

Electrons In, Electrons Out: Electron Beam for Battery Production

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Abstract:

Electricity, and thus, batteries, are sought out as a sustainable alternative to fossil fuels; however, there are aspects of their production, such as the use of solvents, that can be improved to make this green technology even greener. In addition, as the market for batteries grows, production speed needs to be improved to match demand. How electron beam technology addresses these battery production needs is presented, along with proof-of-concept work, and remaining challenges.

It is no secret batteries have become intrinsic to everyday life. Batteries have made mobile technology possible – from the flashlight to the Walkman to the cell phone – and, in turn, technology has demanded battery development keep pace. As batteries become more compact, more powerful, and more flexible, technology already has designs to use those improvements to produce smaller, longer-lasting, wearable devices or electric vehicles with increased range and faster recharging. Thus, it is likely no surprise either that battery production has only increased over the last century. Lithium-ion batteries alone have experienced exponential growth, increasing globally from 0.5 gigawatt-hours (GWh) in 2010 to over 500 GWh in 2020.¹

However, while battery production grows, so too does its environmental impact. Conventional manufacturing for lithium-ion batteries, for example, uses the organic solvent NMP (N-Methyl-2-pyrrolidone).² The components of the electrodes – active materials, conductive additives, and polymer binders – are mixed with the solvent to form a slurry that can be coated onto a metal foil (Figure 1). The NMP must then be evaporated using a thermal oven. Solvent evaporation is well known to be an energy-intensive process with production speeds limited by oven length and required dwell time.³ Solvent recovery is also necessary to reduce the volatile organic compounds (VOCs) released into the environment. Even the environmental impact of shipping the solvent must be considered. In addition, restrictions on the use of NMP have been recently implemented in the EU due to its effects on human health, including reprotoxicity.⁴

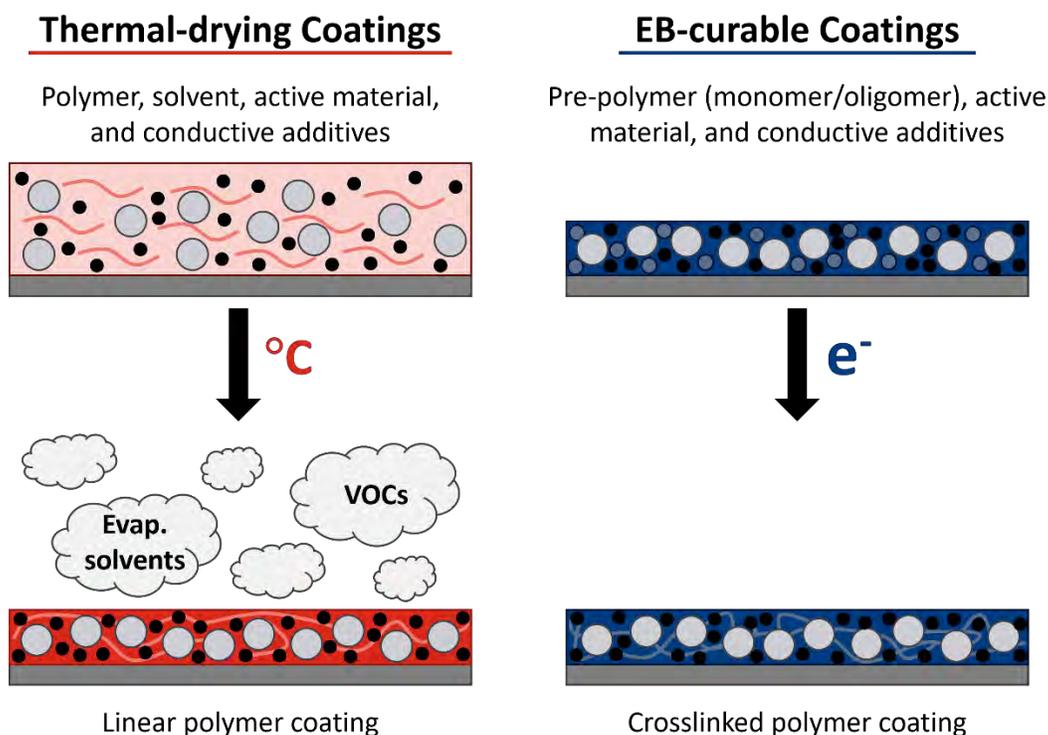


Figure 1. Comparison of thermal-drying electrode coatings (including the conventional NMP/PVDF process) and EB-curable electrode coatings. Thermal-drying coatings require solvent which results in the formation of VOCs when evaporated. EB-curable coatings are solvent-free.

