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Commentary

Advancements in extreme fast charging to foster sustainable electrification

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The transition toward electrified mobility is rapidly accelerating, but sustainability challenges associated with batteries, including costs, raw materials, and manufacturing-related emissions, pose barriers. Here, we discuss the role of extreme fast charging in breaking down these barriers and offering a pathway toward a more sustainable battery-powered electric-vehicle market.

The transport sector accounts for 27% of global greenhouse gas (GHG) emissions,[1] three-quarters of which are associated with road transport. As such, electrifying road transport is key to the transition toward net zero by 2050. Thanks to rapidly falling battery costs and a growing number of countries banning the sale of new combustion-engine cars, the past few years have witnessed an unprecedented market penetration of electric vehicles (EVs). Even during the trying time of the COVID-19 pandemic, global annual EV sales more than doubled from 2.1 million units in 2019 to ~5.6 million in 2021. Nevertheless, despite this growth, EVs still account for only ~7% of annual vehicle sales.[2] The adoption of EVs in heavy-duty vehicles, which have much higher GHG emissions than passenger cars, is yet further behind—with a less than 1% market penetration. There remains a long way to go before we can fully achieve electrified mobility.

Ending range anxiety raises sustainability concerns

There are various hurdles to the widespread adoption of EVs, and range anxiety—the driver's fear that an EV might run out of juice on the road before reaching the intended destination—has long been cited as the critical barrier. One popular way to eliminate range anxiety is to increase battery size to enhance storage capacity. For instance, commercially viable EVs require ~80 kWh batteries to eliminate customers' range anxiety, and numerous automakers have announced plans to develop 600-mile-range EVs that would need ~150 kWh batteries. However, the increase in battery size could raise several socio-environmental concerns. A prominent issue is the related increase in the consumption of raw materials. The exponential rise in EV sales, together with the disruption of material supply chains by the COVID-19 pandemic, has led to skyrocketing prices of battery raw materials—e.g., in 2021, the cost of lithium carbonate increased five times, and that of cobalt doubled.[3] With the continuous electrification of road transport, it's not difficult to imagine a cascade of problems emerging throughout the raw-material value chains in the absence of sustainable governance—i.e., excessive mining, environmental pollution, ecosystem degradation, and increased health risks, just to name a few. Affordability is another concern. Presently, EVs already have a higher upfront cost relative to that of internal combustion engine (ICE) cars. A larger battery is likely to deteriorate EV competitiveness, especially among low-income groups. EVs are believed to reach cost parity with ICE cars once battery costs fall to US$100 per kWh. Even at this price, an 80 kWh battery that can eliminate range anxiety would alone cost US$8,000, already double the cost of the top-selling EV in China: the Hongguang Mini EV, annual sales of which exceeded those of the Tesla Model 3 and Model Y combined. Furthermore, the CO_2 emissions during battery production, estimated to be ~175 kg-CO_2 per kWh,[3] are also a critical issue. If we assume that the annual EV sales will reach 40 million by 2030 as projected by BloombergNEF and battery production emissions remain the same, the associated global CO_2 emissions would amount to 0.56 Gt in 2030 for an average battery size of 80 kWh. As a reference, the current CO_2 emission of the whole transport sector worldwide is ~7.2 Gt per year.[1]

Sustainability potential enabled by fast charging

Fast charging is another effective way to eliminate range anxiety. Statistics show that drivers who have access to fast-charging stations will travel more miles even if fast charging is used less frequently.[4] There is a worldwide race to build publicly accessible fast-charging stations. The global investment in high-power (>100 kW) chargers has increased drastically and driven a rapid increase in the annual installation number of such chargers from 4% of public-charger installations in 2017 to 27% in the first half of 2021.[2] The US and Europe are actively pushing for the development of so-called extreme fast charging (XFC) technology, which, via >350 kW chargers, could add 200 miles of driving range with a 10 min charge.

Although vehicle engineering, charging infrastructure, and techno-economic performance are important considerations in developing XFC technology,

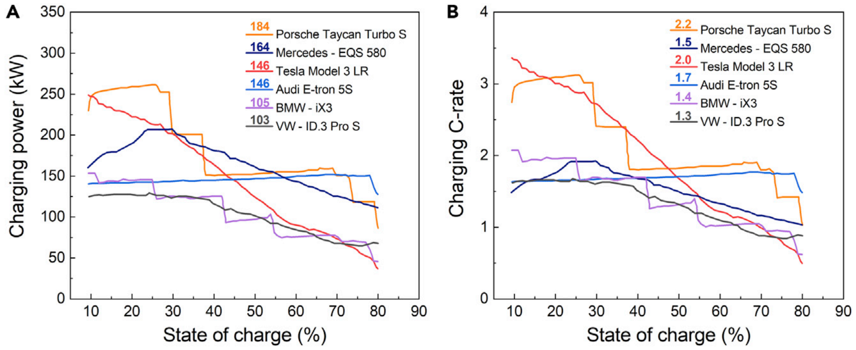

Figure 1. The evolution of charging power and charging C-rate of SOA EVs

(A) Charging power from Hackmann.[5]

