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The impact of battery electric vehicle initial conditions on ultra-fast charging events

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Executive Summary

Ultra-fast charging of battery electric vehicles (BEVs) with a charging time of less than 15-20 minutes has been identified as a solution to combat range anxiety and allow for a higher degree of vehicle utilization, but poses a critical edge case for safe and sustainable management of lithium-ion batteries. Initial conditions of the vehicle, such as starting state-of-charge (SOC) and temperature, are becoming increasingly relevant as they predefine the charging capability of the vehicle. In order to evaluate the influence of initial vehicle conditions on charging times, we deployed an electrochemical battery model to analyze the impact of different initial temperatures and SOC conditions when utilizing an anode potential control strategy to prevent lithium plating. The results reveal that an unconditioned starting SOC in a range of 30–50 % can lead to a more than two-fold increase in charging time as the cells do not heat up sufficiently compared to a starting SOC at 0 %, emphasizing the need for advanced thermal management or operational strategies such as preheating or optimized fast-charge event scheduling.

Keywords: lithium battery, fast charge, battery management, heating, BEV (battery electric vehicle)

1 Introduction

Besides concerns regarding range anxiety, long charging times pose a barrier for the future wide-spread implementation of battery electric vehicle concepts [1]. This has led various institutions and organizations to strive towards faster charging times in the future [2], with the United States Department of Energy (DOE) defining a charge time goal of below 15 min by 2028 in 2017 [3] or the European Technology and Innovation Platform (ETIP) targeting charging durations under 20 min by 2030 [4]. For this reason, novel fast charging methods have been explored in recent literature, such as anode potential control strategies to prevent lithium plating, which has been identified as one of the main degradation processes during fast charging [2]. Despite these strategies showing promising results, fast charging at low ambient temperatures remains a challenge due to the associated speed reductions because of kinetic and transport processes [5], as well as the increased susceptibility to lithium plating [1]. For this reason, past research has proposed the utilization of preheating strategies to operate batteries at the optimal temperature regarding charging speed and degradation processes [6]. Furthermore, recent literature has identified a dependence of achievable fast charging speeds on the initial conditions of the battery, such as temperature and state-of-charge (SOC) [7]. For this reason, future fast-charging implementations could benefit both from preheating, as well as scheduling methods that take the initial conditions of the battery into account to optimize both the charging profile, as well as the timing of fast-charge events.

To evaluate the potential of such preheating and scheduling strategies, the initial conditions of the regarded battery need to be taken into account, as irreversible losses also lead to the battery heating up during fast charging. This implies the existence of a break-even point between achievable charging time reduction from preheating and inherent battery self-heating. To examine this, we deploy an electrochemical battery model with an anode potential control strategy to obtain the charging and self-heating behavior of a high-power cell and compare it to existing preheating strategies at different states of battery degradation.

2 Methodology

To examine the fast charging behavior of the lithium-ion cell, an electro-thermal single particle model from [8] is utilized to deploy an anode potential control strategy, which reduces the initial charging current to maintain an anode potential above an arbitrary threshold of $50\,\mathrm{mV}$ [9]. While the theoretical threshold to prevent lithium plating lies at $0\,\mathrm{V}$ [10], this buffer is required in practical implementations to account for model inaccuracies or measurement errors [9]. For this purpose a simple PID-controller is utilized, which limits the anode potential to remain above the control reserve, while also not exceeding the initial charging current. The model was parameterized through experimental characterization in the context of a previous study [9]. The utilized commercial battery is a Murata US18650VTC5A cell, which possesses a nickel-rich NCA cathode and a silicon-doped anode, making it a suitable candidate for high-power applications and fast-charging. Tab. 1 shows the fundamental properties of the regarded cell [9], taken from the manufacturers datasheet.