Of course, the costs associated with solvent usage are not only environmental but also monetary. Eliminating NMP would reduce material costs (\$1.50 to \$3.00/L) as well as energy consumption; the latter contributing to an estimated 2x reduction in electrode production cost if NMP is replaced with water.^{5,6} Dry room space is a substantial cost in lithium-ion battery manufacturing. Minimizing the process footprint by replacing thermal ovens with a more compact technology also helps minimize cost. Furthermore, increasing production speeds without increasing the process footprint improves on the cost per unit. Cost reduction is an important aspect of consumer accessibility. In the case of electric vehicles (EVs), for instance, costs have been cut from \$1,200/kWh in 2010 to \$132/kWh in 2021; however, the battery price point at which it is estimated EVs become comparable in price to internal combustion vehicles is \leq \$100/kWh.⁷

The elimination of solvent, reduced energy consumption, smaller footprint, and faster processing speeds are all achievable with the incorporation of UV/EB technology in battery manufacturing.^{2,8,9} The conventional polymer binder (typically polyvinylidene difluoride, PVDF)

needs to be dissolved with a solvent (NMP) to be properly mixed with the active materials and conductive additives that form an electrode. In contrast, radiation-curable pre-polymer resins are generally liquid, which allows for mixing, and are polymerized instantaneously (as fast as < 1s) and solvent-free (Figure 1). Figure 2 shows the cost reduction benefit when electron-beam curing is used to replace the NMP drying/recovering process in electrode manufacturing.^{3,6,10} When a similar line speed (50 fpm) is used, EB processing can save approximately 40% of the cost. Yet, when the instantaneous nature EB polymerization is taken advantage of and the faster speed of 500 fpm is used, the cost can be decreased to as little as 6% of the NMP-based process. Furthermore, the energy consumption for NMP/PVDF processing is ~151 MJ/kWh, while EB processing only requires ~27 MJ/kWh. This energy reduction translates into much lower greenhouse gas emissions; the NMP/PVDF process generates ~93 lbs CO₂/kWh vs. ~17 lbs CO₂/kWh generated by the EB process.

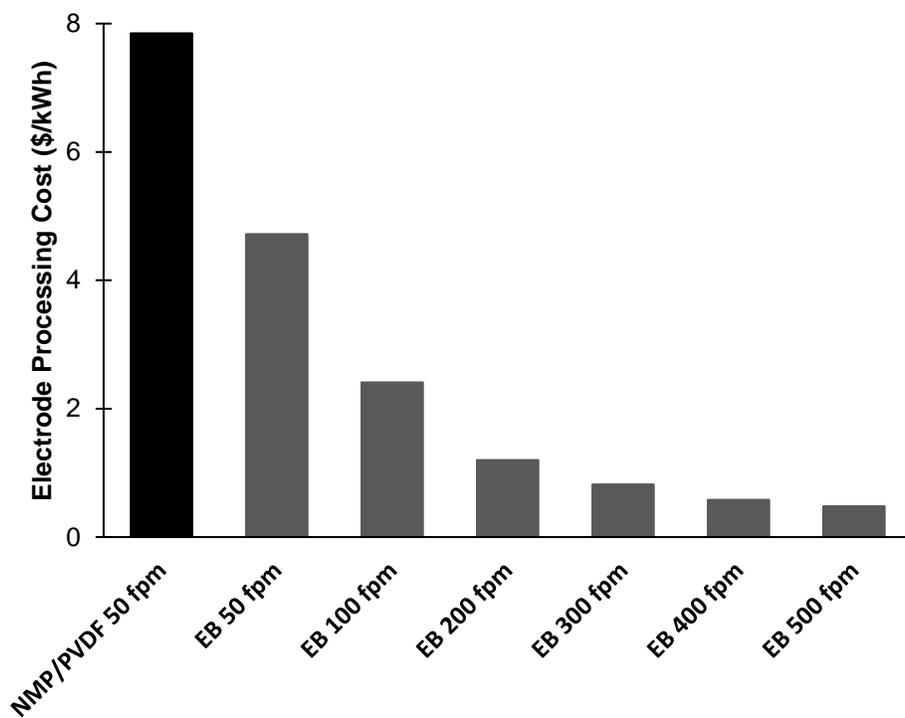


Figure 2. A comparison of the electrode processing cost using the conventional NMP/PVDF method vs. EB.

The method of replacing PVDF electrode binders with ebeam-curable resin is presented in Du, et al. (2019).² Here, cathode coatings were prepared with a low molecular weight, acrylated polyurethane dispersion, irradiated *via* EB at 500 fpm, and made into pouch cell stacks.

The performance of these cell stacks was then compared to cell stacks made with the conventional PVDF binder. Overall, when high polymer conversions were achieved, the EB cell stacks showed cycling rate performance and capacity retention similar to that of the PVDF cell stacks. As with other EB-curing applications, nitrogen inertization proved to be vital.^{11,12} Samples that experienced oxygen inhibition did not fully cure and battery performance suffered as a result.

