

2.1.1 Use case for normal operation during the winter season

The use case describes car usage in typical operating conditions. The car operator drives the EV every day and charges the vehicle at the first possible moment when arriving home. The car is preheated before the daily trips.

The primary actor of the use case is the car operator. Other actors of the use case are the building or charging spot owner, the charging spot manager, the distribution system operator, and the electricity retailer.

The only precondition of the use case is that the primary actor is assumed to possess an EV and have an opportunity to use a charging spot at home when desired. The use case also assumes that the majority of the charging takes place at home.

The use case begins from the preheating event before the operator starts the car. The preheating is initialized or timed so that the cabin temperature reaches 20 °C before the car is unplugged from the charging spot and driving begins. The operator then drives with the car and eventually arrives home for charging. The car operator plugs in the car for charging without delay. The car stays connected to the charger until the battery is fully charged.

2.1.2 Use case for the worst-case scenario

The use case describes car usage in special conditions. The car operator drives with the car but leaves the charging for the next day. The car is parked off-grid overnight before charging.

The primary actor of the use case is the car operator. Other actors of the use case are the building or the charging spot owner, the charging spot manager, the distribution system operator, and the electricity retailer.

The only precondition of the use case is that the primary actor is assumed to possess an EV and have an opportunity to use charging at home when desired. The use case also assumes that the majority of the charging takes place at home.

The basic flow of the use case begins from the preheating event before the operator drives with the car. The preheating is initialized or timed so that the cabin temperature reaches 20 °C before the car is unplugged from the charging spot and the driving begins. The operator then drives with the car and eventually arrives home for charging. The car operator then leaves the car parked overnight without plugging it for charging. In the morning, the car is plugged in for charging. The car remains plugged in until the battery is fully charged.

2.1.3 Background of use case definition

The use cases are generalized so that the laboratory testing would deliver most valuable results for further research purposes. Typically, traditional internal combustion engine (ICE) cars are preheated in the Nordic conditions by an engine block heater. In practice, this means that cars are plugged in an electricity socket every night during the winter season. Many cars also have an electric space heater for preheating the cabin. There is no obvious reason why EV owners would not behave similarly. In most cases, if an EV owner has a dedicated parking spot at home, the car is already plugged in the charging pole or device, making preheating of the cabin a convenient process. Thus, it is considered that preheating should be included in the testing routine. It is also worth mentioning that some cars preheat the battery while heating the car cabin. This increases the battery temperature before the driving event. Furthermore, while driving the car, the battery temperature may slightly increase. Eventually, as the car arrives home for charging, the battery temperature may be slightly over the ambient temperature. This temperature difference may result in a different charging behavior compared with charging without preheating. It is worth remembering that many factors can affect the battery temperature in cold climatic conditions, for instance, battery losses, chemical reactions resulting from the subambient temperature, an additional heater resistor, a heating or cooling fluid circulation system, or battery insulation.

As it was assumed that driving may have an impact on the battery temperature, it was also decided that driving must mimic real-world conditions as close as possible. The Finnish average of kilometers driven per day was used as a rough reference when determining the battery discharge levels. Figure 1 describes the total average traveling distances based on the National Travel Survey (NTS) conducted in 2016 [12]. Further, considering the charging event, it is important to decrease the battery state-of-charge (SoC) enough to reveal the temperature dependence at the last quarter of the charging. When lithium batteries are charged, charging is typically limited by the current until the SoC reaches about 80–90%. The charging then changes to the voltage-limited charging mode as the battery cell voltage reaches the maximum value. While charging in the voltage-limited mode, the charging current decreases until the end of the charging event. The temperature is one of the variables that may change the characteristics of the above-mentioned behavior. To keep the driving behavior as close to real life as possible but also repeatable, the

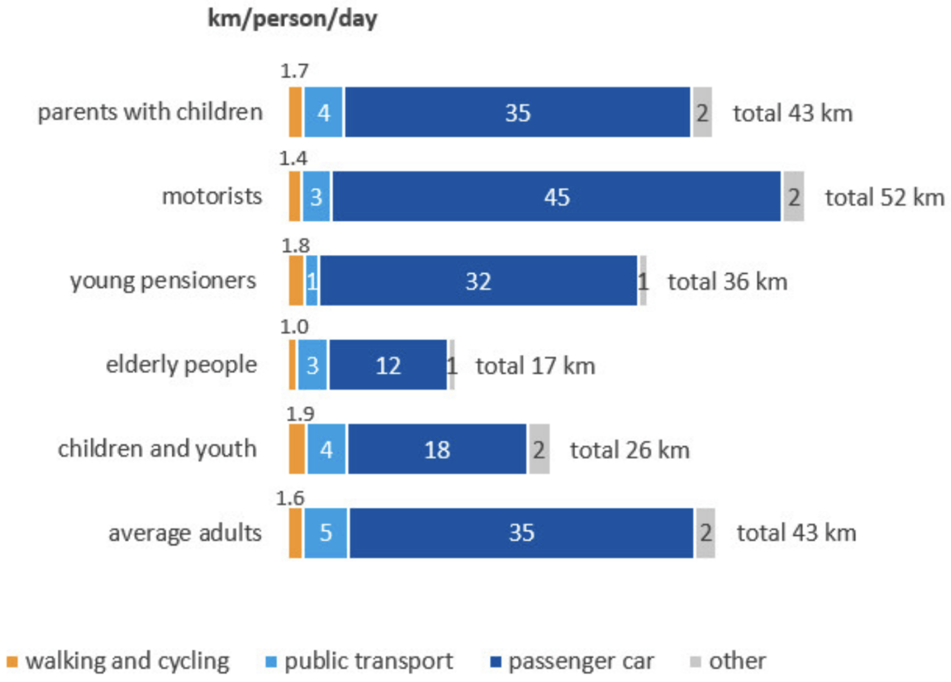

Figure 1: Distances traveled by Finns according to the stage of life. On average, 19% of the Finns did not travel at all during a 24h period. Those traveling at least 1000 m using active travel modes accounted for 38% of the population [12].

Worldwide Harmonized Light Vehicle Test Procedure (WLTP) [13] test cycle was selected. The test cycle was decided to be repeated until the desired SoC level was achieved.

The charging power can be considered to have a minor impact on the charging event, but on the other hand, it plays an important role in determining what can be observed from the results. A higher charging power reveals high SoC characteristics more clearly than a low power. If there are temperature-dependent properties of batteries, it is likely that attempting to use high power charging would reveal the characteristics more clearly. It is also likely that the charging behavior in the limited power condition can be modeled by using the results of unlimited power charging. Figure 2 shows an example of the EV charging curve in different temperatures. Temperature has a major impact on the charging curve profile and possibly also on the total energy content of the charging event.

2.1.4 Test routine implementation

The test routine was implemented so that testing of a single car can be carried out within a single working week. The testing begins by bringing the car to the reference temperature of 20 °C and continues to five test cycles as follows:

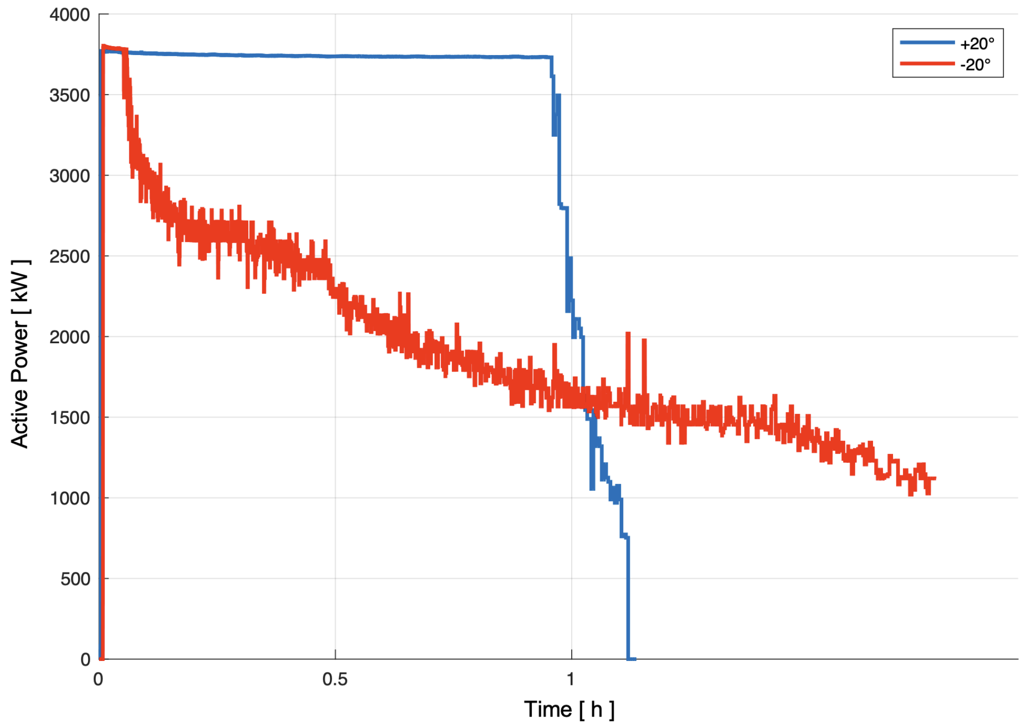

Figure 2: Example of the EV charging curve in the ambient temperature of 20 °C and -20 °C. Both example curves show the shape of the power curve when the battery SoC is approaching 100%.

1. Discharge on the four-wheel drive dynamometer at 20 °C and charging to the full SoC. The car stays connected to the charger until the next test cycle.
2. Cooling down to 0 °C, preheating of the cabin to 20 °C, discharge on the four-wheel drive dynamometer at 0 °C, and charging to the full SoC at 0 °C. The car stays connected to the charger until the next test cycle.
3. Cooling down to -10 °C, preheating of the cabin to 20 °C, discharge on the four-wheel drive dynamometer at -10 °C, and charging to the full SoC at -10 °C. The car stays connected to the charger until the next test cycle.
4. Cooling down to -20 °C, preheating of the cabin to 20 °C, discharge on the four-wheel dynamometer at -20 °C, and charging to the full SoC at -20 °C.
5. Maintaining -20 °C, discharge on the four-wheel drive dynamometer at -20 °C, the car is maintained at -20 °C off-grid, charging to the full SoC at -20 °C.

In the testing, each temperature change was allowed to stabilize overnight to ensure that the car structures and the battery had reached the target temperature before beginning a new testing cycle. The testing cycle can be visualized as illustrated in Figure 3. The first five tests follow a similar pattern except that in the first test there is no need to preheat the cabin. The fifth and last test also breaks the pattern as the car is maintained at -20 °C overnight with the discharged battery before charging to the full SoC.

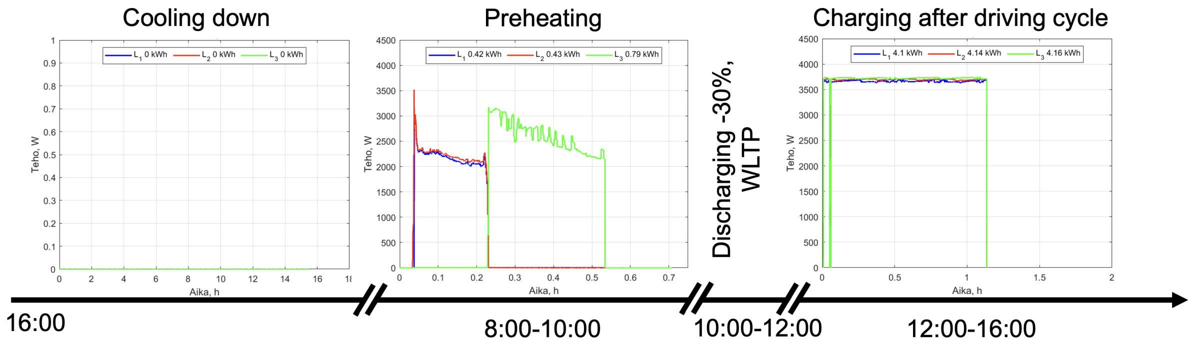

Figure 3: Timeline of the testing routine.

2.2 Selection of cars

The cars were selected for testing based on Finnish car sales statistics. The aim of the selection is to represent the car pool of the Nordic countries as close as possible. The number of cars to be measured was highly limited, and thus, special attention was paid to the car selection process. The car sales per manufacturer are dominated by Tesla as Figure 4 shows. The share of Tesla is mostly due to the early adoption of Model S. Later, the share of Tesla has increased even more as more models have become available. Nissan has the second largest share of sales with a single model. Nissan Leaf and Tesla Model S were selected mostly based on the sales statistics. Volkswagen ID.3 and Kia e-Niro showed an increasing trend in more recent monthly statistics. Nissan, Kia, and Volkswagen represent a class of small family cars, which is a very popular car class. Tesla Model S represents a larger premium segment car class and is also the only secondhand car used in the testing. Volvo has a leading position in the plug-in hybrid electric vehicle (PHEV) sales statistics, and thus, Volvo V60 T6 Recharge was selected for testing.

2.3 Description of the laboratory environment

Testing of the charging events was implemented in the laboratory of Metropolia University of Applied Sciences. The vehicle technology laboratory is temperature controlled and can achieve extremely low temperatures. Vehicles can be mounted on a four-wheel drive dynamometer, which is capable of executing various load scenarios, such as the standard vehicle testing cycle WLTP. Figure 5 shows the testing laboratory. Test cycles can be monitored and logged in data logs to be examined later. For the charging, an Ensto EVF100W-BSAC [15] charging pole was used. The charging current was not limited by the charger or the feeding grid. The charging power was measured by using a Carlo Gavazzi EM340 [16] power analyzer. Data were then logged by using the Modbus interface of the power analyzer by a Modbus logger [17].