Property	**Value**	**Unit**
Manufacturer	Sony/Murata	-
Type	US18650VTC5A	-
Format	18650	-
Anode material	SiC	-
Cathode material	NCA	-
Rated capacity	2.5	Ah
Voltage bounds	2.5 – 4.2	V
Weight	47.1	g
Max. charge current	6.0	A
Max. discharge current	35.0	A

Table 1: Datasheet specifications of the lithium-ion battery under study [9]

Charging processes from various starting SOCs to $80\,\%$ SOC are then simulated with initial C-Rates starting from $1\,\mathrm{C}$ up to $6\,\mathrm{C}$ at different ambient temperatures between $-10\,^{\circ}\mathrm{C}$ and $40\,^{\circ}\mathrm{C}$. It is assumed that the battery cell core temperature matches the ambient temperature at the start of the simulation. Fig. 1 shows a sample charging process for a battery at $0\,\%$ SOC charged with an initial C-Rate of $6\,\mathrm{C}$ at an ambient temperature of $-10\,^{\circ}\mathrm{C}$.

It can be observed that the anode potential decreases as the battery SOC and connected overpotentials increase. When the anode potential crosses the control reserve of $50\,\mathrm{mV}$, the controller reduces the charging current to maintain a constant anode potential, until the target SOC of $80\,\%$ is reached. Towards the end of the charging process a slight increase in charging current can be observed. This is due to thermal effects, as the battery heats up during the process, leading to reduced overpotentials and thus higher anode potentials.

The model is limited to operate within its validation boundaries, namely currents below $15\,\mathrm{A}$ and ambient temperatures between $-10\,^{\circ}\mathrm{C}$ and $50\,^{\circ}\mathrm{C}$ [9]. It should be noted that the model inaccuracies increase for SOCs below $10\,\%$, as the utilized battery cell shows a strong hysteresis behavior, which was not taken into account [9]. Declining model accuracy due to initial voltage overshoots at the beginning of charging processes at subzero temperatures and high C-Rates is a further challenge that should be taken into account [9].

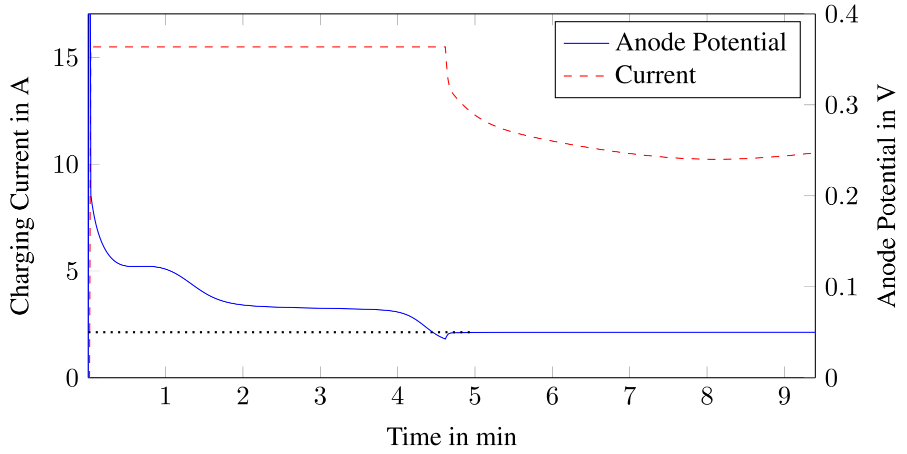


Figure 1: Example charging procedure with an initial charging rate of 6C from $0\,\%$ to $80\,\%$ SOC at a starting temperature of $-10\,°\mathrm{C}$ using an anode potential control strategy showing the charging current and the anode potential. The dotted line represents the arbitrary anode potential reserve of $50\,\mathrm{mV}$.

3 Results

In the following sections, the influence of initial battery conditions regarding cell temperature and starting SOC on fast charge capability in regards to the resulting charging time using the previously demonstrated anode potential control strategy is examined.