While both EB and UV technology can be successful in this application, ebeam was chosen because of several advantages. Electrodes contain carbon black and other optically opaque materials which restrict light penetration, and thus, UV-cured electrodes are limited in thickness.¹² EB penetration is independent of material opacity and, is instead, governed by the material density and the accelerating voltage of the electrons. Du, et al. reports 250 g/m² thick electrodes ebeam-polymerized at 275 kV compared to UV-cured electrodes at just 60 g/m².² Thicker electrodes allow for batteries with higher energy densities. Additionally, photopolymerization requires photoinitiator where EB polymerization does not. Although the photoinitiator is generally only a small fraction of a formulation, in an ebeam-curable electrode, this fraction can be dedicated to increasing the active materials.

An advantage of both UV and EB is that, while nascent to battery manufacturing, these technologies are well established in other industries. Both have decades of success in packaging, architectural products, and adhesives. Although the existing UV/EB knowledge base may not always directly translate to this new application, the foundation is solid, and the basic principles that encourage adoption (*i.e.*, low-energy consumption, instant, solvent-free, *etc.*) remain unchanged.

Moreover, manufacturers should consider the diversity of available opportunities to incorporate UV/EB technology into battery production (Figure 3). In addition to electrode binders, there is potential to make use of UV/EB on just about every component – grafting, coating, and/or crosslinking the separator for robustness, heat resistance, and better Li ion mass transport¹⁴⁻¹⁹; synthesis of nanoparticles to coat the electrodes for improved electrochemical performance²⁰⁻²³; formation of a solid electrolyte for safer batteries^{24,25}; and even polymerization of the inks on the casing for an eye-catching battery! Adoption of most new technology in an existing industry is arduous, but, in the case of UV/EB, the investment in time, effort, and equipment can be distributed over multiple promising avenues.

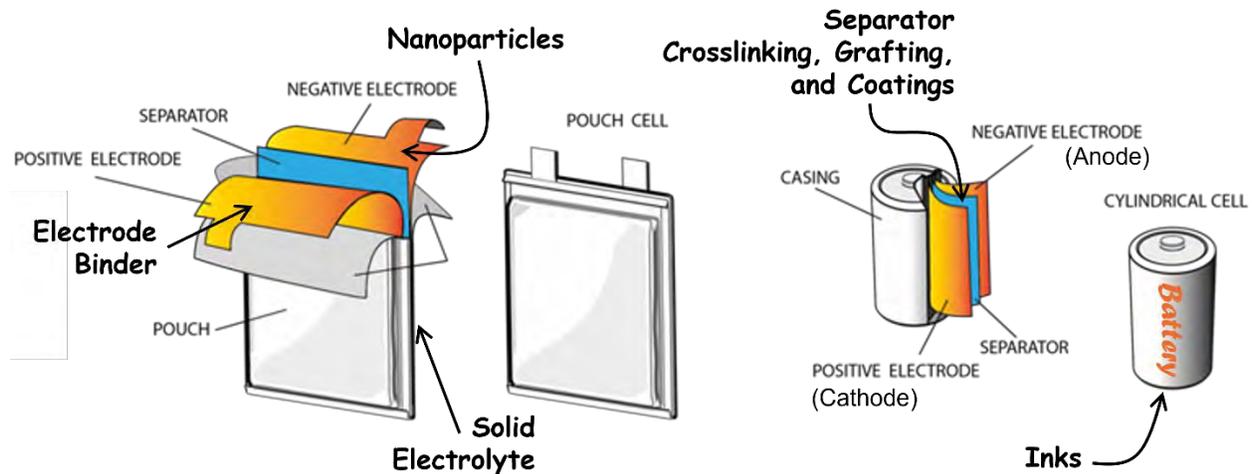


Figure 3. Examples of two common battery forms annotated with possible opportunities for the incorporation of UV/EB technology. Adapted from Ref. 13.

Currently, there is still much progress to be made for UV/EB technology in the battery industry. These innovations exist primarily in academic literature, and it will not be trivial to implement them on the production floor. Specifically, in the case of the EB-curable binder, the reported attempts still needed the addition of water and isopropanol to make a liquid, coatable slurry.² Future endeavors will attempt dry or high-solid-loading paste coating to further eliminate solvent and thermal drying²⁶, but it is unlikely to be the last challenge EB battery processing will face.

Despite these obstacles left to conquer, adoption of UV/EB technology in battery manufacturing holds great promise for the industry. Lower costs, faster processing, and reduced environmental impact are needs that UV/EB can deliver upon in leaps and bounds. With demand for lithium-ion batteries expected to soar to an astounding 9,300 GWh by 2030¹, now is the time to consider how these technologies can support the production of greener, better performing batteries.

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