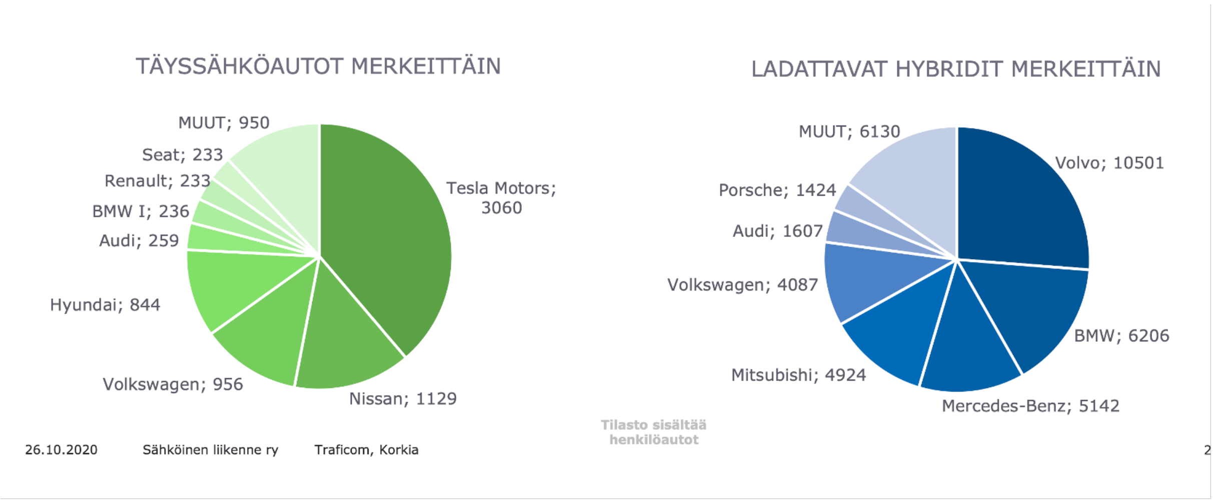

Figure 4: Number of sold EVs (Täyssähköautot merkeittäin) and PHEVs (Ladattavat hybridit merkeittäin) by make of car [14].

2.4 Application notes regarding the document

The report describes the laboratory measurements of five cars. The results give a good idea of what to expect of subambient temperature charging events. As the sample of cars is very small, one should not generalize the outcomes too far based on the report results. In general, it is challenging to state what the average charging behavior is in subambient conditions as the car properties and accessories are selected upon purchase and may have a major impact on the energy consumption and charging power. Achieving a broader understanding would require a much larger sample of cars to be measured. On the other hand, the added value of a large sample may be questionable, as future developments of EVs and PHEVs may change the state of the play. The raw data [18] are available for free for further investigation and analysis on the Fairdata platform [19].

Figure 5: Photo of the testing laboratory. Tesla mounted on a four-wheel drive dynamometer.

3 EV charging in a cold environment—laboratory measurement logs

This chapter describes measurements executed and observations made during the measurements. The data are illustrated as power graphs per each phase. The raw data are available in the CSS IDA Fairdata data storage [19] and can be accessed via a link [18]. The raw dataset includes the following data fields sampled at every 0.5 s:

- Timestamp
- Current of each phase
- Voltage of each phase
- Active power of each phase
- Reactive power of each phase
- Apparent power of each phase
- Power factor
- Active energy
- Reactive energy

3.1 Tesla model S P85, 2016

This section describes the laboratory measurements of Tesla Model S P85. The car selected for testing was produced in 2016. This model represents early-adoption full-size cars in the Nordic countries. The rated energy consumption of the car is well above average. The car is known to draw quite large amounts of energy from the grid in cold climate environments. The car is equipped with a battery heater and a direct electric space heater that can be operated prior to driving. The car details are listed as:

- Manufacturer: Tesla
- Model: Model S P85
- Production year: 2015
- Class: Full-size / Luxury car (F) / Grand tourer (S)
- Layout: Dual-motor, four-wheel-drive
- Battery size: 85 kWh lithium-ion battery
- Range: 407–438 km (EPA)
- Notes: Car had a 22 kW charger option

The testing cycle begins with the reference condition testing at the ambient temperature of 20 °C. The car battery is discharged to the 70% SoC by operating the car on the four-wheel drive dynamometer according to the WLTP test cycle until the target SoC level is achieved. The car is then plugged into the charger and charged with no delay to the 90% SoC. Tesla suggests to keep the battery SoC at 90% to maintain the best performance of the battery. It was assumed that consumers follow the manufacturer's recommendations, and thus, the 90% SoC level was considered the best representation of the real-life operation scenarios.

The tests at 0 °C, -10 °C, and -20 °C include a preheating cycle prior to discharging by operating the car on the four-wheel dynamometer according to the WLTP cycle until the SoC decreases to the level of 70%. After the driving cycle, the car is immediately plugged into the charger and charged until the SoC reaches the target of 90%.

The last testing cycle is executed without the preheating cycle. The battery is discharged to the 70% SoC in the evening before charging in the following morning. The car is kept at the target temperature of -20 °C overnight. In the morning, the car is plugged into the charger and charged until the battery reaches the 90% SoC.

3.1.1 Reference test at 20 °C

Figure 6 shows the power curve of the charging event under the reference operating conditions. 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 reach the maximum allowed value, and the charging current is reduced to avoid overvoltages on the battery cells. The battery charging power continues to decrease steadily until the charging event is automatically terminated at the 90% SoC.

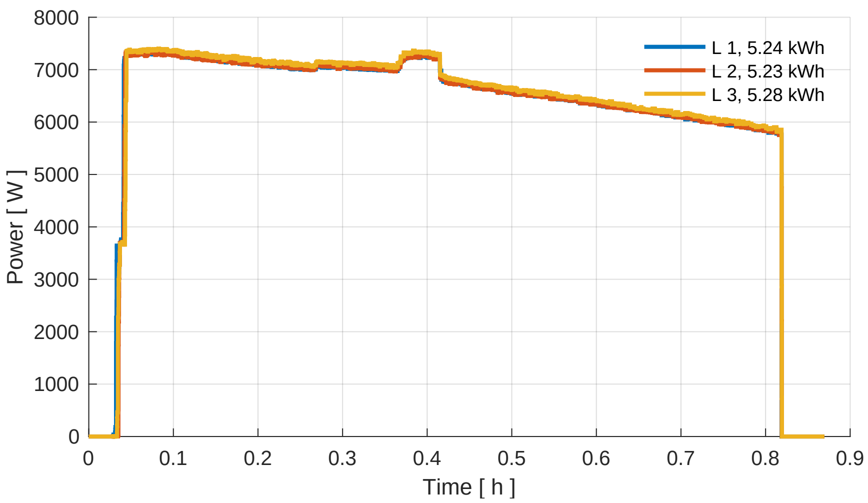

Figure 6: Power curve of three phases at 20 °C ambient temperature in the Tesla charging test.

The charging power curve represents a typical charging curve of lithium-ion battery modules. The charging power decreases steadily toward the end of the charging event. If the battery was charged full to the 100% SoC, the power would decrease even more before termination of the charging event.

3.1.2 Charging at 0 °C

Figure 7 shows the power curve of the preheating event under the 0 °C operating conditions. The total energy of the preheating event is 5.5 kWh. The preheating is triggered by the Tesla mobile app. The car uses two phases to heat up the cabin with a high power for about 20 min and continues to maintain the target temperature until the car is unplugged. It is also noteworthy that in the case of Tesla, the preheating cycle also contains battery heating. The preheating power is very volatile during the high-power starting phase of the preheating event. An indoor temperature of 2 °C was reported in the car before preheating, and the temperature reached 20 °C after 5 min of the preheating cycle. In practice, only a short period of preheating might suffice to raise the comfort level in subambient temperatures.

The car was kept plugged in the charging pole during cooling down to the target temperature before testing. During the cooling time, the car battery SoC decreased from 90% to 86% (reported by the Tesla app). After preheating, the app reported the SoC to be 87%.

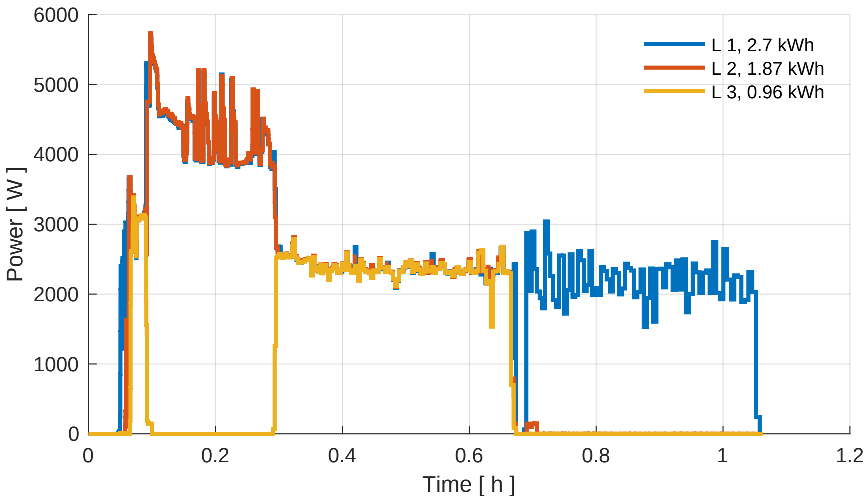

Figure 7: Power curve of three phases at 0 °C ambient temperature in the Tesla preheating test.

Figure 8 shows the power curve of the charging event event under the 0 °C ambient temperature operating conditions. The total energy of the charging event is 15.6 kWh. Then charging begins with the rated power and continues at the full power for a few minutes before the battery cell voltages reach the maximum allowed values, and the charging current is reduced to avoid overvoltages on the cells. The battery charging power decreases slightly more compared with the reference operating environment case. This change is still minor and has virtually no impact on the total charging time.

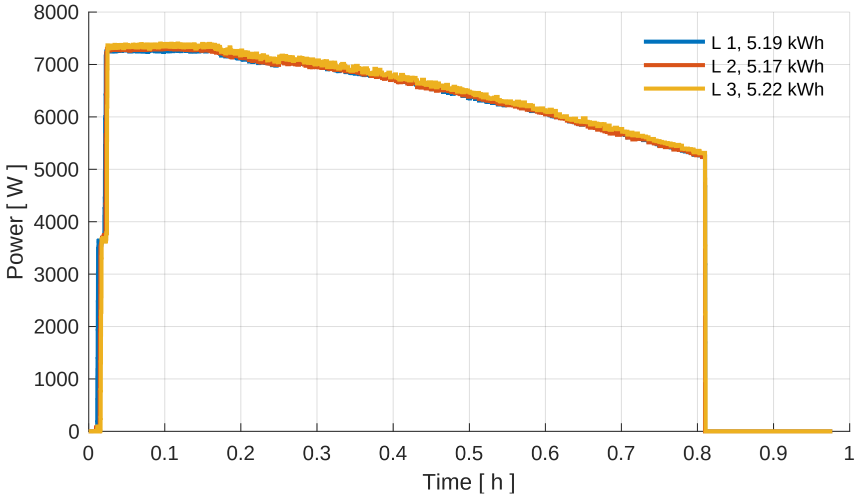

Figure 8: Power curve of three phases in 0 °C ambient temperature in the Tesla charging test.

3.1.3 Charging at -10 °C

Figure 9 shows the power curve of the preheating event in the -10 °C operating conditions. The total energy of the preheating event is 7.9 kWh. The preheating is triggered by the Tesla mobile app. Similar to the previous preheating event, the car draws power from two phases to heat up the cabin with a high power for about 20 min and continues to maintain the target temperature until unplugged. After the first 20 min, the car enables battery heating. The preheating power varies during the high-power starting phase of the preheating event. The car indoor temperature reached the target of 20 °C after about 7 min of preheating.

The car was kept plugged in the charging pole during the cooling down cycle to the target temperature before the testing begun. During the cooling down cycle, no power was consumed from the feeding grid.

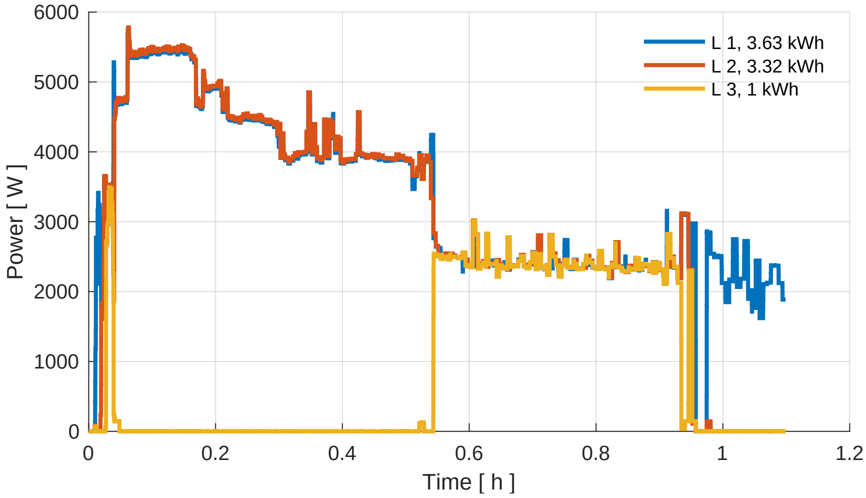

Figure 9: Power curve of three phases at -10 °C ambient temperature in the Tesla preheating test.

Figure 10 shows the power curve of the charging event event under the -10 °C ambient temperature operating conditions. The total energy of the charging event is 15.7 kWh. Thn charging 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 battery charging power decreases more than in the reference operating environment case. The decreased charging power increases the total charging time by about 35%.

