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Climate impact on electric vehicle energy consumption in the Baltic Region

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Abstract. Electric vehicles (EVs) have seen increased interest in recent years as a lower-emission alternative to internal combustion engine (ICE) vehicles, with much of their growth driven by government subsidies and incentives across Europe. However, as these incentives have slowed, the EV market faces new challenges, particularly in the Baltic countries where the climate significantly impacts EV performance. Low temperatures, common in Baltic weather, can notably affect EVs' range and energy efficiency, influencing operational costs and user satisfaction. Understanding how Baltic weather conditions, primarily temperature, influence the energy consumption of EVs is essential to gaining a deeper understanding of their efficiency in low temperatures and harsh weather conditions. The main aim of this study is to assess the impact of varying weather conditions on EV energy consumption, providing valuable insights into their efficiency under cold and variable climatic conditions. The primary goal is to identify the factors most responsible for increased energy consumption in these conditions. In this study, a series of controlled real-world driving tests were conducted, during which an EV (Nissan Leaf) was driven multiple times along identical routes under different weather conditions. The temperatures during these tests ranged from 20 °C to -15 °C. The 2024/2025 winter season was unusually warm in the Baltic region; therefore, tests could not be conducted at lower temperatures. Variables such as distance, temperature, battery state, and the use of accessories were recorded and subsequently analysed. Additionally, energy losses during EV battery charging were measured and evaluated. The collected data was analysed statistically, and mathematical models were developed to provide accurate predictions of battery usage under varying ambient temperatures. The results indicate that low temperatures increase EV energy consumption due to the additional energy required for battery and cabin heating. A more detailed analysis reveals that the most significant increase in energy consumption occurs at an ambient temperature of -10 °C. Overall, this study demonstrates that Baltic weather conditions can lead to a substantial decrease in EV range and efficiency, with low temperatures being the most impactful factor. By providing real-world data, this study contributes to a deeper understanding of EV efficiency in the Baltic region, offering practical insights for EV users and researchers.

Key words: Baltic climate, electric vehicle, energy consumption, range efficiency, real-world driving tests.

INTRODUCTION

Electric vehicles (EVs) have proven essential in cutting greenhouse gas emissions while reducing fuel dependence on petroleum products. The efficiency of EVs depends on various elements, including ambient temperature, driving speed, terrain conditions, and battery technological advancements (Harvey, 2020). All vehicle operations for EVs depend on drawing power from their batteries since they produce no waste heat for cabin heating like traditional internal combustion engine (ICE) vehicles do under adverse climate conditions such as high or low temperatures; electric vehicles' operational range and energy efficiency performance experience significant reductions. The efficiency of lithium-ion battery performance tends to be higher in warm climates since chemical reactions within the cells operate most effectively (Yao et al., 2023). Nonetheless, cold weather conditions reduce peak performance capabilities, thus increasing energy losses. Addressing the impacts of the environment on battery efficiency together with range anxiety reduction demands urgent focus to make EVs acceptable for mass markets.

Temperature is a significant element that affects the operational efficiency of EVs. Electrochemical reactions inside the batteries become slowed, internal resistance grows, and energy availability for propulsion decreases when temperatures are low. Low-temperature conditions decrease battery cell electrolyte fluid flow ability because of increased fluid viscosity, so charging efficiency suffers during regenerative braking. An EV performs worse in frigid climates because its driving range diminishes. At the same time, charging takes longer, and power losses increase relative to operating in normal ambient temperatures (Albatayneh et al., 2020). Evaporator and defrosting operations consume additional energy that negatively affects the vehicles energy efficiency. Battery-powered electric cars must distribute stored energy for cabin heating because they lack the capability of traditional ICE vehicles to heat interiors using engine heat, which increases battery consumption. The combination of high power requirements under such conditions shows why specific methods for improving energy utilisation in cold conditions need implementation. The two factors generally contributing to poor performance are higher internal resistance of the battery, increased heating demand, and reduced regenerative braking efficiency in the cold (Steinstraeter et al., 2021).

The scientific community now focuses research on battery performance in cold regions because the growing EV market expands into colder climates. The EV range decreases substantially during freezing weather conditions, as demonstrated by multiple studies and real-world driving tests, which also depend on battery chemistry, driving conditions, and the necessity of heating. The Nordic region, including Norway, Sweden, Finland, Denmark, and Iceland, as well as the northern parts of Canada and the United States, faces extensive cold winters where temperatures drop to -10 °C and sometimes plunge even to -30 °C or even lower in its northernmost regions (Harvey, 2020). The same conclusion can be drawn about the Baltic climate, as it is similar to the Nordic climate. EV battery functionality is significantly impaired during extreme weather conditions because temperature directly affects battery performance.

Many studies have shown how cold weather impacts EV efficiency (Wilber et al., 2021). According to research by the American Automobile Association (AAA), at -7 °C, EVs can lose 41% of their range when heating the cabin (Sheldon, 2024). A Norwegian Automobile Federation (NAF) comparison of several EV models in winter conditions has returned official Worldwide Harmonised Light Vehicles Test Procedure ranges were significantly reduced (Haber, 2023).

Manufacturers and researchers have investigated several tech-based solutions to reduce these efficiency drops, such as battery preheating, battery compartment insulation, and thermal management systems. Preheating, or thermal conditioning, entails warming a battery before using it via an external power source or drawing energy directly from it (Esch & Shabani, 2025). Preheating effectively mitigates the impacts, yielding up to 20% improvement in range while driving at subzero temperatures. Insulation of the battery has promising potential in that heat can be lost through battery walls, so maintaining an optimal operating temperature ensures minimal heat loss. According to findings some automakers introduced liquid-cooled battery systems capable of keeping battery temperature more stable in hot or cold climates than air-cooled designs (Wankhede et al., 2025).

Considerable research is devoted to the heat pump as an alternative to resistive heating. Unlike conventional electric heaters, heat pumps extract heat from ambient sources and transfer it into the vehicle, making them significantly more energy-efficient (Cortvriendt et al., 2025). The amount of energy needed to generate heat with a heat pump is considerably lower than the heat output itself. EVs equipped with heat pumps consume 30% to 50% less energy for heating, thereby extending their winter range. However, at extremely low temperatures, heat pumps become less efficient, necessitating supplementary resistive heating systems. Therefore, researchers have become interested in phase-change materials (PCMs) and thermoelectric generators (TEGs), which store heat and release it more effectively, thereby siphoning less power from the battery to run the climate control system.

