Advancements in extreme fast charging to foster sustainable electrification

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Summary (50 words)

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 towards 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 towards 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 have more than doubled from 2.1 million units in 2019 to ~5.6 million in 2021. Nevertheless, despite this growth, EVs still only account for ~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 wide adoption of EVs, and range anxiety – the driver's fear that an EV may 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 ~80kWh batteries to eliminate customers' range anxiety, and numerous automakers have announced plans to develop 600-mile-range EVs that would need ~150kWh 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 due to the COVID-19 pandemic, has led to skyrocketing prices of battery raw materials – e.g., in the year 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. Cost is a pivotal factor for the market competitiveness of EVs. At present, EVs already have a higher upfront cost relative to internal combustion engine (ICE) cars. A larger battery means even higher costs, which are 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 80kWh battery that is needed to eliminate range anxiety would alone cost US$8000. On the other hand, the top-selling EVs in China – the Hongguang Mini EV, whose annual sales exceeded that of Tesla model-3 and model-Y combined – sells for just ~US$4000 per car. Such a low cost stems from the use of a light (~10kWh) battery designed only for daily commuting needs, indicating that affordability plays a much bigger role than the vehicles' range in promoting EV penetration. Furthermore, the CO_2 emissions during battery production, estimated to be ~175 kg-CO_2 per kWh[3], is also a critical issue. For the current sales of 5.6 million EVs annually as of 2021, the battery-production related CO_2 emissions amount to 0.078Gt if the average battery size is 80kWh. However, if the annual EV sales soar to 40 million by 2030 as projected by BloombergNEF, assuming that battery production emissions remain the same on the kg-CO_2 per kWh basis, the global CO_2 emissions for manufacturing EV batteries would amount to 0.56 Gt in 2030 for an average battery size of 80kWh. 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 (>100kW) chargers has increased drastically and driven rapid increase in the installation of such chargers from 4% of annual public-charger installations in 2017 to 27% in the first half of 2021.[2] The U.S. and Europe are actively pushing for the development of so-called extreme fast charging (XFC) technology, which, via >350kW chargers, could add 200 miles of driving range with a10 min charge.

Although vehicle engineering, charging infrastructure, and techno-economic performance are important considerations in developing XFC technology, batteries remain the limiting factor of EVs' fast-charge ability. As shown in Fig. 1, reported from Hackmann (2021)[5], the maximum charging power of state-of-the-art (SOA) EVs is ~150-270kW, corresponding to a maximum C-rate of ~2-3C (C-rate is the dimensionless electric current relative to the cell capacity; a 1C rate is the current that would go through the rated ampere-hours of the battery in an hour; a 2C rate is twice that current), and they can be implemented only at a low battery state of charge (SOC). For instance, Tesla's latest V3 supercharger can offer 250kW power, whereas the average charging power of the Tesla Model-3 (LR-version) from 10 to 80% SOC is only 146kW, which translates to an average charging rate of ~2C for its 74kWh battery or an added energy of 24.3kWh in 10 minutes – i.e., ~90 miles of added range, less than half of the expected 200 miles range. Also shown in Fig. 1 is that the Mercedes EQS-580 achieved a higher charging power (i.e., more added miles per minute charging) at a lower charging rate than the Tesla Model 3, but this is at the expense of a much larger (108kWh) 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. (2017)[6], the estimation assumes a constant driving speed of 65mph, energy consumption of 0.3kWh/mile on highways, and a fast-charging from 10 to 80% SOC at each battery charging stop. The 105kWh and 75kWh batteries represent SOA batteries that are charged with an average power of 150kW (Fig. 1). Further, we consider a 45kWh XFC battery that can withstand 250kW power (~5.6C) throughout the 10-80%SOC range. Although the 45kWh battery gives a limited range and hence needs four stops for charging during the trip, the total travel time is pretty similar to that of the other two long-range EVs and only 27 minutes more than the conventional ICE car, indicating a huge potential to eliminate range anxiety. Further, smaller batteries offer advantages such as lower costs, less material-associated sustainability challenges, and low manufacturing-related GHG emissions. The strategic combination of XFC with a small battery, therefore, provides a promising pathway for future mass market EVs that aligns with multiple sustainability criteria. It should be noted that the power and number of public fast chargers would be critical for the above strategy. We note that the small 45kWh batteries only require 250kW charging power to meet the XFC needs (Fig. 2), which is compatible with SOA fast-charging networks (e.g., the Tesla supercharger network). Also, we propose two critical metrics for the deployment of public fast chargers – the number of public fast chargers (PFCs) for every 100 miles (or 100 km), and the number of EVs per PFC. The former refers to the geographical accessibility to a fast charger, and the latter is related to the fear of queueing for fast charging. As of 2021, for reference, the European Union offers 5 PFCs per 100 km and 7.5 EVs per PFC.[7] In the U.S., Tesla's supercharger network has covered >99% of the U.S. population and has been expanding rapidly.[8] Nevertheless, the increase in the number of high-power fast chargers should keep pace with the anticipated exponential rise in EV sales in the coming years.