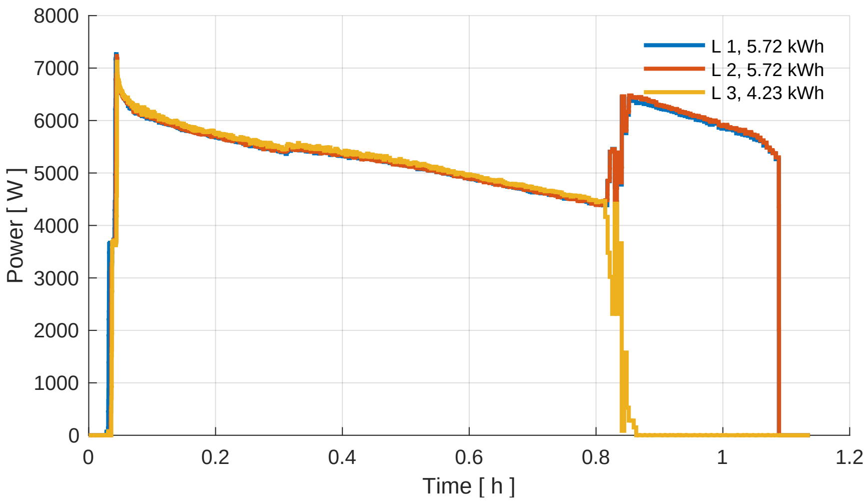

Figure 10: Power curve of three phases at -10 °C ambient temperature in the Tesla charging test.

3.1.4 Charging at -20 °C

Figure 11 shows the power curve of the preheating event at -20 °C ambient temperature. The total energy of the preheating event is 12.30 kWh. The preheating is triggered by the Tesla mobile app. Similar to the previous preheating event, the car draws power from two phases to heat up the cabin with a high power for about 30 min and continues to maintain the target temperature until unplugged. The Tesla mobile app indicated that the car battery heating was enabled over the whole preheating cycle.

The car was kept plugged in the charging pole during cooling down to the target temperature before testing. During cooling down, a minor power draw from the grid was registered.

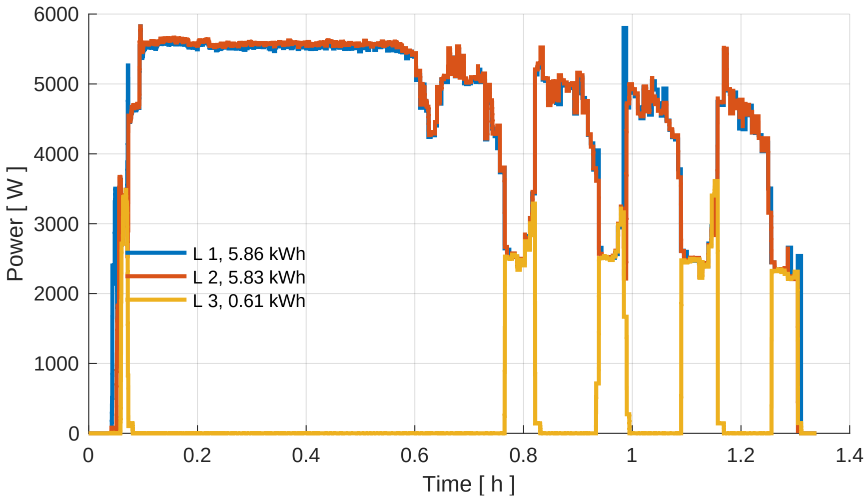

Figure 11: Power curve of three phases at -20 °C ambient temperature in the Tesla preheating test.

Figure 12 shows the power curve of the charging event event in the -20 °C ambient temperature operating conditions. The total energy of the charging event is 16.7 kWh. The charging begins with a limited power and then starts to decrease. The car's battery charger continues to charge with two phases after the current draw falls below the desired levels. The power curve also suggests that the battery is heated during charging. After the heating cycle, the battery's current absorption seems to increase momentarily. The battery charging power is more volatile compared with the charging event in the reference operating conditions at 20 °C. The decreased charging power increases the total charging time by about 80%.

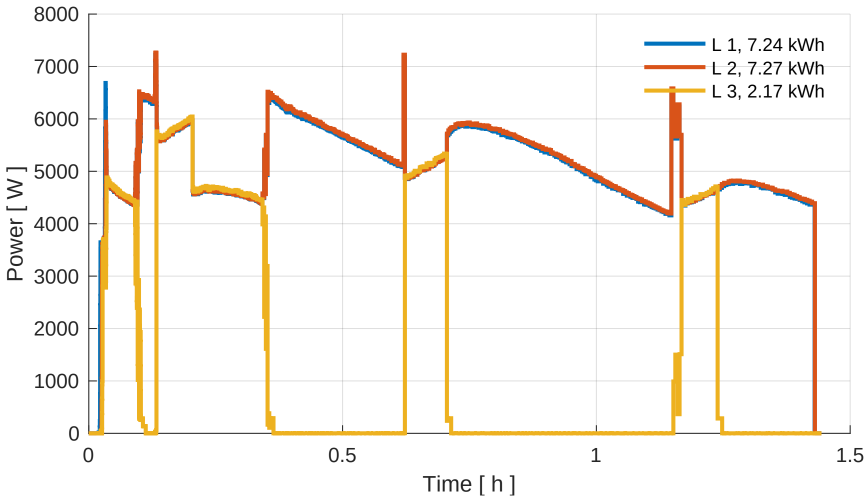

Figure 12: Power curve of three phases at -20 °C ambient temperature in the Tesla charging test.

3.1.5 Charging at -20 °C after cold storage

The last charging test deviates from the previous tests as the car was left at -20°C overnight with the battery discharged to the 70% SoC. The SoC was observed to decrease by 5% overnight according to the on-board information system of the car. It is unclear if the decrease was only an SoC estimation error or if the car consumed energy during overnight parking. The charging event was initialized without a preheating sequence at the beginning. Figure 13 shows the charging power curve of three phases. The charging event begins with an hour-long battery heating sequence before any battery charging takes place. The power curve of the actual charging event from 1 h time tick to 2.55 h tick looks similar to the previous charging test at -20 °C ambient temperature after the preheating and driving cycles. The total energy of the charging event, 23.58 kWh, is notably higher than in the previous tests. Further, the charging time increased by 220% compared with the reference operating environment test at 20 °C.

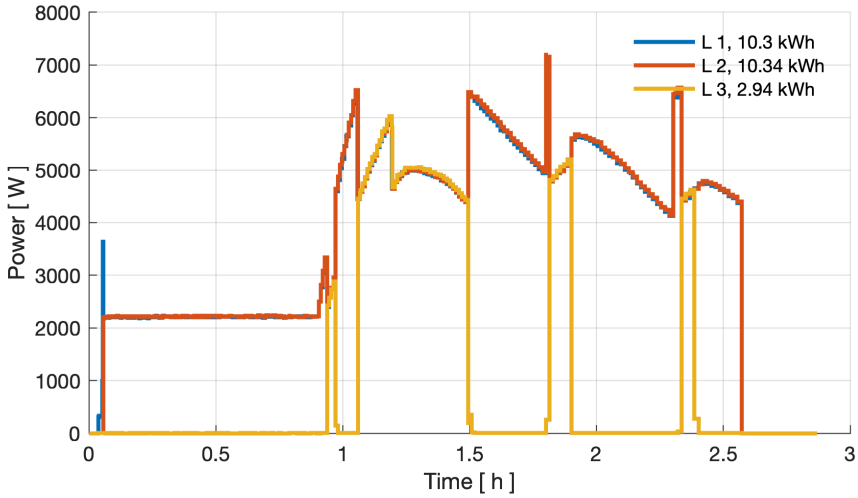

Figure 13: Power curve of three phases at -20 °C ambient temperature after overnight parking at the 70% SoC in the Tesla charging test.

3.1.6 General notes and observations

The Tesla charging test shows clearly how the ambient temperature can affect the EV battery charging time and energy content. It is also noteworthy that the preheating energy consumption of such a car may be comparable with the energy satisfying average daily driving. However, it is pointed out that in the testing, preheating was left on for quite a long time, which might not be the case in a real-life environment. In a real-life environment, it is also likely that the charging power may be limited by the charging hardware. When charging under limited power conditions, the battery heating energy has a larger share of the total energy consumption as there is a constant convection heat loss to the ambient environment. When the ambient temperature decreases, the total energy increases as a result of the increased demand for battery heating but also because of the lower efficiency of the chargers if the charger is operated at low powers.

3.2 Nissan Leaf, 2020

This section describes the laboratory measurements of Nissan Leaf. The car selected for the testing was produced in 2020. This car represents modern compact cars or small family cars in the Nordic countries. The car has energy ratings at the low end of the scale, making it a very efficient alternative. The car is equipped with a battery heater and a direct electric space heater that can be operated prior to driving. The car details are listed as:

- Manufacturer: Nissan
- Model: Leaf 62 kWh
- Production year: 2020
- Class: Compact car / Small family car (C)
- Layout: Front-motor, front-wheel-drive

- Battery size: 62 kWh lithium-ion battery
- Range: 364 km (EPA)
- Charger: 1-phase charger 20 kW

The testing cycle begins with testing in the reference conditions at the ambient temperature of 20 °C. The car battery is discharged to the 70% SoC by operating the car on the four-wheel drive dynamometer according to the WLTP test cycle until the target SoC level is achieved. The car is then plugged into the charger and charged with no delay to the 100% SoC.

The tests at 0 °C, -10 °C, and -20 °C include a preheating cycle prior to the discharging cycle by operating the car on the four-wheel drive dynamometer according to the WLTP cycle until the SoC decreases to level of 70%. After the driving cycle, thee car is immediately plugged into the charger and charged until the SoC reaches the target of 100%.

The last testing cycle is executed without the preheating cycle. The battery is discharged to the 70% SoC in the evening before the charging event in the following morning. The car is kept at the target temperature of -20 °C overnight. In the morning, the car is plugged into the charger and charged until the battery reaches 100% SoC.

3.2.1 Reference test at 20 °C

Figure 14 shows the power curve of Nissan Leaf in the charging event under the reference operating conditions. The total energy of the charging event is 20.3 kWh. The charging begins with the rated power and continues at the full power until the last few minutes of the charging event. The battery charging power is modest compared with the battery capacity, and therefore, the battery cell voltages reach the maximum allowed values only at the very end of the charging event. The battery charging power continues to decrease steadily until the charging event is terminated at the 100% SoC.

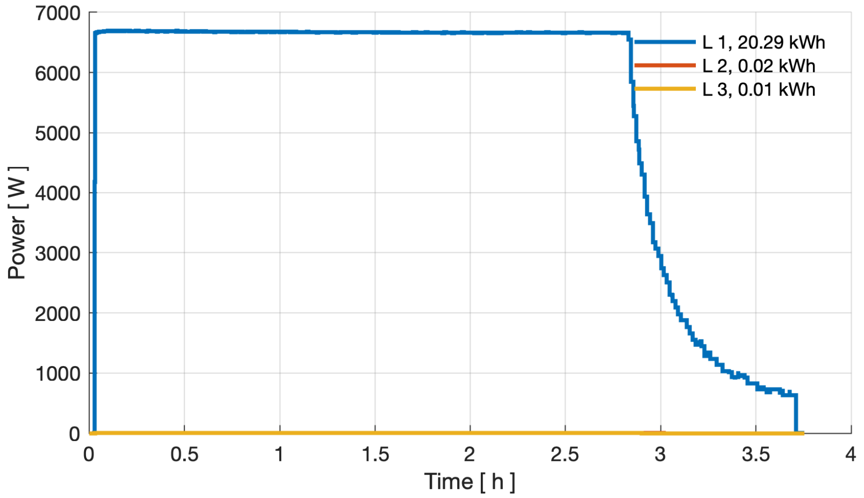

Figure 14: Power curve of three phases at 20 °C ambient temperature in the Nissan charging test.

3.2.2 Charging at 0 °C

Figure 15 shows the power curve of the preheating event under the 0 °C operating conditions. The total energy of the preheating event is 0.7 kWh. The car draws power only from a single phase to heat up the cabin. The preheating event begins with a power of 1.4 kW and varies between 1.0 and 1.7 kW.

The car was kept plugged in the charging pole during the cooling down cycle to the target temperature before the testing begun. During the cooling down time, the car battery SoC remained at the 100% SoC.

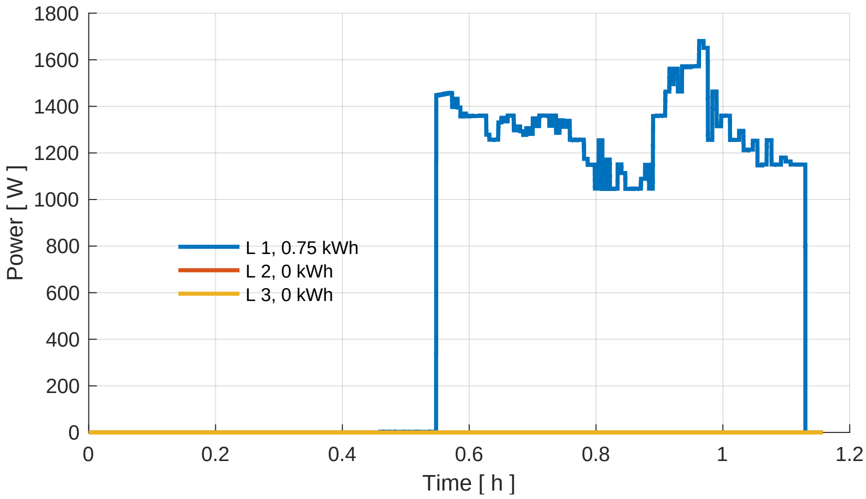

Figure 15: Power curve of three phases at 0 °C ambient temperature in the Nissan preheating test.