Although the studies have yielded fascinating results, there is a lack of real-world quantitative analysis on energy loss for various driving conditions. Many laboratory-based tests do not measure wind resistance, snow accumulation, and real-world charging inefficiencies. This study intends to bridge this gap by analysing extensive on-road monitoring of EV performance under various Nordic-type climate conditions. This research will help provide more practical and efficient solutions for utilising EVs in colder regions by creating a mathematical model for analysing EV energy consumption under different temperatures and speeds, based on real-world driving tests conducted in varying conditions.

The existing research on cold temperature impacts on electric vehicle efficiency contains insufficient evidence because of the lack of real-world monitored testing and data acquisition. Many studies primarily rely on laboratory simulations and controlled driving cycles that fail to replicate actual driving conditions sufficiently (Park et al., 2024). Multiple vehicle energy consumption parameters determine results, including road conditions, wind resistance, traffic conditions, and driver actions, but these factors usually remain absent from experimental tests. Due to variations in battery types and heating methods, results from one EV model may not be transferable to others. Studies on this topic have focused on calculating the reduction of underlying range during cold conditions and concluded that more research needs to be conducted on this subject (Al-Wreikat et al., 2022). The current evidence lacks specific information about individual vehicles' efficiency characteristics, which would help consumers and vehicle makers optimise driving performance under wintry conditions.

The primary research objective focuses on investigating EV energy usage patterns as a response to changes in ambient temperature through real-world driving tests at different temperature points. The fieldwork component of this research will monitor how electrical battery power decreases while tracking efficiency during actual winter driving conditions. The test vehicle will engage in several journeys between +20 °C and -15 °C, during which the metered outcomes for battery discharge and power usage will be documented throughout the process. The gathered data will provide valuable insights to examine the different forms of electricity usage across various heating systems, preheating approaches, and cabin temperature adjustments. Understanding the extent of efficiency reduction across cold weather conditions will occur through quantitative analysis to identify the most effective ways of lowering driving energy usage in winter.

The research addresses the effect that vehicle speed requests have on power consumption. The power demand at different speeds serves as a major element that influences EVs energy usage (Feng et al., 2025). Recent investigations have identified that speed determines energy consumption, yet researchers have not objectively determined the specific speed-dependent model parameters in cold weather conditions. In this work, we will create a mathematical model that uses test data from 40 km h^{-1} to 130 km h^{-1} to develop a power-consumption-velocity relationship. The mathematical model created will determine the appropriate speed ranges for winter operation together with necessary driving practices to maximise the EV's range. Adopting these elements will create an improved comprehensive view of energy losses that depend on vehicle speed within winter conditions because of their integration. Energy-efficient EV driving depends on speed optimisation according to Nordic driving conditions because such climates demand strong range conservation (Egeli, 2023). A proper cruising speed helps EV drivers extend their range while driving at different speeds through the power-speed relationship (Ayevide et al., 2022). EV manufacturing companies benefit from this information to optimise drivetrain effectiveness by enhancing aerodynamics and adding better regenerative braking capabilities.

The third objective involves studying energy consumption losses between domestic vehicle charging stations and fast-charging terminals. The performance of EV charging directly impacts its energy consumption efficiency due to immediate power distributions affecting the overall battery power capacity (Kostopoulos et al., 2020).

Though measurement uncertainty has not been explicitly characterised in this study, it is recognised that applicable uncertainties are inherently associated with both measurement results and the measurement instruments. These may arise from factors such as sensor precision, data logging intervals, environmental fluctuations, and app-based limitations. While efforts were made to minimise external influences, such as maintaining consistent driving routes and weather conditions, the presence of systematic and random errors cannot be entirely excluded. Thus, the reported results must be cautiously interpreted considering possible measurement uncertainties.

Understanding these interrelated factors is crucial for improving EV performance in cold climates and reducing user uncertainty regarding range and energy use. This study addresses these challenges by combining real-world testing with mathematical modelling to evaluate EV behaviour in the context of Baltic climate conditions. The objectives of this research are as follows:

1. To investigate how ambient temperature affects electric vehicle battery energy consumption under real-world driving conditions typical of the Baltic region.

2. To analyse the relationship between vehicle speed and power consumption, and develop a mathematical model describing this dependency.

3. To evaluate charging efficiency under different charging scenarios, including home and fast-charging stations.

4. To assess the impact of cabin heating settings and preheating strategies on overall energy usage during winter conditions.

MATERIALS AND METHODS

Experimental setup and data collection

An experimental setup was conducted to evaluate EV energy consumption under real-world driving conditions based on ambient temperature conditions. A 2019 Nissan Leaf 40 kWh, a Battery Electric Vehicle (BEV) with a lithium-ion battery pack, single-speed transmission, and regenerative braking system functioned as the experimental vehicle. The vehicle operated on a 39.0 kWh usable battery system, which could reach a 235-km real range according to its manufacturer's information. A heat pump-based climate control system was operational in the car. It has a Type 2 home-charging port (6.6 kW AC) and CHAdeMO fast-charging port (max charge power 46 kW DC). This Nissan model does not have a battery pre-conditioning system, meaning it cannot warm the battery prior to departure, which may affect charging efficiency in cold weather (Autospirit Tartu OÜ, 2018).

The tests took place near Tartu, Estonia across blacktop roads, highways, and urban streets, which helped demonstrate actual roadside conditions. Measurements were performed under controlled road conditions to minimise variations in energy consumption caused by differences in road surface and contact friction. The roads were not snowy, although icy surfaces and frost-covered roads occurred during sub-zero temperatures. Testing included driving through a planned route, which reduced braking stops and maintained continuous speed changes. During the study, data collection was carried out using the LeafSpy Pro app. The vehicles built-in analytics system monitored battery consumption, energy consumption and charging data providing kWh and state of charge (SoC) measurements. These measurements were recorded in the LeafSpy Pro app and the results obtained were used in this study. The average elevation of the test route was approximately 55 meters above sea level.