(B) Charging C-rate, calculated by dividing the charging power by the battery energy of the corresponding models.

batteries remain the limiting factor of EVs' fast-charge ability. As shown in Figure 1, reported by Hackmann,[5] the maximum charging power of state-of-the-art (SOA) EVs is ~150–270 kW, corresponding to a maximum C-rate of ~2–3C (C-rate is the dimensionless electric current relative to the cell capacity; a larger C-rate means larger current), and it can be implemented only at a low battery state of charge (SOC). For instance, Tesla's latest V3 Supercharger can offer 250 kW power, whereas the average charging power of the Tesla Model 3 (LR version) from 10% to 80% SOC is only 146 kW, which translates to an average charging rate of ~2C for its 74 kWh battery or an added energy of 24.3 kWh in 10 min—i.e., ~90 miles of added range, less than half of the expected 200 mile range. Also shown in Figure 1 is that the Mercedes EQS-580 achieved a higher charging power (i.e., more added miles per minute of charging) at a lower charging rate than the Tesla Model 3, but this is at the expense of a much larger (108 kWh) battery.

XFC, if strategically utilized, could be the antidote to the dilemma between range anxiety and battery-pack size. That is, an EV can use a small battery to meet the daily commuting needs and use XFC for rapid replenishment of energy in long-distance trips. For instance, Figure 2 compares the driving time from Salt Lake City to Denver via EVs with different battery sizes. Similar to Meintz et al.,[6] the estimation assumes a constant driving speed of 65 mph, an energy consumption of 0.3 kWh per mile on highways, and fast charging from 10% to 80% SOC at each battery-charging stop. The 105 and 75 kWh batteries represent SOA batteries that are charged with an average power of 150 kW (Figure 1). Further, we consider a 45 kWh XFC battery that can withstand 250 kW power (~5.6C) throughout the 10%–80% SOC range. Although the 45 kWh battery gives a limited range and hence needs four charging stops during the trip, the total travel time is pretty similar to that of the other two long-range EVs and only 27 min more than that of the conventional ICE car, indicating a huge potential to eliminate range anxiety. Further, smaller batteries offer advantages such as lower costs, fewer material-associated sustainability challenges, and low manufacturing-related GHG emissions. The strategic combination of XFC and a small battery, therefore, provides a promising pathway for future mass-market EVs in alignment with multiple sustainability criteria. It should be noted that the power and number of public fast chargers (PFCs) would be critical for the above strategy. We note that the small 45 kWh batteries require only 250 kW charging power to meet the XFC needs (Figure 2), which is compatible with SOA fast-charging networks (e.g., the Tesla Supercharger network). Also, two metrics are critical for the deployment of PFCs: (1) the number of PFCs for every 100 miles (or 100 km), which represents geographical accessibility to a faster charger, and (2) the number of EVs per PFC, which affects queueing time for charging. As of 2021, the EU offers five PFCs per 100 km and 7.5 EVs per PFC.[7] In the US, Tesla's Supercharger network has covered >99% of the US population and has been expanding rapidly.[8] But establishing a reliable charging network, especially given the exponentially growing EV market, will require a lot more.

The figure of merit for fast charging

Although fast charging can enable multiple benefits, it isn't perfect yet. The most critical challenge to fast charging SOA Li-ion batteries (LIBs) is Li plating—the deposition of metallic Li onto graphite surfaces instead of intercalation into graphite upon charging. This can drastically reduce battery life and, under extreme circumstances, result in internal shorting with catastrophic consequences, such as explosion.

For sustainable fast charging, we emphasize that three metrics should be fulfilled simultaneously: charge time, energy acquired in Wh/kg (storage capacity), and the associated cycle life (battery lifespan). Unfortunately, the combination of all three metrics excludes the vast majority of existing fast-charging solutions. For example, the entire class of flash charging (e.g., charging with a high power only to ~30% SOC; Figure 1A) cannot acquire sufficient energy to help eliminate range anxiety. Similarly, using ultrathin electrodes to avoid Li plating results in reduced specific energy. Furthermore, when sufficient cycle life is not achieved along with fast charging, this could lead to earlier retirement of batteries, causing various issues such as increased battery waste and demand for raw materials, which don't hold merit.