Figure 16 shows the power curve of the charging event event under the 0 °C operating conditions. The total energy of the charging event is 17.8 kWh. The charging begins with the rated power and remains at the full power until the last quarter of the charging event. At the end of the charging event, the battery cell voltages reach the maximum allowed value, and the charging current is reduced to avoid overvoltages on the cells. At the end of the charging event, the battery charging power decreases earlier than in the reference operating environment case. The observed charging time is similar to the reference environment test case, but the total charging energy has decreased by a few kilowatts. The decrease in the total energy could be a result of an SoC estimation error or intended operation of the car's battery management system (BMS). The SoC was observed to be at 70% before the charging event and full at the end of the charging event. At the end of the charging event, the car stopped charging for a while and continued to charge for a few minutes with a low power.

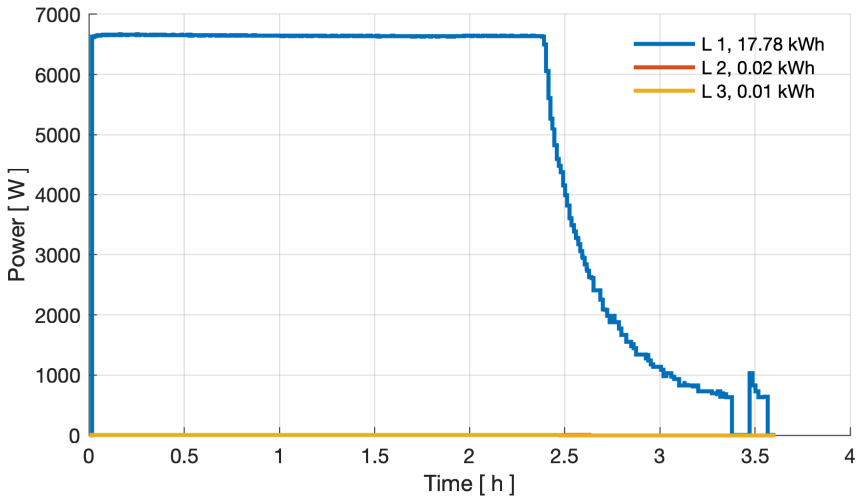

Figure 16: Power curve of three phases at 0 °C ambient temperature in the Nissan charging test.

3.2.3 Charging at -10 °C

Figure 17 shows the power curve of the preheating event in the -10 °C operating conditions. The total energy of the preheating event is 3.1 kWh. The preheating energy quadrupled compared with the -0 °C testing. The power draw over the preheating cycle is less volatile and has a slightly decreasing trend.

The car was kept plugged in the charging pole during the cooling down cycle to the target temperature before the testing begun. During the cooling down cycle, no power was consumed from the feeding grid.

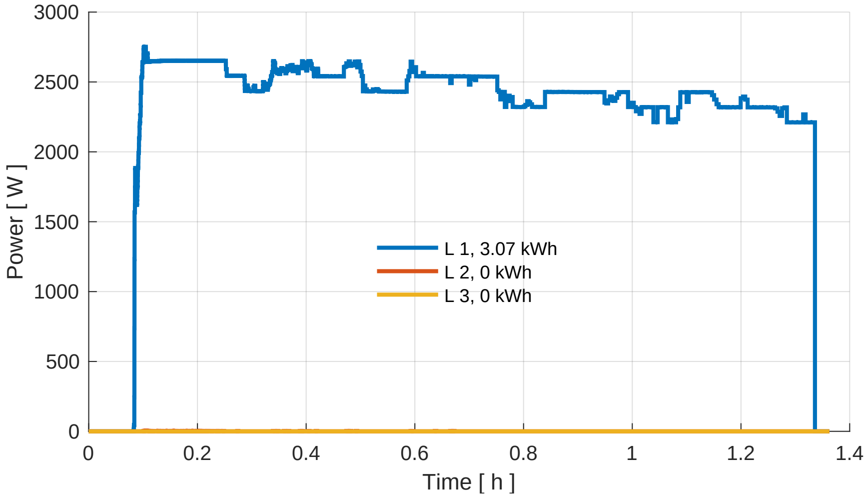

Figure 17: Power curve of three phases at -10 °C ambient temperature in the Nissan preheating test.

Figure 18 shows the power curve of the charging event event under the -10 °C operating conditions. The total energy of the charging event is 18.3 kWh. The charging begins with the rated power and continues steadily until half-way of the cycle before the power starts to decrease. The battery charging power decreases significantly more than in the reference operating environment case and in the -0 °C charging test case. The charging time is approximately 25% longer than in the reference charging conditions at 20 °C ambient temperature. At the end of the charging event, the charging power is intermittent cycling at power and idle states in every few minutes.

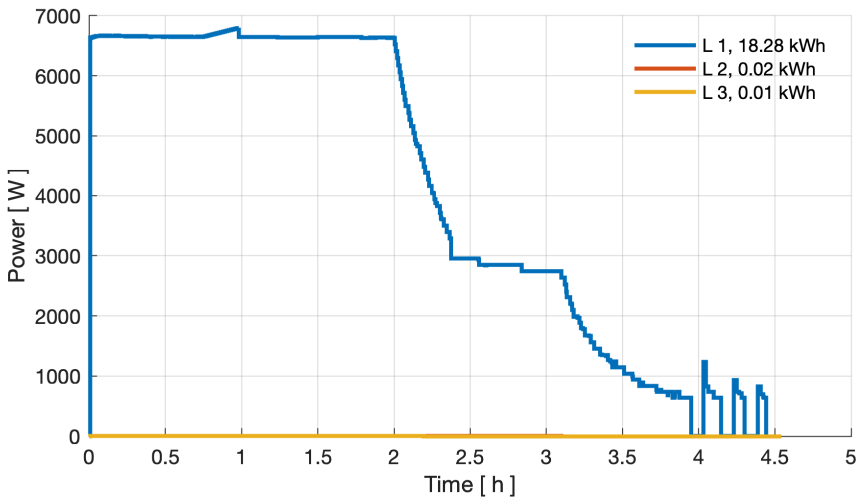

Figure 18: Power curve of three phases at -10 °C ambient temperature in the Nissan charging test.

3.2.4 Charging at -20 °C

Figure 19 shows the power curve of the preheating event in the -20 °C operating conditions. The total energy of the preheating event is 3.1 kWh. The preheating energy increased significantly compared with the -0 °C testing. The power draw over the preheating cycle is less volatile and and has a slightly increasing trend. The -10 °C testing case showed a decreasing power trend for preheating.

The car was kept plugged in the charging pole during the cooling down cycle to the target temperature before the testing begun. During the cooling down cycle, no power was consumed from the feeding grid.

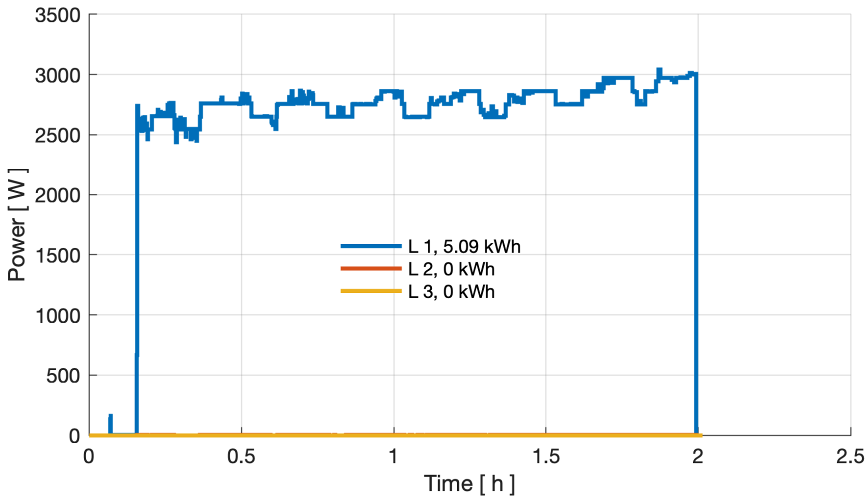

Figure 19: Power curve of three phases at -20 °C ambient temperature in the Nissan preheating test.

Figure 20 shows the power curve of the charging event event under the -20 °C ambient temperature operating conditions. The total energy of the charging event is 15.3 kWh. The charging begins with the rated power, but starts to decrease very soon. The battery charging power decreases significantly more than in the reference operating environment case and in the -0 °C charging test case. The charging time is approximately 25% longer than in the reference charging conditions at 20 °C ambient temperature. According to the infotainment system of the car, the SoC is 100%, but the total charging energy gives a better idea of how much energy is stored in the battery. It seems that the Nissan SoC estimation cannot make temperature corrections for the displayed SoC. This judgment is based on only data measured from the charger and observations logged from the infotainment system. After the charging test, it was also observed that when the car was operated at the four-wheel drive dynamometer, the SoC displayed by the infotainment system dropped rapidly to 92%.

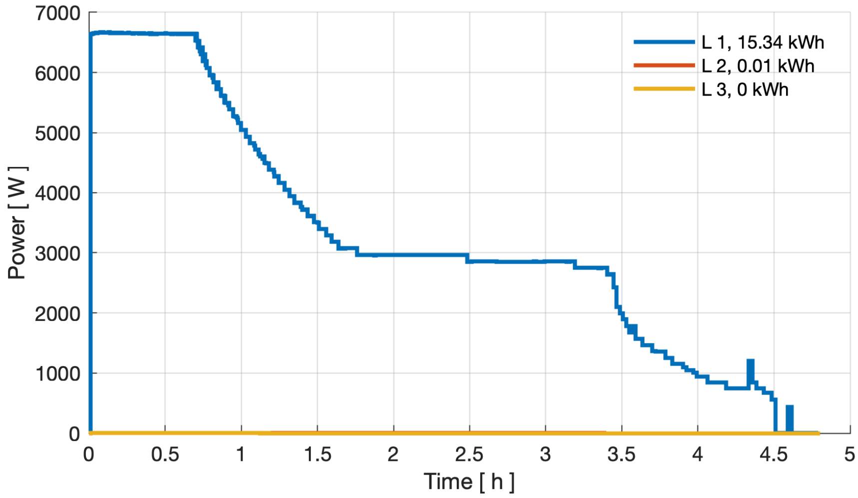

Figure 20: Power curve of three phases at -20 °C ambient temperature in the Nissan charging test.

3.2.5 Charging at -20 °C after cold storage

The last charging test deviates from the previous tests as the car was left at -20 °C overnight with the battery discharged to the 70% SoC. The SoC was observed to remain at 70% overnight according to the on-board information system of the car. The charging event was initialized without a preheating sequence at the beginning. Figure 21 shows the charging power curve of three phases. The charging event begins with the rated power and starts to decrease very soon after the beginning of the charging cycle. The charging profile is very similar to the previous tests. The total energy of the charging event is 15.6 kWh. The total energy of the charging event suggests that the battery is not full after the termination of the charging event. The charging time increased considerably as the car continued to draw a low power of approximately 1 kW for a long period of time until the charging event was manually terminated. The car reported a SoC of 98% at the end of the event.

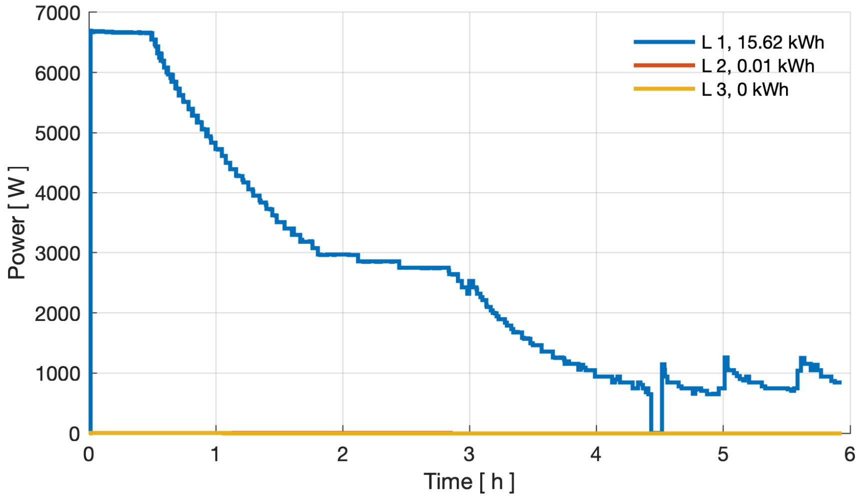

Figure 21: Power curve of three phases at -20 °C ambient temperature after overnight parking at the 70% SoC in the Nissan charging test.

3.2.6 General notes and observations

The charging test of Nissan Leaf showed that the preheating energy is highly dependent on the ambient temperature, but the charging energy seems to have a negative correlation with the ambient temperature. The total charging energy decreased, but the decrease was mostly explained by the SoC estimation and the battery characteristics at cold temperatures. In practice, the car battery is not fully charged at cold temperatures.

3.3 Volkswagen ID.3, 2020

This section describes the laboratory measurements of Volkswagen ID.3. The car selected for the testing was produced in 2020. This model represents modern compact cars or small family cars in the Nordic countries. The car has energy ratings at the low end of the scale, making it a very efficient alternative. The car is equipped with a 5.5 kW battery heater and a 6 kW heat pump space heater that can be operated prior to driving. The car details are listed as:

- Manufacturer: Volkswagen
- Model: ID.3
- Production year: 2020
- Class: Compact car / Small family car (C)
- Layout: Front-motor, front-wheel-drive
- Battery size: 62 kWh lithium-ion battery
- Range: 364 km (EPA)
- Equipped with a heat pump

The testing cycle begins with the reference condition testing at the ambient temperature of 20 °C.