3.1 Charging Time Influence

Fig. 2 shows the resulting charging times at different initial conditions for the regarded cell. While the charging time remains mostly temperature-independent during slow charging at $1\,\mathrm{C}$, increasing charging currents result in a more than two-fold charging time increase at low temperatures and SOC ranges between $30\,\%$ and $50\,\%$ compared to starting SOCs between $0\,\%$ and $20\,\%$, as the battery does not have enough time to heat up before the current is reduced. While this effect is strongest at higher C-Rates, an increasing temperature dependence can be observed starting from an initial charge current of $2\,\mathrm{C}$. For starting SOCs above $50\,\%$ even the 1C initial charge current case shows a slight temperature dependence, emphasizing that the influence of battery initial conditions is not only relevant for ultra-fast charge events. For subzero temperatures with SOCs between $30\,\%$ and $50\,\%$ this effect leads to increasing starting C-Rates having almost no influence on the resulting charging time, as the controller has to reduce the current to maintain the anode potential reserve. This is reflected in Fig. 3, which shows the charging time increases for the regarded cell at different starting SOCs with a starting temperature of $-10\,°\mathrm{C}$, as well as at different starting temperatures with a starting SOC of $50\,\%$, relative to the respective shortest time. At a starting SOC of $50\,\%$, the charge duration is more than four times as long at $-10\,°\mathrm{C}$ compared to a $40\,°\mathrm{C}$ starting temperature. Accordingly, self-heating from low initial SOCs is sufficient to heat the battery to more suitable temperatures, resulting in a smaller decrease in charging speed at negative temperatures despite the utilized plating prevention charging strategy.

3.2 Time-saving Potential using Preheating Strategies

As previously observed, fast charging with increasing C-Rates shows a strong dependence on initial battery conditions, especially regarding temperature. This has led previous authors to propose heating strategies to increase the battery temperature to acceptable levels for fast charging, reducing the charging time [7] and mitigating degradation [6]. By comparing the charging durations in the previous section with hypothetical thermal management heating rates, the time-saving potential of a preconditioning phase before the charge sequence can be estimated. Fig. 4 shows the case of a battery with an SOC of $50\,\%$ charged with increasing C-Rates at an ambient temperature of $-10\,°\mathrm{C}$, since this was previously identified as a critical scenario. By subtracting the charging durations when starting at higher temperatures from the $-10\,°\mathrm{C}$ case, the break-even time for preheating strategies can be estimated. Fig. 4 shows the calculated time differences compared to the $-10\,°\mathrm{C}$ case for different target temperatures and C-Rates. As the C-Rate increases, so do the charging time differences between the $-10\,°\mathrm{C}$ case and higher temperatures, with the latter leading to lower anode potentials allowing longer phases of fast charging.

