Electric Vehicle and Charging Infrastructure Assessment in Cold-Weather Climates: A Case Study of Fairbanks, Alaska

Eliseo Esparza, Dana Truffer-Moudra, and Cabell Hodge

National Renewable Energy Laboratory

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NREL/TP-5400-92113
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National Renewable Energy Laboratory
15013 Denver West Parkway
Golden, CO 80401
303-275-3000 • www.nrel.gov

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List of Acronyms

BTMS	battery thermal management system
DCFC	direct-current fast charger
EPA	U.S. Environmental Protection Agency
EV	electric vehicle
EVSE	electric vehicle supply equipment
GSA	U.S. General Services Administration
HVAC	heating, ventilating, and air conditioning
LFP	lithium iron phosphate
NMC	nickel manganese cobalt
NREL	National Renewable Energy Laboratory
SoC	state of charge
WLTP	Worldwide Harmonised Light Vehicles Test Procedure

Executive Summary

The purpose of this report is to determine the effects that extreme cold temperatures have on electric vehicles (EVs) and electric vehicle supply equipment (EVSE). The adoption of EVs in extreme cold weather presents challenges that require careful analysis of efficiency and charging infrastructure. This report explores how EVs and EVSE perform in temperatures as low as −40°C (-40°F), focusing on real-world data from Teslas in Alaskan winter conditions.

The findings indicate that EVs can successfully function in extreme cold, though efficiency is significantly affected. Vehicles stored in heated environments outperformed those stored outdoors, with range dropping by up to 69% for outdoor storage. Despite these challenges, none of the vehicles experienced failures that prevented travel. Storing EVs indoors led to benefits such as faster preconditioning and improved efficiency, while charging in extreme cold, though slower, remained functional.

Ultimately, the report concludes that with proper precautions and best practices, EVs are viable transportation solutions in cold climates. Investing in enclosed, heated storage is recommended to maximize efficiency and minimize battery strain during extreme cold conditions. It is important to note, however, that while storing an EV inside a garage may maximize its efficiency, building a garage and maintaining its temperature is undoubtedly more carbon and energy intensive. As advancements in battery chemistry and thermal management progress, EV adoption in extreme climates is expected to become even more feasible.

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1 Introduction

The National Renewable Energy Laboratory (NREL) was contracted by the U.S. Army Corps of Engineers to complete an assessment of the requirements and costs of installing electric vehicle (EV) infrastructure at the U.S. Army Corps of Engineers Chena site in North Pole, Alaska, as well as best practices for the operations of EVs in the extreme cold temperatures of Alaska. NREL wrote two technical reports as requested: this report on the impacts of cold weather on EVs and charging infrastructure and a companion report assessing charging needs for the Chena Recreation Area fleet, *Electric Vehicle Supply Equipment (EVSE) Site Assessment Report for the U.S. Army Corps of Engineers Chena Site Near Fairbanks, Alaska* (Truffer-Moudra, Esparza, and Hodge 2024).

As EV adoption continues to rise and vehicle technologies advance, several challenges delay their widespread acceptance. One of the most significant hurdles is range anxiety, as battery range continues to be the highest concern among non-EV drivers (Plug In America 2024). This is especially prevalent in colder climate regions where low temperatures are known to reduce vehicle efficiency and driving range. The impact of cold weather on EV performance is a critical issue that necessitates thorough investigation. There is a substantial research gap regarding real-world data on EV performance in extreme cold climates. Most analyses focus on temperatures down to −10°C (14°F), leaving a void in understanding how EVs operate below this threshold. This report aims to address this gap by focusing on temperatures at 0°C (32°F) and below, with particular emphasis on −10°C (14°F) and lower.

In colder climates, vehicle usage patterns differ notably. Drivers often warm up their vehicles to reach a comfortable operating temperature—a practice common for both internal combustion engine vehicles and EVs. This preconditioning, although valuable and recommended by manufacturers, leads to increased use and strain on the battery in EVs, mostly due to the activation of auxiliary systems designed to maintain cabin comfort. These systems include seat warmers, steering wheel warmers, cabin heating, and defrost functions for the front and rear windshields. These systems continue to use energy when the vehicle is driven. In addition, efficiency decreases for both internal combustion engine vehicles and EVs in cold weather due to conditions such as wet, icy, and snowy roads, which increases the rolling resistance of vehicles and can cause a drop in tire pressure, lower traction, and cabin heating and window defrosting.

This report seeks to answer the following key questions:

- **Can EVs be used in temperatures below −30°C (-22°F)?**
  - How does extreme cold affect their performance and efficiency?
- **Can electric vehicle supply equipment (EVSE) operate effectively in temperatures below −30°C (-22°F)?**
  - How does extreme cold impact charging infrastructure and charging times?
- **What are the best practices for owning an EV in climates subject to extreme cold?**

While it has been observed and tested that EVs lose efficiency as temperatures drop, this report confirms that both EVs and EVSE can and are being used in extreme cold conditions. There are specific routines and practices that enhance EV efficiency and are crucial to prevent the battery pack from reaching harmful temperatures. Notably, EV manufacturers recommend avoiding prolonged exposure of vehicles to temperatures below −30°C (-22°F) (Tesla 2024). However, specific information on duration and effects at these temperatures is limited. This report intends to fill that knowledge gap by providing insights and recommendations based on real-world data and analysis.

2 Locations of Cold-Temperature Climates

Various battery chemistries and thermal management systems exist in EVs today, making it challenging to categorize all EVs uniformly regarding their performance at extreme low temperatures. Typically, longer-range EVs are preferred in colder climates because they have more potential energy from the larger packs that can maintain an acceptable daily range even with the cold weather decrease in efficiency. Understanding the geographical distribution of extreme cold can help assess potential impacts on EV operation and guide EV owners in those regions. Likewise, knowing the lowest temperature a region can reach is helpful when deciding the potential impacts or worst-case scenarios when owning and operating an EV.

2.1 Minimum Temperature by Location

To visualize how different regions are affected by cold temperatures, the authors created maps using data from 2023. These maps employ temperature bands ranging from −55°C to 60°C (-58°F to -76°F) to identify locations at higher risk for EV performance degradation. Another great resource for visualizing regional impacts of temperature is found in the Alaska Center for Energy and Power EV Map (Wilber 2020). In these interactive maps, each region is given an EV score to indicate the range loss of an EV, days an EV must plugged-in (due to temperature), and the maximum expected range loss in that location.

The authors gathered data from the National Centers for Environmental Information nClimGrid-Daily dataset (Durre et al. 2022). This product provides daily maximum, minimum, and average temperatures for every county in the continental United States. The authors queried the Global Historical Climatology Network to add data for Alaska and Hawaii.

Figure 1 displays the minimum temperature reached for each county in the United States in 2023. Fifty-three percent of U.S. counties reached a minimum temperature of −10°C (14°F), 24% reached −20°C (-4°F, spread across 27 states), 5% reached −30°C (-22°F, in 11 states), and the following boroughs in Alaska reached −40°C (-40°F) and below: Denali Borough, Fairbanks North Star Borough, Nome Census Area, North Slope Borough, Northwest Arctic Borough, and Yukon-Koyukuk Census Area. The lowest recorded temperature in 2023 was −53.9°C (-65°F) in Yukon-Koyukuk Census Area, Alaska.

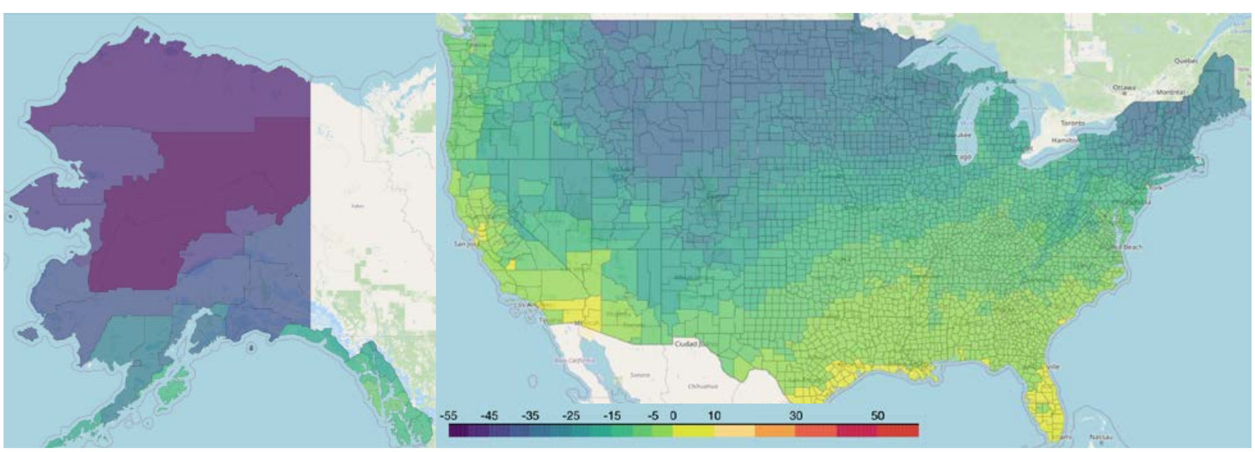

Figure 1. Minimum temperature (°C) reached by U.S. county in 2023

For the 53% of U.S. counties that fell below −10°C (14°F) at some point in 2023, extreme cold can significantly impact EV driving range by dropping average EV range to 60% of the rated driving range. Current and prospective EV owners should become informed of the best practices for owning and operating an EV at these temperatures. The analysis portion of this report focuses on Fairbanks, Alaska; the intent is to focus on the worst-case scenario for any given area.

Figure 2 shows the average daily minimum temperature reached by every county in the United States. With the lowest average minimum temperature reaching -11°C (12.2°F) in Alaska, the drop to harmful temperature ranges is much less likely throughout the year and as a prolonged period of time. Regardless, it is important to identify when temperatures do drop at alarming rates to avoid leaving an EV outside to ambient conditions. For more weather-related figures including a temperature density plot of Fairbanks, Alaska, see Appendix A.

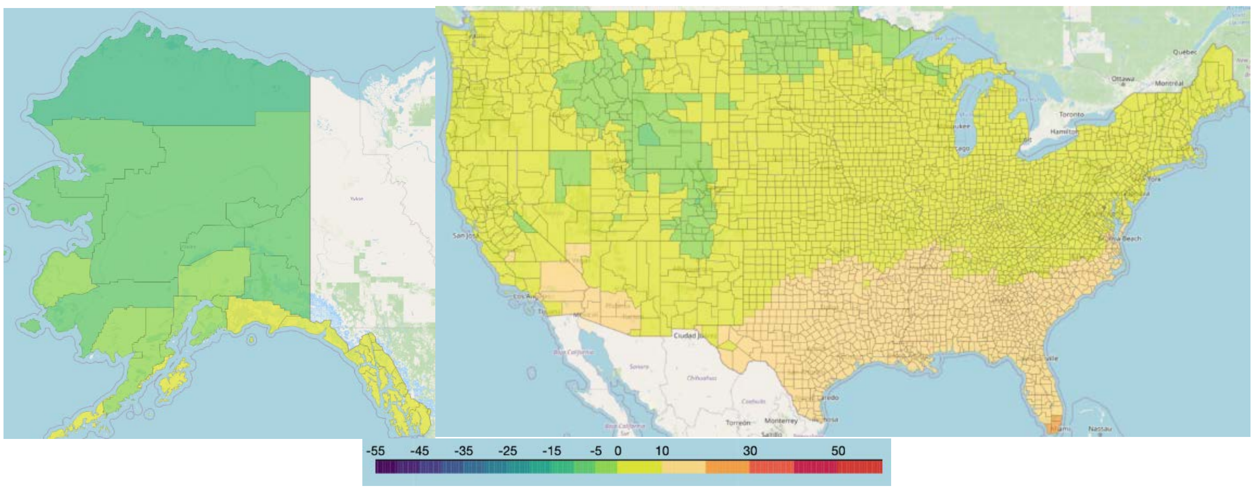

Figure 2. Average minimum temperature (°C) reached by U.S. county in 2023

3 EV Range Impacts

Gasoline-fueled vehicles waste about 60% of their energy on radiator and exhaust heat, some of which can be recaptured to make cabin heating systems use less energy than similar EV heaters would in cold weather (U.S. Department of Energy and Environmental Protection Agency 2015). EV motors are much more efficient, meaning they lose far less energy to heat. As a result, they need to generate heat separately to warm passengers. That is the primary reason that EVs lose range more significantly than gasoline- or diesel-fueled vehicles. They also require heat in cold temperatures to keep their batteries warm enough to function. Therefore, EVs lose efficiency when they operate outside of optimal ranges like the example shown in Figure 3. Range impacts vary significantly depending on battery chemistry, battery thermal management system (BTMS), cabin heating system, vehicle speed, and driver behavior (Hoff and Garberson 2024). NREL further examined how parking vehicles outside in cold weather impacts range versus parking inside.