The car battery is discharged to the 60% SoC by operating the car on the four-wheel drive dynamometer according to the WLTP test cycle until the target SoC level is achieved. The car is then plugged into the charger with no delay and charged to the 80% SoC. The SoC 80% value is suggested by the manufacturer to keep the battery performance at the optimum level over the designed lifetime of the car. It was assumed that the consumers follow the manufacturer's recommendations, and, therefore, the assumption should be the best representation of the real-life operating conditions. The discharge level of 60% was chosen to increase the energy content of the charging event in order to make the results more comparable with the tests conducted with the other cars.

The tests at 0 °C, -10 °C, and -20 °C include a preheating cycle prior to discharging by operating the car on the four-wheel drive dynamometer according to the WLTP cycle until the SoC decreases to the level of 60%. After the driving cycle, the car is immediately plugged into the charger and charged until the SoC reaches the target of 80%.

The last testing cycle is executed without the preheating cycle. The battery is discharged to the 60% SoC in the evening before the charging event in the following morning. The car is kept at the target temperature of -20 °C overnight. In the morning, the car is plugged in the charger and charged until the battery reaches the 80% SoC.

3.3.1 Reference test at 20 °C

Figure 22 shows the power curve of the Volkswagen ID.3 charging event under the reference operating conditions. The total energy of the charging event is 13.0 kWh. The charging begins with the rated power and remains unchanged until the end of the charging event. The battery charging power is modest compared with the battery capacity, and further, the battery is only charged to the 80% SoC. Therefore, the battery cell voltages do not reach the maximum allowed value, and the power remains unchanged over the whole charging cycle.

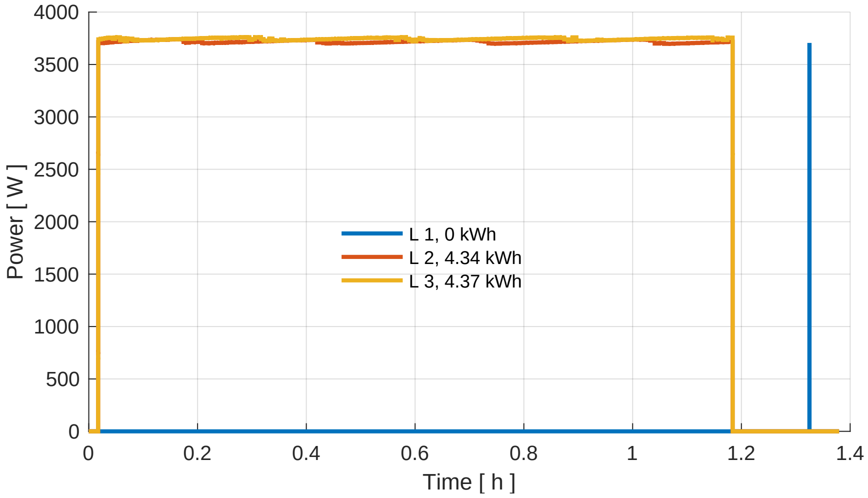

Figure 22: Power curve of three phases at 20 °C ambient temperature in the Volkswagen charging test.

3.3.2 Charging at 0 °C

Figure 23 shows the power curve of the preheating event under the 0 °C operating conditions. The total energy of the preheating event is 1.6 kWh. The preheating event begins with a high power of 3.5 kW from phases 1 and 2, but decreases rapidly to 2.4 kW per phase. After 10 min of operation, the car switches load to the third phase, peaking at 3.2 kW. The power decreases toward the end of the preheating event. The car was kept plugged in the charging pole during the cooling down to the target temperature before the preheating cycle. During the cooling time, the car battery SoC remained at the 80% SoC.

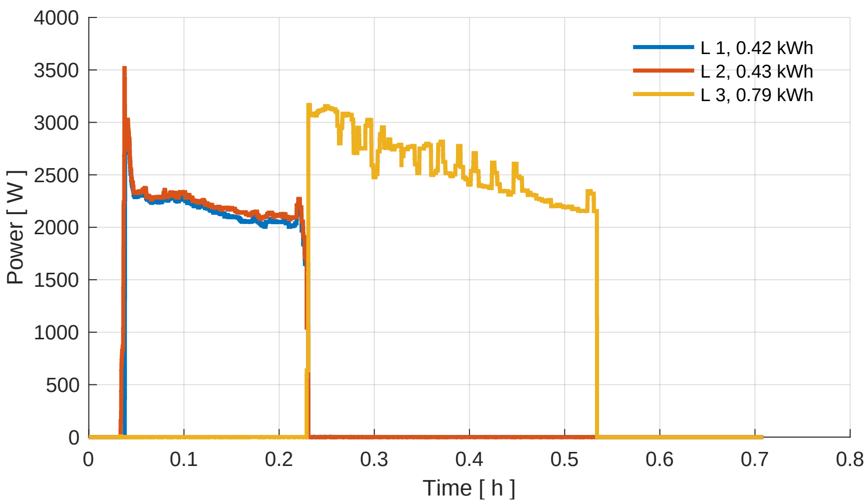

Figure 23: Power curve of three phases at 0 °C ambient temperature in the Volkswagen preheating test.

Figure 24 shows the power curve of the charging event event under the 0 °C ambient temperature operating conditions. The total energy of the charging event is 12.4 kWh. The charging event is very similar to the test conducted at the reference operating temperature of 20 °C.

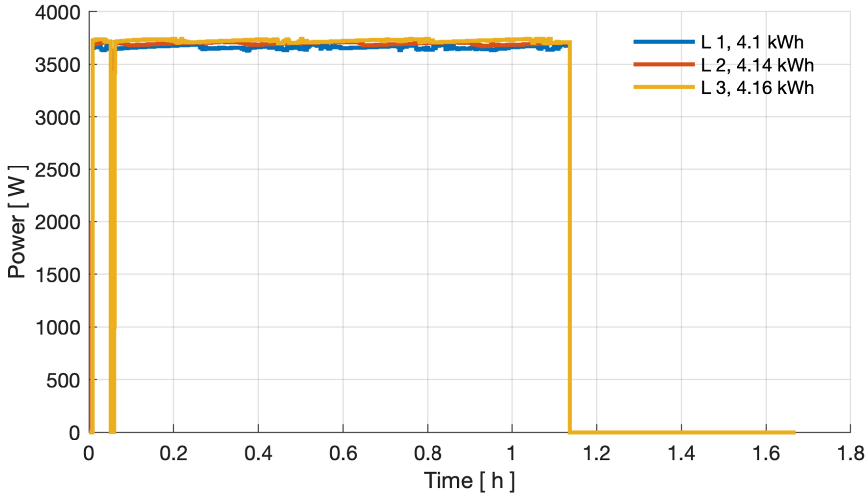

Figure 24: Power curve of three phases at 0 °C ambient temperature in the Volkswagen charging test.

3.3.3 Charging at -10 °C

Figure 25 shows the power curve of the preheating event in the -10 °C operating conditions. The total energy of the preheating event is 2.9 kWh. Similar to the previous test, the car switches load between phases, but instead of idling one phase at the beginning, the car keeps about a 2.4 kW load on all phases for over approx. 20 min. In the last part of the preheating cycle, the car uses only two phases while the load slowly decreases toward the end of the cycle.

The car was kept plugged in the charging pole during the cooling down to the target temperature before the testing begun. During the cooling down, no power was consumed from the feeding grid.

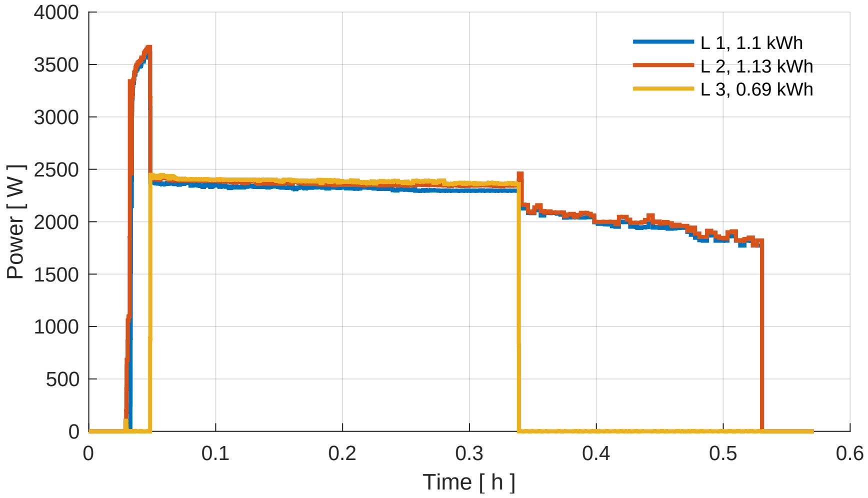

Figure 25: Power curve of three phases at -10 °C ambient temperature in the Volkswagen preheating test.

Figure 26 shows the power curve of the charging event event under the -10 °C ambient temperature operating conditions. The total energy of the charging event is 12.6 kWh. The charging event is very similar to the test conducted at the reference operating temperature of 20 °C. There are no signs that the 30 °C drop in the ambient temperate would affect either the charging power or the charging time.

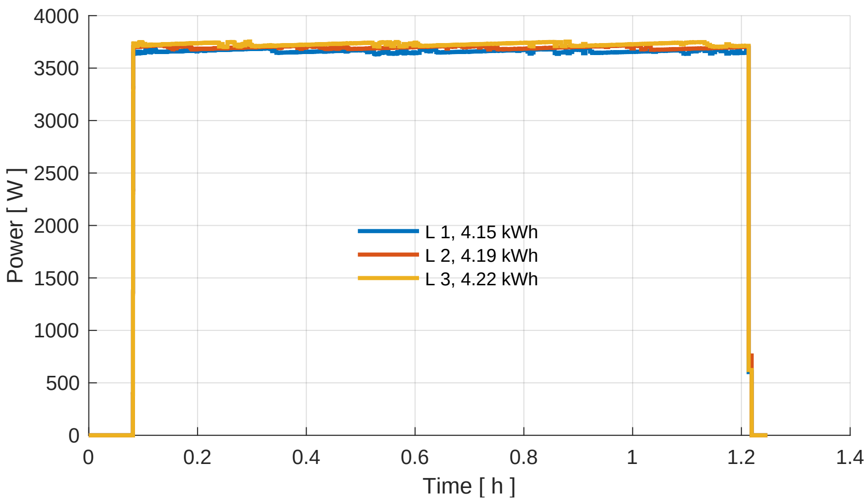

Figure 26: Power curve of three phases at -10 °C ambient temperature in the Volkswagen charging test.

3.3.4 Charging at -20 °C

Figure 27 shows the power curve of the preheating event in the -20 °C operating conditions. The total energy of the preheating event is 2.4 kWh. Once again, similar to the previous test, the car does not use phases symmetrically. Almost over the whole event, only phases 1 and 2 are used. The power remains nearly unchanged over the preheating cycle. There is no significant increase in the energy demand compared with the previous tests.

The car was kept plugged in the charging pole during the cooling down to the target temperature before the testing begun. During the cooling down, no power was consumed from the feeding grid.

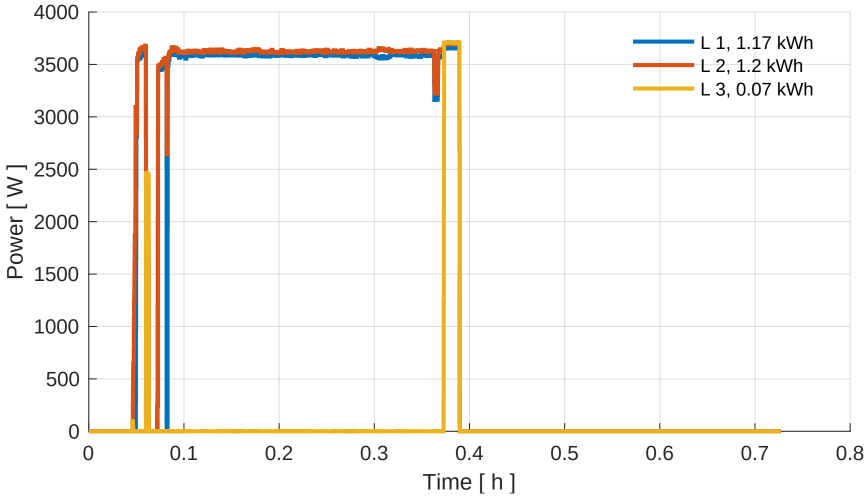

Figure 27: Power curve of three phases at -20 °C ambient temperature in the Volkswagen preheating test.

Figure 28 shows the power curve of the charging event event under the 20 °C operating conditions. The total energy of the charging event is 12.6 kWh. Even in the low-temperature charging test, the car is able to maintain the reference charging power over the full charging test cycle. There is no noticeable increase in either charging or charging time.

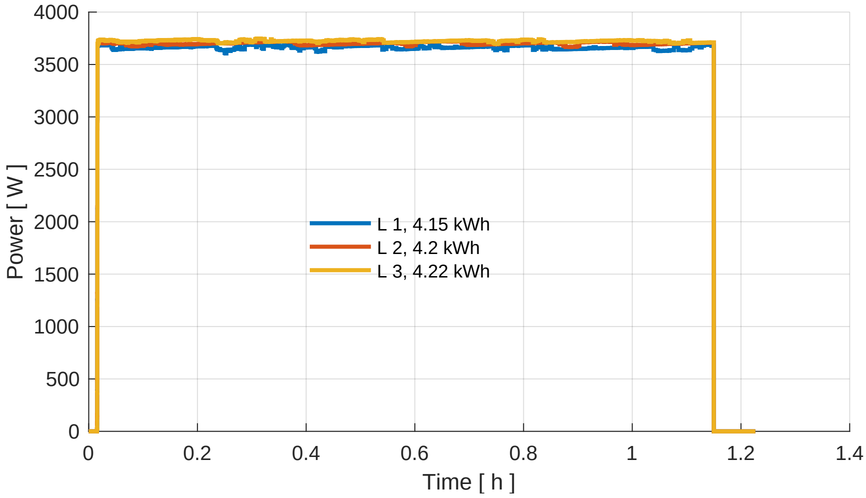

Figure 28: Power curve of three phases at -20 °C ambient temperature in the Volkswagen charging test.