Thus, an important sustainability feature for XFC is the ability to charge a substantial amount of energy rapidly without compromising the safety or lifespan of batteries, which essentially requires the Li-plating issue to be addressed. Fundamentally, Li plating occurs as a result of competing interaction between three physicochemical processes: (1) ion transfer in the electrolyte, (2) reaction at graphite-electrolyte interfaces, and (3) solid-state diffusion in graphite particles. XFC in LIBs signifies a fundamental transition from a reaction-limited to an ion-transport-limited regime.[9] The ion-transport resistance is further exacerbated in the thick and dense electrodes required for energy-dense LIBs.[10] Research efforts have focused on optimizing electrolyte recipes to enhance the conductivity, diffusivity, and transference number and on developing novel

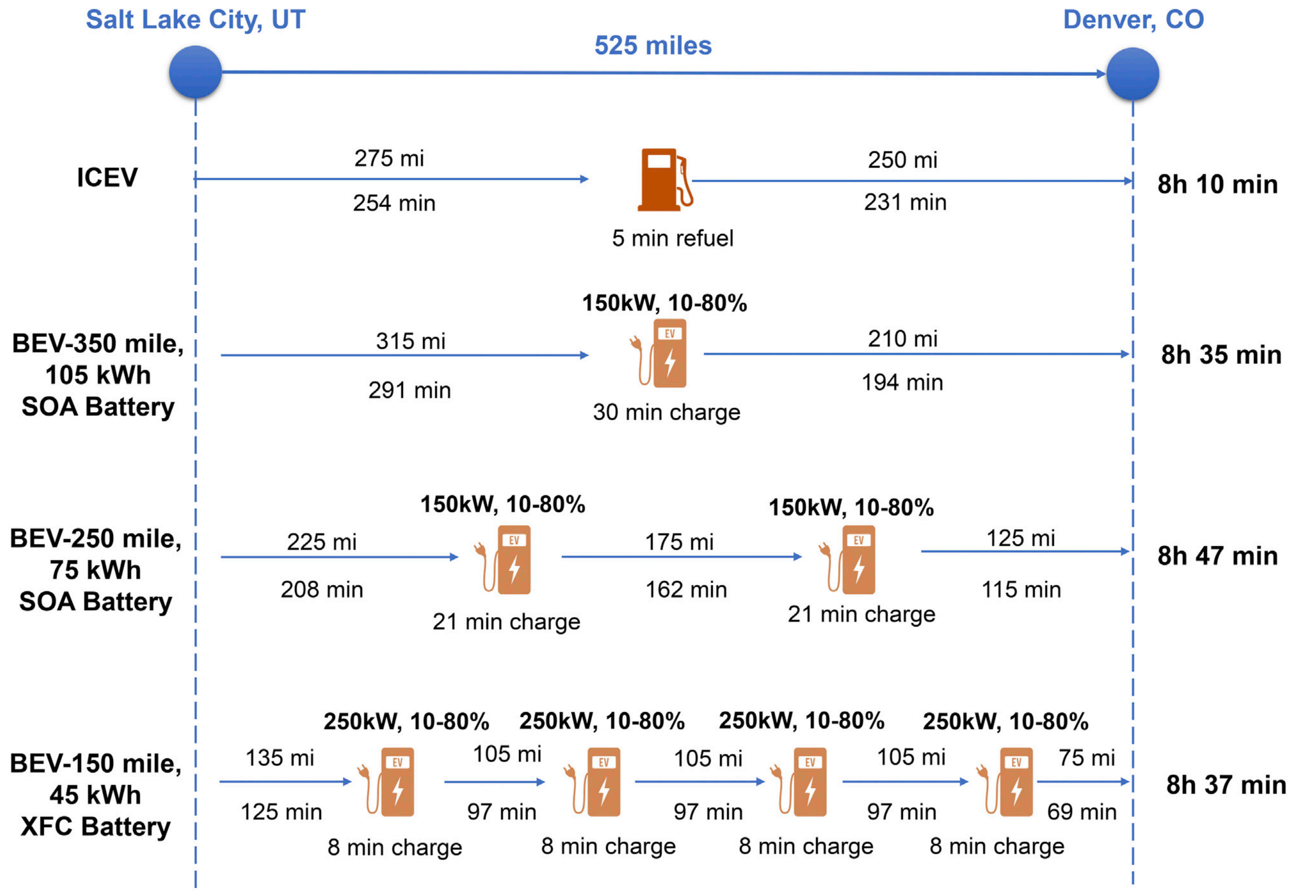

Figure 2. Comparison of the total driving time from Salt Lake City to Denver via an ICE vehicle and EVs with different battery sizes