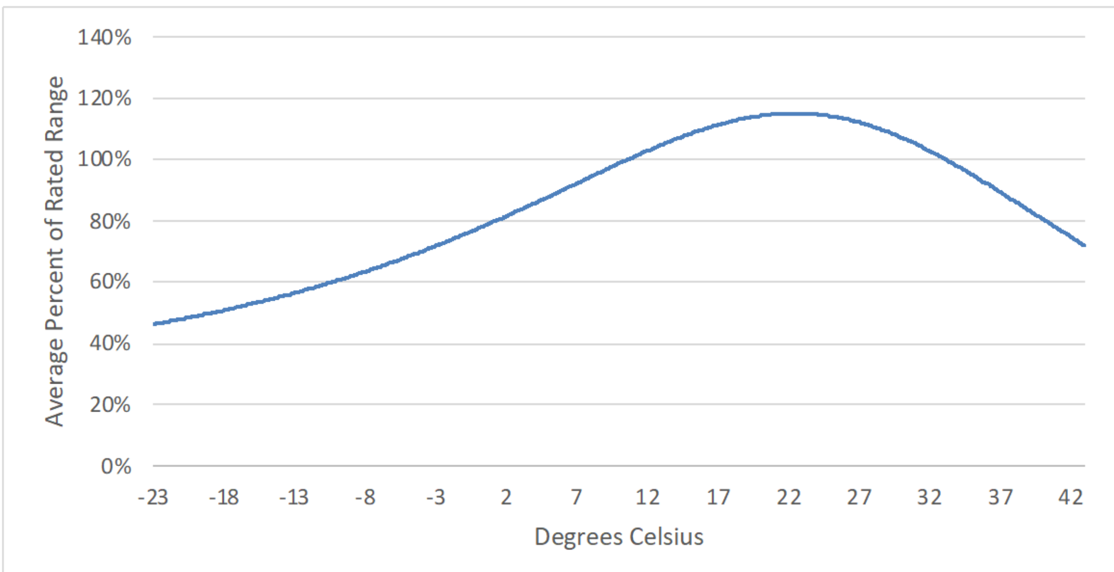

Figure 3. Average EV range as a percentage of rated driving range.

Data from Geotab

In the following section, the authors explore how EV components are affected by cold temperatures, with a focus on the battery storing the energy to propel the vehicle. A good overview of the vehicle-related impacts of cold weather are given in Senol et al. (2023), and a summary of cold (and hot) weather impacts on EVs and EVSE is provided in Powell and Johnson (2024). Some Alaska-specific information was provided by Wilber and Schmidt (2024) and Wilber et al. (2021).

While other factors such as road conditions, driving behaviors, the charger come into play, and air resistance (see Appendix C), the EV battery pack is what differentiates its performance from internal combustion engine vehicles and alternative fuel vehicles. The following sections give a broad overview of the battery chemistry to give an understanding of what is going on in the EV battery pack, as well as an idea of the various types that are designed into an EV. The following sections provide an overview of the vehicle data collected, as well as findings from the data analysis of three vehicles owned and operated in Fairbanks, Alaska.

3.1 Battery Chemistry

Lithium-ion batteries are the dominant energy storage solution for EVs due to their superior energy density, efficiency, and power characteristics. These battery chemistries are typically nickel manganese cobalt (NMC) or lithium iron phosphate (LFP), each offering different trade-offs between energy density and cost. While batteries have different chemistries (Houache et al. 2022), all are impacted by cold temperatures. For cold-weather applications, NMC batteries are best because they provide higher nominal voltage and range, critical for long-range EVs. Regardless, cold temperatures drastically affect lithium-ion batteries, slowing ion mobility, increasing internal resistance, and reducing both power output and charging efficiency.

At temperatures below 0°C (32°F), the electrolyte in lithium-ion batteries becomes more viscous, making it harder for lithium ions to flow between the anode and cathode. As a result, there is a reduction in energy storage capacity which leads to lower range and decreased power availability which leads to less power for propulsion and charging. Battery chemistries are designed to perform optimally around 23°C (73°F), meaning colder conditions necessitate more robust thermal management systems. A simulation analysis found that the BTMS can consume up to 0.15 kWh at −10°C (14°F), while the heating, ventilating, and air conditioning (HVAC) can consume 0.2 kWh (Lindgren and Lund 2016). Meanwhile, at a more ideal temperature of 20°C (68°F), the maximum load on BTMS cooling reached 0.02 kWh. Chacko and Chung (2012) found that the usable energy at -10°C (14°F) is 75% of that at 25°C (77°F). Figure 4 shows the decrease in capacity and increase in resistance of lithium batteries in cold temperatures.

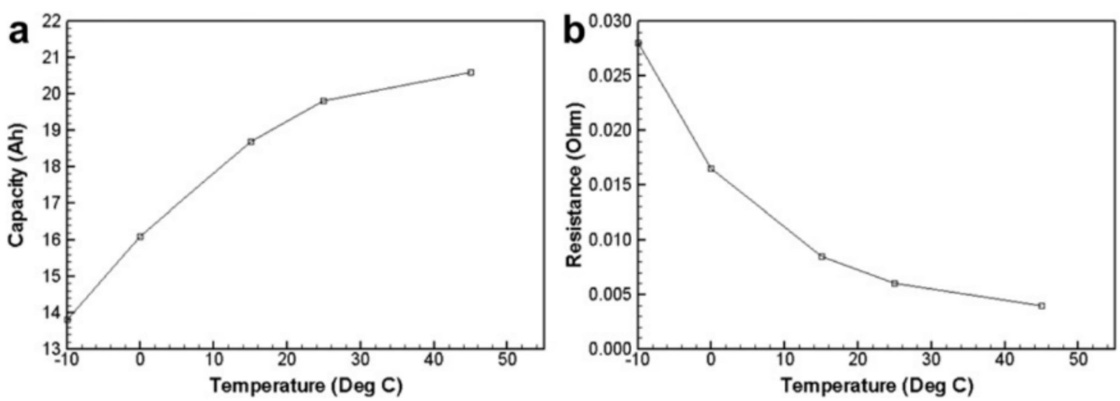

Figure 4. Lithium battery capacity decreases and resistance increase in cold temperatures.

Source: Chacko and Chung (2012)

In extreme cold, auxiliary systems such as the battery and cabin heater and engage to maintain the battery's temperature and cabin comfort. These systems prevent battery damage from the cold as well as extreme power and capacity losses but do so by using power from the battery contributing to range reduction in cold climates.

Batteries also deteriorate, both when used and when resting. Deterioration is faster in colder temperatures. "Calendar aging" refers to aging when not in use, and "cycle aging" is the aging that happens during usage. Both of these happen faster the colder it is relative to room temperature (Senol et al. 2023). Decreased capacity and increased aging all lead to decreased range for EVs. Decreased power means acceleration may be lower, or the vehicle may not have enough power for all the demands. Additionally, discharging or charging aged batteries under extreme cold temperatures increases the risk of thermal runaway in batteries—an uncontrolled electrochemical reaction that produces large amounts of heat (Senol et al. 2023).

3.2 Vehicle Heating Systems

Cabin heating systems are responsible for the greatest efficiency and range losses for EVs operating in cold weather. AAA tested five vehicle models in 2019 and found that the efficiency losses at -7°C (20°F) were far worse with cabin heating systems operating than when they were turned off (AAA 2019). For example, the 2018 BMW i3 used nearly twice as much energy per mile in the urban dynamometer driving cycle (UDDS) with the HVAC system operating than when it was off (Figure 5).

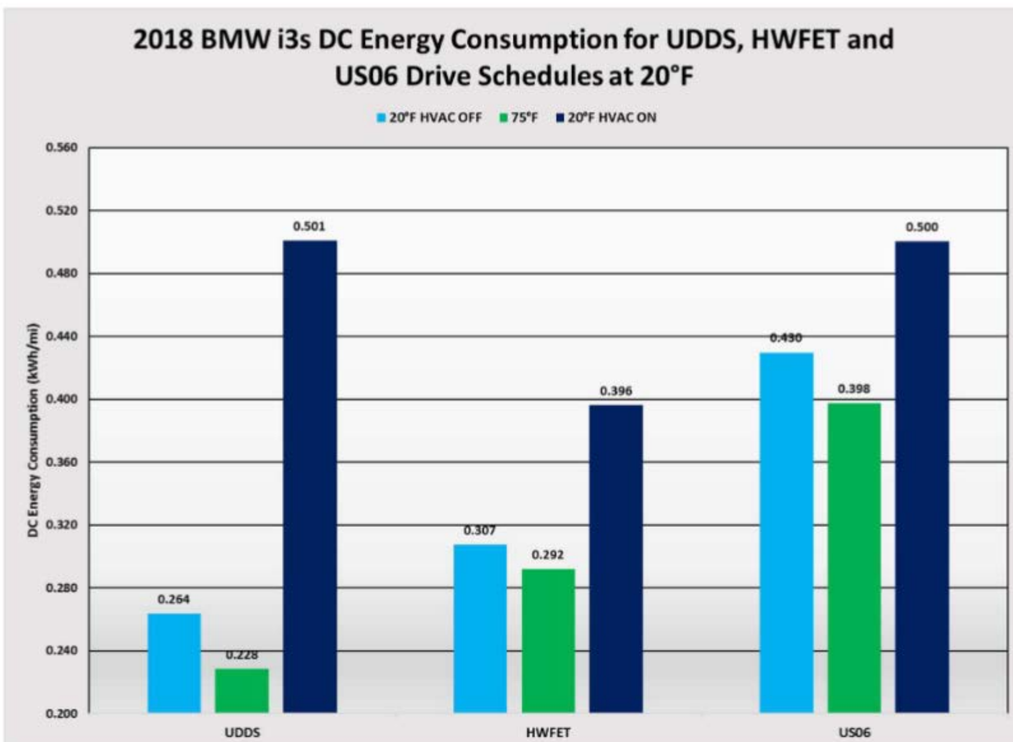

Figure 5. AAA test results for 2018 BMW i3 at 20°F.

Source: AAA (2019)

Efficient thermal management systems like heat pumps can minimize the impact and maintain longer EV range in cold-weather regions. Researchers have found that driving range of EVs with heat pumps is 15%–22.6% higher than EVs with electrical resistance heaters at −10°C (14°F) (Chowdhury, Leitzel, Santacesaria 2018; Li et al. 2021). However, projecting the same impacts down to -40°C (-40°F) requires more tests and studies as it possible to have little to no impact. Recurrent visualized the impacts across these studies as shown in Figure 6 (B. August 2023).

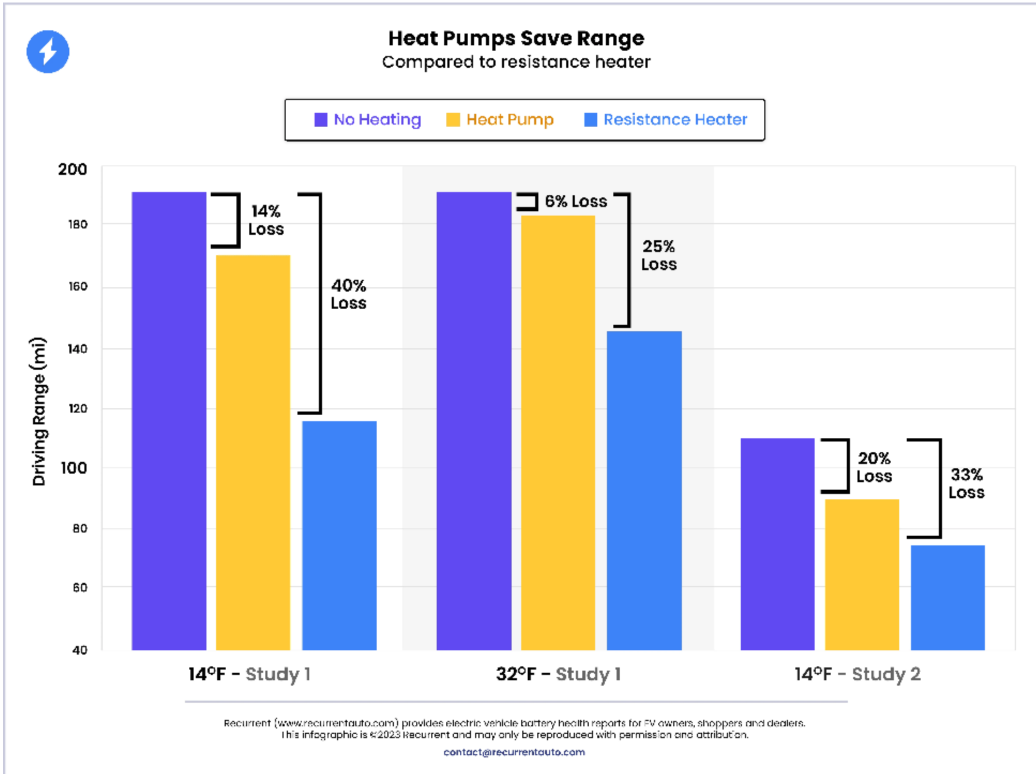

Figure 6. EV driving range difference between heat pumps and resistive heaters.