Battery energy consumption tests at different temperatures

The vehicle was tested at five different temperatures: +20 °C, +10 °C, 0 °C, -10 °C and -15 °C, to assess how ambient temperature affects the energy efficiency of EVs. Therefore, a seasonal range from mild weather to Baltic winter was covered. The winter of 2024/2025 was unusually warm for the region; therefore, tests could not be conducted at lower temperatures. The standardised distance of 23.6 km per trial during test drives also ensured that the intake data on energy consumption was comparable under temperature conditions. Each test drive began and ended at precisely the same location and took approximately 29 minutes to complete, resulting in an average speed of about 48.8 km h^{-1}. Weather conditions were kept as similar as possible for each ambient temperature to ensure the highest possible accuracy of the test results. The energy consumed was calculated from the moment the drive started until it finished, covering 23.6 km, and the total energy consumed in each test passing was recorded at the end of that drive. SoC was also recorded before and after the test drive. To evaluate battery energy consumption, a total of 9 test drives were conducted with each outside temperature, but with -15 °C only 3 because of the mild winter this year. In total, 39 test drives were made on a 23.6-km track, so ca 1,000 km was driven to obtain the necessary results.

The research also looked into how the heating settings of the cabin affected battery energy consumption. The cabin heater was fixed at four temperature settings – 16 °C, 19 °C, 22 °C, and 25 °C – and a test where the cabin heater was turned off completely served as the baseline. The study varied regarding how these settings were set and how the performance in terms of added energy for the heater and this energy cap is compared to overall battery drain to measure the impact of the heater settings on battery use. Heating needs are fundamental in cold climates, as heating can consume considerable energy. The impact of cabin preheating on energy consumption was also examined, as cabin preheating is often used in cold environments. The study tested for two scenarios: the tests started with a cold cabin and a preheated cabin before the drive began.

Power demand at constant speeds

Our road testing was conducted on a horizontal track section that did not alter our results because of any uphill or downhill terrain. Takeover measurements for power consumption required us to maintain constant speed for an equivalent period to achieve steady-state power conditions. The recorded energy consumption data was displayed in near real-time on the LeafSpy Pro app. During each segment, the test driver maintained uniform throttle control for measuring power consumption while avoiding effects from regenerative braking and high-speed accelerations.

A polynomial regression model was developed to detect links between speed and power usage relationships. Power demand correlated directly to vehicle speed increases; however, the data indicates that this relationship remained nonlinear. The obtained best-fit equation comes from the least-squares curve fitting strategy, which describes the relationship between speed and power usage.

The resulting equation is

$$P = ax^2 + bx + c \tag{1}$$

where P is the power consumption (kW); x is the vehicle speed (km h^{-1}); a, b, and c are empirically determined constants derived from regression analysis of test data.

Power demand rises at a steady rate, as the equation demonstrates. The application of the quadratic function provides fundamental insights into automotive aerodynamics study. Therefore, the relationship follows this pattern. Knowledge has grown about opposing forces that significantly increase power consumption at high speeds compared to urban driving.

Charging efficiency analysis

This research examined charging situations involving home charger usage together with public charger operation. The installed home-charging system includes a 22 kW three-phase AC charger, which obtains power from the electrical grid to produce power for the battery storage. However, the EV used in this experiment is limited to receiving 6.6 kW single-phase AC power. To calculate the total charging losses in percentage, the following formula was used:

$$\text{Energy Loss (\%)} = \left(\frac{\text{Energy Supplied} - \text{Energy Stored}}{\text{Energy Supplied}}\right) \times 100 \quad (2)$$

In the case of home charging, energy consumption is measured at the point before the AC/DC conversion by the vehicles onboard charger. This means that the recorded energy not only includes the energy delivered to the battery but also the losses associated with the AC/DC conversion process. When using a fast charger, the energy measurement is taken after the AC/DC conversion has already occurred within the charging infrastructure. As a result, the reported energy consumption only reflects the energy delivered directly to the vehicles battery, excluding conversion losses.

Mathematical model for energy consumption prediction

The comprehension of EV energy efficiency in cold conditions requires empirical data and a mathematical model that forecasts energy consumption across untested situations. The testing of this study was conducted at five ambient temperature points ranging from +20 °C to +10 °C, 0 °C, -10 °C and -15 °C. The actual driving environment comprises temperatures between intermediate ranges and extreme conditions, which the authors did not evaluate through direct outside testing. The practical energy consumption rates diverge significantly from test measurements due to various real-world impacting factors, including the impact of the wind and the condition of the vehicles battery, as well as the current snow conditions on the road. Developing a predictive mathematical system requires implementation to forecast the efficiency of EV energy across different environmental situations. The predictive mathematical model provides essential insights to drivers and other stakeholders about range computations while helping them manage energy resources during cold weather conditions. When there is no predictive model available, EV users need to make decisions using imperfect empirical data that cannot reflect their particular situation.

The investigation of temperature-dependent utilisation required analysing the experimental data for patterns that described battery charge consumption per kilowatt-hour consumption. The fitted regression model for data trends used polynomial functions. A quadratic regression model was established from the test results to explain the connection between energy consumption E (kWh per 23.6 km) and ambient temperature t (°C). The model enables the prediction of energy consumption across a range of ambient temperatures based on empirical data.

The resulting equation is

$$\mathrm{E} = \mathrm{at}^2 + \mathrm{bt} + \mathrm{c} \quad (3)$$

where E is energy consumption per 23.6 km (kWh); t is the ambient temperature (°C); a, b, and c represent the empirically determined constants derived from regression analysis of test data.

The regression model produces distinct parameter values depending on the test drive conditions. Users of EVs can better predict their driving performance through the mathematical model when they need to assess range and energy spending across untested temperature conditions. The model needs additional variables for vehicle dynamic variables, such as wind resistance, snow-traction losses, and speed differences, in order to improve its prediction accuracy. Moreover, more values are needed for more extreme temperatures like -25 °C or -30 °C, because this formula might not apply there.