The estimation assumes a constant driving speed of 65 mph and energy consumption of 0.3 kWh/mile on highways. The vehicle starts from 100% battery SOC and stops to recharge when it reaches 10% SOC. The driving distance between two stops (ΔL) is calculated as $\Delta L = E_{bat} \times \Delta SOC / E_c$, where E_{bat} is the battery size (in kWh), and E_c is the energy consumption rate (0.3 kWh/mile). At each stop, we assume that the battery is fast charged from 10% to 80% SOC with the power noted in the figure, i.e., the charging time (Δt_{char}) is $\Delta t_{char} = 0.7 E_{bat} / P_{char}$.

electrode architectures with lower tortuosity. However, the LIB is well known for its trade-off nature: it is always challenging to improve one parameter without sacrificing others. For instance, adding esters as co-solvents can enhance electrolyte diffusivity and hence fast-charging ability, but it often considerably deteriorates electrolyte stability and battery life in normal operations.[11]

Overall, the XFC technology for LIBs requires synergistic improvements at the material, structure, and cell levels to address challenges pertaining to degradation, safety, and life. In this regard, although next-generation technologies such as solid-state batteries (SSBs) hold the theoretical promise to deliver higher energy density and safety,[12] these systems are confronted with major limitations due to ionic transport, electro-chemo-mechanics interplay, and morphological instability at various solid-solid interfaces.[13] A fundamental understanding of the myriad mechanistic interactions is imperative for designing stable interfaces, improving electrochemical performance, and enabling fast charging, which is undoubtedly a critical challenge.[11] We note that, analogous to LIBs, SSBs also present a fundamental trade-off between energy and power density depending on the cathode material and microstructure.

Thermal modulation: The holy grail of fast charging

A promising approach to preventing Li plating is thermal modulation. For years, it has been believed that the optimal temperature for LIBs is around room temperature (RT)—lower temperature aggravates Li plating, whereas higher temperature accelerates material aging, primarily solid-electrolyte-interphase (SEI) growth. With numerical analysis, we have revealed that the optimal battery temperature increases as the charging rate and cell energy density rise and that it is beneficial to fast charge energy-dense cells at elevated temperatures.[14] Thereafter, Tesla adopted this strategy and developed an on-route battery-warmup method that heats the battery to 45°C–55°C before a fast charger is reached. The slow heating speed (~0.5°C/min), however, leads to a long duration at high temperatures, which negatively affects battery life. Recently, we reported an asymmetric temperature-modulation method that (1) rapidly heats a cell (>60°C/min) to an elevated temperature (~60°C) for charging and (2) discharges or stores the cell at the cool ambient temperature.[15] The elevated temperature significantly enhances mass transfer and reaction rate, eliminating Li plating during fast charging. On the other hand, the limited time of the cell at the high temperature (e.g., $\sim$10 min/cycle or 0.1% of the lifespan of an EV) controls material degradation. We showed that the temperature-modulation approach could charge an energy-dense cell at 6C by 167 Wh/kg in 10 min at the beginning of life and 144 Wh/kg after 2,500 cycles, far exceeding the US Department of Energy target (i.e., an XFC life of 500 cycles). The mechanistic role of temperature as a fast-charge modulator is also significant in the context of Li-metal batteries.[16] Given the strong asymmetry that underlies the plating and stripping behavior, designing an optimal thermal-modulation approach is critical for achieving stable interfaces and minimizing degradation in such battery systems. Leveraging the fundamental correlation between temperature and the intrinsic response (e.g., transport, kinetic, and mechanical) of electrode and electrolyte materials unlocks an exciting opportunity for the XFC technology.

EVs should retain good performance, life, and safety at all temperatures. However, battery materials that are active at low temperatures are often unstable at high temperatures (and vice versa). As such, SOA batteries have to make sacrifices between the materials' activity and stability. The thermal-modulation method offers a solution to this dilemma. With rapid heating, a battery always operates at its optimal temperature irrespectively of the ambient condition; thereby, the materials do not need to make a sacrifice for low-temperature activity. Thus, the battery can use highly stable materials for enhanced life and safety. For instance, we presented a TM-LFP battery that uses highly stable anodes (graphite with low Brunauer-Emmett-Teller area) and cathodes (lithium iron phosphate).[17] The thermal modulation enables high power and fast charging in all climates, and the stable materials bring a long lifespan, superior safety, and low cost, fulfilling multiple requirements for more sustainable EV batteries.

Fast charging can enable a sustainable transition to electrified mobility by downsizing batteries and lowering battery costs, material consumption, and GHG emissions. The deployment of fast-charging infrastructures, apart from meeting the technological requirements, must, however, also align with broader sustainability goals, including affordability, accessibility, land-use change, and ecological integrity. Further, synergistic improvements at the material, structure, cell, and charging-strategy levels are essential for freeing batteries from trade-offs and enabling a reliable and resilient fast charging that fulfills the merits of charge time, acquired energy, and cycle life simultaneously.

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DECLARATION OF INTERESTS

The authors declare no competing interests.

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