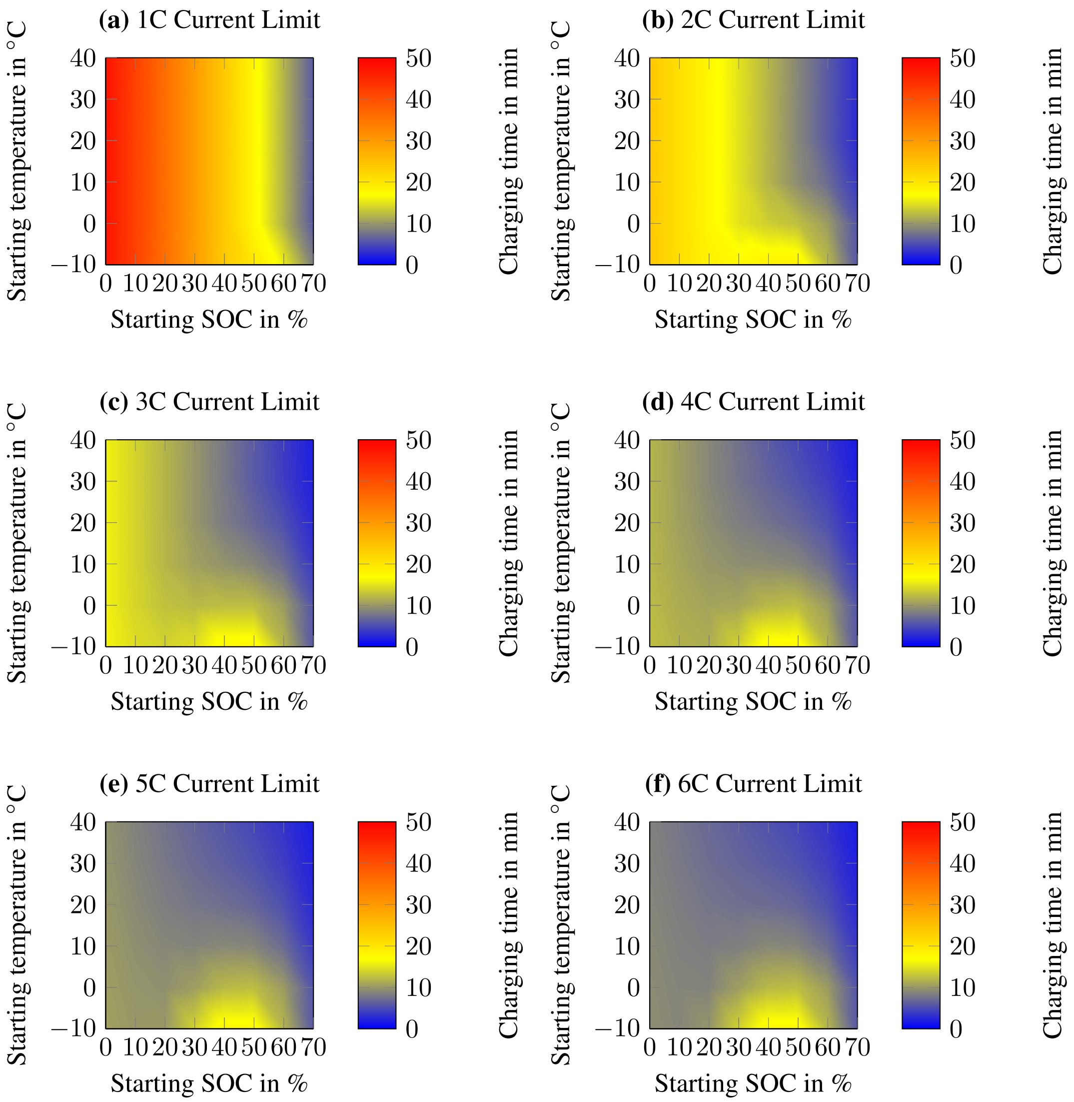


Figure 2: Sensitivity of the charging time until 80 % SOC to variations in starting temperature and state-of-charge of the battery electric vehicle for a lithium-ion battery cell when utilizing an anode potential control strategy. (a)-(f) 1C to 6C maximum current limit

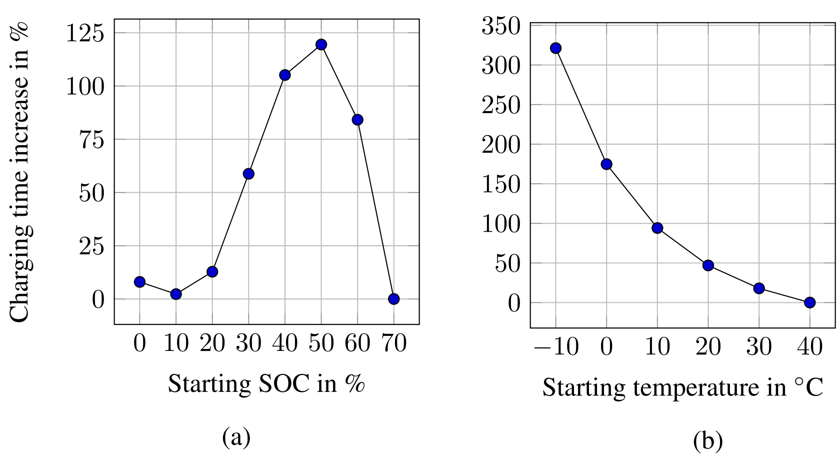


Figure 3: Charging time increase until 80 % SOC due to variations in starting temperature and state-of-charge at (a) $-10\,^{\circ}C$ starting temperature and (b) 50 % starting state-of-charge, relative to the shortest respective charging time.

This trend however shows diminishing returns, with the greatest time difference increase occurring between the 1C and the 2C charging case, as higher C-Rates reduce the absolute charging duration. Simultaneously, higher target temperatures result in a higher time difference, as negative anode potentials occur more frequently at lower temperatures. Here a saturating behavior can be observed, with increasing temperatures leading to diminishing time benefits past a certain point. This point of decreasing returns shifts with increasing C-Rates, with higher C-Rates reaping time benefits from higher temperatures. This is explained by higher currents leading to higher overpotentials, reducing the anode potential which requires the controller to reduce the charging current earlier than the slower charging cases.