Source: B. August (2023)

BTMS maintain battery temperature to protect them from degradation, improve charging rates, and ensure EVs function properly. However, these heating systems use energy stored in the batteries to maintain the battery temperature close to the ideal operating temperature, often considered as 59°F to 77°F (15°C to 25°C). The BTMS heats (or cools) the battery appropriately for the conditions. The energy that the BTMS uses comes from the battery itself unless the vehicle is plugged in. Figure 7 visualizes the combined impact of HVAC and BTMS at various temperatures (Lindgren and Lund 2016).

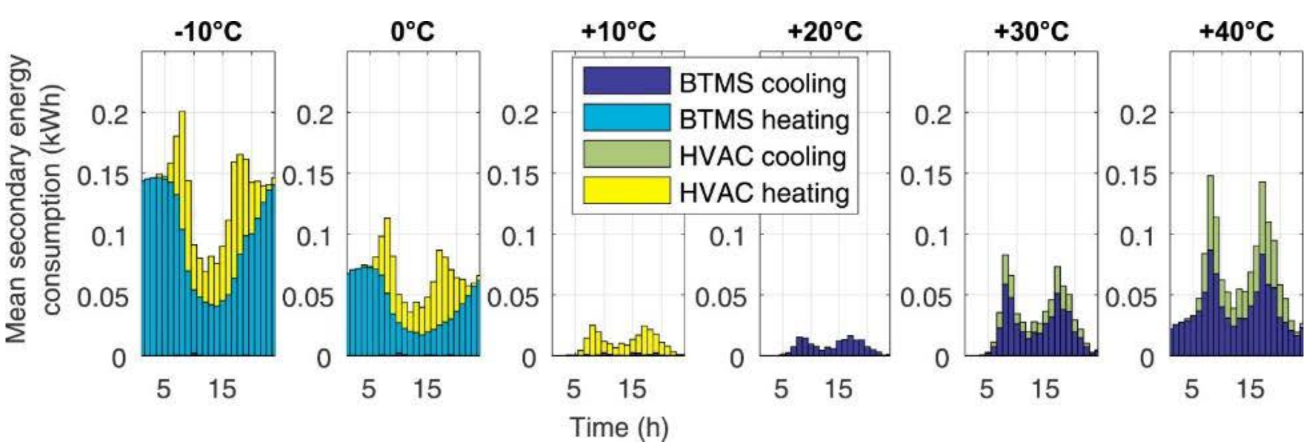

Figure 7. Heating and cooling energy consumption from HVAC and BTMS.

Source: Lindgren and Lund (2016)

3.3 Real-World Performance of EVs in Alaska

To assess the real-world performance of EVs in extremely cold conditions, the authors collected data from three Tesla vehicles operated in Fairbanks, Alaska. The data collected spanned 17 months from deep winter cold to milder summer temperatures. These vehicles provided an overview of cold-weather EV operation, ranging from a privately owned 2016 Tesla Model S Dual Motor (Tesla 1) stored inside to two fleet-operated 2023 Tesla Model Y Long Range vehicles (Tesla 2 and Tesla 3) stored outside.

Tesla 1 is a privately owned vehicle stored in a heated garage (typically heated to around 10°C in colder months) and almost always charged with a Tesla wall-mounted Level 2 charger. This vehicle was driven 9,998 miles in the span of one year, which is an average of 832 miles per month. The vehicle went through a consistent routine. It was driven to and from work on weekdays, in addition to regular weekend driving, and was consistently plugged into a Level 2 charger for overnight charging. The longest trip taken with the vehicle was from Fairbanks to Anchorage, about 360 miles away, where a direct-current fast charger (DCFC) was used along the way. The vehicle never reached a state of charge (SoC) of 0%, and only charged to 100% on extremely cold days or prior to long trips.

During an extreme freeze test of Tesla 1, the vehicle was left outside without charging for 1.5 days in temperatures that reached −37°C (-35°F). Although it did eventually start, charging was first required to warm the battery to an operable temperature. After the freeze, the vehicle was plugged in to a Level 2 charger for eight hours where the battery dropped from 21% to 15%. To speed up the warming process, heating fans were used. The Tesla then returned to normal vehicle operation after about 40 minutes of charging, and no significant damage was found for the battery.

Tesla 2 and Tesla 3 were fleet vehicles stored outside and almost always connected to a Level 2 charger. Tesla 2 drove 14,564 miles over 17 months, while Tesla 3 covered 8,451 miles over 12 months, showcasing the ability to maintain moderate vehicle usage even during severe winter conditions. During a cold snap from January to February, both vehicles' efficiency dropped below 1.2 miles per percent charge, but they were still able to meet normal operating conditions of the fleet.

Miles per percent charge was used for this analysis because energy consumption in kWh was not available in the data collected. Miles per percent charge is the distance traveled in one percent of the vehicles full charge and thus is dependent on the battery capacity of the vehicle. For these Teslas with a 90kWh battery capacity at 100% charge, one percent charge equates to 0.9kWh. The conversion to miles per kWh looks like this: 1.2 miles / 0.9 kWh = 1.33 miles/kWh. The authors summarized efficiency data by day and found that the Teslas stored outdoors functioned as needed for the fleet.

The authors compared vehicle efficiency to ambient temperatures in the storage environment for each of the three Teslas. They aggregated data by day and month, with temperatures recorded based on drive cycles (i.e., when the vehicles were driven and actively collecting data). This method means that temperature readings might be slightly skewed toward warmer parts of the day when the vehicles were in use. Nonetheless, this study's temperature range—from a chilly −24.14°C in February 2024 to a warm 21.88°C in July 2023 (-11.45°F to 71.38°F)—provides a broad spectrum for analyzing the effects of temperature on EV performance. Trips under 1 mile were eliminated from the analysis, as they indicated efficiency above 10 and below 0.5 miles per percent charge, which is drastically outside the common ranges for efficiency.

The lowest recorded average monthly temperature as recorded by the vehicles was −24.14°C (-11.45°F), observed in February 2024, during a prolonged cold snap that occurred from the last 2 weeks of January through the first week of February, with another spike in cold at the end of February. The lowest overall temperature was -39.4°C (-39.4°F) recorded on 1/26/2024 and 2/2/2024. The months with the longest driving distances were May and June, while November and December saw the shortest driving distances, which aligns with the decreased efficiency observed during colder months. This could be due to a number of reasons, with drivers likely limiting time on the road during dangerously cold temperatures and associated road conditions.

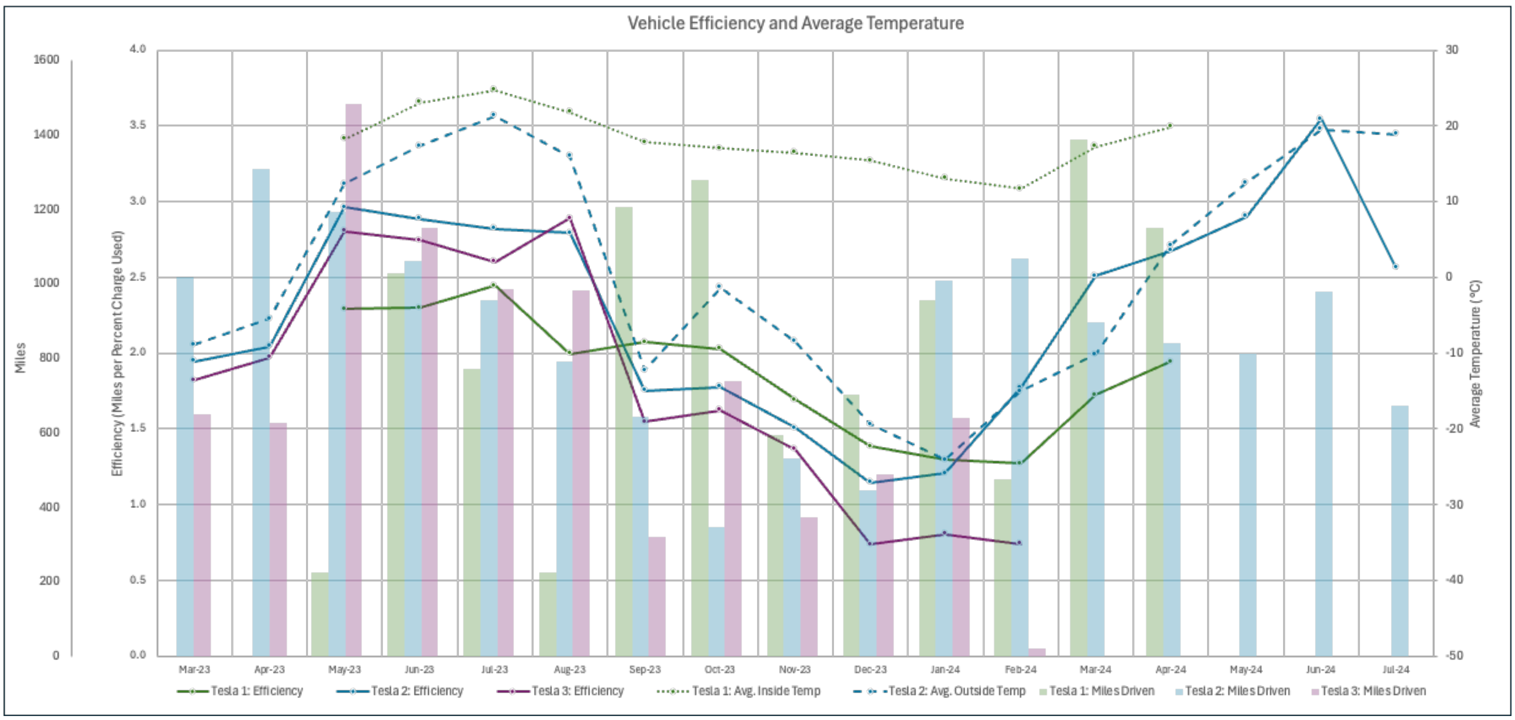

Figure 8. Vehicle efficiency and average temperature

Figure 8 illustrates each vehicle's efficiency over time, with solid lines representing efficiency trends, and the blue dashed line indicating average monthly outside temperatures as recorded by Tesla 2 and Tesla 3. The green dotted line represents the average inside cabin temperature recorded from Tesla 1, which was stored indoors. All three vehicles operated within the same general area.

The average cabin temperature was about 20°C (68°F) when the outside temperature was above 0°C (these months averaged an outside temperature of 14°C or 57°F) and about 15.5°C (59.9°F) when the outside temperature was below 0°C (these months averaged an outside temperature of -12°C or 10°F), indicating that the HVAC system worked significantly harder during colder months to maintain a comfortable cabin temperature. The average difference between the inside and outside temperatures was approximately 17°C during cold months, inferring an increased energy demand in maintaining internal warmth.

EV efficiency and range dropped during colder months for all three vehicles. For instance, as illustrated in Table 1, the efficiency fell 48% for Tesla 1, 57% for Tesla 2, and 69% for Tesla 3 from their warmest to coldest recorded months. Tesla 3 can be considered an outlier, but it is not known why. It was driven more than 250 less miles than the other two and is possible it was only driven on extreme cold days or only driven in high-speed driving. A linear regression analysis yielded an R-squared value of 0.7551, indicating a strong relationship between temperature and efficiency. Extrapolating from this linear relationship, it was estimated that at −40°C, efficiency would drop to around 0.47 miles per percent charge.

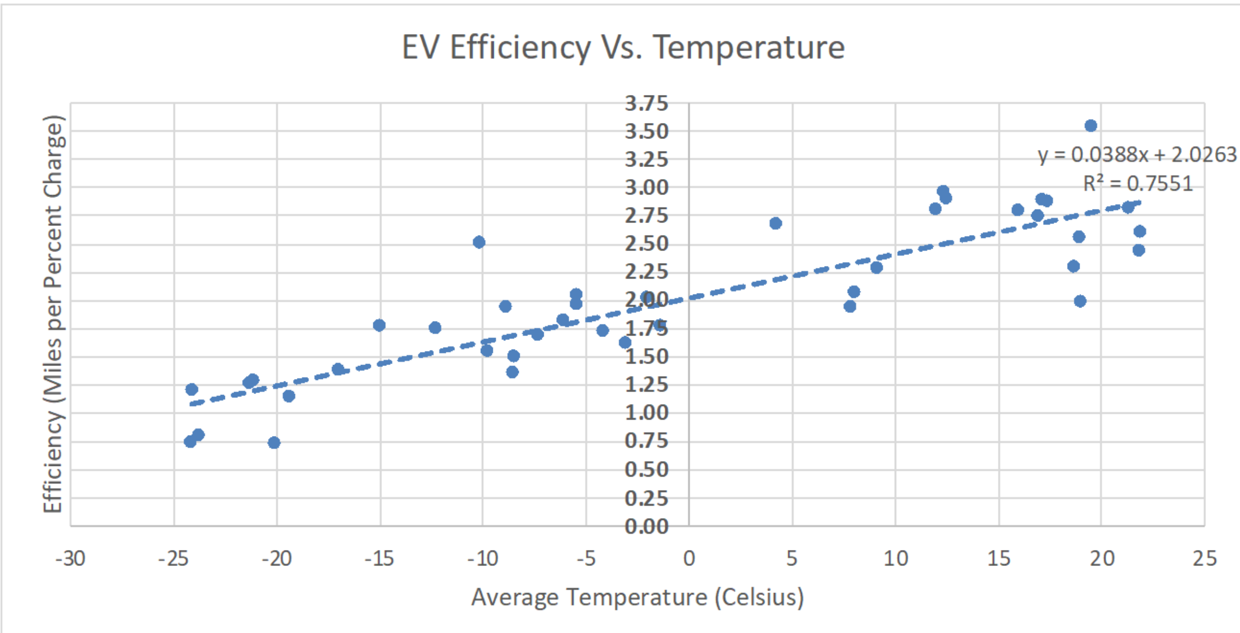

Figure 9. EV efficiency versus temperature for three tesla in Fairbanks, Alaska

Table 1 summarizes the warmest, highest efficiency, coldest, and lowest efficiency months for each Tesla vehicle. The efficiency data demonstrate a clear decline during colder months. Notably, on average, efficiency dropped by 58% from the warmest to coldest months across all vehicles. This represents a real-world scenario for vehicle owners specifically in Fairbanks, Alaska. The average temperature in Table 1 is as recorded by the vehicle during driving operations because the data was aggregated by drive cycles. Additionally, this table also represents the efficiency during Fairbanks' most recent cold snap from January 22–February 5. During this period, vehicles averaged 0.98 miles per percent charge, and two of the three vehicles were driven more than 500 miles.