3.3.5 Charging at -20 °C after cold storage

The last charging test deviates from the previous tests as the car was left at -20°C overnight with the battery discharged to the 60% SoC. The SoC was observed to remain at 60% overnight according to the on-board information system of the car. The charging event was initialized without a preheating sequence at the beginning. Figure 29 shows the charging power curve of three phases. Volkswagen's charging behavior remains predictable with minor changes when the temperature decreases even as low as to -20 °C. At the beginning of the charging event, it is likely that the battery heater is enabled. The total energy content of the cycle is 2.5 kWh higher compared with the previous test cycles, the total energy being 15.0 kWh. It is noteworthy that there is a substantial energy impact caused by the battery heating prior to charging of the battery.

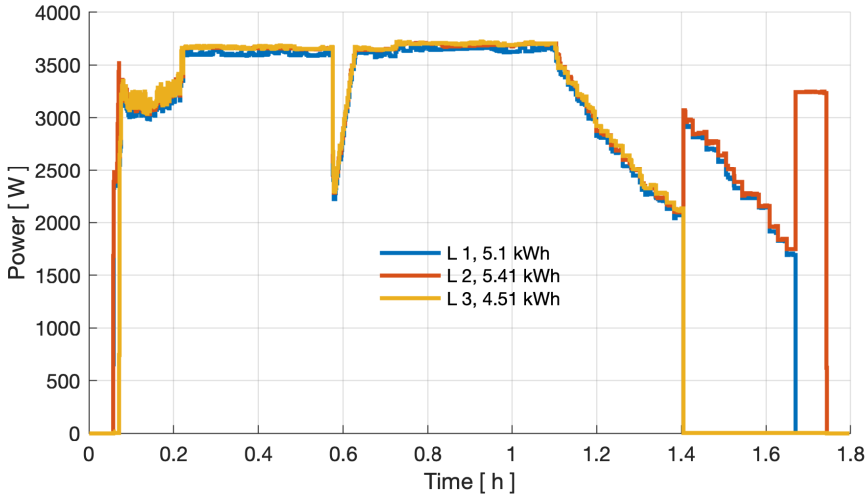

Figure 29: Power curve of three phases at -20 °C ambient temperature after overnight parking at the 60% SoC in the Volkswagen charging test.

3.3.6 General notes and observations

The testing series of the Volkswagen ID.3 charging shows that charging is not heavily impacted by the ambient temperature. Only deviations in the behavior were observed after the car was left unplugged at -20 °C ambient temperature with a partially discharged battery. The car's battery heater was operated over preheating cycles, and thus, the car had a preheated battery prior to the driving cycle. During the driving cycle, the battery temperature was observed to increase even more. As soon as the battery charging started after the driving cycle, the battery temperature was close to ideal charging temperatures, and thus, the ambient temperature had only a minor impact on the Volkswagen ID.3 charging behavior. Further, in the case where the car was left unplugged in a cold environment, the battery heater was able to efficiently heat up the battery to charging temperatures.

3.4 Kia e-Niro, 2020

This section describes the laboratory measurements of KIA e-Niro. The car selected for the testing was produced in 2020. This model represents modern compact cars or small family cars in the Nordic countries. The car has energy ratings at the low end of the scale, making it a very efficient alternative. The car is equipped with a battery heater and a direct electric space heater that can be operated prior to driving. The car details are listed as:

- Manufacturer: Kia
- Model: e-Niro 64 kWh
- Production year: 2020
- Class: Compact car / Small family car (C)
- Layout: Front-motor, front-wheel-drive

- Battery size: 64 kWh lithium-ion battery
- Range: 455 km (WLTP)

The testing cycle begins with the reference condition testing at the ambient temperature of 20 °C. The car battery is discharged to the 70% SoC by operating the car on the four-wheel drive dynamometer according to the WLTP test cycle until the target SoC level is achieved. The car is then plugged into the charger with no delay and charged to the 100% SoC.

The tests at 0 °C, -10 °C, and -20 °C include a preheating cycle prior to discharging by operating the car on the four-wheel drive dynamometer according to the WLTP cycle until the SoC decreases to the level of 70%. After the driving cycle, the car is immediately plugged into the charger and charged until the SoC reaches the target of 100%.

The last testing cycle is executed without preheating. The battery is discharged to the 70% SoC in the evening before charging in the following morning. The car is kept at the target temperature of -20 °C overnight. In the morning, the car is plugged into the charger and charged until the battery reaches the 100% SoC.

3.4.1 Reference test at 20 °C

Figure 30 shows the power curve of the Kia e-Niro charging event under the reference operating conditions. The total energy of the charging event is 23.3 kWh. The charging begins with the rated power and continues at the full power until the last few minutes of the charging event. The battery charging power is modest compared with the battery capacity, and thus, the battery cell voltages reach the maximum allowed value only at the very end of the charging event. The battery charging power continues to decrease steadily until the charging event is terminated at the 100% SoC.

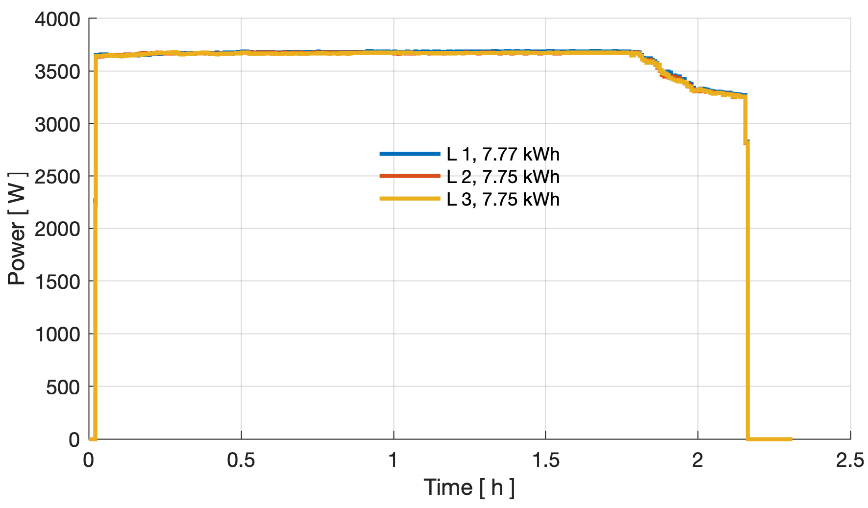

Figure 30: Power curve of three phases at 20 °C ambient temperature in the Kia charging test.

3.4.2 Charging at 0 °C

Figure 31 shows the power curve of the preheating event under the 0 °C operating conditions. The total energy of the preheating event is 1.4 kWh. The car uses three phases symmetrically to heat up the cabin. The preheating event begins with a high power of 3.3 kW but decreases rapidly to less than 1 kW per phase. During the testing it was unclear what the target temperature of the preheating was as the infotainment system of the car did not allow setting up the target temperature.

The car was kept plugged in the charging pole during the cooling down cycle to the target temperature before the testing begun. During the cooling time, the car battery SoC remained at the 100% SoC.

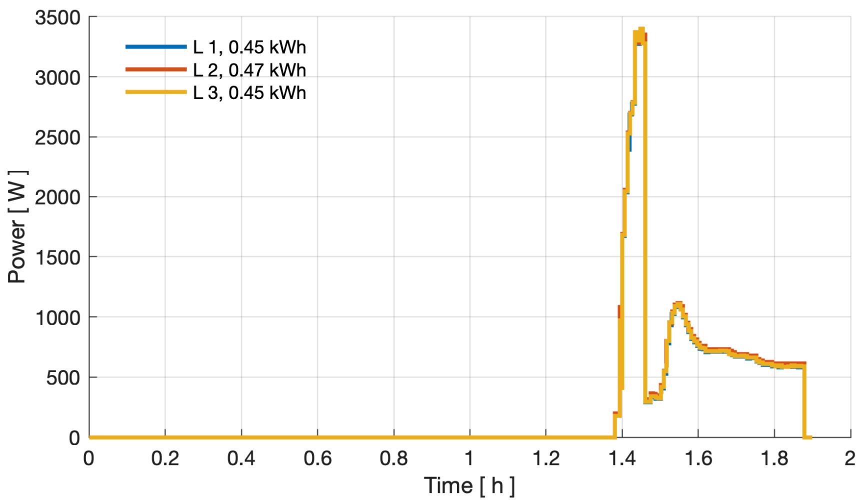

Figure 31: Power curve of three phases at 0 °C ambient temperature in the Kia preheating test.

Figure 32 shows the power curve of the charging event event under the 0 °C operating conditions. The total energy of the charging even is 23.0 kWh. The charging begins with the rated power and keeps charging at the full power until the last fifth of the charging event. At the end of the charging event, the battery cell voltages reach the maximum allowed values, and the charging current is decreased to avoid overvoltages on cells. At the end of the charging event, the battery charging power decreases slightly more than in the reference operating environment case. This change is minor and has virtually no impact on the total charging time or the total charging energy.

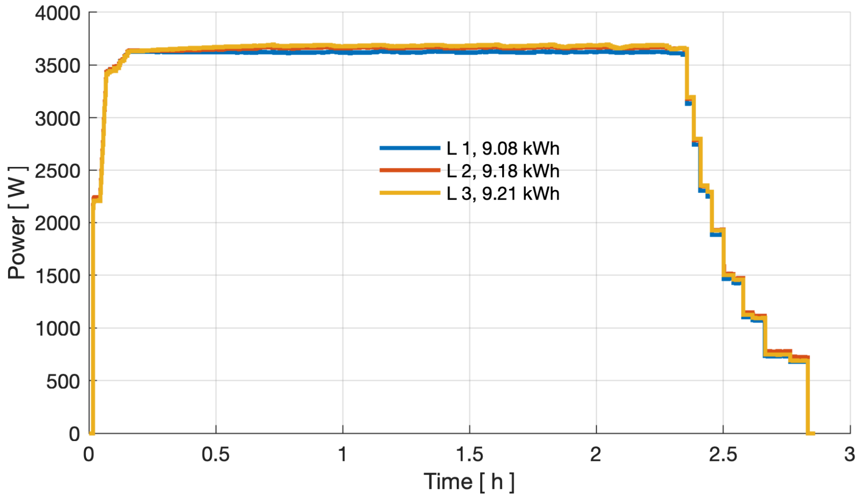

Figure 32: Power curve of three phases at 0 °C ambient temperature in the Kia charging test.

3.4.3 Charging at -10 °C

Figure 33 shows the power curve of the preheating event in the -10 °C operating conditions. The total energy of the preheating event is 0.5 kWh.

The car was kept plugged in the charging pole during the cooling down cycle to the target temperature before the testing begun. During the cooling down cycle, no power was consumed from the feeding grid.

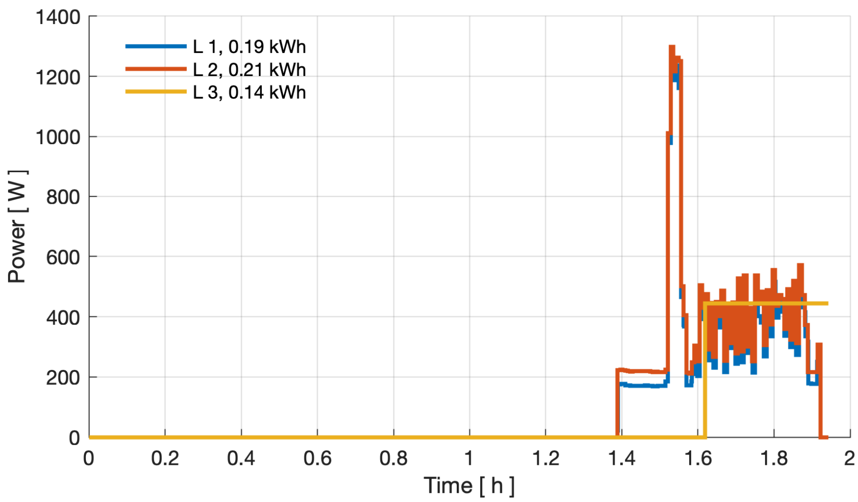

Figure 33: Power curve of three phases at -10 °C ambient temperature in the Kia preheating test.

Figure 34 shows the power curve of the charging event event under the -10 °C ambient temperature operating conditions. The total energy of the charging event is 25.5 kWh. The charging begins with the rated power and continues steadily until near the end of the charging event before the power begins to decrease. The battery charging power decreases more than in the reference operating environment case, but is very similar to the -0 °C charging test. The charging time is approximately 20% longer than in the reference charging conditions at 20 °C ambient temperature.