For a preheating stage before the charging process to be beneficial regarding overall charging time, the utilized thermal management system has to be capable of heating the battery to the target temperature in a shorter duration than the plotted break-even times. Assuming no change in SOC, this would mean that the resulting charging process can be shortened by the remaining time. Various methods for preheating electric vehicle batteries have been proposed in past literature, which differ substantially in the achievable heating speeds. These can be divided into external and internal preheating strategies, with the former describing methods that rely on the existing vehicle cooling medium such as air or liquid, as well as electrothermal heating technologies such as peltier elements [11]. External heating methods are generally easy to implement, but only offer limited temperature rise rates typically below $1\,\mathrm{K/min}$ [11], which has been argued to be insufficient for potential automotive preheating applications [12]. Heating strategies based on phase change materials have also been proposed, potentially promising heating rates of up to $13.4\,\mathrm{K/min}$ [13], but have so far only been implemented in laboratory environments [11]. Internal preheating methods achieve temperature rise by generating heat inside the cell, either through heat losses produced through targeted current excitations or by implementing self-heating methods by inserting foils into the battery structure to generate ohmic heat [11]. By applying an alternating current (AC) to a battery, past literature demonstrated an achievable heating rate of up to $3.73\,\mathrm{K/min}$ [11, 14], while proposed pulse heating strategies have shown heating rates of up to $6.82\,\mathrm{K/min}$ [11, 15]. As the battery experiences an additional current through these methods, degradation is however expected to increase [11]. By inserting a nickel foil for heating purposes into a battery cell, heating rates of up to $60\,\mathrm{K/min}$ have also been experimentally demonstrated [16]. While the latter method achieves significantly higher heating rates, safety issues remain a concern and specially constructed batteries are required [11, 16]. To evaluate the time saving potential when preheating before fast-charge events, four exemplary heating rates of $1\,\mathrm{K/min}$, $3\,\mathrm{K/min}$, $6\,\mathrm{K/min}$ and $60\,\mathrm{K/min}$ are also plotted in Fig. 4, representing the range of currently proposed thermal management concepts.

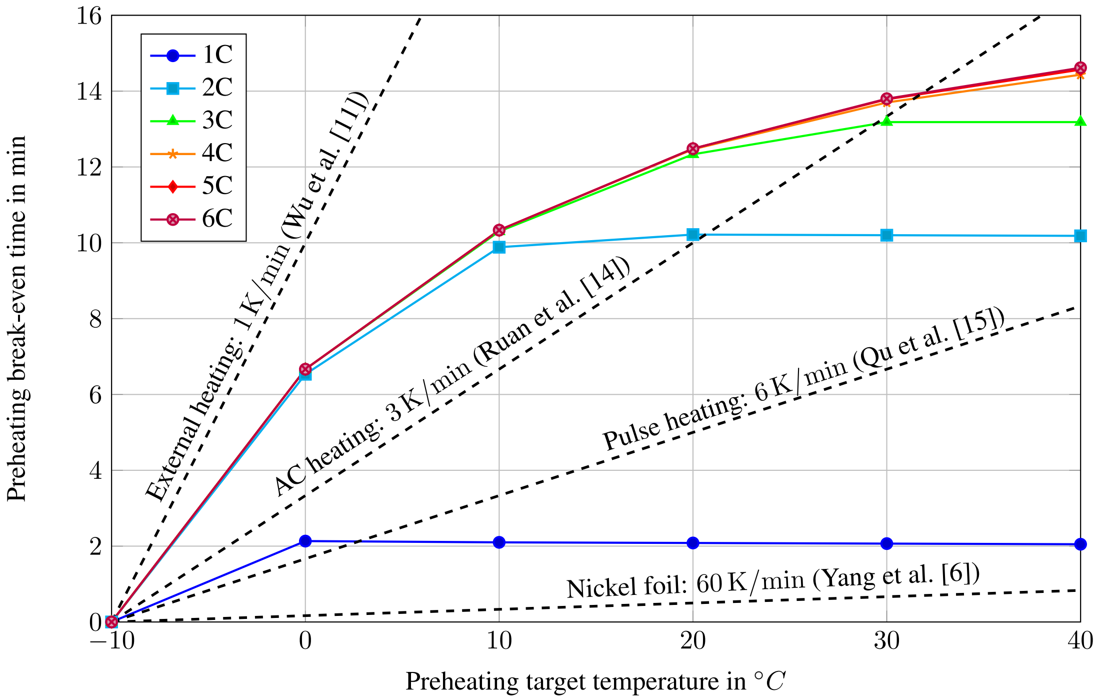
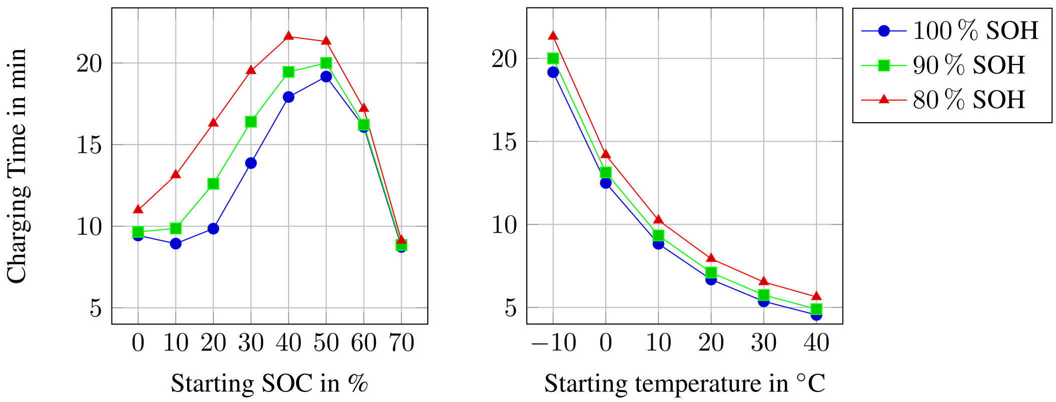


