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Effect of extreme temperatures on battery charging and performance of electric vehicles

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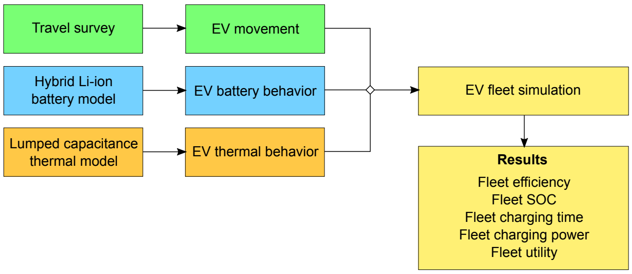
HIGHLIGHTS

- Electric vehicle fleet performance at extreme temperatures is investigated.
- Efficiency (km/kWh) is maximized near +20 °C.
- Battery thermal management improves charging at low temperatures.

GRAPHICAL ABSTRACT



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ABSTRACT

Extreme temperatures pose several limitations to electric vehicle (EV) performance and charging. To investigate these effects, we combine a hybrid artificial neural network-empirical Li-ion battery model with a lumped capacitance EV thermal model to study how temperature will affect the performance of an EV fleet. We find that at −10 °C, the self-weighted mean battery charging power (SWMCP) decreases by 15% compared to standard 20 °C temperature. Active battery thermal management (BTM) during parking can improve SWMCP for individual vehicles, especially if vehicles are charged both at home and at workplace; the median SWMCP is increased by over 30%. Efficiency (km/kWh) of the vehicle fleet is maximized when ambient temperature is close to 20 °C. At low (−10 °C) and high (+40 °C) ambient temperatures, cabin preconditioning and BTM during parking can improve the median efficiency by 8% and 9%, respectively. At −10 °C, preconditioning and BTM during parking can also improve the fleet SOC by 3–6%-units, but this also introduces a “base” load of around 140 W per vehicle. Finally, we observe that the utility of the fleet can be increased by 5%-units by adding 3.6 kW chargers to workplaces, but further improved charging infrastructure would bring little additional benefit.

1. Introduction

Electric vehicles (EV) are an interesting future option to gradually replace conventional internal combustion engine vehicles in decarbonizing the transportation sector. EVs exhibit several environmentally beneficial features such as zero tailpipe greenhouse gas and pollutant emissions and generally lower well-to-wheels emissions [1–4], but special measures may be required to integrate them with the existing power system, as the instantaneous charging power demand of a large uncontrolled fleet of EVs can become very high [5–8].

Due to the importance of power adequacy of EVs, an abundance of studies have investigated their charging under various scenarios

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Nomenclature

Abbreviations

ANN	Artificial neural network
BEV	Battery electric vehicle
BTM(S)	Battery thermal management (system)
HVAC	Heating, ventilation and air conditioning
SOC	State of charge
SWMCP	Self-weighted mean charging power

Subscripts

C	Coulombic
a	Ambient air
ab	Between ambient air and battery pack
ac	Between ambient air and vehicle cabin
b	Battery pack
BTMS	Battery thermal management system
bc	Between battery pack and vehicle cabin
c	Vehicle cabin
HVAC	Heating, ventilation and air conditioning of vehicle cabin
int	Internal heating of battery
inv + EM	Inverter and electric motor in series
max	Maximum
min	Minimum
propulsion	Vehicle propulsion
series	Series configuration of cells in a battery pack
i,j	Lumped capacitance thermal model element
t	Time step

Symbols

C	Ampere-hour capacity (Ah)
I	Current (A)
M	Thermal mass (J/K)
N	Number of cells
P	Power (W)
T	Temperature (°C)
V	Voltage (V)
Z	Normalized state of charge
q	Heat flux (TODO)
s	Current scaling factor
t	Time (s)
v	Vehicle
Ψ	Artificial neural network
Δt	Length of time step (s)
η	Coulombic efficiency

[9–12]. However, the temperature dependency of charging and power consumption, and especially low temperatures effects, have often been overlooked, even though the temperature affects the performance of EVs in several ways [13–15].

At freezing temperatures (<0 °C), charging is impaired because the internal resistance of the battery increases [16–19] and the maximum voltage is reached earlier [20]. Applying a higher voltage could damage the battery [21], meaning that the charging current must be reduced, which will increase the charging time. For the same reason, during driving, the minimum voltage is reached earlier and the current drawn from the battery must be reduced [14], weakening e.g. acceleration. Other adverse effects include reduced regenerative braking capability, and increased heating, ventilation and air conditioning (HVAC) [15,22]. At higher temperatures (>+40 °C), the charging and discharging performance generally remain good as the internal resistance decreases further [23], but battery degradation and self-discharge may be faster due to higher chemical activity [13,14,19,24]. The HVAC load is also increased [13].

In cold climates such as Finland, the outdoor temperature may vary from −30 °C to +30 °C, which requires careful consideration of the temperature effects in EVs [25]. However, the existing literature is rather limited concerning the temperature limitations on EV utility, charging and driving range [13,15,26,27].

Neubauer & Wood [27] studied the sensitivity of the battery electric vehicle (BEV) utility to range anxiety and charging infrastructure, but excluded cold temperatures. In Refs. [13], the BEV utility was studied with a simple zero-order equivalent circuit battery model with a temperature and SOC-dependent resistance [27], concluding that the utility of a BEV in cold environment was only minimally affected by an inefficient cabin heating system and that cabin preconditioning was found to improve the utility.

Kupiainen [15] studied Nissan Leaf and Opel Ampera EVs experimentally in winter and summer conditions and found that power consumption increases in winter conditions, but this can be reduced with cabin preheating and lowering the HVAC minimum temperature. Farrington & Rugh [26] arrived at same conclusions, claiming that the HVAC is the single largest auxiliary load of an EV.

In this study, we investigated further and in more detail the impact of extreme temperatures on EVs using a more detailed battery model that explicitly considers cut-off voltages. Unlike in earlier studies, the sequence of trips in our model is not determined by the battery SOC, but instead by the battery voltage, which may better reflect the real-life limitations of the battery performance, For example, even if the SOC of a battery is high, the voltage may drop below the cut-off limit e.g. due to a high internal resistance at low temperature and consequently, there may not be sufficient power for propulsion. We pay special attention to the power requirements of the HVAC and BTM systems as their use may have a significant impact on the vehicle's range [15], safe operation and long battery life [15,28].

2. Method

In this study, we employ a MATLAB-based EV fleet simulation model which combines three elements: EV traffic data from the Finnish national travel survey [29], a hybrid battery model [30] and a lumped capacitance EV thermal model [13]. The main parameters and their values used in the simulation are shown in Table 3. For more information, see Supplementary Material. The individual submodels are explained in more detail in the following.

2.1. Travel data

The EV driving behavior is based on the Finnish national travel survey [29], in which the respondents filled out a travel diary for one specific day. We used a data subset for the Metropolitan Helsinki, for which a travel diary for a workday (Monday to Friday) was available. The raw survey data yields two driver-specific input parameters for the simulations, namely car location and speed on a 1-min scale. In order to better capture the “equilibrium” behavior, we selected only those vehicles that start and end the day at home,