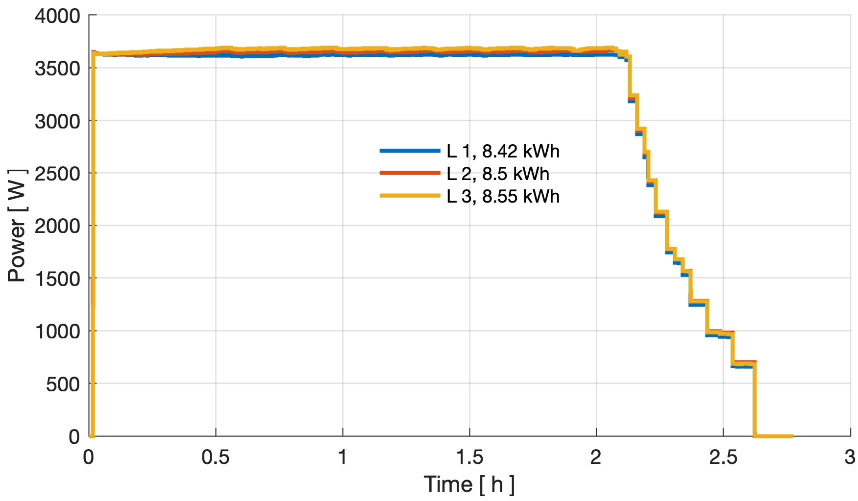

Figure 34: Power curve of three phases at -10 °C ambient temperature in the Kia charging test.

3.4.4 Charging at -20 °C

Figure 35 shows the power curve of the preheating event in the -20 °C operating conditions. The total energy of the preheating event is 2.5 kWh.

The car was kept plugged in the charging pole during the cooling down cycle to the target temperature before the testing begun. During the cooling down cycle, no power was consumed from the feeding grid.

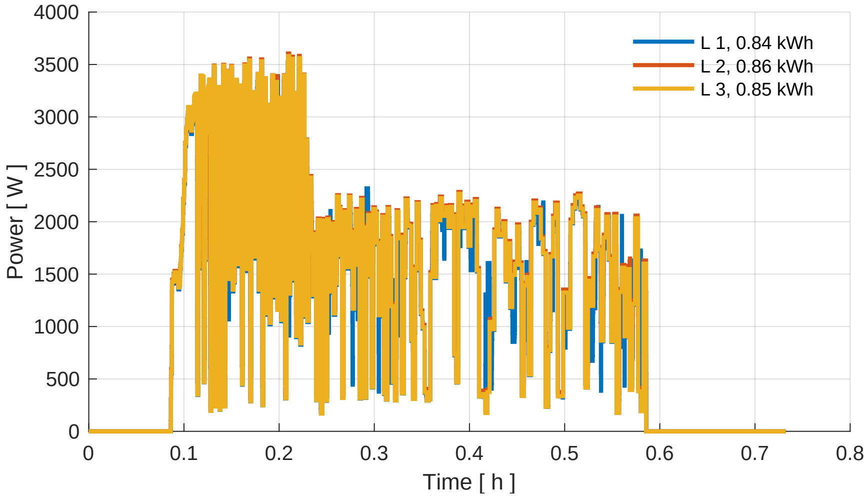

Figure 35: Power curve of three phases at -20 °C ambient temperature in the Kia preheating test.

Figure 36 shows the power curve of the charging event event under the 20 °C ambient temperature operating conditions. The total energy of the charging event is 24.3 kWh. The charging begins with the rated power and continues steadily until near the end of the charging event before the power begins to decrease. The battery charging power decreases more than in the reference operating environment case, but is very similar to the -0 °C charging test. The charging time is approximately 20% longer than in the reference charging conditions at 20 °C ambient temperature.

Kia's charging behavior remains predictable with minor changes when the temperature decreases even as low as to -20 °C. It is also noteworthy that there are no major energy impacts caused by the battery heating prior to charging the battery.

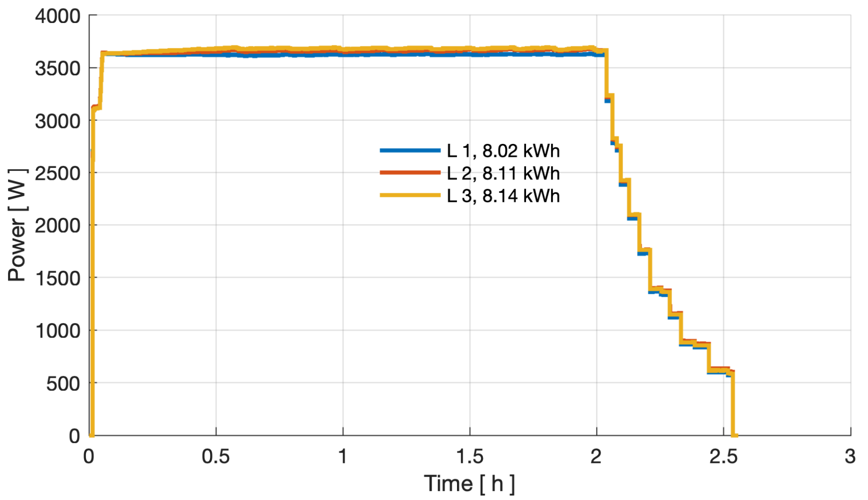

Figure 36: Power curve of three phases at -20 °C ambient temperature in the Kia charging test.

3.4.5 Charging at -20 °C after cold storage

The last charging test deviates from the previous tests as the car was left at -20°C overnight with the battery discharged to the 70% SoC. The SoC was observed to remain at 70% overnight according to the on-board information system of the car. The charging event was initialized without a preheating sequence at the beginning. Figure 37 shows the charging power curve of three phases. The charging event begins with a slightly decreased power but reaches the rated charging power in a few minutes. The charging profile is very similar to the previous tests. The total energy of the charging event is 27.5 kWh, approximately 3 kWh higher than in the previous tests. Further, the charging time increased approximately by 30% compared with the reference operating environment test at 20 °C ambient temperature.

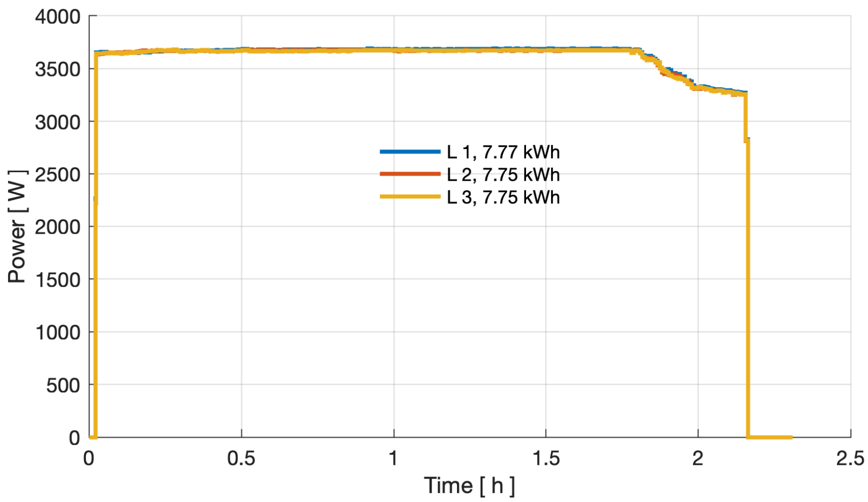

Figure 37: Power curve of three phases at -20 °C ambient temperature after overnight parking at the 70% SoC in the Kia charging test.

3.4.6 General notes and observations

The testing series of the Kia e-Niro charging shows that charging is not heavily impacted by the ambient temperature. The total charging energy increased roughly by 10% when the temperature decreased to -20 °C. The increase in charging time was more notable, about +20%, in the charging event after the preheating and driving cycle at -20 °C and +30% at the charging event after cold storage overnight.

3.5 Volvo V60 T6, 2020

This section describes the laboratory measurements of Volvo V60 T6 Recharge. The car selected for the testing was produced in 2020. This model represents modern family plug-in hybrids in the Nordic countries. The car has a typical electric range seen in many other plug-in hybrids. The car details are listed as:

- Manufacturer: Volvo
- Model: V60 T6 Recharge
- Production year: 2020
- Class: Compact executive car / Family car (D)
- Layout: Front-motor, four-wheel-drive
- Battery size: 11.6 kWh lithium-ion battery
- Range: 55 km (NECD)
- Petrol-operated preheating

The testing cycle begins with the reference condition testing at the ambient temperature of 20 °C. The testing routine differs from the battery electric vehicle (BEV) testing as the battery capacity of the PHEV car is much smaller, and thus, it is likely to be fully utilized in daily driving. The BEV testing routine has an assumption that the battery would be drained to the 70 % SoC. For the PHEV testing, it is assumed that the battery is fully drained after the driving cycle.

The tests at 0 °C, -10 °C, and -20 °C include a preheating cycle prior to discharging by operating the car on the four-wheel dynamometer according to the WLTP cycle until the SoC decreases to the level of 0%. After the driving cycle, the car is immediately plugged into the charger and charged until the SoC reaches the target of 100%.

The last testing cycle is executed without the preheating cycle. The battery is discharged to the 0% SoC in the evening before charging in the following morning. The car is kept at the target temperature of -20 °C overnight. In the morning, the car is plugged into the charger and charged until the battery reaches the 100% SoC.

3.5.1 Reference test at 20 °C

Figure 38 shows the power curve of the Volvo V60 T6 Recharge charging event under the reference operating conditions. The total energy of the charging event is 10.3 kWh. The charging begins with the rated power and continues at the full power until near the end of the charging event before the power starts to decrease. Further, typical to the PHEV is that the charging power is drawn from a single phase as shown in the case of the present testing routine.

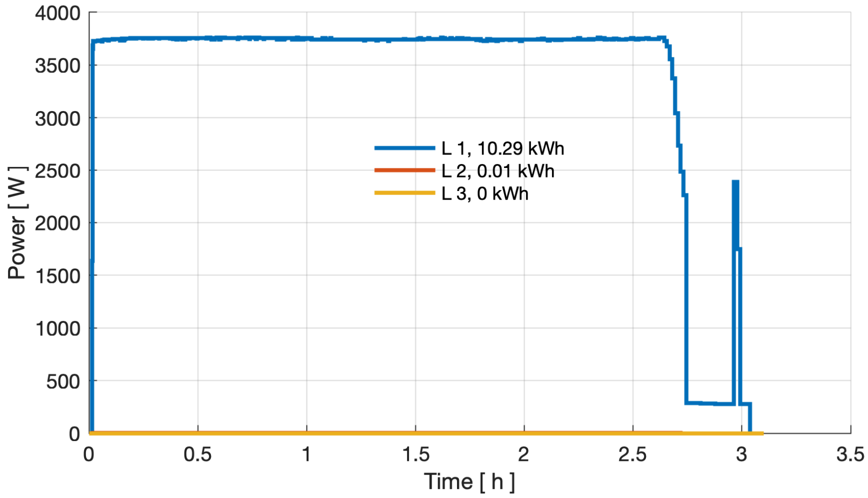

Figure 38: Power curve of three phases at 20 °C ambient temperature in the Volvo charging test.

3.5.2 Charging at 0 °C

Figure 39 shows the power curve of the preheating event under the 0 °C operating conditions. The total energy of the preheating event is 0.3 kWh. The preheating event begins with the single-phase power of 1 kW, but decreases rapidly to 0.4 kW. The power consumed by the car is mostly used to cover the consumption of auxiliary devices during the preheating cycle of the petrol-operated auxiliary heater. The car was kept plugged in the charging pole during cooling down to the target temperature before the preheating cycle. During the cooling time, the car battery SoC remained at the 0% SoC.

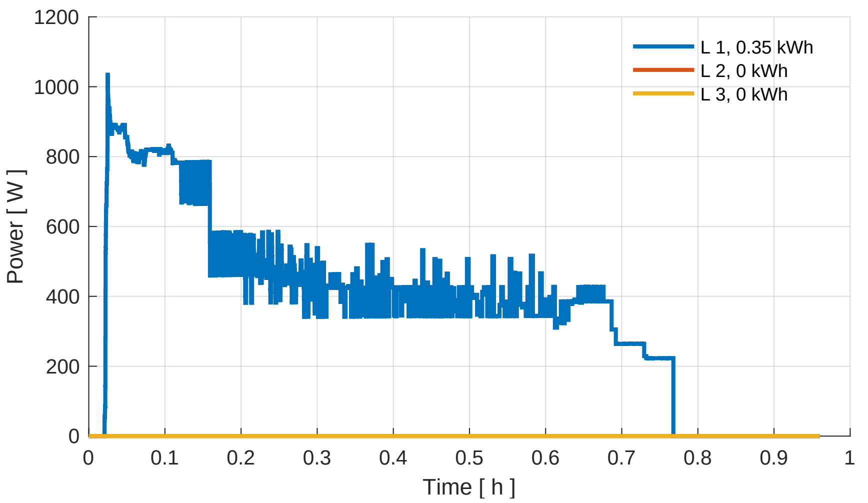

Figure 39: Power curve of three phases at -0 °C ambient temperature in the Volvo preheating test.

The car was kept plugged in the charging pole during the cooling down cycle to the target temperature before the testing begun. During the cooling time, the car battery SoC remained at the 100% SoC. Figure 40 shows the power curve of the charging event event under the 0 °C ambient temperature operating conditions. The total energy of the charging event is 10.2 kWh. The charging event is very similar to the test conducted at the reference operating temperature of 20 °C.

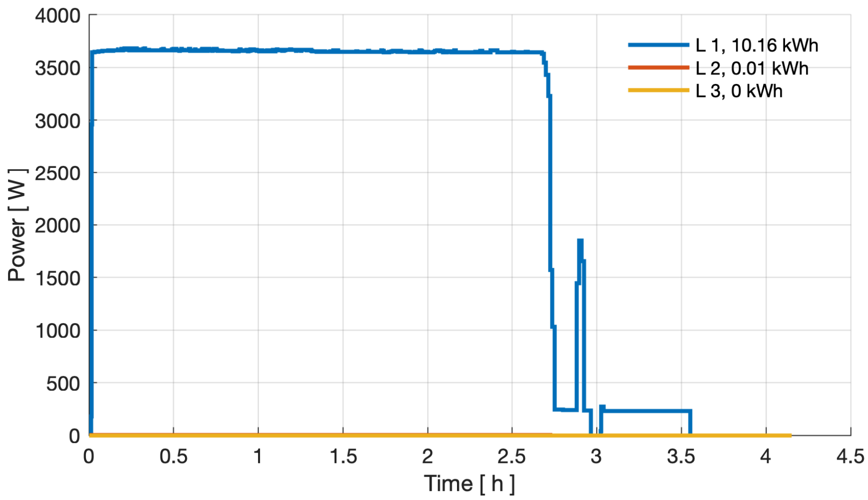

Figure 40: Power curve of three phases at -0 °C ambient temperature in the Volvo charging test.