Table 1. Tesla Data Summary

		Month	Miles Driven	Average Temperature (°C)	Efficiency (miles/% charge)
Tesla 1	Warmest month	July 2023	770	21.81	2.45
	Highest efficiency	July 2023	770	21.81	2.45
	Coldest month	Feb. 2024	474	−21.36	1.27
	Lowest efficiency	Feb. 2024	474	−21.36	1.27
	Cold snap	Jan. 22–Feb. 5, 2024	616	−30.79	1.15
	% Efficiency drop (from warmest to coldest month)				**48%**
Tesla 2	Warmest month	July 2024	955	21.33	2.82
	Highest efficiency	June 2024	978	19.51	3.55
	Coldest month	Jan. 2024	1,009	−24.14	1.20
	Lowest efficiency	Dec. 2023	444	−19.42	1.15
	Cold snap	Jan. 22–Feb. 5, 2024	512	−29.68	1.13
	% Efficiency drop (from warmest to coldest month)				**57%**
Tesla 3	Warmest month	July 2023	985	21.88	2.60
	Highest efficiency	Aug. 2023	981	17.10	2.89
	Coldest month	Jan. 2024	639	−23.77	0.81
	Lowest efficiency	Dec. 2023	487	−20.10	0.74
	Cold snap	Jan. 22–Feb. 5, 2024	250	−25.28	0.65
	% Efficiency drop (from warmest to coldest month)				**69%**

The data show a clear impact of cold weather on EV efficiency. EVs experienced a significant drop in efficiency as temperatures decreased, resulting in reduced driving range. This finding is crucial for EV owners and manufacturers, as it underscores the importance of considering climate and temperature impacts when designing, using, and planning for EV performance, especially in colder regions.

Based on the data, the authors assessed the potential impact of real-world driving range on the Ford F-150 Lightning Extended Range. This analysis requires two major assumptions:

1. The relationship between temperature and vehicle efficiency remains linear below −25°C. This assumption is supported by a previous study mentioned in Section 3.3.1 below which modeled energy use per unit distance using a third-order polynomial equation (Wilber and Schmidt 2024). Their analysis incorporated temperature and the vehicles EPA-rated energy use per mile in kWh/mile to determine the energy consumption.
2. The Ford F-150 Lightning is impacted by temperature in the same way as the Teslas used in this analysis.

Nevertheless, the authors explored the potential implications. They first converted miles per percent charge to miles per kilowatt-hour for the Tesla. This is done using the original vehicle's battery capacity—in this case 90 kWh would equate to 100%. This results in 0.53 mi/kWh. Then, they transferred this efficiency to the desired vehicle's battery range using its battery capacity—in this case, the Ford F-150 Lightning is 131 kWh. This extrapolation results in 69 miles at 100% SoC in −40°C at an efficiency of 0.53 mi/kWh.

The authors explored an alternative methodology using the equivalent drop in efficiency shown in Table 1 for a Ford F-150 Lightning Extended Range. That would result in a driving range of 85–142 miles in −40°C (efficiency of 0.64–1.08 mi/kWh). This range falls within the study previously mentioned that uses a third order polynomial and yields a range of 1.23 kWh/mile which converts to 0.812 miles/kWh.

The authors also compared these calculations to a real-world test explored in Section 3.3.3 in which a Ford F-150 Lightning was driven in −22°C to −40°C weather in Alaska and resulted in an efficiency of 1.23 mi/kWh, which would correspond to 161 miles of driving range. The difference in efficiency between the real-world test and the calculation can be due to several factors that differentiate the vehicles, including different thermal management systems, tire rolling resistances, snow conditions, a larger battery pack that can withstand the change in temperatures, and driving patterns.

Whether the actual range of the Lightning Extended Range at −40°C is 69, 85–142, or 161 miles, in all cases, there is a significant reduction from its 320-mile rated range. This is intended to give a range of efficiency at -40°C.

3.3.1 Crowdsourced Alaska Data

In Alaska, Wilber and Schmidt (2024) crowdsourced Alaska EV data and estimated a polynomial fit to the data. Although NREL's analysis shows a linear representation of the real-world data gathered, Wilber and Schmidt explain that there is a linear relationship in temperatures between −40°C and 20°C (-40°F and -4°F), but once combined with crowdsourced data that reach warmer temperatures where vehicle air conditioning is used, a third-order polynomial is needed.

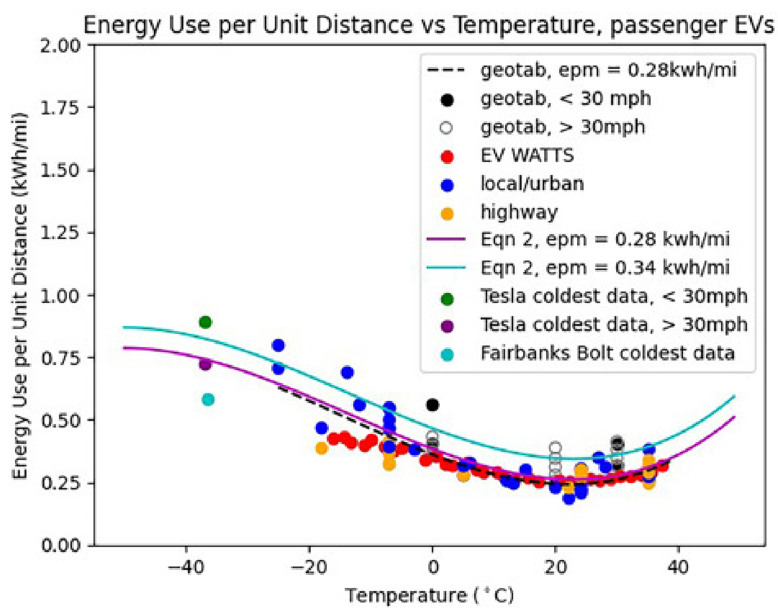

Figure 10. Energy use as a function of temperature, crowdsourced from Alaska EV users.

Source: Wilber and Schmidt (2024)

Wilber et al. (2021) published an online EV energy estimator for Alaskans, also outlining the issues with EVs in Alaska. Figure 11 shows a graphic from the publication.

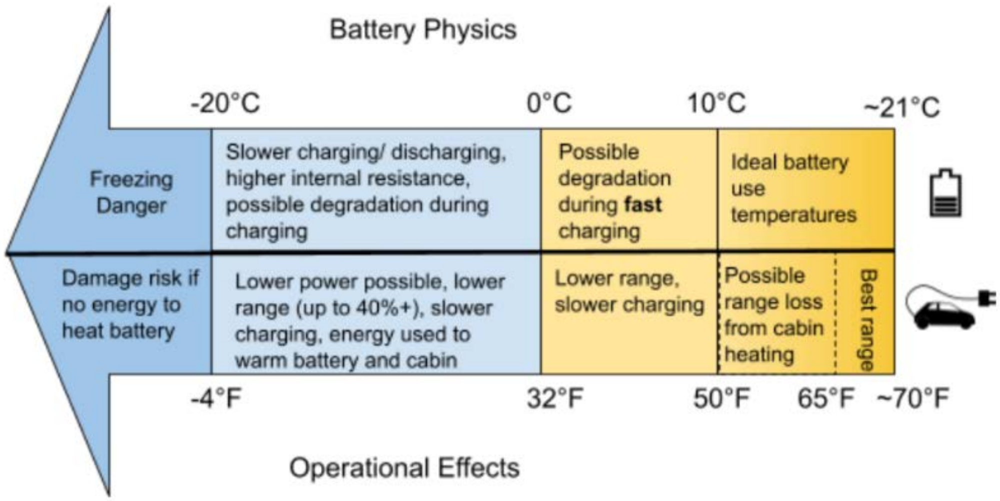

Figure 11. Battery effect (upper portion) and operational effects (lower portion) of cold temperatures on EVs.

Source: Wilber et al. (2021)

3.3.2 Norwegian Winter Driving Test

In Europe, the Norwegian Automobile Federation (Norges Automobil-Forbund) has been test-driving multiple EVs in wintertime under the same conditions, annually for the last few years. For this “Grand Prix” effort winter edition (Stuestøl 2024), they leave vehicles plugged in and charged to 100% in a heated garage, then leave and drive the same course with all vehicles, checking the distance driven at 90% and 100% of battery usage. They compare this to the international standard Worldwide Harmonised Light Vehicles Test Procedure (WLTP). This procedure is similar to the way the U.S. Environmental Protection Agency (EPA) tests EVs, but EPA then multiplies its laboratory results by 70% to account for factors such as cabin heating (EPA 2015), whereas the WLTP does not. The 2024 Norwegian test was conducted during temperatures ranging between 10°C and -2°C (−14°F and 28°F). The actual range of a selection of cars from the Norwegian test, for which an EPA range was found, is shown in Figure 12 as bars, together with the EPA range as a background. Each bar showing the range is marked with the percentage it represents of the EPA range. The range is the mileage that the vehicles achieved going from 100% charged to 0% charged in the below-freezing (though not extreme cold) temperatures.

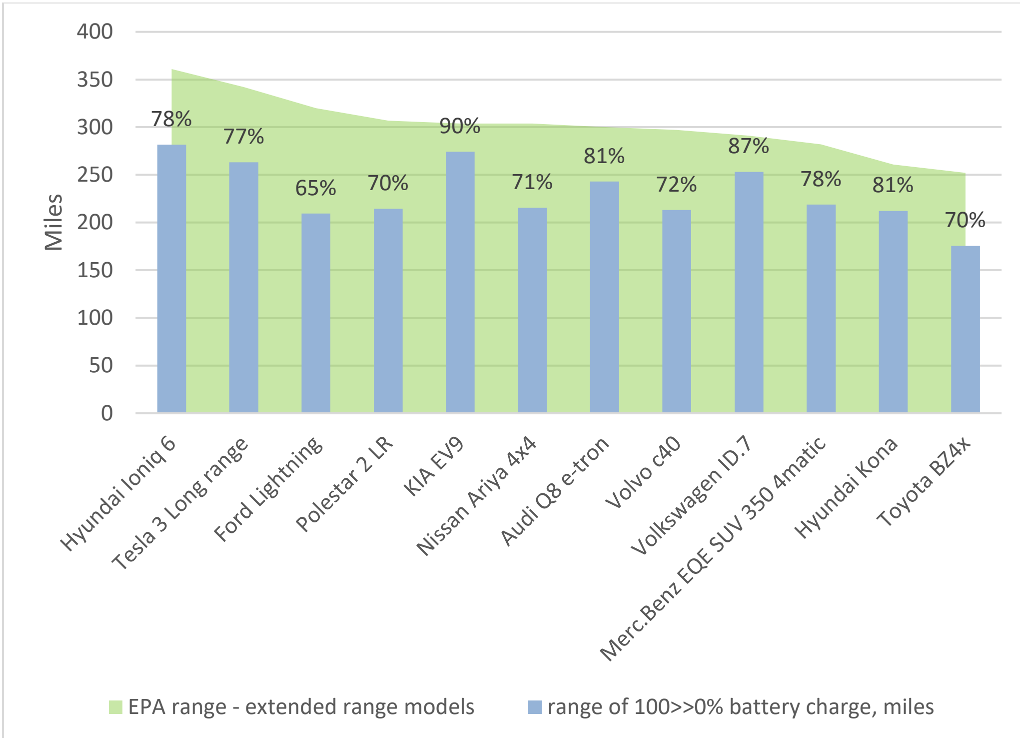

Figure 12. The range (miles) of some EVs tested in Norway at 14°F–28°F weather, in comparison to the stated EPA range for the models.

The Norwegian Automobile Federation published their data comparing the range, in kilometers, to the WLTP range. For this figure, the range was translated to miles and compared to the EPA range instead, for a subset of the vehicles tested by the Norwegians. Green background area shows the published EPA range for each EV. Blue bars show the actual range achieved from a full charge (100%) to empty (0%), for the test done during 14°F–28°F outside temperatures. The actual range, as a percent of EPA range, is shown as the label for each bar.