RESULTS AND DISCUSSION

Effect of temperature on battery energy consumption

A clear inverse relationship is shown with ambient temperature and battery efficiency, where the charge loss is more significant at lower temperatures based on data gleaned from test drives at various temps. Fig. 1 shows the battery energy consumption per test drive for temperatures between +20 °C and -15 °C, using various cabin heater settings. The results confirm that, at hot temperatures of +20 °C and +10 °C, the battery preserves more charge, while at subzero temperatures like 0 °C, -10 °C, and -15 °C, there is a significant increase in the energy consumption and therefore in the battery emptying. For the coldest test parameters (-15 °C), setting the heater at 25 °C caused the EV to drain 6.8 kWh of energy from the battery, compared to 3.2 kWh for a 16 °C heater setting at 20 °C, which is roughly double the difference in energy consumption. This demonstrates the impacts of outside temperature and energy use while driving an EV. All the results from test drives in different temperatures and cabin heating are shown in the table below.

Table 1. Energy consumption on the specific outside temperature

Test drive	Energy consumption on the specific outside temperature				
	20 °C	10 °C	0 °C	-10	-15
Test drive 1 (cabin heater at 16 °C, no preheater)	3.2	3.2	3.9	4.2	4.4
Test drive 2 (cabin heater at 19 °C, no preheater)	3	3.6	4.2	5.1	
Test drive 3 (cabin heater at 22 °C, no preheater)	2.9	3.3	4.6	6.1	
Test drive 4 (cabin heater at 25 °C, no preheater)	2.9	3.4	4.8	6.3	6.8
Test drive 5 (cabin heater at 16 °C, start with preheated cabin)	3.2	3.8	4.6	5.2	
Test drive 6 (cabin heater at 19 °C, start with preheated cabin)	3.1	3.5	5.2	6.5	
Test drive 7 (cabin heater at 22 °C, start with preheated cabin)	3.6	3.9	5.8	7.2	
Test drive 8 (cabin heater at 25 °C, start with preheated cabin)	3	3.3	6.2	7.6	
Test drive 9 (cabin heater is turned off)	2.5	3.1	3.2	3.3	3.2

The trend seen in Fig. 1 is consistent with other research on battery performance in cold weather, which finds that lithium-ion batteries experience around a 30% to 40% percent drop in efficiency when the temperature drops below 0 °C. There are some significant reasons why charge loss increases as temperatures fall. First, electrochemical reactions in the battery are slower at low temperatures than at high temperatures, resulting in higher internal resistance and lower energy supply (Senol et al., 2023). The second reason is that EVs depend on considerable battery power for cabin heating, resulting in higher energy consumption (Doyle & Muneer, 2019). Finally, the decreasing efficiency of regenerative braking at lower temperatures means that less energy is recovered, which leads to a more significant overall depletion of the battery. The findings show that thermal management strategies must practically apply thermal insulation to the battery, enabling maximum performance to be calculated in freezing temperatures (Steinstraeter et al., 2021).

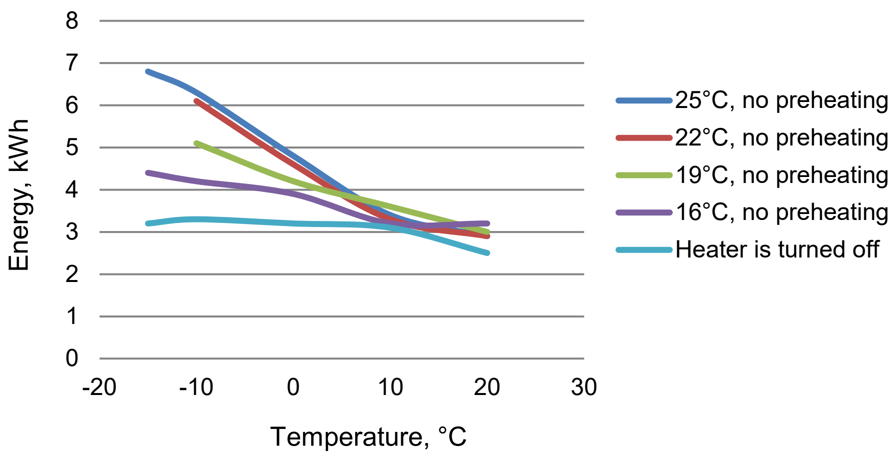

Figure 1. Test drives with no preheating.

Temperature and battery energy consumption are not linear when approaching lower temperatures. The rate of energy loss accelerates. In the warmer part of the experiment, the energy at +20 °C and +10 °C was not noticeably different, with just a tiny charge loss of 0.3%. As the temperature dropped from 0 °C to -10 °C, the energy consumption of the EV increased more sharply, exceeding 12% in some cases. For example, the values of the constants were established for test drive 4 (cabin heater at 25 °C, no preheater) at $a = 0.0015$, $b = -0.13$, and $c = 4.71$ by applying regression techniques to the assembled data. Therefore, the model equation is:

$$E = 0.0015t^2 - 0.13t + 4.71 \tag{4}$$

With an equation like this, the study can estimate energy consumption for temperatures that were not explicitly tested, for example, at -20 °C or intermediate values like -5 °C, as well as more general trends that we expect based on EV efficiency behaviour. Temperature has a negative coefficient; increasing it should reduce energy consumption. The constant c is the energy consumption without considering the linear extra losses caused at the level of heating systems that are applied without the temperature effect at 0 °C.

The results show that temperature is critical in determining the range of an EV, especially in cold climates because heating energy can make up more than 40% of total battery use. While internal combustion engine (ICE) vehicles can capture some waste heat produced by the engine for heating the cabin, EVs have no such benefit. The cars must generate heat through resistive heaters or heat pumps, requiring potentially significant additional energy costs. This is especially evident in examples of higher cabin temperatures, shown in Fig. 1. An EV with a cabin heater set to 16 °C used

4.2 kWh of energy from the battery at -10 °C, while the same model used 6.3 kWh with the heater at 25 °C – indicating that roughly one-third of the energy went to heating the additional 9 °C. Moreover, if the cabin heater was completely turned off, the EV only used 3.3 kWh for the test drive at the same outside temperature. These results demonstrate the apparent correlation between heating demand and total battery usage.

To further strengthen the analysis of temperature effects on energy consumption, a statistical correlation analysis was conducted. This included the Pearson correlation coefficient, which measures linear relationships, and the Spearman correlation coefficient, which assesses monotonic associations.