3.5.3 Charging at -10 °C

Figure 41 shows the power curve of the preheating event in the -10 °C operating conditions. The total energy of the preheating event is 0.5 kWh. The car preheating was triggered multiple times before the actual heating cycle started. The start of the preheating can be spotted in Figure 41 at the 1.1 h mark. The power demand curve is very similar to the previous test. The car was kept plugged in the charging pole during cooling down to the target temperature before testing. During cooling down, no power was consumed from the feeding grid.

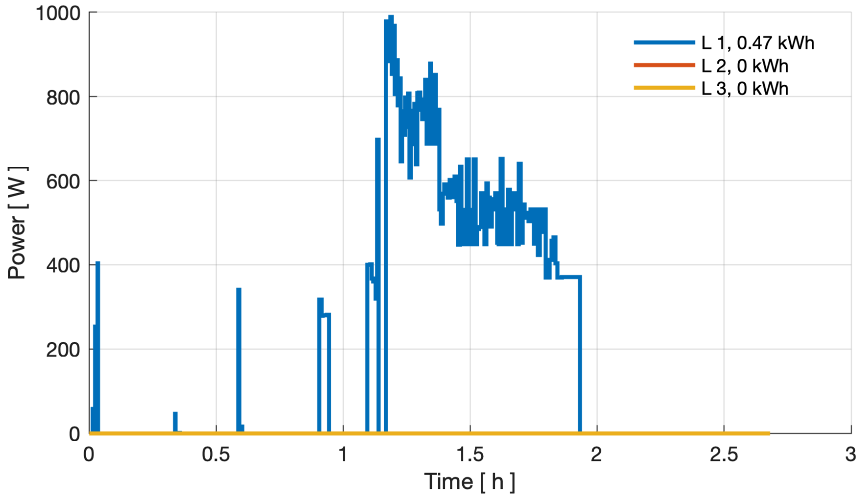

Figure 41: Power curve of three phases in -10 °C ambient temperature in the Volvo preheating test.

Figure 42 shows the power curve of the charging event event under the -10 °C ambient temperature operating conditions. The total energy of the charging event is 10.0 kWh. The charging event is very similar to the test conducted at the reference operating temperature of 20 °C. There are no signs that the 30 °C drop in the ambient temperate would have any effect on either charging power or charging time. The battery temperature had increased slightly after the driving cycle.

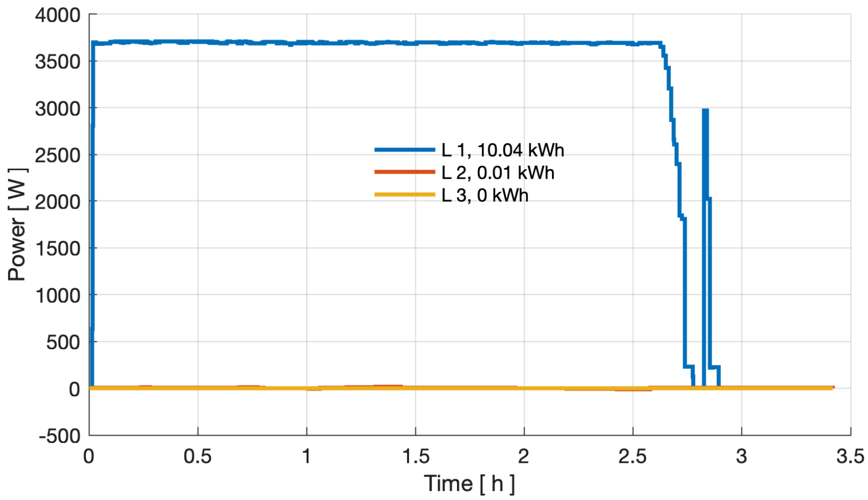

Figure 42: Power curve of three phases at -10 °C ambient temperature in the Volvo charging test.

3.5.4 Charging at -20 °C

Figure 43 shows the power curve of the preheating event in the -20 °C operating conditions. The total energy of the preheating event is 0.4 kWh. There is no increase in the energy demand compared with the previous tests.

The car was kept plugged in the charging pole during the cooling down cycle to the target temperature before the testing begun. During the cooling down cycle, no power was consumed from the feeding grid.

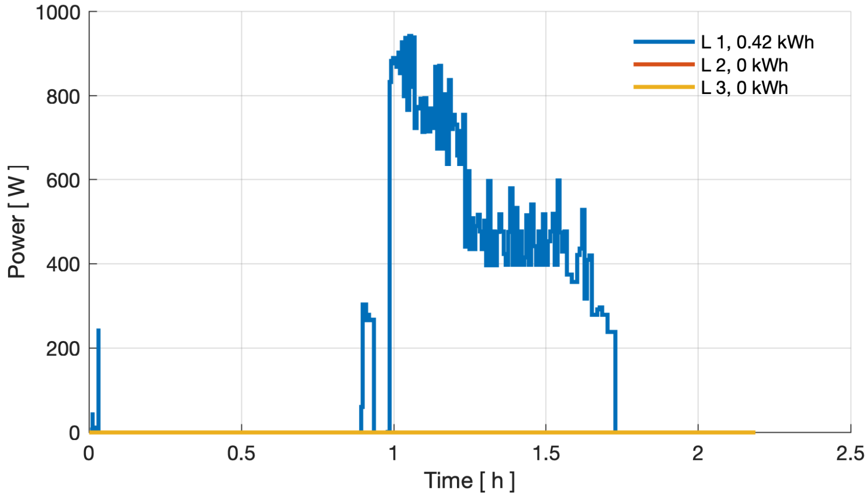

Figure 43: Power curve of three phases at -20 °C ambient temperature in the Volvo preheating test.

Figure 44 shows the power curve of the charging event event under the 20 °C ambient temperature operating conditions. The total energy of the charging event is 9.7 kWh. Even in the low-temperature charging test, the car is able to maintain the rated charging power almost over the full charging test cycle. There is no noticeable increase in either the charging or charging time. It seems that driving the car increases the battery temperature enough to enable charging at the rated power. The battery maintains the temperature over the charging period if charging is not delayed too much.

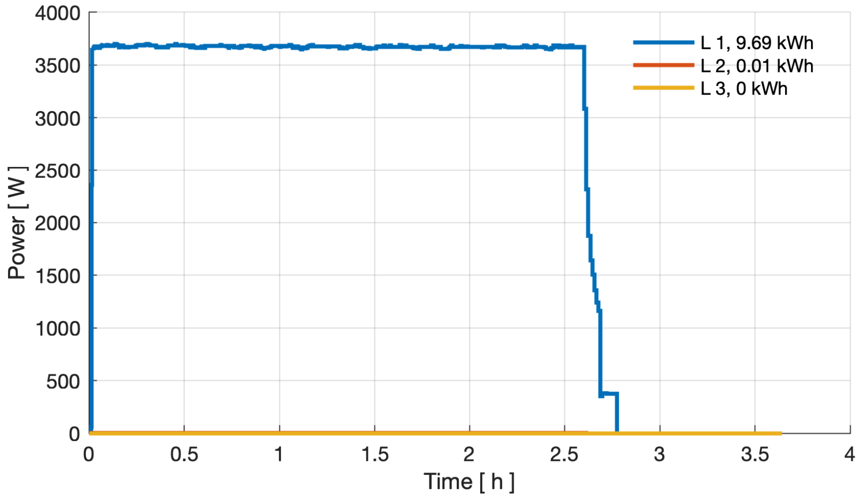

Figure 44: Power curve of three phases at -20 °C ambient temperature in the Volvo charging test.

3.5.5 Charging at -20 °C after cold storage

The last charging test deviates from the previous tests as the car was left at -20°C overnight with the battery discharged to the 0% SoC. The SoC was observed to remain at 0% overnight according to the on-board information system of the system. The charging event was initialized without a preheating sequence at the beginning. Figure 45 shows the charging power curve of three phases. The car's battery charger draws only 1 kW of power from the grid, making the charging event substantially longer. It seems that the car is still capable of charging even without the battery heater. As the charging event prolonged more than anticipated, the charging was manually terminated after 7 h. The SoC had reached 82% at the termination point. The full charging energy can be estimated by extrapolating from the termination point, and thus, the estimated full charge energy would be 7.6 kWh. Similar to Nissan Leaf, the cold-temperature battery seems to reach the full capacity earlier compared with the reference operating temperature. This is most likely due to the battery chemistry properties or the BMS. The battery temperature at the beginning of the charging was -20 °C, and at the termination point of the charging event it had increased to -10 °C.

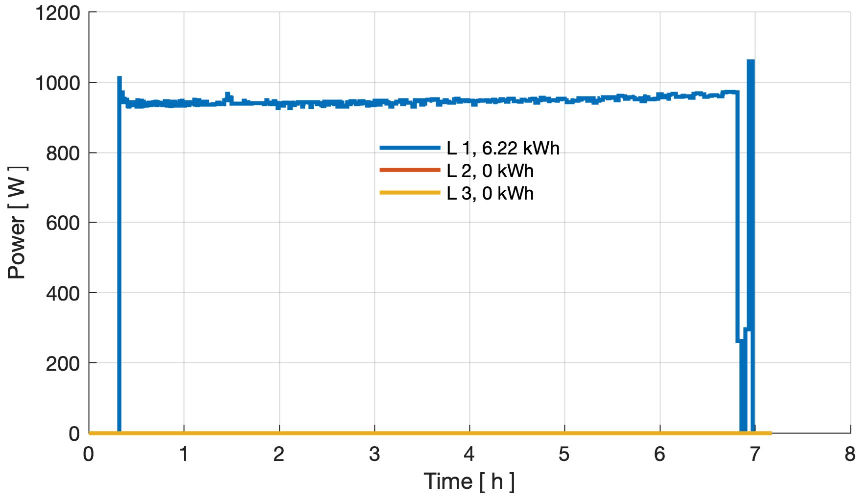

Figure 45: Power curve of three phases at -20 °C ambient temperature after overnight parking at the 0% SoC in the Volvo charging test.

3.5.6 General notes and observations

The testing series of the Volvo V60 T6 Recharge charging shows that charging is not heavily impacted by the ambient temperature if the car is charged immediately after the driving cycle. Only deviations in the behavior were observed after the car was left unplugged at -20 °C ambient temperature with the fully discharged battery. The car was not able to charge the battery with full power, and the estimation showed that the total energy content would not reach the rated capacity of the battery. It was also observed that the WLTP driving cycle is sufficient to increase the battery temperature enough to enable charging at the rated charging power. It is important to bear in mind that if the car is operated in cold conditions, it is critical that the car is charged immediately after the driving event to maintain the reference charging features.

4 Summary and conclusion

The report described testing of four EVs and one PHEV. The results show that the subambient temperature has an 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, car manufacturer's preferences in cold climate operation, battery chemistry, and probably also battery age. It is also noteworthy that the battery is likely to warm up when the car is operated, and thus, also the timing of the charging start time is a critical factor when observing the shape of the charging power curve or accumulation of the total charging energy. Especially, if smart charging applications are considered in subambient conditions, delaying or timing of the charging event plays a crucial role in scheduling and optimization of the operation.

Tables 1 and 2 summarize the total preheating and charging energies of each test. Absolute values are car-specific and should not be compared, as the reference charging energy varies according to the tested car. The relative change in charging energy varies between a 33 % increase to 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 less than it would have been in the reference operating temperature. 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.

In addition, the cars were preheated before driving. The total energy content of preheating is highly dependent of the ambient conditions, technical boundaries, and user preferences. Table 2 shows that the total energy content of preheating may be comparable with the total charging energy content. The cars equipped with heat pumps had a much lower energy impact.

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.

Car	Testing temperature				
	20 °C kWh	0 °C kWh (%)	-10 °C kWh (%)	-20 °C kWh (%)	-20 °C** kWh (%)
Tesla model S P85	15.7	15.6 (-1)	15.7 (0)	16.7 (6)	23.6 (33)
Nissan Leaf	20.3	17.8 (-14)	18.3 (-11)	15.3 (-33)	15.6* (-30)
Volkswagen ID.3	13.0	12.4 (-5)	12.6 (-3)	12.6 (-3)	15.0 (13)
Kia e-Niro	23.3	23.0 (-1)	25.5 (9)	24.3 (4)	27.5 (15)
Volvo V60 T6 Recharge	10.3	10.2 (-1)	10.0 (-3)	9.7 (-6)	7.6* (-36)

Table 2: Total preheating energy of the tested cars.

Car	Testing temperature 0 °C kWh	Testing temperature -10 °C kWh	Testing temperature -20 °C kWh
Tesla model S P85	5.5	7.9	12.3
Nissan Leaf	0.7	3.1	3.1
Volkswagen ID.3	1.6	2.9	2.4
Kia e-Niro	1.4	0.5	2.5
Volvo V60 T6 Recharge	0.3	0.5	0.4

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ISBN 978-952-335-715-0
ISBN 978-952-335-715-0 (PDF)
ISSN-L 2243-3376
ISSN 2243-3376
Lappeenranta 2021