3.3.3 Individual Drivers in Interior Alaska

Interviews were conducted with several individuals in interior Alaska (for the focus of this studt) that drive EVs, including in winter. Additionally, some experiences documented on the internet were consulted.

The interior Alaska drivers interviewed drove Teslas. A summary of the interviews follows:

- Drivers are overall very satisfied with their experience, both in summer and winter.
- Overall, drivers felt that range decreased significantly in winter.
- The drivers always kept the vehicles plugged in overnight, set to charge to 80% or 85%, unless they were heading on a longer road trip, such as to Anchorage.
- One Tesla driver reported that on the coldest days, a Level 1 charger may provide enough power to keep the charge level constant or decreasing slightly (as opposed to it decreasing more significantly due to cold if it was not plugged in).
- On the coldest days (nearing -40°C), one Tesla vehicle showed an estimated time of 8–12 hours to charge from 50% to 85% battery charge with a Level 2 charger.
    - A higher battery discharge would have required more than overnight to charge to 85% battery charge.

- The drivers used the vehicle app daily to set departure time. This allowed for the vehicle to preheat to a comfortable temperature by the time the drivers were ready to go.
- Stock tires did not hold pressure well, and one driver had to fill their tires with air daily on the coldest days.

From an experience documented on the internet, one owner of a Ford Lightning extended version in Fairbanks documented driving in −40°C on a 95-mile trip (each way) to Delta Junction (Bandit216 2022). The driver used 76 kWh for the one-way 95-mile trip to the destination, resulting in approximate usage of 1.23 mi/kWh, starting from a warm garage and a preheated vehicle cabin. At 1.23 miles per kWh and a 118kWh battery, this equates to a total range of 145 miles which is less than half of the factory number of 320 miles. Once at their destination in Delta Junction, the driver reported it took 76 minutes to add 51 kWh, writing this was possibly because he had cabin heat on during this time, as it was −29°C (−20°F). The driver reported that other than range reduction, increased charging time, and decreased comfort (cabin cooler than usual), he did not experience any other issues, mechanical or otherwise, driving the Ford Lightning in the −40°C to −29°C (−40°F to −20°F) temperatures.

3.3.4 EVs With Trailers

It is expected that EVs pulling trailers under cold conditions will see a significant decrease in range. Under summertime conditions, MotorTrend reported that a Ford Lightning Platinum pulling a trailer had a range of 90–115 miles instead of the 320-mile EPA range (Tingwall 2022), and compared to 255 miles when the trip was done with only a single person on board and no trailer. The trailers ranged from 3,000 to 7,000 lb. The decrease in range is about 60%–70% for an EV truck pulling a trailer in summertime conditions. When a heavy load of a trailer is combined with very cold conditions, the expected decrease in range may potentially be another factor of 2, so potentially a decrease in range of 83% of the EPA range.

3.4 Overview of Recommendations

Best practices for operating EVs in cold climates include using efficient occupant comfort features, taking care of the battery, and being aware of the decreased range in cold temperatures.

- Passenger comfort:
  - Use heated seats (less energy consumption than cabin heating).
  - Use heated steering wheel (less energy consumption than cabin heating).
  - Turn down cabin heat as much as possible. Wear jackets in order to do so.
  - For temperatures above roughly −25°C (-13°F), heat pumps are more efficient than resistive heaters. Below that temperature they do not hold as significant of an advantage.
- Battery:
  - Use preconditioning before charging.
  - Use preconditioning before driving.
- Vehicle:

- Store/charge in a garage if possible. This is for increased efficiency and ease of maintenance but comes with other tradeoffs such as increased costs.
- Keep plugged in when not in use during cold periods so the vehicle can draw grid power to keep battery from degrading.
- Turn down regenerative braking on icy roads for increased efficiency.

- Expectations:
  - Expect decreased range.
  - For coldest days (falling below -20°C or -4°F), range may be one-half to one-third of official range.
  - Expect significantly larger range decrease if pulling a trailer.
  - Expect longer charge times.

4 EVSE Cold-Weather Issues

EVSE face similar challenges to the EV when being used in extreme cold climates. Both the EV and its charger experience potential performance degradation as temperatures drop. This section provides an overview of the data used for this analysis. There are two primary specifications with EVSE in cold weather. First, the EVSE units themselves are only rated to charge within a certain temperature band, most commonly above −30°C. They are often rated to sit in colder weather so they can function again when the temperature warms up. Second, charge rates are limited due to the EV itself.

4.1 Charging in Cold Temperatures

A charging study of 2012 Nissan Leafs in the mid-2010s (Motoaki, Yi, and Salisbury 2018) found that DCFC duration was highly dependent on temperature, even for temperatures close to freezing (i.e., not extreme cold temperatures). Figure 13 shows that a high SoC was achieved faster for warmer temperatures (warm-colored points) than cold temperatures (blue-colored points). The charger was limited to 60 minutes of charging, and the study was of EVs used as taxis in New York.

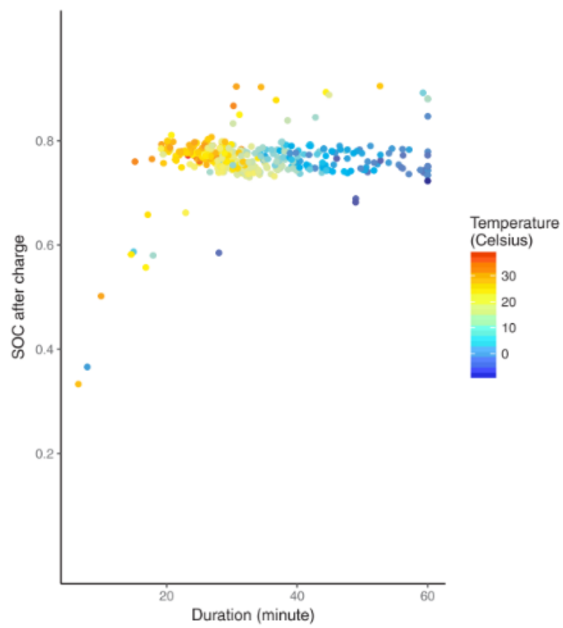

Figure 13. Dependance of DCFC final SoC on temperature.

Source: Motoaki, Yi, and Salisbury (2018).

SoC is shown as a decimal instead of a percentage. The temperature range covers temperatures below 0°C (32°F), shown in blue, to room temperatures, shown in orange (not labeled; orange 25°C = 77°F) and warmer.

Charging EVs in cold weather has time-related impacts on some makes and models, and hardly any impacts on other models, per a technical report published by a Finnish team (Tikka, Lassila, and Laine 2021) that tested five models from different manufacturers. They tested charging vehicles at 20°C, 0°C, −10°C, and −20°C (68°F, 32°F, 14°F, and −4°F) after being "driven" (wheels moving, but under lab conditions), as well as after cold storage—not being used overnight. They reported that while Teslas charged significantly longer in colder temperatures, other makes and models of EVs do not show such a temperature dependence. Specifically, the report tested a 2016 Tesla S P85, a 2020 Nissan Leaf, a 2020 Volkswagen ID.3, a 2020 Kia e-Niro, and a 2020 Volvo V60 T6.

The report did not specify whether the difference is due to difference in battery thermal management or whether longer charging time may result in a better lifetime for the battery. Two anecdotal reports by an EV enthusiast from the Denver area reported that after leaving his Tesla and Nissan Leaf unplugged for 2 nights in −20°F temperatures in 2022, the Tesla took a significant amount of time to heat the battery before it started charging it, while the Nissan Leaf started charging the cold battery immediately (Out of Spec Reviews 2022).

It is possible that longer charge times may be due to the system initially conditioning the battery to a warmer temperature before charging it, and—based on Senol et al. (2023)—therefore decreasing battery aging and increasing battery lifetime.

Another study published in 2018 also focused on fast chargers (i.e., Level 3) found that charging rate decreased significantly in cold temperatures (Trentadue et al. 2018).

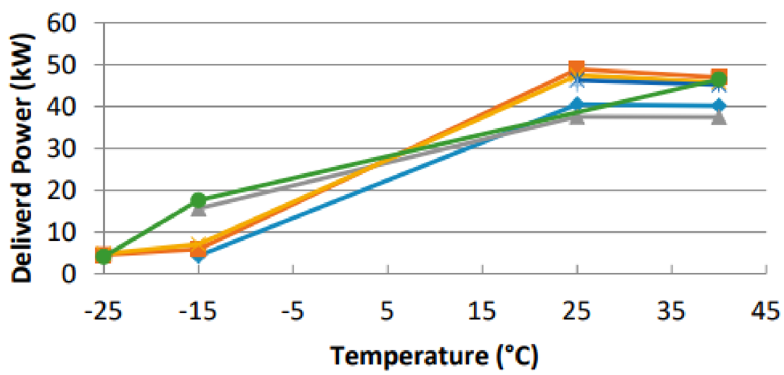

Figure 14. DCFC (i.e., Level 3 charger) delivered power as a function of temperature.

Source: Trentadue et al. (2018)

The lowest temperature the DCFCs were tested at was −25°C (−13°F).

4.2 EVSE Unit Operational Temperatures

The authors examined the U.S. General Services Administration (GSA) blanket purchase agreement EVSE options as of May 2024 and found the temperature ratings for charging EVs for each of the units. The results show that the only Level 2 charging models rated to operate down to −40°C are offered by ChargePoint (Figure 15). All the DCFC models on the GSA schedule were rated to operate at −35°C (-31°F) or higher (Figure 16). Most of the Level 2 EVSE on the market is temperature rated to −30°C (−22°F). A few are rated to only −20°C (−4°F), and a few are rated down to −40°C. See Appendix D for the list in Figure 15 filtered for those rated −30°C (−22°F) and colder, and the categories expanded to include the amperage rating of the EVSE. Per that figure, the EVSE rated to −40°C (−40°F) is available at a maximum of 50-A rating. No 80-A Level 2 EVSE is rated to that temperature on the GSA schedule. However, one charger that is not included in the GSA blanket purchase agreement but is well known for its use in extreme cold climates is the FLO SmartDC charger (available for 100 kW) that has an operating temperature of −40°C (Flo 2022).

In addition, there are several reports of EVs charging at lower temperatures than the equipment ratings. As noted in Section 3.3, a Tesla parked outside at −37°C (-35°F) was able to charge its battery, although the charger first warmed the EV battery to an operable temperature. Similarly, a Ford Lightning charged on a 50-kW DCFC in Fairbanks charged at 45–46 kW when the ambient temperature was −29°C (-20°F) and 34 kW at −40°C (Bandit216 2022). For those charging events, 7–8 kW went toward heating the driver or 10–11 kW went toward heating the battery, but heat was not directed toward both the driver and the battery at the same time.