The analysis was based on energy consumption data from test drive 1 (cabin heater at 16 °C, no preheater) across five temperature points (+20 °C to -15 °C). The results showed a very strong negative correlation between ambient temperature and battery energy use:

- Pearson correlation coefficient: −0.980
- Spearman correlation coefficient: −1.000

These results confirm that lower temperatures consistently increase EV energy consumption, and the perfect Spearman value indicates that this trend is strictly monotonic. The correlation analysis supports the earlier polynomial regression and underlines the significance of temperature as a dominant factor affecting winter EV efficiency.

Impact of cabin heater settings on overall efficiency

Fig. 2 demonstrates how cabin heater settings affect the total energy consumed, directly proportional to heater temperature and the amount of drained battery. Therefore, if the expectation is that higher heater settings draw significantly more power from the battery than lower settings, reducing climate controls role on battery efficiency is evident as even a difference in heater setting of around 9 °C in subzero temperatures leads to a nearly 30% difference in consumption.

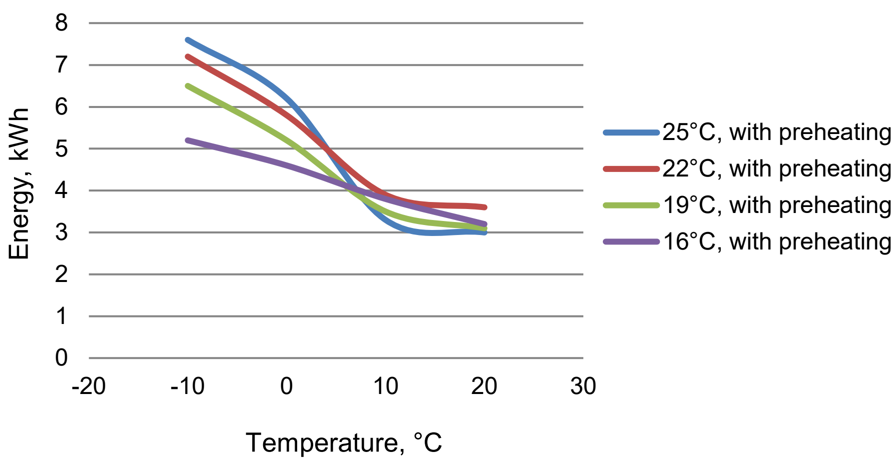

Figure 2. Test drives with preheating.

The most remarkable observation is that the vehicles overall range is sensitive to heater use, and extreme cold is widespread. When the temperature was warmer, above 10 °C, the difference in heater settings mattered less due to some outdoor passive heating as the external environment was also hot. While things were better at zero and below, the energy required to maintain higher cabin temperature increased sharply, becoming one of the more significant contributors to range cuts. This means that other heating solutions, like seat warmers, steering wheel heaters, and preheating strategies, may save considerable battery power while keeping passengers comfortable.

Input data, more commonly seen between graphs, such as energy consumption at different cabin heater settings, indicates that temperature changes of only several degrees significantly impact output. For example, when the heater's temperature was changed from 22 °C to 19 °C, the energy consumption decreased by almost 10%. Still, when changed from 22 °C to 25 °C, the energy consumption increased by 15%. This shows that the connection between heater settings and energy loss is not linear. As the heater runs at higher temperatures, the energy use grows exponentially and is not a linear function. Test drives with preheating at -15 °C were not conducted in this study due to the unusually mild winter conditions in the region.

Relationship between vehicle speed and power consumption

In this section, we examine the dependency of power consumption on vehicle speed. The unit of speed used is km h^{-1}, as it is the standard convention in European traffic systems. The following analysis is based on the results obtained from real-world driving tests. Fig. 3 shows the correlation between vehicle speed and instantaneous power demand (kW). It shows a clear upward trend in power consumption as speed increases. The results show that the power demand is not too high at low speeds like 40 km h^{-1} (~2.9 kW). However, increasing speed does increase power consumption significantly: it is 10.15 kW at 80 km h^{-1} and jumps to 32.65 kW at 130 km h^{-1}, which means that more energy is needed per km at higher speeds, and the data confirms this.

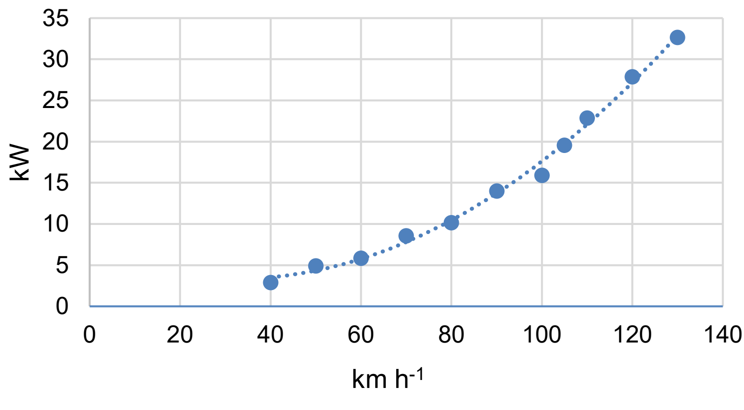

Figure 3. Power consumption compared to car speed.

The curve has a non-linear relationship. Thus, increasing speed results in a rise in demand for power. This is primarily due to aerodynamic drag and rolling resistance, both growing at speeds. Although there are power demands due to mechanical losses, such as drivetrain and tyre friction, the aerodynamic forces dominate at highway speeds, so that EVs can be vastly less efficient at higher speeds. Driving an EV above 90 km h^{-1} drastically increases its power consumption, primarily due to air drag. Therefore, driving on highways or high speeds becomes an area where considerable efficiency can be present.