Figure 4: Break-even times for preheating strategies at $50\,\%$ starting SOC and an initial temperature of $-10\,°\mathrm{C}$ depending on the targeted starting temperature, as well as linear assumed heating rates for different preheating concepts, the difference of which represents the theoretical time saved through preheating

As can be seen in Fig. 4, heating rates of $3\,\mathrm{K/min}$ could be sufficient to shorten the charging duration by almost $4\,\mathrm{min}$ or $20\,\%$, if the targeted charging C-Rate is high enough. This time saving potential increases with faster preheating strategies, with the $60\,\mathrm{K/min}$ preheating method leading to a time saving potential of almost $14\,\mathrm{min}$ or $72\,\%$ for a maximum charging C-Rate of $6\,\mathrm{C}$, if the battery is first heated from $-10\,°\mathrm{C}$ to $40\,°\mathrm{C}$. It can also be observed that, depending on the regarded C-Rate and heating speed, warming up the battery past a certain temperature leads to diminishing charge time saving potential. For this reason, real-world implementations of preheating strategies for charge time reduction should not only take the initial conditions and desired charge rate into account, but also consider the achievable preheating speed to determine the optimal target temperature for maximum time saving potential. While the heating rates are assumed to be linear in the context of this study, it should be noted that the regarded methods usually show non-linear behavior in the literature [11], which is expected to influence the results. It should also be noted that the charging strategies regarded in the context of this study do not take aging caused by all degradation mechanism into account, instead focusing on a charging strategy aimed at minimizing lithium plating. While higher temperatures reduce lithium plating, other aging mechanisms such as solid electrolyte interphase (SEI) formation are accelerated [17], which is why fast charge preheating prototypes have to take the aging effect of higher temperatures into account. Previous studies have however predicted an increase in achievable lifetime when higher charging C-Rates are accompanied by higher battery temperatures, depending on the regarded battery type [6].