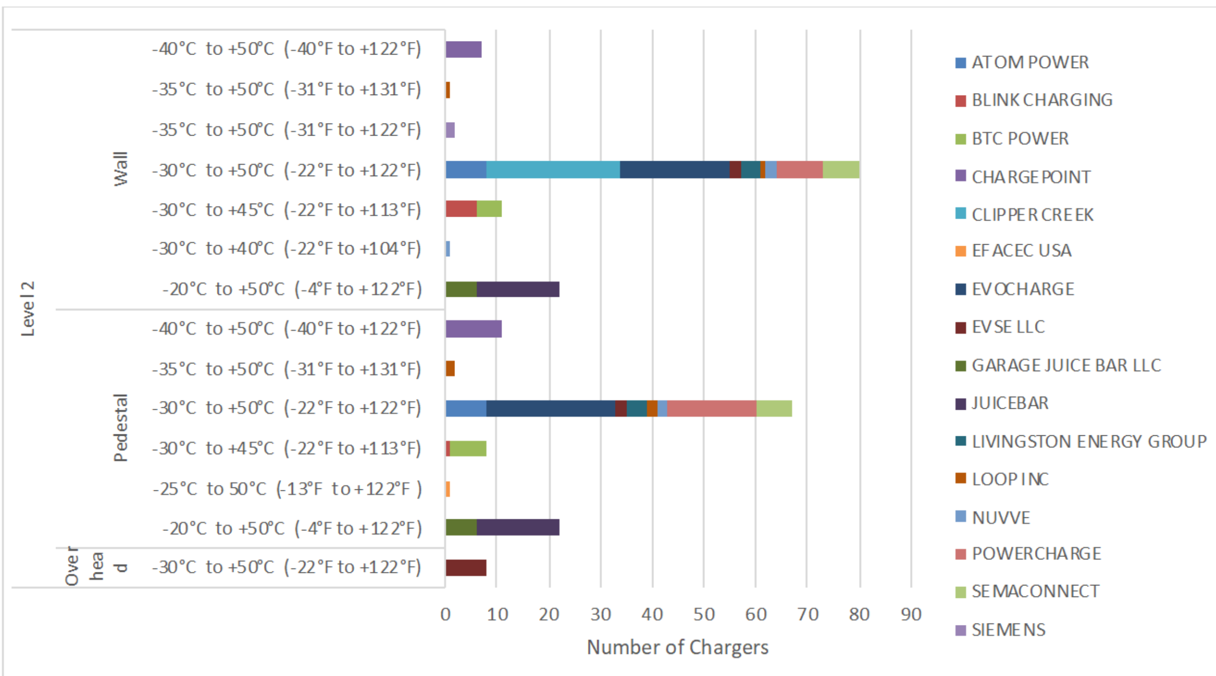

Figure 15. Charging temperature ratings for Level 2 chargers on GSA schedule

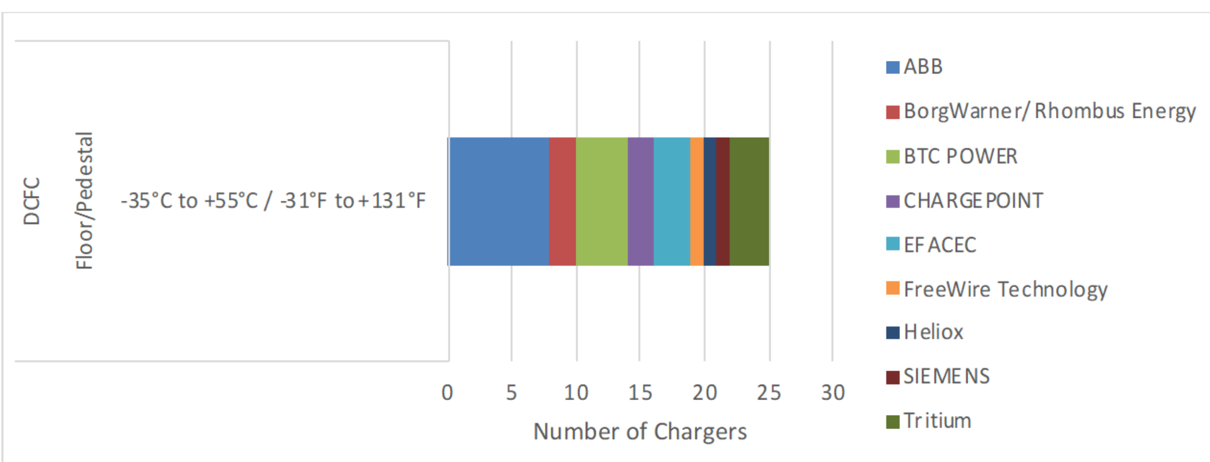

Figure 16. Charging temperature ratings for DC charging on GSA schedule

The authors also looked at the charging temperature ratings for several EVs available through GSA. Most of the vehicles are rated to operate down to −40°C, but only the charger sold with the Silverado is rated to operate at that temperature (Table 2). Additionally, some vehicle owner manuals contained instructions not to leave the vehicle in extreme cold for long periods of time (e.g., do not leave Nissan Ariya in temperatures below −25°C (-13°F) for more than 7 consecutive days). Most owner's manuals recommend plugging vehicles in below 0°C (32°F).

Table 2. Temperature Ratings for EV Models and Stock Chargers

Vehicle Make	Vehicle Model	Vehicle Type	Rated Maximum Range (mi)	Minimum Operating Temperature (°C)	Minimum Charger Temperature (°C)
Nissan	Leaf	Sedan	212	−40	−20
Tesla	Model 3	Sedan	315	−40	−30
Hyundai	Ioniq 6	Sedan	361	−35	−30
Ford	Mach-E	SUV	312	−40	−22
Tesla	Model Y	SUV	330	−40	−30
Subaru	Solterra	SUV	228	−30	−20
Ford	F-150 Lightning	Pickup	320	−40	−30
GM	Silverado	Pickup	450	−40	−40

4.2.1 Charging Equipment Issues

An article in Green Car Reports from March 2023 indicated that the Ford Lightning truck the author was testing stopped charging via the standard Ford Level 1 charger rated to -30°C (−22°F) when that temperature was reached (Feder 2023). The author had to bring the charger inside, let it thaw out, and then was able to proceed with charging the EV.

A similar situation happened to an editor from Pickup Truck + SUV Talk who was testing a different make/model in December 2022, and whose Level 2 charger stopped working in cold conditions, though warmer than the temperature rating (Pickup Truck Plus SUV Talk 2022). After the charger was brought inside and thawed out, it worked again.

4.3 Charging Rates at Cold Temperatures

As temperatures decrease, charging times increase due to several factors. First, the EV requires more energy to compensate for losses while driving, particularly the energy used by the BTMS and HVAC systems. Additionally, energy is required to maintain battery and cabin warmth while the vehicle is parked in cold ambient conditions. This is particularly true during charging sessions in which drivers are inside the car and need the cabin temperatures to remain within a tolerable range. Lastly, charge times can increase due to the internal resistance of ions in colder climates; this is related to the slowed movement inside the vehicle's battery that requires more energy from the charger to reach an operable condition.

Research shows that at temperatures between −20°C and −40°C (-4°F and -40°F), electrolytes within lithium-ion batteries may begin to freeze. This leads to increased internal resistance, higher impedance within the cells, and a subsequent reduction in both capacity and performance.

However, it is important to note that this refers to the battery temperature itself, not the ambient temperature (Warner 2024).

One comprehensive study investigating the effects of extreme cold on EV fleets used lithium-ion battery models to simulate performance. These simulations, while insightful, primarily focused on lithium manganese dioxide batteries, a chemistry commonly found in vehicles such as the Nissan Leaf and Chevrolet Volt. However, this limited scope excludes other widely used battery chemistries such as nickel cobalt aluminum used in the 2016 Tesla Model Y (Tesla 1), nickel cobalt manganese found in the 2023 Tesla Model Y (Tesla 2 and Tesla 3), and LFP batteries found in some other EVs. Additionally, real-world conditions introduce variability—such as driver habits and changing ambient temperatures—that cannot be fully captured in controlled simulations, further emphasizing the need to validate models against actual fleet operations (Lindgren and Lund 2016).

The study demonstrated that charging times significantly increase in cold temperatures. Charging time was shown to increase by 70% when moving from 20°C to 0°C, rising from 65 minutes to 110 minutes. At −10°C, charging time increased by a further 88%. In contrast, warmer ambient conditions (30°C–40°C) led to a 15%–31% increase in charging time due to additional loads imposed by the vehicle's HVAC and BTMS, which work to maintain operational safety and comfort. Another key finding from the study highlighted the impact of preconditioning and standby battery management on charging efficiency in cold climates. For instance, preconditioning the vehicle before charging at −10°C reduced charging times by 28%, from 167 minutes to 120 minutes. Additionally, battery heating during workplace charging at −10°C increased the self-weighted mean charging power by 33%, further demonstrating the importance of thermal management in maintaining charging performance under extreme conditions (Lindgren and Lund 2016).

In terms of overall fleet performance, the study noted that fleet utility and charging power efficiency were heavily influenced by temperature. At −10°C, the self-weighted mean charging power decreased by 15% compared to 20°C, primarily due to the increased energy required for battery heating during charging. Additionally, fleet utility—a measure of the realized versus planned travel—dropped to 82% when standby operations were not enabled. Utility was highest near 20°C, with only marginal improvements from increasing charger power (e.g., 20 kW versus 3.6 kW) at workplace charging locations. This reinforces the conclusion that simply increasing charger power may not significantly benefit cold-weather fleet operations without effective battery preconditioning and thermal management strategies (Lindgren and Lund 2016).

4.4 Real-World Charging Performance

For this analysis, Tesla 1 charging data were utilized due to the lack of available real-world EVSE data within the scope of the project. These data were collected from a privately owned 2016 Tesla Model Y in Fairbanks, Alaska. It was charged primarily at home in a garage, using a Tesla wall-mounted Level 2 charger. It was occasionally charged using a DCFC or at workplace Level 2 chargers. The Tesla was very rarely charged to 100% SoC. As per manufacturer recommendations, it was set to a maximum SoC of 80%. These data allow for detailed analysis of charging behavior in cold climates, with insights into how extreme temperatures affect both the charging process and overall energy consumption. Figure 17 explores these insights through data and visualization derived from the charging sessions. The figure shows a drop in charge rate during colder months, although the lowest charge rates were recorded in May and June most likely due to the difference in the level of chargers used during those months. It is possible that more level 1 and 2 charging was used causing a lower overall charge rate. This suggests that charging sessions tend to take longer during colder periods due to the power from the charger being used to heat the battery to an operating temperature before increasing its SoC.

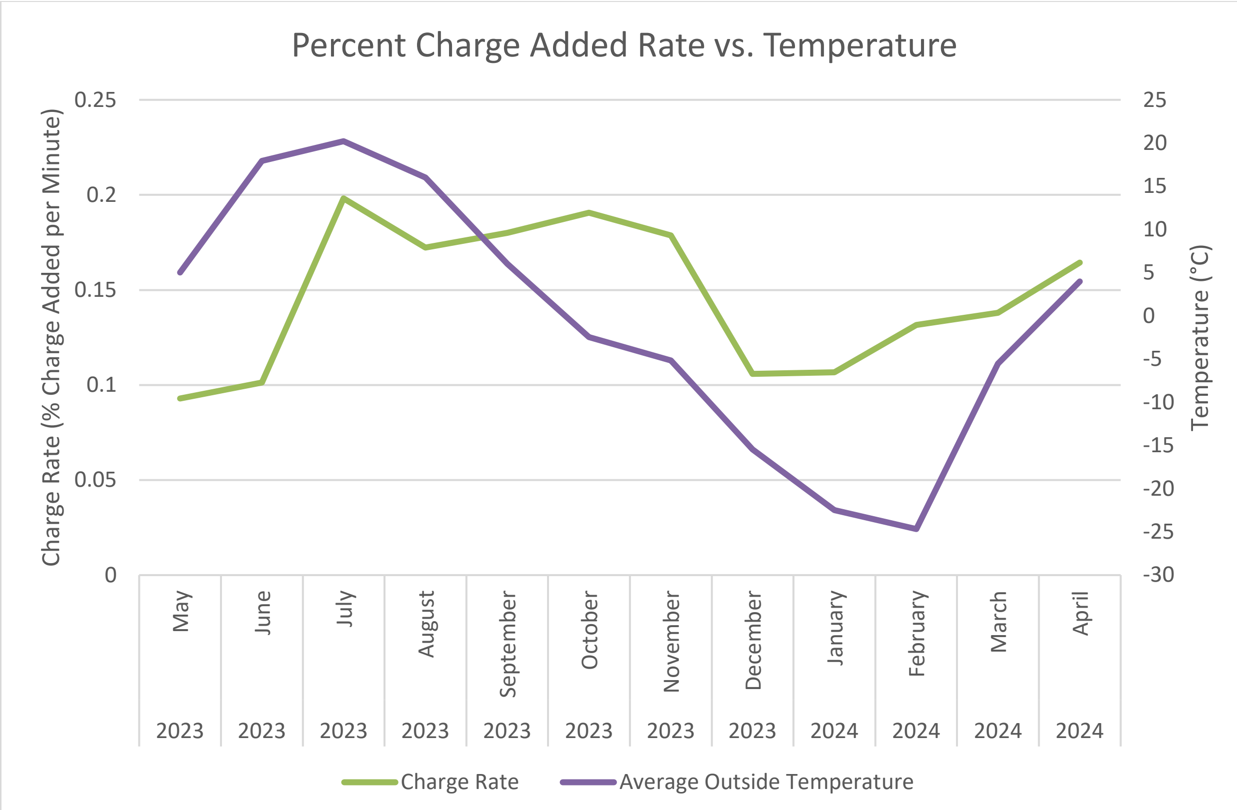

Figure 17. Percent charge added rate versus temperature

5 Conclusion

In this report, we examined the effects of extreme cold-weather conditions on the efficiency and performance of EVs and EVSE. Through the analysis of real-world data collected from three Tesla vehicles operating in Fairbanks, Alaska, we observed a clear correlation between declining temperatures and reduced vehicle efficiency, which impacts range, charging times, and overall vehicle performance. Nonetheless, it is evident that EVs can and are being successfully used in temperatures as low as −40°C. The combination of appropriate battery management, strategic charging, and the use of advanced vehicle thermal systems enables these vehicles to function reliably even under severe climatic conditions.

The efficiency data from Tesla 1, which was stored in a heated garage, demonstrated better performance than Tesla 2 and Tesla 3, which were stored outdoors and exposed to ambient cold. As shown in Table 1, the efficiency of Tesla 1 decreased to 1.15 miles per percent charge, which was slightly higher than Tesla 2 at 1.13 miles per percent charge and much better than Tesla 3 at 0.65 miles per percent charge (during the Fairbanks cold snap). However, Tesla 3 was only driven 250 miles during that period, while Tesla 1 and Tesla 2 were driven more than 500 miles. Neither of the Teslas reached a point of concern when being driving in which drivers were stranded or unable to complete their trips. Likewise, the same is found with charging. Although charging cords can become frozen and difficult to use, the power efficiency does not drop to point of extreme concern. This finding suggests that storing EVs indoors, particularly in extreme climates, offers tangible benefits in maintaining efficiency and reducing battery strain. Similarly, while cold weather did lead to increased charging times and potential usability challenges, such as frozen charging cables, none of the vehicles analyzed experienced failures that would compromise the safety or completion of the intended trips. Therefore, while extreme cold does impact EV performance, it does not make EVs unsuitable for such environments. This is dependent on the type of usage of the vehicles, as larger loads and off-roading capabilities will likely limit the capabilities and range of the vehicle.