The figures further emphasise that the increase in power draw from travelling 40 km h^{-1} (2.9 kW) to 80 km h^{-1} (10.15 kW) is relatively moderate in comparison to that of 80 km h^{-1} to 130 km h^{-1} (~10.15 kW to 32.65 kW). Moreover, the system consumed 2.9 kW at 40 km h^{-1}, which increased to 10.15 kW at 80 km h^{-1} and further to 32.65 kW at 130 km h^{-1}, demonstrating this quadratic relationship that principally resulted from aerodynamic properties. The total power increase between 40 km h^{-1} to 120 km h^{-1} speed became more than 10 times greater beyond a simple factor of 3 because of increased air resistance effects. This shows that the faster they go, the higher their power demand, which is a basic power consumption for EVs. Based on the data, driving at moderate speeds between 50 and 80 km h^{-1} maximises energy efficiency, while higher speeds of 100 km h^{-1} and beyond negatively impact the range. This result is particularly relevant in cold climates where battery efficiency is decreased. As such, one of the top strategies for maximizing driving range in winter should be speed optimisation for EV drivers in the Nordic and Baltic territories.

Finally, a polynomial regression was applied that provided insights into the observed signal, including speed (x) versus power consumption (P), as presented below.

The equation of the trend line fitting the test data is

$$\mathrm{P} = \mathrm{ax}^2 + \mathrm{bx} + \mathrm{c} \qquad (5)$$

where P is the power consumption (kW); x is the vehicle speed (km h^{-1}).

Constants in the model were determined by applying polynomial regression techniques to the observed dataset, resulting in the values a = 0.003, b = -0.193, and c = 6.358. Consequently, the model equation is:

$$\mathrm{P} = 0.003\mathrm{x}^2 - 0.193\mathrm{x} + 6.358 \qquad (6)$$

This equation allows the estimation of power consumption at speeds not explicitly tested. It demonstrates that power consumption will increase dramatically as speed rises until highway velocities where the quadratic part of the equation controls the result. The polynomial nature of this model has been verified since it follows known aerodynamic principles leading to quadratic velocity-dependent drag forces. The model functions as a useful method for evaluating EV power consumption beyond the standard speed range, and this enables drivers and manufacturers to check their efficiency regarding range at other speeds.

The quadratic growth of power demand at high speed is primarily related to aerodynamic drag, rolling resistance, and drivetrain inefficiencies, all growing factors as speed increases (Kozłowski et al., 2024). At lower speeds below 60 km h^{-1}, up to 90% of power consumption is determined by rolling resistance and tyre friction, with relatively low aerodynamic drag. However, as the car speeds up past 80 km h^{-1}, air resistance takes over and quickly outgrows progress, demanding exponentially more power to compensate (Puma-Benavides et al., 2024). This trend agrees with the fundamental laws of fluid dynamics, which state that counteracting aerodynamic drag requires power proportional to speed cubed (Broniszewski & Piechna, 2022). The results obtained from our test drives support the findings presented in the referenced articles.

This means that when a driver increases vehicle speed, they increase aerodynamic drag power requirements by 8, reducing vehicle efficiency at highway speeds. Indeed, as the data in this study demonstrates, at 40 km h^{-1}, the vehicle pulls 2.9 kW, while 130 km h^{-1} leads to 32.65 kW energy consumption, a steep and nonlinear increase that highlights the impact of aerodynamic drag on power demand at higher speeds.

Air resistance is one of the significant aspects that leads to energy inefficiency at high speeds, and it also plays an essential role in the efficiency of EVs (Kozłowski et al., 2024). Rolling resistance is the effort needed to keep the tyres moving over the road surface, and it rises with speed due to extra tyre deformation, more internal friction between rubber elements, and a higher contact pressure with the road. In winter, driving conditions such as snow and ice accumulation increase rolling resistance, which also causes inefficiency at higher speeds (Challa et al., 2025). Opting for the correct set of tyres, ideally winter-rated, low-rolling-resistance EV tyres, can minimise energy waste in the cold.

Drivetrain inefficiencies also contribute to increased energy consumption at higher speeds. EV motors, in contrast to internal combustion engines, produce almost no heat, but they are not necessarily energy efficient at all speed ranges (Jeong et al., 2025). At lower to moderate speeds, EV motors operate at their most efficient range, so almost all energy fed from the battery is transformed into motion with minimal losses. When speeds are high, motors rotate faster, translating to more heat waste, more electrical impedance, and, eventually, less overall efficiency. Consequently, with rising speed, the energy loss in the motor and drivetrain becomes exponential. Therefore, the energy consumption to travel the same distance increases.

Driving inefficiencies at high speeds are compounded in cold weather as rolling resistance increases, regenerative braking is less effective, and heating requires significant energy with an EV (Kaleli & Sungur, 2025). Even snow-covered roads, icy surfaces, and colder tyre compounds present higher friction and rolling resistance, making the motor work harder to maintain the same speed. In winter, however, regenerative braking is less effective, so less energy is recovered upon deceleration from high-speed travel (Steinstraeter et al., 2021), creating higher net energy consumption. This highlights the need for improved EV driving behaviour throughout winter, as lower speeds have a real benefit in stretching range while avoiding unnecessary energy losses.

The findings indicate that EV drivers could benefit from implementing a speed-management strategy to maximise energy efficiency, particularly in those areas where winter efficiency drops are notably high. For ICE vehicles, fuel efficiency is optimum at moderate to high speeds between 80 and 110 km h^{-1}, but EVs are most efficient at lower speeds between 50 and 80 km h^{-1}, especially in cold weather. This calls for the further education of consumers on how speed affects energy usage, as many drivers might unwittingly give up range by travelling at higher speeds than necessary without being aware of the impact on both aerodynamic drag and rolling resistance.

Driving at moderate speeds remains one of the best strategies for maximising the range of an EV, especially in cold-weather setups where the battery is already less effective. As vehicle speeds increase, aerodynamic losses, rolling resistance, and drivetrain inefficiencies increase, resulting in disproportionate energy consumption. An energy-efficient driving style can increase EV battery range and decrease frequent charges.

Charging efficiency comparison

The energy losses when charging at home and fast-charging facilities are compared in Fig. 4, showing the difference between the energy extracted from the grid and the energy stored in the vehicles battery. The findings suggest a limited range from home charging instead of fast charging, with average energy losses of 17.8% and 8.0%, respectively as seen in Fig. 5. The losses occur owing to various inefficiencies such as losses in AC/DC conversion, loss of energy in charging components due to heat dissipation, and differing rates of charge acceptance by the battery. Home charging, which relies on alternating current (AC) from the grid, requires an onboard inverter within the EV to perform an AC/DC conversion before the energy can be stored in the battery. The conversion is not 100% efficient, and energy is dissipated as heat due to electrical resistance power dissipation in the inverter and wiring system. The elements result in a net less effective amount of energy being taken from the grid to the battery. Therefore, the energy from the grid is always much higher than the battery that is charged when using a home charger, which leads to an increase in energy consumption for electric vehicles and longer charging times.