3.3 Influence of Battery Degradation

By modeling the internal parameters of a lithium-ion cell, fast charging strategies can be devised which operate along the safety boundaries of the battery, allowing increased charging speeds with simultaneously reduced aging. However, as cells degrade over time, the initial parameters change, leading to a changed behavior and charging constraints that vary over time. To take this into account, future fast charging strategies have been argued to require derating strategies, which take degradation into account when determining the safe maximum current to apply [2]. To examine the potential effects of such derating strategies in the context of initial condition sensitivity, we adjust the utilized electrochemical battery model to account for a hypothetical increase in resistance and a reduction of usable capacity. For this purpose, example degradation values were taken from measurements on a commercial 18650 NCA cell in the literature [18]. The cell was cycled with a real-world electric vehicle driving cycle, leading to a resistance increase of $12\,\%$ at $90\,\%$ remaining capacity and $38\,\%$ at $80\,\%$ remaining capacity [18]. While these values depend on the specific cell used and the operating conditions under which the cell was cycled, other studies in the literature have achieved comparable results, which is why the values can be used to make a qualitative assessment of the fast charge performance of aged cells [19, 20, 21]. Using these updated values, the simulations from the previous sections are repeated to examine the achievable charging speeds at different stages of the batteries lifetime. Figure 5 shows the resulting charging duration for different starting SOCs at $-10\,°\mathrm{C}$, as well as different starting temperatures with a starting SOC of $50\,\%$ for a new cell and the two aged cases.



(a) (b)

Figure 5: Sensitivity of the charging time until $80\,\%$ SOC to variations in starting temperature and state-of-charge at (a) $-10\,°\mathrm{C}$ starting temperature and (b) $50\,\%$ starting state-of-charge respectively at different stages of degradation, marked by $90\,\%$ and $80\,\%$ remaining capacity

As can be seen from Fig. 5, charging capability decreases as the battery ages. Although the capacity is smaller over time, the increased resistance through aging mechanisms, such as SEI growth, leads to higher overpotentials, reducing the anode potential and increasing the likelihood of lithium plating. This leads to the charging current being reduced at an earlier point in time, prolonging the charging duration.

This increase in charging duration is especially pronounced in a starting SOC range from $10\,\%$ to $50\,\%$, where increasing overpotentials lead to earlier charging current reductions, in turn reducing the heating potential of the battery which further reduces the fast charging capability. Thus, implementations of preheating strategies for fast-charge applications should also take the degradation state of the battery into account when scheduling fast-charge events.
To examine the implications of battery degradation on the time saving potential of preheating strategies for fast-charge events, Fig. 6 again shows the resulting break-even times and preheating speeds for the regarded battery at $80\,\%$ remaining capacity under the same initial conditions of $-10\,°\mathrm{C}$ starting temperature and $50\,\%$ initial SOC. As the charging times increase for all regarded C-Rates, it can be observed that the time saving potential of preheating strategies increases over the battery lifetime, reaching almost $15\,\mathrm{min}$ or around $77\,\%$ for a 6C fast-charge when preheating from $-10\,°\mathrm{C}$ to $40\,°\mathrm{C}$. The aged break-even time curves also go into saturation towards higher temperatures than the previous examination, which leads to higher time saving potentials for higher target preheating temperatures. Furthermore, even a slow $1\,\mathrm{C}$ maximum current anode potential control charging event can be observed to benefit from preheating regarding charging speed. Preheating could thus become more relevant as the battery degrades over time and future fast-charge scheduling strategies should take aging into account when utilizing preheating methods. It should again be noted here, that this does not account for all occurring degradation mechanisms. As the dominance of different aging mechanisms changes over a batteries lifetime [17], the real-world implications of fast-charge preheating and scheduling is expected to differ from the predictions in this study, requiring further research and experimental validation. This would also have to be weighed against increases in weight, cost and energy consumption which are to be expected when implementing preheating strategies. As most currently used preheating technologies only achieve heating rates in the range of $1\,\mathrm{K/min}$, future automotive batteries would require more advanced preheating methods which are yet to be proven in state-of-the-art vehicles [11].