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 being intercalated into graphite upon charging. This can drastically reduce battery life and, under extreme circumstances, result in internal shorting with catastrophic consequences such as explosion.

To ensure the sustainability of 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, Fig. 1A) cannot acquire sufficient energy to help eliminate range anxiety. Similarly, using ultrathin electrodes to avoid Li plating results in reduced specific energy. Furthermore, EV batteries require a lifespan of at least 8 years; thereby, showing fast charge performance without sufficient cycle life does not hold merit. When sufficient cycle life is not achieved along with fast charging, this could lead to earlier retirement of batteries, causing various issues including increased battery wastes and demand for raw materials.

Thus, an important sustainability feature for XFC is the ability to charge a substantial amount of energy rapidly without compromising the safety and lifespan of batteries, which essentially requires the Li plating issue to be addressed. Fundamentally, Li plating occurs due to 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 ion transport-limited regime.[9] The ion-transport resistance is further exacerbated in thick and dense electrodes that are 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 electrode architectures with lower tortuosity. However, 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 level to address challenges pertaining to degradation, safety, and life. In this regard, while 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 to design stable interfaces, improve electrochemical performance, and enable fast charging, which is undoubtedly a critical challenge.[11] Analogous to LiBs, we note that SSBs also present a fundamental trade-off between energy and power density, dependent on the cathode material, and microstructure.

Thermal modulation: the holy grail of fast charging

A promising approach to prevent 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 materials aging, primarily solid-electrolyte-interphase (SEI) growth. With numerical analysis, we revealed that the optimal battery temperature increases with the rise of charging rate and cell energy density 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 its battery to 45-55ºC before reaching a fast charger. The slow heating speed (~0.5ºC/min), however, leads to a long duration at high temperatures that negatively affect battery life. Recently, we reported an asymmetric temperature modulation method that 1) rapidly heats a cell (>1ºC/min) to an elevated temperature (~60ºC) for charging, and 2) discharges/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., ~10 min per cycle, or 0.1% of the lifespan of an EV) controls materials degradation. We showed that the temperature modulation approach could charge an energy-dense cell at 6C by 167Wh/kg in 10 min at the beginning of life (BOL) and 144Wh/kg after 2500 cycles, far exceeding the U.S. DOE 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] Cognizant of the strong asymmetry that underlies the plating and stripping behavior, designing an optimal thermal modulation approach is critical toward achieving stable interfaces and minimized degradation in such battery systems. Leveraging the fundamental correlation between temperature and the intrinsic response (e.g., transport, kinetic, 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 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 irrespective of the ambient condition; thereby, the materials do not need to 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 (low BET-area graphite) and cathodes (Lithium Iron Phosphate, LFP).[17] The thermal modulation enables high power and fast charging in all climates, while the stable materials bring a long lifespan, superior safety, and low cost, fulfilling multiple requirements for more sustainable EV batteries.

Quick, convenient replenishment of energy via fast charging enables the downsizing of batteries, which is critical for lowering battery cost, materials consumption, and GHG emissions and hence for a more sustainable transition to electrified mobility. The investment in fast-charging infrastructure should keep pace with the increase in EV sales, and two important metrics – the number of fast chargers per 100 km, and the number of EVs per fast charger – are stressed. Further, synergistic improvements at the materials, 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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List of Figure Captions