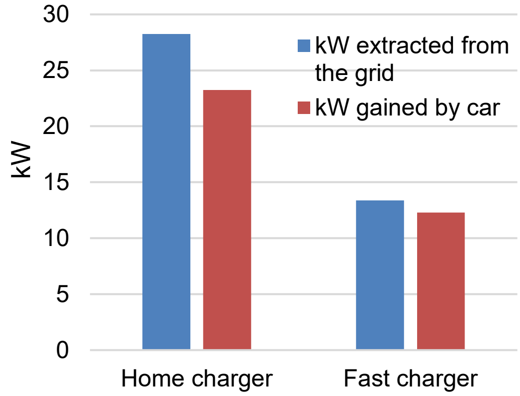

Figure 4. Consumed energy and actual received energy.

From a home-charging perspective, high energy loss is primarily due to the AC/DC converter within the EV onboard charger. This conversion process is not totally efficient, as some distributed energy is lost as heat power dissipation, electrical resistance, and inverter inefficiencies contribute to this loss. In this study, the home-charging configuration was a 22 kW three-phase AC charger with an internal power inverter for AC/DC conversion. According to the test data, for each 28.3 kWh of electricity drawn from the grid, only 23.2 kWh can be effectively stored in the battery, with an average energy loss of 17.8%. The numbers reveal how much energy can be lost with a home charger. The study notes that charging at low power levels can cause energy loss because of longer charging times, leading to increased power dissipation. The longer an EV is plugged into a home charger, the more

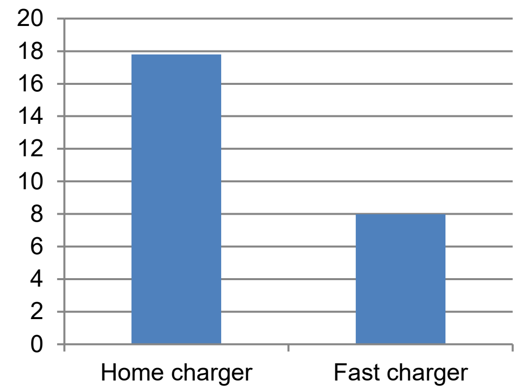

Figure 5. Energy loss % in home charger and fast public charger.

energy is lost through heat dissipation and passive energy consumption from auxiliary systems (Feng et al., 2025).

Fast charging offers many benefits, like a quicker charge and increased efficiency, especially for battery-charged systems (Martini et al., 2025). In this study, a 50 kW fast charger was used to charge the EV's battery. In a fast charger the energy extracted from the grid was measured after the AC/DC converter, so fast charging was, on average, 92% efficient, while home charging had only an 82% efficiency rate, making fast chargers nearly two times more efficient in preventing lost energy. The increased efficiency of fast chargers may be ascribed to various reasons, such as the fact that they run at higher voltage, have fewer steps in energy conversion, and, more importantly, can accept charge much faster (Prasad & Gudipalli, 2025).

In EV models that have a battery preheating system, fast charging also has an advantage in that it can grow the preheat on the battery before starting charging, allowing for improved charge acceptance and efficiency in colder conditions. Cold lithium-ion batteries show lower ion mobility and poorer charge acceptance at lower temperatures, resulting in longer charging phases and increased accumulated energy loss when charged at non-ideal temperatures (Tai et al., 2025). Preheating the battery before the charging process reduces the loss of charging efficiency. Temperature gets to the optimum point before charging is started. Therefore, fast chargers enable quicker charging with minimal energy loss, making them preferable for EV use in winter conditions. Lithium-ion batteries have high internal resistance and lower charge acceptance in cold conditions. Therefore, manufacturers must offer innovative isolation techniques and active heating solutions to minimise performance loss (Murugan et al., 2025).

The comparison between home and fast charging highlights significant differences in energy efficiency, power conversion losses, and charging effectiveness. Charging losses tend to be higher when using a home charger compared to public fast-charging stations. However, the overall cost of charging at home can still be lower, as electricity prices for residential consumers are often significantly cheaper. Additionally, home charging allows users to schedule charging sessions based on fluctuating electricity prices in the stock market, further optimising costs. Moreover, slow home charging is generally more beneficial for the long-term health and lifespan of an electric vehicle's battery compared to frequent fast charging, which can accelerate battery degradation due to increased heat generation and higher charging currents (Leijon, 2025).

Importance of adaptive heating strategies to minimise energy waste

As heating systems significantly impact EVs' efficiency, implementing adaptive heating strategies is necessary to reduce energy waste and maximise winter range. The analysis proved that the cabin temperature setting firmly influences battery consumption. Higher heating requests cause more considerable energy losses. Therefore, an intelligent climate control system that can synchronise heating based on occupancy, ambient temperature, and battery charge levels is a crucial solution. For instance, a vehicle that can intelligently control its climate based on its charge could automatically make the cabin cooler and rely on more seat and steering wheel heat when the EV's battery is critically low. Using energy-efficient heating approaches will allow EVs to keep passengers comfortable without pulling extra power (Swami et al., 2025).

Preconditioning is another effective way to mitigate energy losses. The vehicle's battery and cabin can be warmed up while remaining plugged into a charging station, lowering the energy demand of the battery during the drive (Esparza et al., 2025).

Aside from the updates to software, battery insulation improvements might also retain heat better, meaning there would not need to be continuous heating requirements (Yang et al., 2025). A certain amount of thermal insulation is already included in many modern EVs. Still, there is a need for further research into more advanced thermal insulation materials that can keep heat trapped within the battery pack while not adding too much weight. Insulation technologies could help EVs use less energy for battery heating, so more of that energy can go toward propulsion, which means a better range in cold climates.