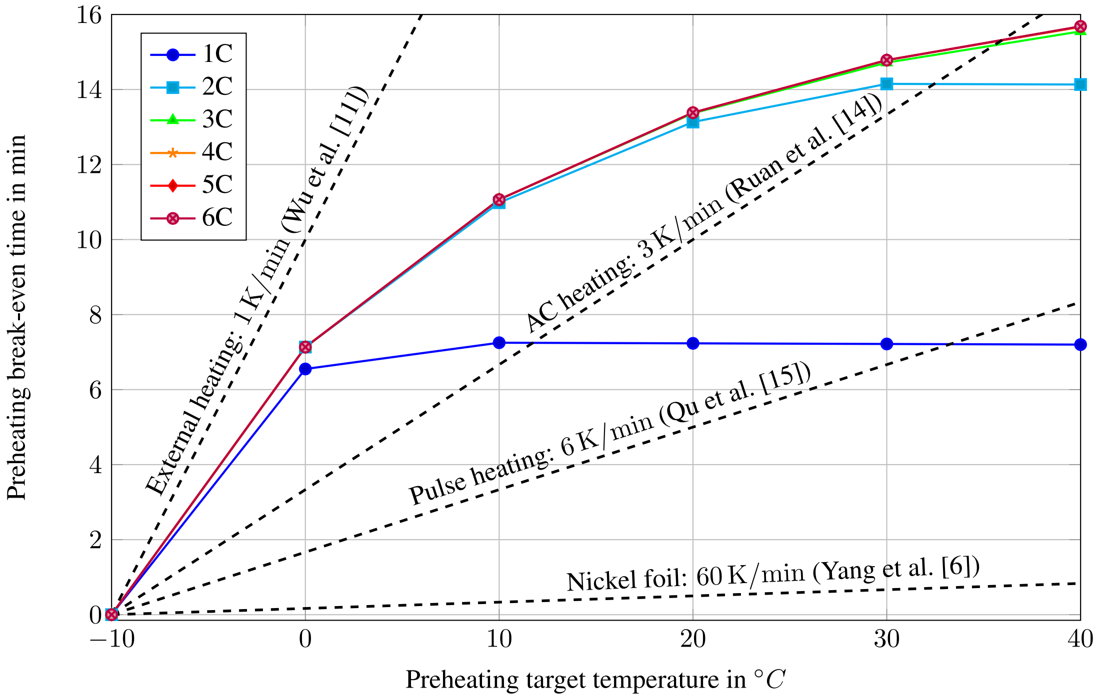


Figure 6: Break-even times for preheating strategies at $50\,\%$ starting SOC and an initial temperature of $-10\,°\mathrm{C}$ depending on the targeted starting temperature for a battery with a remaining capacity of $80\,\%$, as well as linear assumed heating rates for different preheating concepts, the difference of which represents the theoretical time saved through preheating

4 Conclusions and Future Research

In this study, an electrochemical battery model was utilized to demonstrate that achievable fast-charging speeds vary significantly depending on the initial conditions of the regarded lithium-ion battery when utilizing an anode potential control strategy to generate the charging current profile. While charging times increase for lower temperatures, medium starting state-of-charge ranges between 30 % and 60 % were observed to increase charging times more than two-fold at higher C-Rates and lower temperatures, compared to lower and higher states of charge, as the battery does not have enough time to heat up before the current is derated to prevent lithium plating. Proposed preheating strategies from previous literature were examined, promising time-saving potentials between 20 % and 72 % depending on the regarded initial conditions and C-Rates, when a preheating step is added before the fast-charge event. By repeating the simulations for the case of an aged battery, it could be observed that charging durations increase, leading to higher potential benefits from preheating as well as an increased dependence of charging time on the initial state-of-charge. Future fast charge strategies could thus benefit both from preheating strategies and scheduling algorithms that account for the initial battery conditions, as well as the available charging power and preheating methods throughout the lifetime of the deployed battery system.

As the predictions in this paper rely on simulation results, future research should examine experimental implementations to confirm these observations. Future work should also extend the model by an examination of battery aging caused by different temperatures and current profiles, allowing statements to be made that regard both achievable charging times as well as resulting battery degradation. This could reveal optimization potential for future fast-charge implementations. Finally, future work should apply the utilized method to both a high-power and a high-energy battery cell, as the latter are more prone to lithium plating and both cases can be attractive depending on the application.

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Presenter Biography

Kareem Abo Gamra received his bachelor’s and master’s in electrical engineering from the Technical University of Munich (TUM) in 2019 and 2021. He is currently pursuing a Ph.D. degree with the Institute of Automotive Technology at the TUM, where his research focuses on operating strategies for ultra fast-charged electric vehicles.