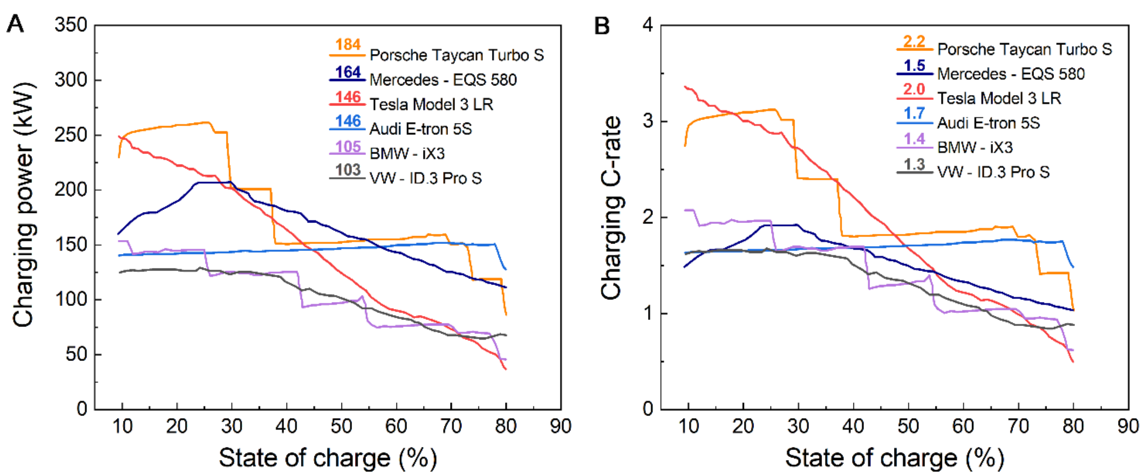

Figure 1. The evolution of charging power, and charging C-rate of state-of-the-art electric vehicles. The data in (**A**), charging power, is from Hackmann (2021)[5], and that in (**B**), charging C-rate, are calculated by dividing the charging power by the battery energy of the corresponding models.

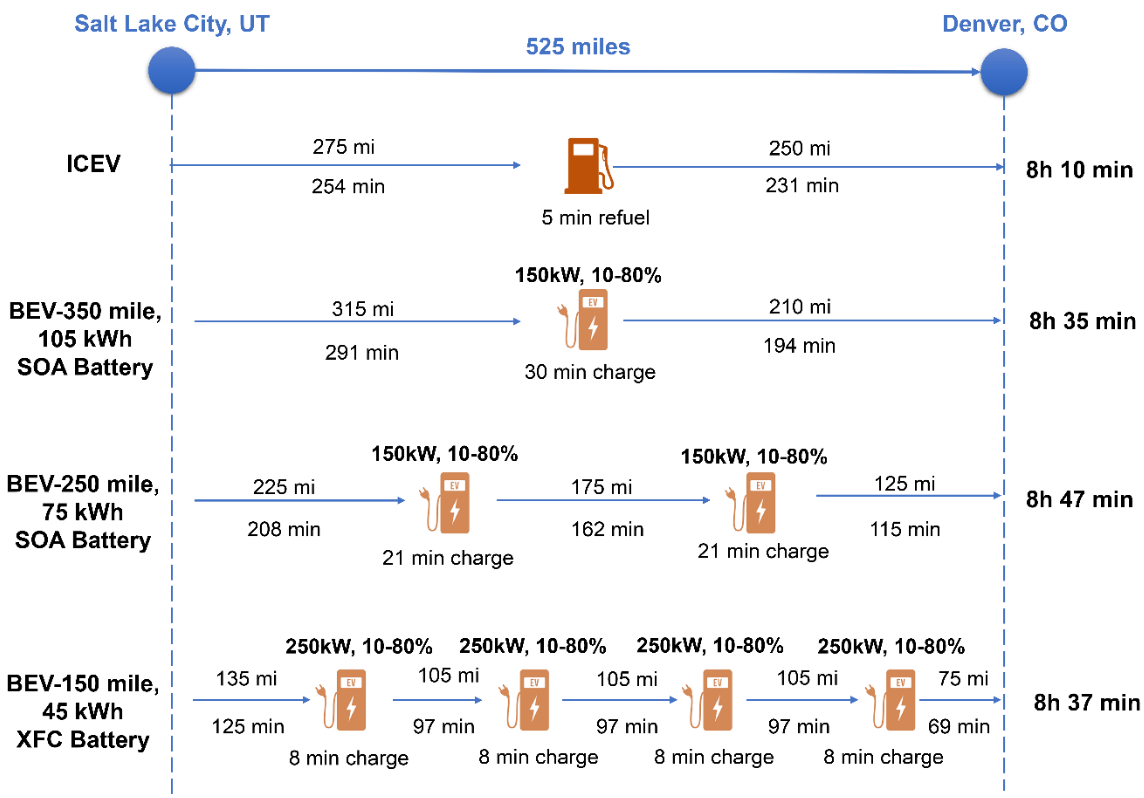

Figure 2. Comparison of the total time for driving from Salt Lake City to Denver with EVs having different battery sizes. The estimation assumes a constant driving speed of 65 mph and energy consumption of 0.3kWh/mile on highways. The vehicle starts from 100% battery state of charge (SOC) and stops for charging when reaching 10%SOC. The driving distance between two stops (ΔL) is calculated as: $\Delta L = E_{bat} \cdot \Delta SOC/ec$, where E_{bat} is the battery size (in kWh), and ec is the energy consumption (0.3kWh/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: $\Delta t_{char} = P_{char}/0.7E_{bat}$.