Future research directions

This study-based mathematical model is a valuable tool for estimating the energy consumed by an EV at different temperatures. However, further field validation is needed to enhance its accuracy and applicability. The present model uses test drive data from one vehicle. Therefore, its predictions may not be generalisable across all EVs, especially those with different battery capacities, thermal management systems, and drivetrains. Since different EV manufacturers use different battery management strategies, which may include both passive and active heating levels, preconditioning methods, and regenerative braking optimisations, it is essential to validate the model for various brands and vehicle models. In addition, expanded validation of the model would help to identify efficiency variations that could be used to refine predictive algorithms to ensure drivers and manufacturers can depend on it for winter range estimation. Other variables not modelled in this study that are critical to real-world EV efficiency include vehicle age and battery degradation. For a car that has been in service for a long time, research could be conducted on how that affects cold-weather performance because older batteries can lose more energy than newer ones at subzero temperatures.

Further model refinement should also incorporate extreme temperature conditions outside of this study's evaluation. The experimental dataset was limited to temperatures of +20 °C to -15 °C, but temperatures may be colder during winter driving, even below -30 °C in some cases. Including data for the extremes could help improve the model's predictive power in that range, allowing for more accurate assessments of the likely range under extreme winter conditions. Moreover, this study mainly focused on urban and highway driving over dry roads. However, winter often includes snow-covered roads, icy surfaces, and slush, all of which increase the rolling resistance and create a lower energy efficiency. It is essential to conduct controlled tests on multiple types of road surfaces to determine traction loss, excess energy required to maintain stability, and variations in tyre efficiency under differing winter conditions. By incorporating the variables, the model may become a more dynamic predictive tool used in various winter driving climates.

Another feature that needs to be included in future model versions is the impact of cold weather on regenerative braking efficiency. The current equations primarily consider temperature-dependent battery losses and speed-related power demand and do not explicitly include the lowered regenerative braking yield at low temperatures. Regenerative braking can recover up to 30% of an EV's lost energy in perfect conditions, drastically enhancing range and efficiency. Nonetheless, when temperatures drop below zero, battery charge acceptance decreases, making energy recovery from braking less effective. Because EVs use regenerative braking as a central strategy for efficiency, inaccurate modelling of its variability in cold weather risks overinflating range predictions. Future studies will need to be performed to build a more comprehensive multi-variable equation that would include analyses of temperature, speed, regenerative braking efficiency, and battery preconditioning effects to create a better tool to estimate a winter range.

CONCLUSIONS

The energy efficiency of electric vehicles (EVs) during cold temperatures has been thoroughly explored in this study, with a detailed investigation of the effects on battery charge loss, power demand at different speeds, and charging efficiency in both home and fast-charging situations. The results show temperature has a key impact on overall EV efficiency, with below-freezing conditions causing increased energy consumption with reduced driving range. Battery degradation rate nearly doubles at -15 °C compared to +20 °C, indicating a need for battery thermal-management systems to minimise cold-weather efficiency losses. Moreover, this study has examined the speed-versus-power-draw relationship, finding that energy consumption based on velocity increases as speed increases. The polynomial linear regression built in this study indicates that power demand is a quadratic function, with the significant impact of faster driving on EV range evident from 80 km h^{-1} onwards. The predominance of aerodynamic drag while driving slowly from 40 km h^{-1} to 120 km h^{-1} would imply a compound speed increase of three times. It is associated with the demand for more than ten times the power, underlining the effect of high-speed driving on EV range. Moderate driving speeds between 50 and 80 km h^{-1} provide the best energy efficiency in the vehicles. Therefore, speed is a significant component that drivers should pay attention to in order to maximise their range.

The findings from this study provide some actionable recommendations for EV operators seeking to maximise efficiency during wintertime driving. One of these strategies is preheating the whole vehicle. While the vehicle remains connected to an external power source, preheating reduces the battery's initial heating requirement and minimises energy loss during driving. Since charging losses, especially in home-charging systems, are relatively high, electricity prices should be kept in mind and the charging should be adjusted accordingly. By strategically timing charging sessions according to energy price fluctuation, users can minimise costs and improve overall charging efficiency. Driving speed should remain within moderate levels, as speeds exceeding 90 km h^{-1} significantly increase energy consumption. The higher the speeds, the greater the aerodynamic drag and the efficiency of the vehicle goes down. Reducing speed helps optimise energy usage and increase the EV's driving range.

Limitations of the study

Although this study offers essential insights into EV energy efficiency in cold climates, some limitations should be acknowledged. The key limitation is that the trials were performed with only one EV car, so the findings may not necessarily reflect those of other EVs, especially those that use different battery chemistries and thermal management systems. The tested temperature range between -15 °C to +20 °C does not include extreme temperatures, for instance, -30 °C or lower, which might lead to even more significant energy losses. Testing under even harsher temperatures will give us a better idea of how EVs perform in winter weather. At the same time, recent climate trends, including this year's unusually warm winter, indicate that the Baltic region is experiencing a warming climate. As a result, extreme cold events are becoming less frequent, which positively affects EV energy efficiency.

Also, the study was mostly based on controlled test drives, which followed identical routes and steady driving behaviour, which does not reflect real-world driving situations that encounter highly variable factors, such as traffic jams, elevation changes, or varying road surface conditions. This particular study did not specifically test the types of surfaces on the road, for example, and therefore a requirement of more power to move the vehicle. Furthermore, real-world EV drivers likely have varying driving habits − such as increased acceleration and regenerative braking − and that should impact overall efficiency as well. To increase the real-world relevance of our results, future research should examine a wider range of driving scenarios, including stop-and-go urban driving and driving on highways with varying speed limits.

To summarise, future work can address the limitations identified in this study by applying heavier techniques for EV energy efficiency studies. This means testing a variety of EV models involving different battery chemistries and thermal management systems so that the findings have wider applicability. Further experiments need to be performed at even lower temperatures, for instance, -30 °C or below to evaluate the total energy losses over the coldest winter months. Although climate trends in the area indicate warming in the Baltic region, episodes of extreme cold still occur, and can substantially affect the performance of an EV. In addition, future studies must include more realistic driving scenarios that include variations in factors such as traffic flow, elevation gain, and road surface conditions (e.g., snow and ice). A greater focus in the research on how specific driving behaviours like aggressive acceleration, braking with energy recuperation and their overall efficiency would also add practical value to the benefits of the research.

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