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Appendix A. Daily Temperature Plots

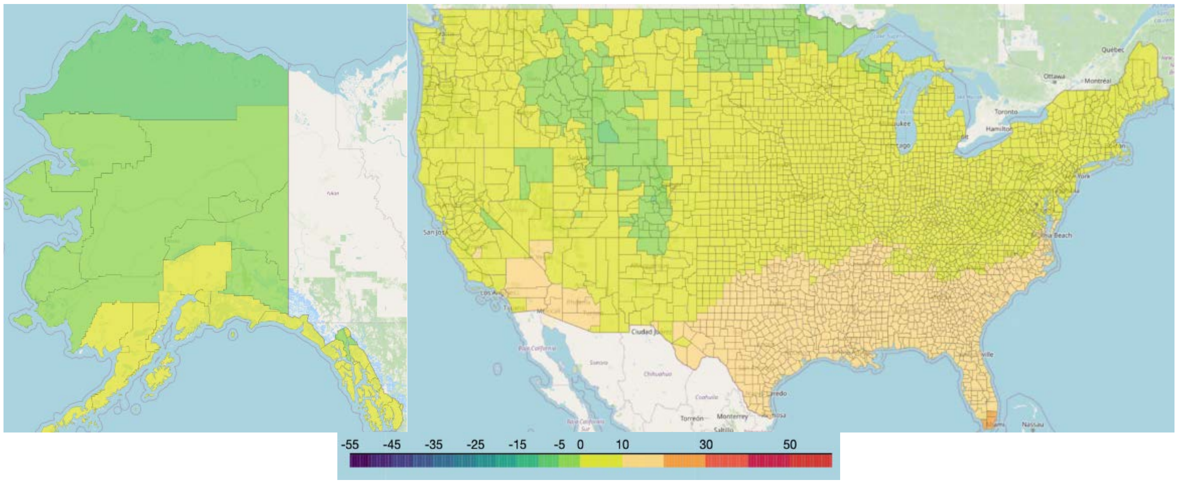

Figure A-1. Average daily temperature by county (°C).

This is derived by capturing the average recorded temperature for each day in 2023 (365 days) and then averaging that number for each county.

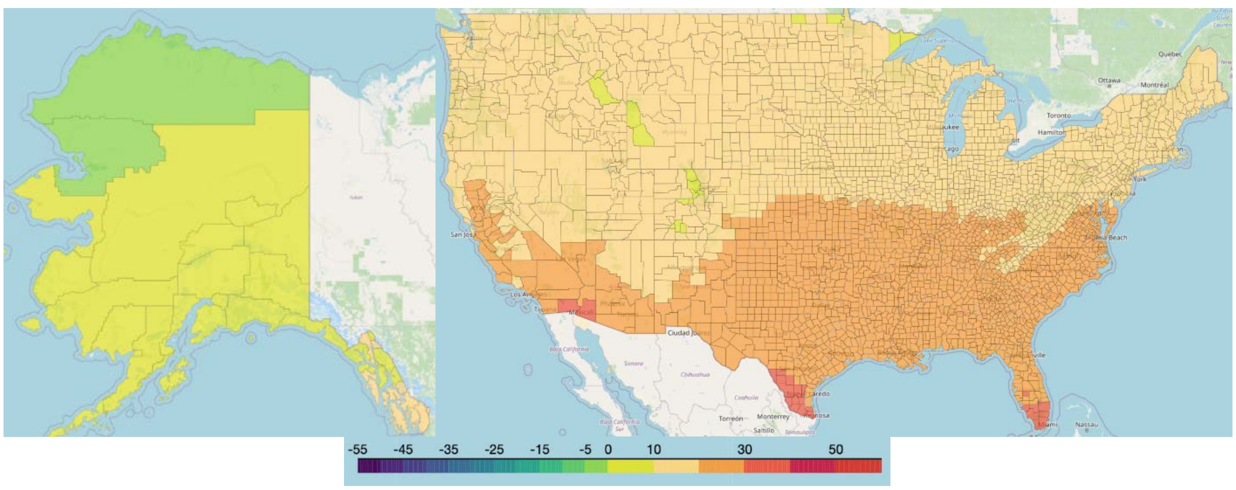

Figure A-2. Average maximum temperature by county (°C).

This is derived by capturing the maximum recorded temperature for each day in 2023 (365 days) and then averaging that number for each county.

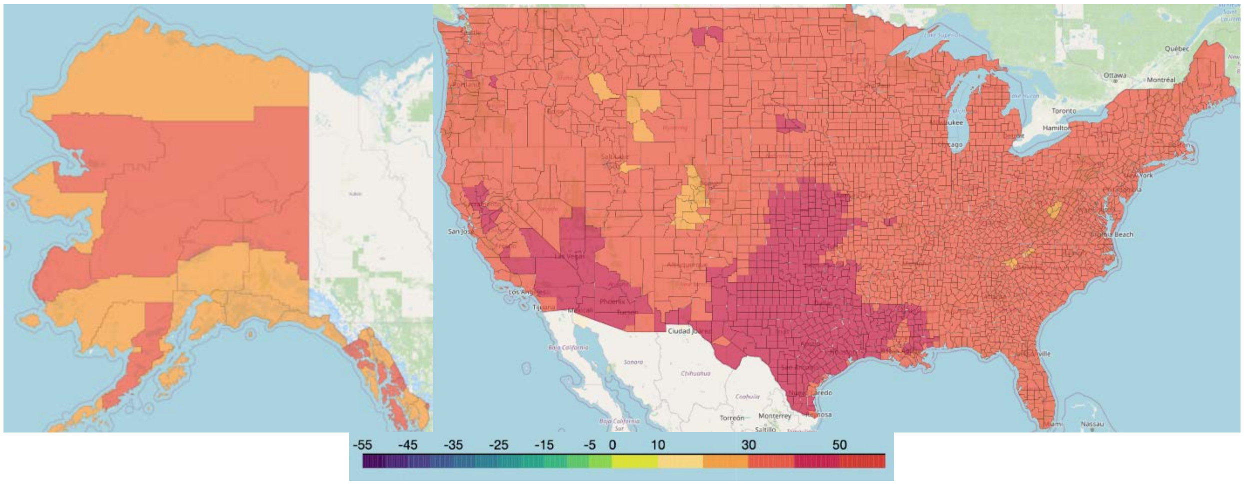

Figure A-3. Maximum daily temperature by county (°C).

This is derived by capturing the maximum recorded temperature for each day in 2023 (365 days) and then taking the overall maximum for each county.

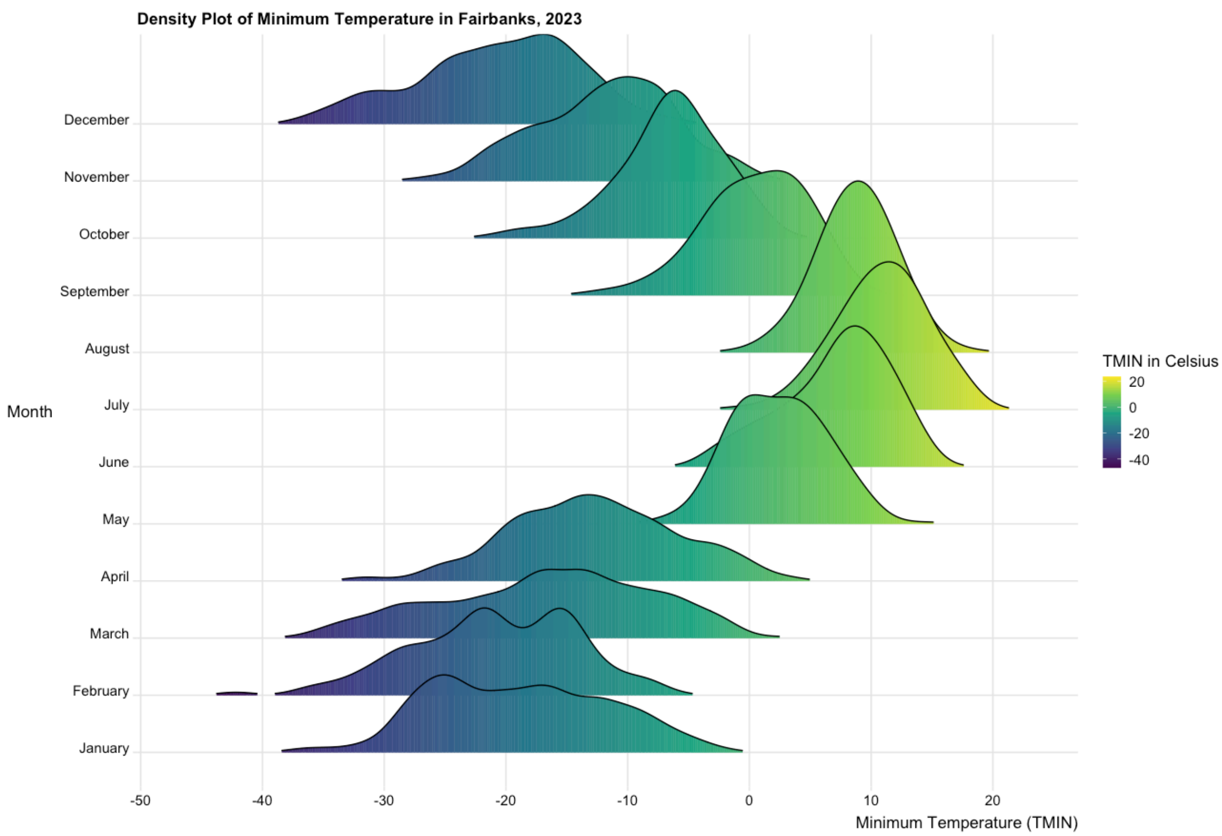

Figure A-4. Minimum Temperature Density in Fairbanks, AK

This is derived by capturing the minimum recorded temperature for each day in 2023 (365 days) and then plotting the density of the temperatures reached by month.

Appendix B. EVSE Charging Plots

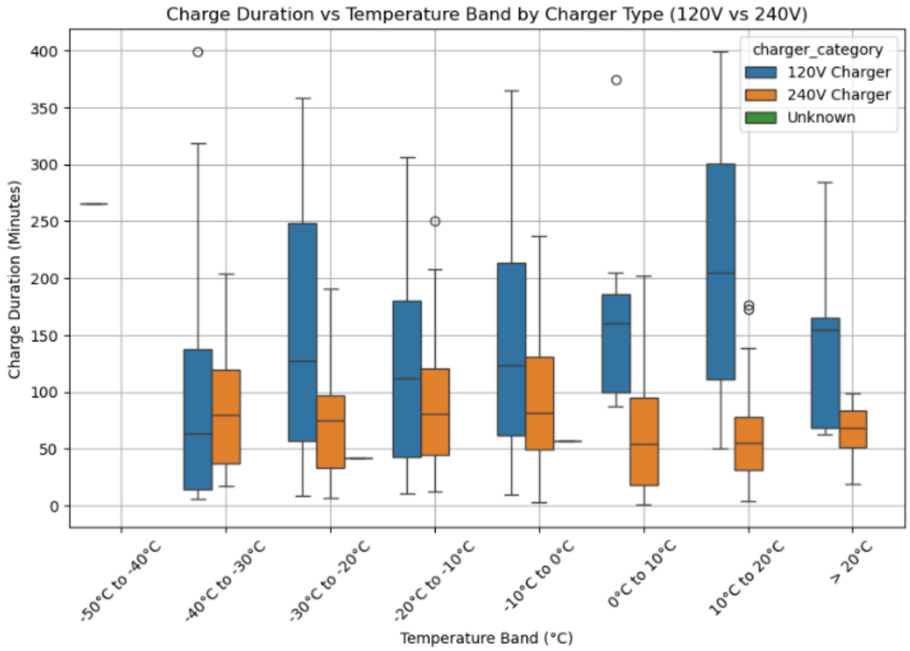

Figure B-1. Charge duration versus temperature by charger type

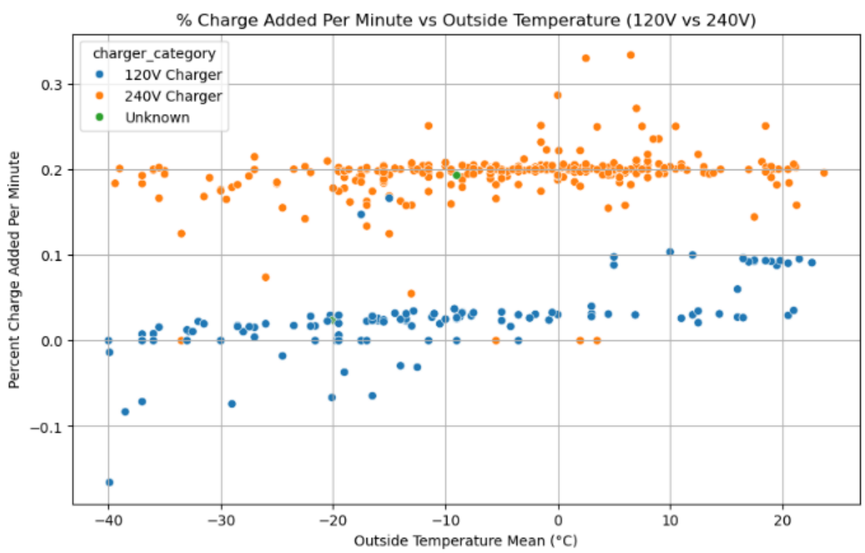

Figure B-2. Percent charge added per minute versus outside temperature

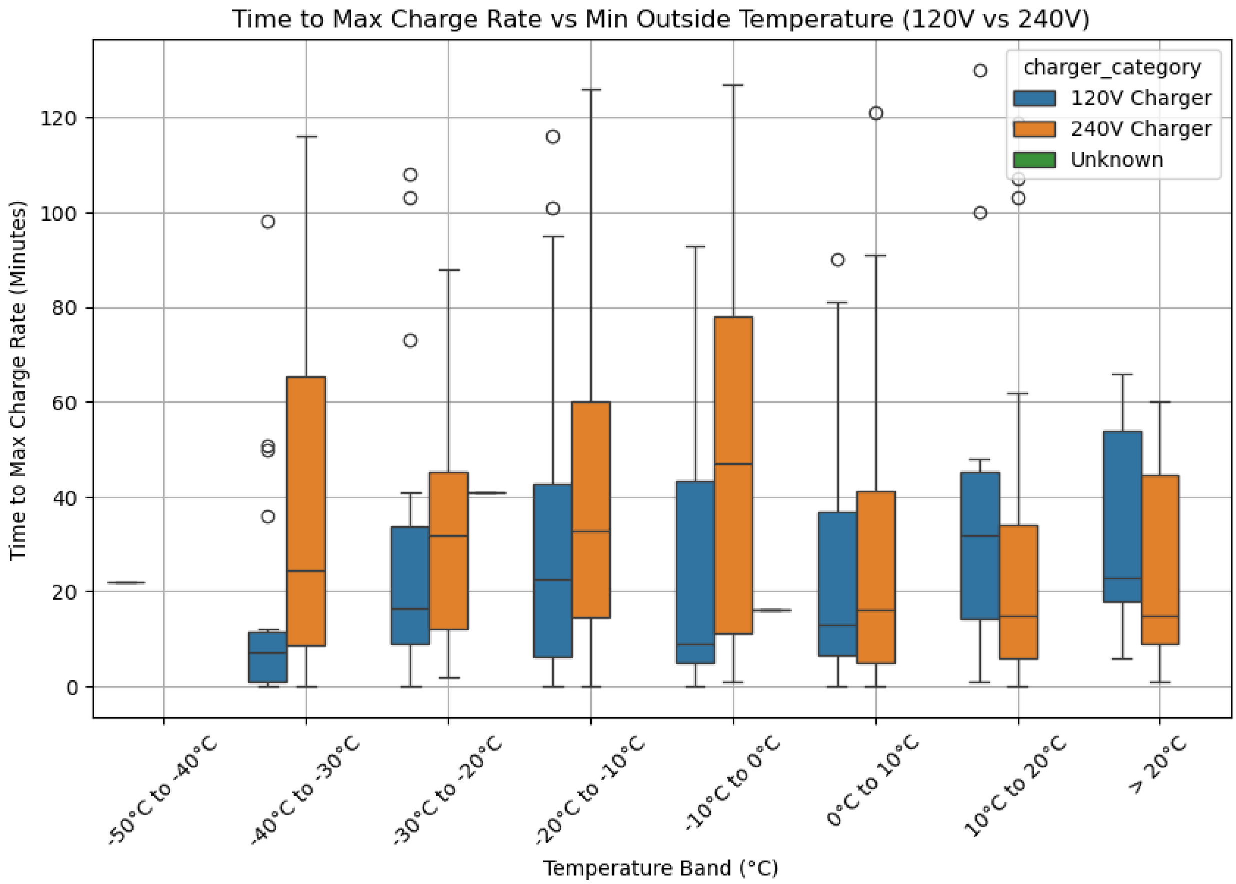

Figure B-3. Time to maximum charge rate versus minimum outside temperature

Appendix C. Air Friction

Air drag accounts for an average 5% of combustion engine energy use, with a range from 3% to 12%. Cold temperatures increase the air density and hence air drag. The ideal gas law, $PV = nRT$, allows one to estimate how the density of air changes under very cold conditions (P = pressure, V = volume, n = number of particles, R = universal gas constant, and T = temperature in Kelvin—i.e., Celsius + 273). The density of air influences the vehicle air drag, and thus the amount of energy required to keep the vehicle moving forward. The density of air is proportional to n/V. From the ideal gas law, n/V is proportional to P/T (times a constant, which does not change).

Data were pulled from the Fairbanks International Airport's METAR notifications to get the pressure and temperature (in Celsius, converted to Kelvin) for both the cold period (Jan. 15–Feb. 4, 2024) and June 2024 time frame. All the data were normalized to the lowest P/T ratio, which occurred in the June time frame. This resulting graph (Figure C-1) shows the percent increase in air density during the cold snap relative to warm June temperatures, which can be 20% to more than 30% for temperatures around −20°C to −40°C, respectively. Increased air density means a vehicle must push harder to get through it.

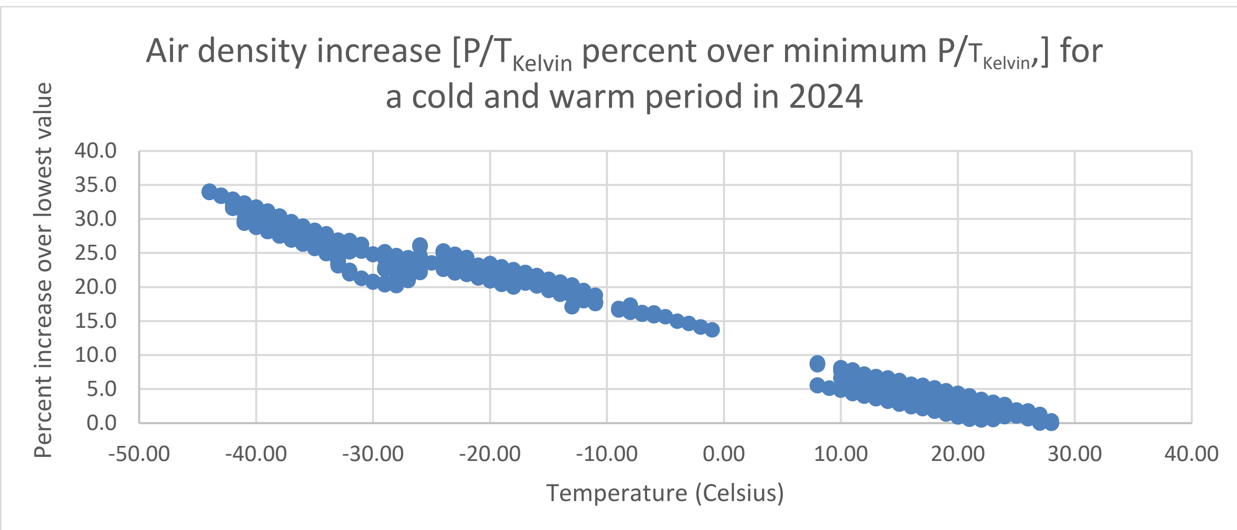

Figure C-1. Air density increase in cold temperatures compared to warm ones.

Data for Jan. 15–Feb. 4 and all of June 2024 for Fairbanks, Alaska, from METAR data provided for aviation. At −40°C/−40°F, the air density is 30% higher than at room (i.e., June) temperatures.

Appendix D. List of Level 2 EVSE Rated −30°C and Below, With Amperages

Figure D-1 shows the count of Level 2 chargers split into type (overhead, pedestal, and wall), the ampere rating (ranging from 15 to 80 amperes), and temperature rating for EVSE available on the GSA website in May 2024, filtered to EVSE rated to −22°F and below. Not included are about two dozen EVSE options with temperature ratings not yet reviewed or with no temperature data available.

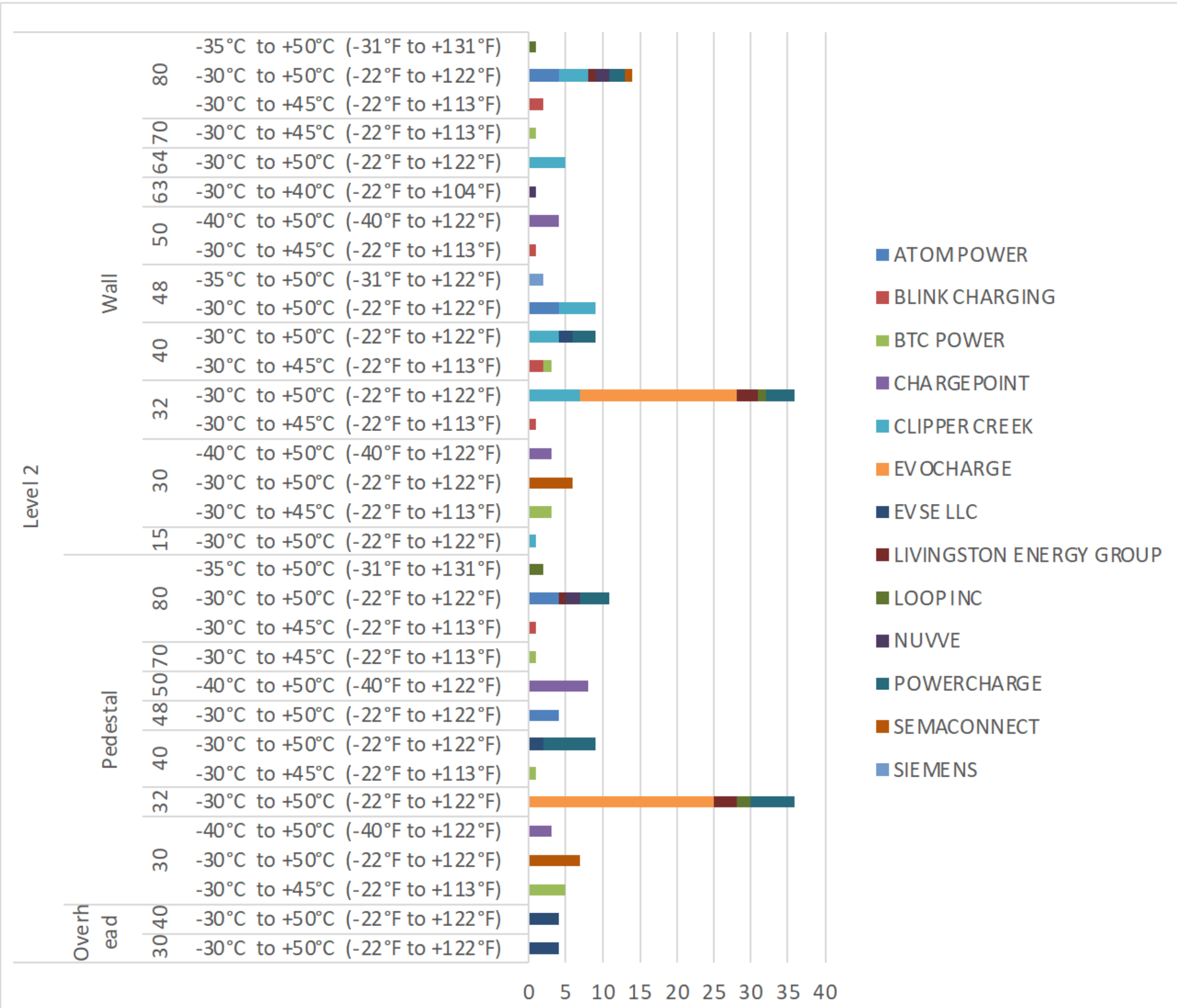

Figure D-1. GSA-available EVSE listed as Level 2, 80-ampere or less power draw, and temperature rating −22°F (−30°C) and below.

The columns in this figure show, from left to right, the charger level (all shown are Level 2); whether they are overhead, pedestal, or wall chargers; the ampere rating (at 15, 30, 32, 40, 48, 50, 70, or 80 amperes); and the temperature range based on company websites and documentation. The bars show the count of how many chargers fit the specified configuration, and are color-coded by manufacturer. The data are based on EVSE available on GSA's website in May 2024, and about two dozen EVSE options were not yet reviewed for temperature ratings.

The coldest-rated EVSE, to −40°C (−40°F), has a maximum amperage rating of 50 A. Higher-current EVSE is rated to a minimum temperature of −35°C (−31°F).

Most of the charging equipment on the market is rated to −30°C (−22°F)—i.e., warmer temperatures. During procurement, the temperature rating of the model considered should be examined to determine if it is appropriate for the location.